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SINGAPORE

**PHOTONIC STRUCTURE ENHANCEMENT ON
PHOTODETECTION**

SUO FEI

**SCHOOL OF ELECTRICAL & ELECTRONIC ENGINEERING
2021**

PHOTONIC STRUCTURE ENHANCEMENT ON PHOTODETECTION

SUO FEI

School of Electrical & Electronic Engineering

A thesis submitted to the Nanyang Technological University
in partial fulfillment of the requirement for the degree of
Doctor of Philosophy

2021

Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research, is free of plagiarised materials, and has not been submitted for a higher degree to any other University or Institution.

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Supervisor Declaration Statement

I have reviewed the content and presentation style of this thesis and declare it is free of plagiarism and of sufficient grammatical clarity to be examined.

To the best of my knowledge, the research and writing are those of the candidate except as acknowledged in the Author Attribution Statement. I confirm that the investigations were conducted in accord with the ethics policies and integrity standards of Nanyang Technological University and that the research data are presented honestly and without prejudice.

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Prof. Zhang Dao Hua

Authorship Attribution Statement

This thesis contains materials from 7 papers published in the following peer-reviewed journals in which I am listed as an author.

Chapter 2 is partially published as J. Tong[†], F. Suo[†], J. Ma, L. Y. M. Tobing, L. Qian, and D. H Zhang, “Surface plasmon enhanced infrared photodetection”, *Opto-Electronic Advances* **2**(1), 18002601–18002610 (2019). DOI: 10.29026/oea.2019.180026.

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As the co-first author, I prepared the manuscript draft together with Dr. Tong for the review article.

Ms. Ma, Dr. Landobasa and Dr. Qian helped collect data for the article.

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Dr. Tong guided me and edited the manuscript drafts.

I performed the simulations, co-prepared the manuscript drafts and co-designed the study with Dr. Tong and performed all the experimental work including device fabrication and characterization.

Dr. Landobasa and Dr. Yao assisted in analyzing the data.

Prof. Huang and Prof. Zhang revised the manuscript.

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I performed all the simulation and calculation work, prepared the manuscript draft. Dr. Tong helped me in all the experimental work including device fabrication and characterization.

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List of Abbreviations

2DSHA	two-dimensional subwavelength hole array
AFM	atomic force microscope
CVD	chemical vapor deposition
DC.....	direct-current
DWELL	quantum dots-in-a-well
EBL	electron beam lithography
ECR.....	electron cyclotron resonance
EOT	extraordinary optical transmission
EHP	electron-hole pair
FDTD.....	finite-difference time-domain
FIB	focused ion-beam
FPA.....	focal plane array
FOM	figure of merits
FTIR	Fourier transform infrared spectroscopy
FWHM	full width half maximum
HR-XRD	high-resolution X-ray diffraction
ICP-RIE	inductively coupled plasma-reactive ion etching
IR.....	infrared
I-V.....	current-voltage
LIR.....	long infrared

LSP	localized surface plasmon
MBE	molecular beam epitaxy
MCT	mercury cadmium telluride
MIBK	methyl isobutyl ketone
MIR	middle infrared
NEP	noise equivalent power
NIR	near infrared
OMSM	ohmic metal–semiconductor–metal
PL	photoluminescence
PML	perfectly matched layer
PMMA	poly-methyl-methacrylate
PT	photon-trapping
PTHA	photon-trapping hole array
QDIP	quantum dot infrared photodetectors
QWIP	quantum well infrared photodetector
ROIC	readout integrated circuit
SEM	scanning electron microscope
SPP	surface plasmon polariton
SPR	surface plasmon resonance
SRH	Shockley Read Hall
SRR	split ring resonator

TAT	trap-assisted tunneling
TE	transverse electric
TEC	thermoelectric cooling
THz	terahertz
TM	transverse magnetic
UV	ultra-violet
U-SRR	U-shape SRR
U4-SRR	rotated fourfold U-shape SRR
VLIR	very long infrared
XRD	X-ray diffraction
ZED-N50	<i>n</i> -amyl acetate

Abstract

Infrared photodetectors have been extensively used in military and civilian applications. Currently, antimony (Sb) based III–V semiconductors are considered as viable alternatives to Mercury-Cadmium Telluride material which takes the dominant position in middle infrared range. Among them, $\text{InAs}_{1-x}\text{Sb}_x$ has gained much interest owing to their various benefits for realizing high-performance middle infrared photodetectors. However, it still faces the challenge in realizing high-temperature operational photodetection. This PhD program will primarily deal with the optimization of InAsSb-based heterojunction photodiode and enhancement of photodetection performance by integrating with different two-dimensional photonic structures.

In this thesis, InAsSb-based photodiodes with heterojunction architectures are proposed to achieve middle infrared photodetection with low dark current. The photodiode includes wide bandgap and thin quaternary layers to reduce the bulk dark current. Photodiodes with square mesas from 500 μm to 20 μm were fabricated and their dark currents are characterized at temperatures from 77 K to room temperature (293 K). The results indicate that the methods we adopted for reducing dark current are effective. The dark current densities achieved are lower than or comparable with that of the state-of-the-art middle infrared photodetectors.

To further improve the detection performance, various photonic structures are investigated for manipulating photoresponse capability. As the raised light-matter interaction in active region can facilitate light absorption without sacrificing the response speed, the quantum efficiency of the device can be significantly improved without involving a very thick

absorption layer. Detailed simulations have been done to demonstrate the broadband absorption enhancement. The internal resonance phenomenon is also studied to figure out the physical mechanisms.

Different plasmonic structures were selected for integration with the heterojunction photodiode to enhance quantum efficiency. It is because the metallic nanostructures at sub-wavelength scale own the capability to concentrate light and produce strong electric field in the extremely small volume, thus facilitating the significant absorption of electromagnetic waves. Using this strategy, a maximum one order of magnitude of enhancement in middle infrared room-temperature detectivity (to about 2.0×10^{10} Jones) is achieved under zero bias without sacrificing the response speed.

Another enhancement technique we applied is to fabricate a photon-trapping hole-array structure in the heterojunction photodiode. With the help of the photon-trapping structure, the combined effects of the formed lateral propagating modes and reduced effective refractive index can lead to polarization-independently enhanced absorption. Broadband photoresponse improvements of 26% to 170% are demonstrated in 2-5 μm range under zero bias at temperatures from 293 K to 78 K.

Furthermore, the photon-trapping hole-array structure is also fabricated in the InAsSb-GaSb heterostructure for the dual-band photoresponse enhancement in near- and mid-infrared regions. The responsivity enhancement factors under zero bias are 12% and 33% for the near- and mid-infrared, respectively, at room temperature, and they are increased to 71% and 79% at 220 K.

Chapter 1. Introduction

1.1 Motivation

Infrared photodetection has been widely used in both military and civilian purposes, including biomedical, surveillance, communication and astronomy. Currently, Mercury-Cadmium Telluride (MCT)-based photodetector is the primary commercially available technology for middle infrared (MIR) applications, due to their tunable cut-off wavelengths, high sensitivity and fast response [1]. However, it usually has a low yield due to their material non-uniformity, and suffers large dark current from the excessive leakage caused by the low electron effective mass.

In recent years, antimony (Sb) based III-V semiconductors demonstrate great potential in competing with MCT for MIR photodetection, benefiting from their superior bond strength and material stability, well-behaved dopants, and high-quality III-V substrates compared to MCT [2]. Among them, the InAsSb-based detectors, owing to their large-area uniformity, mature fabrication technique, low electron effective mass, low Auger recombination rate and wide bandgap tunability [3]–[5], have attracted lots of attention. Over last decades, various types of InAsSb-based MIR photodetectors have been investigated [6]–[9]. But it still faces the problem of large dark current, and needs to operate in low-temperature environment, leading to the demand of bulky and complicated cooling system for high-performance operation [10], [11]. To promote the high-temperature performance, decreasing dark currents originated from both bulk and surface leakage becomes the most important task, where the bulk dark current mainly

consists of minority carrier diffusion, Shockley-Read-Hall (SRH) generation and tunneling through thin layers [12].

During last several years, some effective measures have been taken to overcome this obstacle. The current research focus is on developing barrier structures for blocking the dark current generation [13]–[15]. One of the most popular strategies is the nBn structure proposed in 2006 [16], where a wide-bandgap layer functions as the barrier layer which is inserted between the contact layer and absorber to block the majority carrier but allow minority flow. In doing so, there is no depletion region anymore, resulting in the elimination of SRH dark current [5], [17], since the SRH current is generated through the activated mid-gap trap states in depletion region [18]. However, the significant difficulty in realizing ideal band-offset structure which has no barrier for minority carrier but large barrier for majority carrier obviously limits the practical performance. The other popular barrier structure is the type-II superlattice, for its theoretical potential to surpass the performance of MCT-based detectors due to a reduced Auger recombination lifetime [14]. However, it has not well achieved as the SRH generation-recombination is the mechanism for limiting dark current [19].

Besides, the photodetection relying on the absorption by sensitive optoelectronic materials has been inherently limited by the absorption law $\exp(-\alpha d)$ [1], where α is the absorption coefficient and d is thickness of the absorption layer. For sufficient photon absorption, the detection structure on one hand, requires high α , and on the other hand, requires large d to give high quantum efficiency. However, for an optimized absorber, α is fixed, therefore, very large d is required to ensure that. Nevertheless, the large reflection loss still limits the maximum

quantum efficiency. Besides, the large value of d will bring some realistic difficulties, such as large stress and high cost of products in material growth and complex process in device manufacturing [20]. There are many strategies used to overcome the above challenges. Integrating the plasmonic structure is one of the most popular strategies, which can localize electromagnetic wave in deep subwavelength scale to provide the possibility for MIR photodetectors operating at room temperature [21]. So far, the metallic nanostructures with different configurations have been integrated with traditional detection structures such as heterojunction structure [22], Schottky diode [23], quantum structures [24], and thermal detector [25]. Combined with these structures, the photoresponse of those detectors can be significantly improved. These advances on one hand, improve the performance of existing detection structures, on the other hand, they show a new generation of infrared detection technologies.

Recently, a new strategy of built-in photon-trapping structure is considered to be a good choice for better light manipulation. With the help of the photon-trapping structure, the combined effects of formed lateral propagating modes and reduced effective refractive index can bring various advantages, for example, polarization-independent broadband absorption enhancement, reduced bulk dark current due to reduced bulk volume, no anti-reflectance coating with narrow band spectroscopy being required, no extra metal being required, and allowing utilizing thin absorption layer to achieve high photoresponse. So far, photon-trapping structure has been proven useful to improve optical performance in visible wavelengths for the applications of solar cell, optical communication links [26], [27], as well in near infrared

regime for single-photon avalanche detectors [28].

1.2 Objectives

1. To design and fabricate the InAsSb-based heterostructure MIR photodetectors with low dark current. Through careful heterostructure design, proper fabrication process and performance characterization, the candidate wants to confirm if the measures taken for reducing dark current are effective. By analyzing the temperature and size effect, the role of bulk dark current and surface leakage current in the hetero photodiodes are investigated. The dominant mechanism of dark current under different conditions is also discussed through the derived activation energy. The investigated results can enhance our understanding on high-operating-temperature photodetectors and are useful for further improvements in these devices.

2. To comparatively investigate the resonance behavior of regularly arranged U-shape SRR and fourfold rotated U-shape split ring resonator (SRR) arrays, which are fabricated on Si substrate and designed in near- and mid-infrared region by tuning the U size. Finite-difference time-domain (FDTD) method is performed to interpret the nature of optical responses of the SRR-based arrays by simulating the reflectance spectra, local electric field and magnetic field distribution. All SRR arrays are fabricated using electron beam lithography (EBL). Fourier transform infrared spectroscopy (FTIR) is adopted to characterize the resonance behavior of SRR arrays. For sensing application, the effects of resonator size on both resonant wavelengths and sensitivity are also investigated, to prove that polarization-invariant higher sensitivities can be obtained in the fourfold rotated U-shape SRR arrays because of its larger

interaction volume between the plasmonic mode and the analyte.

3. To design and fabricate various plasmonic structures for integration with the optimized InAsSb-based heterostructure photodiodes to realize strong MIR photodetection enhancement. By using FDTD method, different kinds of plasmonic structures are simulated and optimized to obtain the resonance modes in corresponding to the spectral response range of the basic heterojunction photodiode. The optimal metallic patterns are defined by EBL, deposited by electron beam evaporation and created by standard lift-off process. The characterized responsivity is expected to be significantly increased, due to the strong light confinement at the metal-dielectric interfaces.

4. To design the photon-trapping hole-array structure for incorporation in the optimized InAsSb-based heterostructure to boost MIR photoresponse. FDTD method is used to analyze the light confinement capability and wave propagation condition in photon-trapping assisted detector. Through the simulation of size effects, the structure with maximal absorption enhancement is obtained. The photon-trapping hole-array pattern is defined by EBL and etched by Inductively Coupled Plasma-Reactive Ion Etching (ICP-RIE). The polarization-independent broadband MIR photodetection improvement is expected to observe in the fabricated photon-trapping assisted detector.

5. To apply photon-trapping structure on the InAsSb-GaSb heterostructure for polarization-independent dual-band photoresponse enhancement. For obtaining an optimal photon-trapping structure, we use FDTD method to perform simulations on absorption maximization in both NIR and MIR spectra. The photon-trapping structure are fabricated based

on the optimal geometrical parameters, defined by EBL and transferred to InAsSb layers by high-temperature ICP-RIE. The measured room-temperature responsivities are expected to observe enhancement in both NIR and MIR, without sacrificing the amplitude frequency response and speed.

1.3 Major contribution of the thesis

The major contributions of this thesis are as follows:

1. The dark current characteristics of the heterojunction photodiodes are studied. The photodiodes include wide bandgap and quaternary layers to reduce the bulk dark current. Photodiodes with square mesa size varying from 500 μm to 20 μm are fabricated and their dark currents are characterized at temperatures from 77 K to 293 K. The results confirm the measures taken for reducing dark current are effective as the dark current density for the photodiodes are limited to a lower level, where the room-temperature value is lower than or comparable with that of the state-of-the-art mid-infrared photodetectors.

2. Detailed comparative investigation of resonance behaviors and sensing capability of gold U-shape SRR and fourfold rotated U-shape SRR arrays in near and middle infrared range are reported. All the resonant modes of the fourfold rotated SRR arrays occur at longer wavelengths compared to the U-shape SRR arrays with the same U size. Stronger field intensities are observed in all the three resonance modes of the fourfold rotated U-shape SRR arrays and the intensity in the fundamental magnetic (m_0) mode is almost three times of that of U-shape SRR array under unpolarized incidence. All the three peak resonance wavelengths

shift to longer wavelengths and the sensitivity increases with the increase of U size. A sensitivity of 642 nm/RIU is obtained in the fourfold rotated U-shape SRR array for unpolarized incidence. The provides an excellent candidate for high-performance sensing in the near- and mid-infrared region without polarization concern.

3. The photodetection enhancement of resonant modes of U-shape SRR array in the mid-infrared (2-5 μm) range is studied. For the first time, the strong enhancement of photodetection by superimposition of high-order magnetic mode (m_1) and electric mode (e) is reported in an integrated photodetector consisting of a U-shape SRR array and an InAsSb-based heterojunction photodiode. Using superimposed m_1 and e modes, about an order of enhancement in room-temperature detectivity (to about 2.0×10^{10} Jones) is achieved under zero-power-supply without sacrificing the response speed. In addition, polarization-resolved photoresponse between m_1 and e modes and tunable enhancement of photoresponse are also demonstrated. The remarkable enhancement makes middle infrared photodetection possible to operate at room temperature.

4. A rotated fourfold U-shape SRR array for polarization-insensitive strong enhancement of mid-infrared photodetection is reported. The integrated photodetector consists of a rotated fourfold SRR array and an InAsSb-based heterojunction photodiode. A photosensitivity enhancement factor as high as 11 has been achieved by adoption of superimposed high order magnetic and electric resonant modes in the SRR array. This work provides a promising pathway for exploring high performance polarization-insensitive photodetection in different electromagnetic wave ranges.

5. A built-in photon-trapping structure is reported for efficient confinement of incident photons, therefore facilitating optoelectrical conversion of a photodetector. The integrated device consists of a middle infrared InAsSb-based heterojunction photodiode and an embedded photon-trapping hole array, which enables thinner absorption layer, lower dark current, broadband absorption improvement, and polarization-independence of photoresponse. Broadband photoresponse improvement of 26% to 170% is achieved in 2-5 μm for the integrated device under zero power supply at temperatures from 293 K to 78 K. This proposed approach provides a new strategy to boost optoelectrical conversion of photodetectors.

6. A hole-array structure dry-etched on the *nip* InAsSb-GaSb heterostructure for enhancement of photoresponse in both near- and mid-infrared regions is proposed. The designed symmetrical hole array can increase the photon lifetime inside the absorption layer and reduce reflection without polarization dependence. Significant enhancements in absorption and photoelectric conversion efficiency are demonstrated in near- and mid-infrared bands for unpolarized incidence. The enhancement factors of responsivity at room temperature under zero-bias are 1.12 and 1.33 for the near- and mid-infrared, respectively, and they are increased to 1.71 and 1.79 when temperature drops to the thermoelectric cooling temperature of 220 K. Importantly, such a hole array also improves working frequency bandwidth and response speed. This work provides a promising way for high-efficiency polarization-independent photoelectric conversion in different electromagnetic wave ranges.

1.4 Organization of the thesis

The thesis consists of 7 chapters and 1 appendix, organized in following manner:

Chapter 1 is the introductory chapter. It discusses the motivation, objectives, major contribution, and organization of the thesis.

Chapter 2 is the background chapter. It introduces the infrared radiation and the basics of infrared photodetection, including the history and development, classification, figure of merits, and recent development for high-operating-temperature photodetectors. Then this chapter gives a brief introduction on the fundamentals of plasmonics, showing the surface plasmon, mechanisms of surface plasmon enhanced photodetection, plasmonic structures and modern plasmonic photodetector.

Chapter 3 introduces the methods used for simulation, fabrication and characterization. It includes the finite-difference time-domain simulation method, details of electron beam lithography, inductively coupled plasma - reactive ion etching, electron beam evaporation and Fourier-transform infrared spectroscopy.

Chapter 4 discusses the characteristics of dark current for the InAsSb-based heterostructure photodiodes. The hetero-layer design of the photodiode is presented with the purpose of reducing high-temperature dark current. The photodiodes with square mesa size varying from 500 μm to 20 μm are then fabricated and their dark currents are characterized at temperatures from 77 K to room temperature (293 K). Through detailed study of activation energy, the dominant dark current mechanisms for different temperatures and voltage biases are analyzed. The effectiveness of our hetero-layer design is finally confirmed by the obtained lower dark current density in the heterostructures.

Chapter 5 discusses the photodetection enhancement by integrating plasmonic structures with heterojunction photodiode. The integrated MIR photodetector consisting of an InAsSb-based heterojunction photodiode and a metallic array incorporated on the top surface. The capability of the plasmonic structure to confine light in the vicinity of the metal-dielectric interface is studied. The electrically controlled enhancement of the integrated photodetector is observed. The optical field distribution of resonant modes under different polarizations are analysed. The arrays are fabricated by EBL and characterized by an FTIR incorporated with a microscope. Through appropriate fabrication techniques, a maximum one order of magnitude enhancement on uncooled photosensitivity is demonstrated without polarization-selectivity.

Chapter 6 presents the role of photon-trapping hole-array structure on promoting photodetection performance. Firstly, an InAsSb-based heterostructure photodiode with the assistance of photon-trapping hole-array structure is designed to improve absorption efficiency, thus obtaining a MIR photodetector with enhanced detection performance. In the following a hole-array structure dry-etched on the *nip* InAsSb-GaSb heterostructure is also designed for enhancement of photoresponse in both NIR and MIR regions. The light confinement capability and wave propagation condition is investigated by simulation. The fabrication process and performance characterization techniques for the integrated and reference detectors are presented in detail. Significant enhancements in absorption and photoelectric conversion efficiency are demonstrated in infrared for unpolarized incidence. The physical mechanisms for the enhancement are investigated in detail.

Chapter 7 shows the conclusions of this thesis and outlines the recommendations for

further research.

Appendix presents the characteristics of plasmonic structures in IR region. U-shape SRR and fourfold rotated SRR arrays are comparatively studied as the typical plasmonic structures. The resonance behaviors and sensing capability of both arrays are investigated in detail in NIR and MIR range. The effects of resonator size on both resonant wavelengths and sensitivity are also explored. This appendix serves as the guide for the following plasmonic detector design.

Chapter 2. Background

Infrared photodetection is of great interests in both physics and applications. In this chapter, the candidate first introduces infrared wave radiation and reviews the basics of infrared photodetectors, including the history and development, classification, figure of merits, and recent development for high-operating-temperature detector. Then the fundamentals of plasmonics which include surface plasmon, photodetection enhancement mechanism by plasmon, plasmonic structures and plasmonic enhanced photodetectors are discussed.

2.1 Infrared radiation

All objects with temperature above absolute zero (0 K) emit infrared radiation. Infrared spectrum covers all the electromagnetic spectrum from 0.7 μm to 1000 μm in wavelength. The earth's atmosphere has strong absorption to IR radiation. The corresponding transmission spectrum from 0.7 μm to 15 μm is shown in Figure 2.1. There are three atmospheric windows, 1-3 μm , 3-5 μm and 8-12 μm , which are of most interests for the detection of IR radiation [29]. It is basically due to two facts: (1) The radiation energy of objects at room temperature is mainly concentrated in the wavelength range of 1-14 μm [30], and (2) Infrared radiation has the highest atmospheric transmittance in these three Windows.

Fig. 2.1 Transmission spectrum of the atmosphere [31].

Because of the poor response of human eyes to IR radiation, one cannot directly receive the information stored in IR radiation region. In this way, IR detection becomes the most fundamental building blocks in IR related sciences and technologies. Remarkable progress has been made in the widespread applications of IR detectors, including military (e.g., night vision), civilian (e.g., surveillance), environmental (e.g., meteorology) and academic (e.g., biomedical) fields. Most applications are based on the passive IR detection of thermal radiation, usually treated as the blackbody and described by the Planck's law, as shown in the Equation (1) [1]:

$$R(\lambda, T) = \frac{2\pi hc^2 \lambda^{-5}}{\exp\left(\frac{hc}{\lambda kT}\right) - 1} \quad (1)$$

where $R(\lambda, T)$ is the spectral radiant exitance (the amount of power emitted per unit wavelength and unit surface area), λ is the wavelength, T is the absolute temperature in K, $h = 6.6256 \times 10^{-34} \text{ J}\cdot\text{s}$ is the Planck's constant, $c = 2.998 \times 10^8 \text{ m}\cdot\text{s}^{-1}$ is velocity of light in vacuum, and $k = 1.38054 \times 10^{-23} \text{ J}\cdot\text{K}^{-1}$ is the Boltzmann constant. Planck's law states that the higher the temperature of an object, the higher the radiant energy [32]. Because of its successful

interpretation of the observed radiation spectrum, Planck's radiation law is regarded as a milestone in IR radiation. As a result, it provides a reliable pathway to realize IR photodetection.

2.2 Basics of Infrared photodetector

2.2.1 History and Development

The history of infrared research began with the discovery of infrared light by William Herschel in 1800. When he used mercury thermometer to study the thermal effects of the solar spectrum, he found that the region where the most significant thermal effects located was not in the visible light band, but in the outside of the red light. Thus, the existence of IR radiation was discovered for the first time [33]. Since then, the thermal detectors that use thermal effects to detect IR radiation have appeared one after another, such as thermocouple (1821, Seebeck), thermopile (1829, Nobili) and bolometer (1880, Langley). Throughout the 19th century, scientific research was mainly on the thermal detectors. But when entering the 20th century, the most significant development of IR detectors was in the photon detectors.

In 1873, Smith discovered the photoconductive effect. This discovery opened up a broad field of research, and scientists began to study photosensitive materials. In 1917, Theodore W. Case developed the first IR photoconductor, which used materials containing sulfur and thallium. Subsequently, people began to pay attention to the research of photon detectors. Figure 2.2 shows the important research progress in the infrared detector development history.

Fig. 2.2 History of the infrared detector development [1].

In 1933, Kutzscher discovered at the University of Berlin, that PbS had the photoconductive effect with a response wavelength of about 3 μm . After that, a PbS thin-film photoconductive detector was made, which is one of the most important developments in modern infrared detectors. In World War II, Germany used this detector to make a series of military infrared detection systems. After World War II, Britain, the United States, and the Soviet Union became interested in infrared technology. Infrared detectors developed rapidly from PbS to PbTe and PbSe thin-film detectors. The longest response wavelength can reach 7 μm at liquid nitrogen temperature. The development of semiconductor physics in the 1950s also greatly promoted the development of infrared photon detectors.

In the early 1950s, it is reported that the first extrinsic photoconductive detector used impurity copper, zinc and gold-doped germanium materials, suitable for detecting 8-14 μm (LIR) and 14-30 μm (VLIR). At that time, infrared detectors using narrow bandgap

semiconductors as photosensitive materials also developed rapidly, among which InSb was the first discovered III-V group compound narrow bandgap semiconductor. This semiconductor family has small bandgap and simple single crystal preparation technology, which is beneficial to expand the wavelength range of detection and improve the sensitivity of the detector. In 1959, Lawson and his collaborators studied the variable bandgap HgCdTe alloy and announced two responses of photoconductive and photovoltaic at the wavelength of 11 μm . Due to the property of tunable bandgap, the alloy can detect infrared light in a wide spectral range, leading to a research boom. From the 1970s to the present, with the maturity of material preparation technologies such as molecular beam epitaxy (MBE), micro-nano lithography and other technologies, the emergence of various new types of infrared materials such as three- and quaternary alloys, low-dimensional structures – quantum wells, quantum dots, nanowires, etc. has greatly improved the performance of infrared detectors.

For the development of modern infrared detector research, it can be divided into four generations according to its characteristics: the first generation of infrared detection technology is the linear-array scanning to image system based on photoconductive detection units, which has the complex structure and low sensitivity. The second generation is the two-dimensional array detectors based on photovoltaic detection units, with about 10^6 elements in the array. The time delay integration of the signal is integrated into a single detector, which greatly simplifies the system. Besides, the indium bumps are commonly used to connect these photodiode arrays to ROIC chips to form hybrid structures. The third generation is a staring infrared FPA that pursues large area, multi-band, miniaturization, intelligence, low cost and high performance.

The current development of IR technologies for industrial applications requires the IR imaging systems with larger-array format size and higher-resolution imaging system, which is usually regarded as the fourth generation.

2.2.2 Classification of IR detectors

According to the different presented physical effects through the interaction between IR radiation and dielectric matter, IR detectors can be divided into thermal detectors (photothermal effect) and photon detectors (photoelectric effect). Figure 2.3 shows the spectral detectivity of commonly used commercial IR detectors.

Fig. 2.3 Comparison of spectral detectivity of various modern commercial IR detectors [1].

Thermal detectors utilize the thermal radiation effect to detect signal, where the

corresponding schematic diagram is shown in Fig. 2.4. After the photosensitive element (detector absorber) receives the IR radiation, its temperature is raised, which in turn causes the change of electric signal (or first causes the change of other physical quantities, then converting into electric signal change). The temperature change of photosensitive material is only related to the radiation energy, not to the wavelength, so there is no wavelength selectivity in thermal detectors.

Fig. 2.4 Schematic diagram of thermal detector [1].

In theory, the thermal detector should have the same response to all IR wavelengths. But in fact, the response to different wavelengths is often different. The response speed of the thermal detector is determined by the thermal capacity and the speed of heat dissipation, that is, the speed of heat transfer. Reducing the heat capacity and increasing the heat transfer rate can speed up the response speed. Compared with photon detectors, thermal detectors have lower detectivity and slower response speed. However, because the thermal detector has a

broad and relatively flat spectral response, the response range can be extended to the entire IR region, and it can work at room temperature and easy to operate, so the thermal detector is still widely used in modern society.

With the need of high detectivity and fast response speed for modern applications, photon detectors have been rapidly developed in recent years. Photon detectors use the photoelectric effect to detect. Under the IR radiation, the electrons in bound states of the semiconductor material are excited into conduction electrons, causing changes in electrical signals, and the magnitude of electrical signal changes is proportional to the number of absorbed photons. The energy of the absorbed photons must be sufficient to excite the electrons in bound states, that is, the energy of the incident IR light must be greater than the bandgap of semiconductor material. So the spectral response of photon detectors has wavelength selectivity, only responding to the IR radiation shorter than the cutoff wavelength of material.

Fig. 2.5 Basic optical detection mechanism in semiconductors: (1) intrinsic absorption (interband transition), (2) free carrier absorption and (3) extrinsic absorption (impurity transition) [21].

Here, we use a simple photodiode as an example to further explain photodetection mechanism, which will later help to understand the contribution of plasmonic resonance. The operation of photodiode is that when photons with energy larger than the semiconductor energy bandgap incident on the device, the absorption of these photons can create free electron-hole pairs in the absorption region. Then the electron-hole pairs are separated by a strong electric field, moving to their respective contacts [1]. In this way, a photocurrent is generated at contacts. This kind of photodetection is based on intrinsic optical transition in optoelectronic semiconductors. There are also some other basic mechanisms for photodetection, such as photodetection based on free carrier absorption of photons and impurity band absorption of photons, as shown in Fig. 2.5.

For the extrinsic detection, its impurity ionization energy determines the response wavelength of the detector, and the response wavelength in one to several hundred microns can be obtained by different impurities. The device using intrinsic absorption, compared to that using extrinsic absorption, has a higher absorption coefficient, especially for direct bandgap semiconductors. Moreover, the operating temperature of the intrinsic device is higher than that of the extrinsic device. The difference between the free carrier detector and the above two detectors is the number of carriers after absorbing photons remains constant, but the carrier mobility is changed [34]. The radiation incident on the high-mobility semiconductor causes in-band transitions and increases the average energy of conduction electrons. Such devices need to work at extremely low temperatures to reduce energy transferring to the crystal lattice. Besides, there is also quantum well type infrared detector. In this case, two kinds of

semiconductor materials are grown alternately in thin layers by artificial methods to form a superlattice, which can have abrupt changes at the interface. Electrons and holes are confined in the low potential energy layer, and the energy is quantized, which is called quantum well. Infrared detectors can be made using the principle of electron transitions in the sub-energy levels of quantum wells.

In addition, according to different working principles, photon detectors can also be divided into the types of photoconductive, photovoltaic, photoemissive and photoelectromagnetic detectors. Among them, photoconductive and photovoltaic detectors have been widely studied and applied, so that we will mainly discuss them in the following:

- Photoconductive detector

When IR waves incident on the semiconductor material, if the incident photon energy is greater than the semiconductor bandgap, it will cause the valence band electrons in the semiconductor to absorb the photon energy and enter the conduction band, which can increase the semiconductor conductivity. This phenomenon is called photoconductive effect, where the working principle diagram is shown in the Fig 2.6. Commonly used IR photoconductors are radiation-sensitive resistor type, and the corresponding semiconductor materials include PbS, PbSe, InSb, HgCdTe, etc. Photoconductors usually need cooling and a certain voltage bias when operating, otherwise the responsivity will reduce and the noise will increase.

Fig. 2.6 Schematic of a photoconductor [35].

- Photovoltaic detector

When IR waves incident on the p-n junction of semiconductor materials, if the incident photon energy is greater than the semiconductor bandgap, electron-hole pairs will be generated in the junction area and its vicinity. Under the built-in electric field of p-n junction, the free electrons in the p-side move to the n-side, and the holes in the n-side move to the p-side, which will generate an electric field at both ends of the junction with the direction opposite to built-in field. The photon detector made by this effect is called photovoltaic detector, and its diagram of working principle is shown in Fig 2.7. This type of detector can be self-powered and does not require an external electric field and load resistance, so it consumes low power and is often used to make an IR focal plane array.

Fig. 2.7 Schematic of a photovoltaic detector [36].

2.2.3 Figures of Merit

The basic parameters that characterize the performance of the detector mainly include responsivity, dark current, noise equivalent power, detectivity and so on. This section will briefly introduce these figures of merits.

- Responsivity

The responsivity R , defined as the output signal per unit incident power on the detector, is an important measure of the detector performance,

$$R = \frac{V_s}{P_{in}} \text{ (V/W)} \text{ or } R = \frac{I_s}{P_{in}} \text{ (A/W)} \quad (2)$$

where V_s , I_s , P_{in} are the output signal voltage, output signal current, optical power incident on the infrared detector respectively. The greater the responsivity, the better the performance of the detector. In addition, the responsivity of the photon detector is related to the wavelength of the incident light and is determined by the material of the detector. Therefore, when selecting

an infrared detector for practical applications, it is necessary to consider the agreement between the optical signal spectra and the response spectra of the material.

- Dark current

Dark current has a great influence on the detection performance. Therefore, analysing the mechanism of dark current can help to find ways for reducing noise power, thereby improving the detectivity of the detector. There are many factors that generate the dark current, including diffusion dark current, generation-recombination current, surface leakage current, tunnel current and so on. In the following, the above factors will be separately analysed.

The diffusion dark current originates from the diffusion of minority carriers to the depletion layer, generated by thermal excitation in the p- and n- regions at the edge of the depletion region. Increasing the doping concentration of p- and n-region can effectively reduce the diffusion dark current, so the diffusion dark current of a p^+-i-n^+ homojunction structure is very small after the i-layer is fully depleted.

The generation-recombination dark current is originated from the drift movement of carriers generated by the thermal excitation in the barrier region to the sides of barrier region under the effect of electric field. Lattice defects and impurities can produce deep energy levels in the forbidden band. These deep levels can capture or emit carriers, thereby forming a recombination current, which is stronger in the space charge region. For a p^+-i-n^+ structure, due to the doping concentration, when the intrinsic layer is completely depleted, the width broadening of the depletion layer is very small, and the generation-recombination current will not increase significantly.

The causes of surface leakage current are very complicated. One of the reasons is the existence of surface states on the semiconductor surface, which causes the surface dark current of the detector. Increase the bandgap of the surface layer can reduce the surface dark current. Therefore, a wide bandgap material is generally used as the cap layer to reduce the surface dark current. The surface dark current also comes from many other factors such as the ion movement on the step surface and the movable charge of the dielectric layer. The surface dark current caused by the fabrication process often determines the reverse dark current of the detector.

The tunnel current mainly originates from the tunnelling effect of carriers passing through the forbidden band. When the applied voltage bias is higher, the tunnel current will determine the dark current of the detector. Tunnel current can be divided into band-to-band tunnel current and defect tunnel current. The band-to-band tunnel current is, when the Fermi level on both sides of the PN junction within the energy band, electrons can take advantage of the tunnelling effect and directly from the valence band enter the conduction band, thus form a direct tunnel current through the PN junction. The indirect tunnel current is that electrons in the valence band can move to the deep-level impurity center in the forbidden band by tunnelling effect, and then enter the conduction band by thermal excitation to form a current through the junction. The smaller the forbidden bandgap, the greater the tunnel current. The detection wavelength of the detector is inversely proportional to the bandgap width of the material. Therefore, as the detection wavelength increases, the tunnel current gradually dominates. For the PN junction current of the narrow bandgap semiconductor, the tunnel current must be considered.

- Noise equivalent power

When the infrared radiation signal is incident on the detector response surface, if the output signal voltage or current generated by this radiation power is equal to the noise voltage or current, the corresponding incident power is called the minimum detectable power, that is, noise equivalent power. The smaller the minimum detectable power or NEP , the better the performance of the detector, which means the higher its detection capability.

$$NEP = \frac{noise}{R} (W) \quad (3)$$

- Detectivity

In order to compare the performance of different detectors, the reciprocal of NEP is used to express the detector capability of detecting weak signals, which is called the detectivity. The detectivity is related to the measurement conditions. For many types of detectors, it is proportional to the square root of the measurement system bandwidth (Δf). In order to facilitate comparing the performance of different detectors, the normalized detectivity is defined as:

$$D^* = \frac{R \times \sqrt{area}}{noise/\sqrt{\Delta f}} (cm \cdot Hz^{1/2}/W) \quad (4)$$

the impact of different detector areas and bandwidths can be avoided by using D^* to compare the performance.

2.2.4 Recent development for high-operating-temperature IR detector

High-temperature operational IR focal plane arrays have always been pursued for various important applications, such as remote-sensing, night-vision, security, and medical diagnosis. However, the performance of state-of-the-art products is always limited by large dark currents in IR detectors, which is mainly due to inherent material property. Thus, cryogenic technologies

such as thermoelectric cooling, helium compression refrigeration and liquid nitrogen refrigeration have been introduced to make them operate optimally, which results in high cost and bulky configuration. To increase the operating temperature, inhibiting or decreasing dark currents originated from both surface leakage and bulk diffusion, Shockley Read Hall, and tunneling process becomes the most important task [1], [37].

Recently, antimony (Sb) based III-V semiconductors have demonstrated their potentials for NIR and MIR applications. Among them, $\text{InAs}_{1-x}\text{Sb}_x$ is promising for its wide bandgap tunability, low electron effective mass, low Auger recombination rate and good uniformity in material growth [38]. Among various types of InAsSb based photodetectors, photovoltaic diodes attract much more attention, owing to their fast response speed and near zero bias operation [39]. To reduce the dark current therefore increase the operational temperature of InAsSb photodiodes, several innovative architectures have been proposed and realized [40], [41].

Fig. 2.8 Band diagram of an nBn photodetector [16].

One of the most popular strategies is the nBn structure proposed in 2006, as shown in Fig. 2.8 [16]. In this strategy, a wide bandgap barrier layer is usually inserted between absorption and contact layers to reduce the excessive dark current induced by diffusion of carriers. Ideally, a unipolar barrier should be adopted to block one type of carrier transport, but meanwhile allows the unimpeded flow of the other type [42]. Another strategy is to use the superlattice structure (Fig. 2.9), through carefully heterostructure design and layer growth, the detector with less Shockley-Read-Hall recombination dark current can be obtained [14], [43], [44]. These photodetectors offer promising pathways to improve high-temperature operational performance.

Fig. 2.9 Schematic diagram of superlattice structure [44].

2.3 Fundamentals of Plasmonics

The field of plasmonics studies the unique properties of light arising from the interaction between light with metallic nanostructures at sub-wavelength scale [45]–[48]. Those

nanostructures own the capability of supporting collective electron excitations, known as surface plasmons. As surface plasmon resonance (SPR) occurs, the ability to concentrate light or produce large local-field in extremely small volume enables the significant absorption of electromagnetic waves, therefore, facilitating the interaction between light and optoelectrical absorbers. This kind of property has been widely utilized for improving the quantum efficiency of solar cells [49]. At IR range, metallic nanostructures are also integrated with semiconductor detectors to enhance the absorption of photons, therefore, to improve the photoelectrical conversion efficiency. In this section, we will briefly introduce the plasmonic fundamentals and recently reported plasmonic detectors.

2.3.1 Surface plasmon

The quasi particle of light and collective electron oscillations along the metal-dielectric interface is referred to as surface plasmon polariton (SPP), which supports intense electromagnetic confinement in the deep subwavelength dimension [50]. The SPPs can be conventionally divided into two groups: propagating SPPs and localized SPPs. As shown in Fig. 2.10(a), single metal-dielectric interface can enable the excited SPPs to propagate for typically tens of micrometres near the interface. The solutions of Maxwell's equation require the moment matching between the SPP and incident light for exciting the propagating SPPs, as shown in the following equation [51]:

$$k_{SPP} = k_0 \sqrt{\frac{\epsilon_m \epsilon_d}{\epsilon_m + \epsilon_d}} \quad (5)$$

where k_{SPP} is the wavevector of the SPPs, k_0 is the wavevector of light in free space, ϵ_m and ϵ_d

are the permittivity of metal and dielectric, respectively. Equation (5) requires an additional structure, like prism and corrugated-grating coupling structures, to be involved to assist in increasing the wavevector of light for satisfying the moment matching [52].

The excitation of localized SPPs (Fig. 2.10(b)) can be obtained by directly illuminating light on the curve surface of nanoparticles [11]. As localized SPR occurs, the optical electric field within (E_{in}) and out of (E_{out}) the subwavelength particle can be expressed as [51]:

$$E_{in} = \frac{3\varepsilon_d}{\varepsilon_m + 2\varepsilon_d} E_0 \quad (6)$$

$$E_{out} = E_0 + \frac{3n(np) - p}{4\pi\varepsilon_0\varepsilon_d} \frac{1}{r^3} \quad (7)$$

where E_0 is the static electric field, p is the electric dipole moment, r is the position vector of particle and ε_0 is the permittivity in vacuum.

There is another unique property of surface plasmon that should be mentioned here as it has been widely studied for photoelectrical conversion, especially for solar cells. This method is based on the decay of surface plasmons, which can induce electron-hole pairs [53] or nonequilibrium electrons [54] in the metals or in semiconductors. The high energy electrons can contribute to photocurrent with appropriate architecture design.

Fig. 2.10 (a) Surface plasmon polariton at single interface [55]. (b) Localized surface plasmon resonance for subwavelength metal nanoparticles [56].

2.3.2 Surface plasmon enhanced photodetection

For an ideal photodiode, there exists a trade-off between quantum efficiency and thickness of absorption layer. According to the definition of quantum efficiency, higher quantum efficiency is achieved in a thicker absorption layer, but at the expense of longer transit time and thus slower response, as well as the cost of product in material growth. Therefore, optimizing the detector itself can no longer solve this problem, one needs to find other ways beyond the limitation of detector itself to increase the absorption coefficient in thin absorption layer, which can reduce the physical thickness of the absorption layer but maintain the optical thickness constant. Integrating a plasmonic structure with the detector is one of the popular strategies for realizing this objective, since at the metal-dielectric interface, the optical field can be enhanced by SPR. The interaction between SPP fields and absorption area results in trapping and concentrating light in subwavelength dimension, which can increase absorption inside detector, especially at the resonance frequency, and therefore enhance the photoresponse without sacrificing the physical thickness.

2.3.3 Plasmonic structures

In the infrared spectral region, the plasmonic structures of various geometrical shapes have been fabricated and integrated with the detectors, facilitating further in-depth exploration of plasmonic effect on photodetection performance. Due to the advanced fabrication techniques, like EBL which provides high resolution for features down to sub-10 nm, and FIB milling which can process the existing planar film [55], as well as the commercially available designing

software packages like FDTD and Comsol, the design and fabrication of metallic nanostructures for infrared range become very effective. One of the popular structures is plasmonic grating [57] whose resonant modes are excited through phase matching between incident light and SPPs. As this structure is easily fabricated and integrated just by depositing the grating metal on top of detector [58], it has been adopted in various detector types which will be discussed later. The plasmonic gratings have strong polarization-dependence on the incident electromagnetic waves, which is suitable for polarization-resolved photodetection. By changing the period of the grating, the resonant wavelength can be tuned. The other popular structure is two-dimensional metallic hole array structure which can achieve the extraordinary optical transmission at resonant frequency [59]–[61], thereby increasing the absorption efficiency in detector. For the normal incident light and square lattice array, the resonant wavelength can be deduced by the following equation:

$$\lambda_{i,j} = \frac{a_0}{\sqrt{i^2 + j^2}} \left(\frac{\epsilon_m \epsilon_d}{\epsilon_m + \epsilon_d} \right)^{\frac{1}{2}} \quad (8)$$

where (i, j) are mode orders in x- and y- directions, a_0 is the lattice constant for the hole array structure. Therefore, according to this equation, one can roughly determine the geometrical dimension of the structures for specific wavelength. The complementary structure of the hole array is the plasmonic metal cube array structure (Fig. 2.11(f)) with resonant wavelength determined similarly by Equation (8). The hole array and its complementary structure have been intensively studied on enhanced photodetection owing to their simplicity. Usually, for these structures, the duty cycle is chosen to be 50% to allow largest enhanced absorption. In addition, the thickness of metals should be larger than the penetration depth of incident IR

radiations to avoid disturbance of direct IR absorption.

Fig. 2.11 Different plasmonic structures. (a) Grating structure [57]. (b) Two-dimensional hole array structure [59]. (c) Nanorods inserted in absorber [62]. (d) Nanoparticle [63]. (e) Nanopyramids [64]. (f) Micropatch.

There are other plasmonic structures based on the field enhancement associated with the localized SPR, such as nanorod [62], nanoparticle [63], nanopyramid [64], and micropatch [65], etc., as shown in Fig. 2.11. Usually, the typical size of the particles should be much smaller than the detected wavelength to form subwavelength configuration. And they usually allow broadband enhancement compared to those plasmonic structures with propagated SPPs. These kinds of structures are widely used in improving the quantum efficiency of solar cells. They sometimes only require very simple spin-coating solution rather than relatively complicated EBL or FIB fabrication. Examples of different types of infrared photodetector integrated with different plasmonic structures to enhance the photodetection performance will be discussed in the following sections.

2.3.4 Plasmonic photodetector

- Heterostructure type

Recently group III-V materials have shown great potential for MIR detection, especially the InAsSb-based material as it has better bandgap tunability and uniformity in material growth relative to the dominant MCT material. To further reduce the dark current and increase the operating temperature, InAsSb-based heterostructure photodetectors have attracted much more attention. However, due to the low absorption efficiency in MIR range, increasing responsivity without sacrificing the device speed becomes an important issue to be solved. One popular approach is to integrate the plasmonic structure with the hetero device. An InAsSb-based heterojunction photodiode integrated with a two-dimensional square-lattice hole array structure has been proposed, as sketched in Fig. 2.12(a) [60]. From patterning two-dimensional subwavelength hole array (2DSHA) structure on top of device by using EBL, metal evaporation and lift-off process, the incident light can be strongly confined near the metal-dielectric interface. In order to position the fundamental resonance around the peak spectral response of the heterojunction photodiode (3.5 μm), the authors designed the 2DSHA plasmonic structure with period of 900 nm as derived in the Equation (9), and the hetero photodiode with an active region of $\sim 1 \mu\text{m}$ which is the same as the SPP penetration depth (δ_d) as obtained from the following equation:

$$\delta_d = \frac{1}{k_0} \left| \frac{\varepsilon_m' + \varepsilon_d}{\varepsilon_d^2} \right|^{1/2} \quad (9)$$

where ε_m' and ε_d are the real permittivity of the gold and hetero device, respectively. As shown

in Fig. 2.12(b), the numerically calculated electric field enhancement ($|E_{x,int}/E_{x,in}|^2$) at the hot spot position indicates that the 2DSHA plasmonic effect can indeed contribute to the significant increase of field intensity for fundamental mode as well as other higher order modes. The obvious increase in the measured room-temperature responsivity and detectivity (Fig. 2.12(c) & (d)) for the 2DSHA-hetero detector also confirms the strong plasmonic effect. A room-temperature detectivities of 8×10^9 Jones at $3.4 \mu\text{m}$ is demonstrated. In addition, it is observed that the improvement of performance can be well controlled by modulating the overlap region between the depletion layer and SPP working region (penetration depth). In practice, this can be achieved by tuning the depletion layer width (W) of the active region via adjusting the applied voltage bias (V), i.e., $W \propto (V_{bi}-V)^{1/2}$. In this manner, the 380% tuning depth (enhanced percentage) over 0.32 V bias change (from -0.15 to 0.17 V) could be realized.

Fig. 2.12 Plasmonic 2D SHA heterostructure photodetector [60]. (a) Schematic diagram of the device. (b) Spectra of electric field enhancement in 2D SHA with a period of 900 nm at the hot spot position, as indicated in the inset. (c) Room-temperature responsivity. (d) Room-temperature blackbody detectivity.

Except for the plasmon-enhanced single-band detection, a plasmonic structure enhanced dual-band detector can be realized by integrating the 2D SHA with a n-InAsSb/n-GaSb hetero-detector (Fig. 2.13(a)) [66]. Through matching the resonant modes of the 2D SHA with InAsSb and GaSb absorption bands, it is found that the room-temperature photocurrent spectral demonstrates obvious enhancement in two separate bands which are 3.4 μm (MIR) for InAsSb and 1.7 μm (NIR) for GaSb, respectively, as shown in Fig. 2.13(b). The highest room-temperature detectivities of 1.4×10^9 Jones at 3.4 μm and 1.5×10^{11} Jones at 1.7 μm were

achieved, which are comparable with state-of-the-art MIR and NIR photodetectors for single-band detection. The other work [67] also studied this dual-color plasmonic enhancement and found that at a forward applied bias, the plasmonic detector can achieve the dual-band detection with highest responsivity. Several studies have also been carried out on explaining the plasmonic effect for the n-InAsSb/n-GaSb hetero-detector [68], [69]. In addition to the heterostructure photodiode, the plasmonic structure has been integrated with the nBn barrier detector [70], [71]. The quantum efficiency was increased to 57 % via the 2D plasmonic grating patterned on top of device.

Fig. 2.13 Plasmonic 2DSHA-hetero n-InAsSb/n-GaSb photodetector. (a) Schematic diagram of the device [68]. (b) Photocurrent spectral measured at room temperature [66].

- Schottky type

A Schottky type photodetector can be used to detect radiation below the bandgap energy of the semiconductor via internal photoemission. Figure 2.14(a) shows the sketch of a grating-assisted Schottky photodetector [57]. It consists of an Au grating layer on an n-silicon wafer,

with a very thin titanium layer in between to determine the height of Schottky barrier and adhere the grating layer to the silicon substrate. With the plasmonic grating configuration [72], this Schottky detector combines narrow spectral response at resonant wavelength with the hot electron-assisted photodetection. Compared to the previous antenna based Schottky photodetector, a significant increase in its responsivity and internal quantum efficiency is observed. Alavirad et al. [58] further designed a broadband silicon plasmonic Schottky photodetector with an Au grating on top of a thin Au patch, defined by EBL and optical lithography, respectively, as sketched in Fig. 2.14(b). They observed strong responsivity enhancement in the sub-bandgap regime by exciting the SPPs at the gold-silicon interface. Another type of broadband plasmonic Schottky detector [64] is shown in Fig. 2.14(c), where Al was patterned on the apex of pyramid-shaped silicon wafer. The designed pyramidally shaped plasmonic concentrators are used to get high responsivity, as the light can be collected from the large cross-section of pyramid and converge on the peak region where it is absorbed and creates hot electrons with sufficiently high energy to overcome the Schottky barrier. Such a detector can achieve the nanoscale confinement together with large collection efficiency. These detectors have important advantages such as speed, simplicity, compatibility with silicon, and low-cost fabrication.

Fig. 2.14 Schematic diagrams of plasmonic Schottky detectors. (a) A gold grating layer on silicon substrate with a thin Ti layer in between [57]. (b) A gold patch on p-Si substrate with a gold grating on top [58]. (c) The silicon pyramid with the patterned Aluminium apex [64].

- Photoconductive type

The photoconductive type detector operates for the photons with energy $h\nu$ larger than the bandgap energy $h\nu$ which change the semiconductor electrical conductivity by exciting electron-hole pairs [1]. It is well known that graphene material is a good choice for photoconductor because of its fast and broadband response. However, it is difficult for graphene photoconductor to achieve high responsivity due to its short photocarrier lifetime and low absorption efficiency. One promising approach is to utilize the plasmonic structures [65], [73]. An end-to-end plasmonic antenna structure was fabricated on a graphene sheet, as shown in Fig. 2.15(a) [74]. With assistance of the plasmonic nanoantenna, the electric field intensity is strongly enhanced inside the nanoantenna gaps [75], thereby the light can be better

concentrated into the gap region for realizing high responsivity in MIR photodetection. In terms of the traditional MCT photoconductive detector, Jaksic et al. [63] applied transparent conductive oxide plasmonic nanoparticles on top of the MCT detector (Fig. 2.15(b)) to directly increase light absorption inside active region through the local electric field enhancement, via the existence of evanescent plasmon modes. In this manner, the MCT photoconductor obtains a significant increase in responsivity in the MIR range. Germanium photoconductive detector with a plasmonic structure has also been explored by Salamin et al. It consists of a metal-semiconductor-metal waveguide with Ge as the active region in between the plasmonic gold antenna [76], as shown in Fig. 2.15(c). The light absorption inside the active region is increased via the SPPs generated by the evanescently coupled photons.

Fig. 2.15 Schematic diagrams of plasmonic photoconductive detectors. (a) Antenna assisted graphene detector [74]. (b) The MCT photoconductor integrated with the randomly placed plasmonic nanoparticles [63]. (c) MSM plasmonic waveguide with Ge as absorber and Au as plasmonic cladding [76].

- Low dimensional Solid type

As the epitaxial growth technique develops, the device structure can be engineered to low dimension, such as quantum well structure, where the size of semiconductors can be downscaled to the nanometer level. The quantum-sized devices often exhibit appealing characteristics including quantized energy levels and tunable wavelength of detected photons [77]. However, similar to the graphene photoconductor, the major obstacle for low-dimensional MIR detectors is the low light absorption inside the absorber layer due to the limited thickness of active region. One solution is to incorporate the plasmonic structure inside absorber layer or in other places. It has been reported that integrating a periodic hole array structure patterned in the gold film with the InGaAs/InP quantum well infrared photodetector (QWIP) can convert the normal-incident photons into SPPs, which in turn excites the carrier intersubband transition in the QWIP, leading to an enhancement in the detector spectral response and detectivity in the MIR region [24].

In recent years, Quantum dot infrared photodetectors have demonstrated great potential for MIR detection mainly due to their carrier confinement in all directions, in contrast to QWIP which can only confine carriers in one direction. One of the popular plasmonic structures for enhancing quantum dot infrared photodetector (QDIP) response is the periodic hole array structure, where the metal film was patterned on the front- or back-side of QDIP detector. Here, we take the Ge/Si QDIP shown in Fig. 2.16(a) [59] as an example. The 2DSHA extraordinary optical transmission (EOT) effect for exciting the SPPs at the interface of metal hole array and dielectric layer significantly enhances the QDIP quantum efficiency and responsivity [78]–[81].

In addition to the 2DSHA structure, there are also reports on plasmonic dipole arrays in an MCT QD layer (Fig. 2.16(b)) [82] and the gold nanodisk arrays in the HgSe QD film (Fig. 2.16(c)) [83] for enhancement in MIR range.

Except for the QDIP structure, quantum dots-in-a-well (DWELL) architecture was proposed by Liu et al., in which the quantum dots are located inside the quantum well layer [84]. The DWELL detector combines the advantages of quantum well and quantum dots, such as easy control of operating wavelength range for quantum well structure, and low dark current for quantum dot structure. Lee et al. [85] improved this detector by incorporating a 2DSHA plasmonic structure on the top of the InAs/InGaAs DWELL structure, as sketched in Fig. 2.16(d). They observed a $\sim 160\%$ increase in the voltage signal to noise ratio at the resonant wavelength. Besides, the quantum cascade detectors are also very promising for large-scale FPA [86]. It is found that a 2DSHA fabricated on top of the detector active region could also increase the light absorption in quantum cascade detectors via the same plasmonic EOT effect [87].

Fig. 2.16 Schematic diagrams of plasmonic quantum type detectors. (a) 2DSHA gold structure fabricated on the Ge/Si QDIP [59]. (b) Au nanoantenna embedded in the QD layer on SiO₂ substrate [82]. (c) Plasmonic nano-disk arrays on QDIP [83]. (d) Plasmonic hole array patterned on top of the DWELL detector [85].

- Thermal type

Figure 2.17(a) shows a thermal detector consisting of a plasmonic perfect absorber on a pyroelectric ZnO layer, which was fabricated by colloidal-mask lithography and reactive-ion etching [88]. The metamaterial absorber leads to a strong optical field and high thermal concentration in pyroelectric detector. By tuning the resonance wavelength of the plasmonic 2DSHA, excellent spectrally selective absorptivity at plasmonic resonances and significantly enhanced responsivity can be achieved. Apart from the 2DSHA structure, a new architecture whose unit cell is a symmetrical split cross resonator (Fig. 2.17(b)) was proposed, and a narrowband and high absorption in long infrared (LIR) was demonstrated [89].

Fig. 2.17 Schematic diagrams of plasmonic thermal detectors. (a) A gold 2DSHA structure on top of ZnO pyroelectric layer [88]. (b) A unit cell of the plasmonic absorber consisting of symmetrical gold split cross resonator [89].

- Other type

There are also reports on other types of detectors which show enhanced detection performance. One example is the LIR quantum-well photodetector which consists of plasmonic sub-wavelength metallic resonators, where the square metallic patches cover the absorber and are connected via leads, as sketched in Fig. 2.18(a). The enhancement in responsivity occurs because the plasmonic resonators increase the local field-intensity in absorption layer, and the plasmonic antenna extends the photon collection area without increasing the electrical area [90]. In another example, Huang et al. introduced periodic axe-like plasmonic electrodes to the carbon nanotube detector (Fig. 2.18(b)). In this device, the photogenerated carriers can be collected more effectively and light absorption inside the detector can be significantly increased [91].

Fig. 2.18 Schematic diagrams of plasmonic detectors. (a) Scanning electron microscope (SEM) image of the detector integrated with plasmonic patch resonator array [90]. (b) SEM image of the CNT detector with plasmonic electrodes [91].

2.4 Summary

In this chapter, we review the basics of infrared radiation, infrared photodetectors, and fundamentals of plasmonics, to facilitate better understanding of the basic mechanisms behind surface plasmon enhanced photodetection. Thanks to the state-of-the-art fabrication techniques and simulation tools, the design and fabrication of metallic nanostructures for infrared range become very effective. Metallic nanostructures with different configurations can be used to integrate with traditional detection structures such as heterojunction structure, Schottky diode, quantum structures, and thermal detector. Combined with these plasmonic structures, the photoresponse of those detectors can be significantly improved. These advances on one hand,

improve the performance of existing detection structures, on the other hand, point out the direction of a new generation of infrared detection technologies.

Chapter 3. Simulation and Experimental Methods

In this chapter, critical methods of simulation, fabrication, and characterization are discussed. To study the internal mechanism of photodetection enhancement by various photonic structures, the integrated photodetectors are first simulated and optimized using finite-difference time-domain method. For the fabrication technique, electron beam lithography is used to define the plasmonic patterns and photon-trapping structures on photodetectors, the inductively coupled plasma - reactive ion etching is used to etch group III-V material with high quality, and electron beam evaporation is used to deposit metal materials according to the pattern formed in lithography. The reflection and photocurrent spectra are characterized using a Fourier transform infrared spectroscopy.

3.1 Finite-difference time-domain simulation method

In 1966, Yee first proposed a new method for electromagnetic field calculation - the finite-difference time-domain (FDTD) method. This method adopts a discrete way to alternate sample electromagnetic field E and H components in space and time. Each E (or H) component is surrounded by four H (or E) components. The following time-dependent Maxwell curl equations can be transformed into a set of difference equations by means of this discrete method [92].

$$\vec{\nabla} \times \vec{H} = \epsilon_0 \frac{\partial \vec{E}}{\partial t} + \vec{J} \quad (10)$$

$$\vec{\nabla} \times \vec{E} = -\mu_0 \frac{\partial \vec{H}}{\partial t} \quad (11)$$

$$\vec{\nabla} \cdot \vec{B} = 0 \quad (12)$$

$$\vec{\nabla} \cdot \vec{D} = \rho \quad (13)$$

$$\vec{\nabla} \cdot \vec{J} = -\frac{\partial \rho}{\partial t} \quad (14)$$

where

H - magnetic field,

E - magnetic field,

J - electric current density,

B - magnetic flux density,

D - electric flux density,

ρ - electric charge density,

ε_0 - free-space permittivity,

μ_0 - free-space permeability.

FDTD belongs to the direct time domain method. In the calculation process, the E (or H) of a certain point in space is directly related to the H (or E) of the surrounding grid points, and the medium performance parameters have been assigned to each cell in the space, so the FDTD method can be used to deal with the electromagnetic scattering problems of complex or even non-uniform medium systems. The spatial arrangement of each node for E and H in FDTD discretization is called Yee cell, as shown in Fig. 3.1 [93].

Fig. 3.1 Yee cell.

In addition, the progress of the method over time can conveniently give the time evolution process of the electromagnetic field, which is convenient for analysis. The spatial distribution of electromagnetic components in Yee cell helps to solve the Maxwell equations with second-order accuracy in the following discretized form:

$$H_{x,i,j,k}^{n+0.5} = H_{x,i,j,k}^{n-0.5} + (E_{y,i,j,k+0.5}^n - E_{y,i,j,k-0.5}^n) \frac{\Delta t}{\mu_0 \Delta z} + (E_{z,i,j-0.5,k}^n - E_{z,i,j+0.5,k}^n) \frac{\Delta t}{\mu_0 \Delta y} \quad (15)$$

$$H_{y,i,j,k}^{n+0.5} = H_{y,i,j,k}^{n-0.5} + (E_{z,i+0.5,j,k}^n - E_{z,i-0.5,j,k}^n) \frac{\Delta t}{\mu_0 \Delta x} + (E_{x,i,j,k-0.5}^n - E_{x,i,j,k+0.5}^n) \frac{\Delta t}{\mu_0 \Delta z} \quad (16)$$

$$H_{z,i,j,k}^{n+0.5} = H_{z,i,j,k}^{n-0.5} + (E_{x,i,j+0.5,k}^n - E_{x,i,j-0.5,k}^n) \frac{\Delta t}{\mu_0 \Delta y} + (E_{y,i-0.5,j,k}^n - E_{y,i+0.5,j,k}^n) \frac{\Delta t}{\mu_0 \Delta x} \quad (17)$$

$$E_{x,i,j,k}^{n+1} = E_{x,i,j,k}^n + (H_{z,i,j+0.5,k}^{n+0.5} - H_{z,i,j-0.5,k}^{n+0.5}) \frac{\Delta t}{\epsilon_0 \Delta y} + (H_{y,i,j,k-0.5}^{n+0.5} - H_{y,i,j,k+0.5}^{n+0.5}) \frac{\Delta t}{\epsilon_0 \Delta z} \quad (18)$$

$$E_{y,i,j,k}^{n+1} = E_{y,i,j,k}^n + (H_{x,i,j,k+0.5}^{n+0.5} - H_{x,i,j,k-0.5}^{n+0.5}) \frac{\Delta t}{\epsilon_0 \Delta z} + (H_{z,i-0.5,j,k}^{n+0.5} - H_{z,i+0.5,j,k}^{n+0.5}) \frac{\Delta t}{\epsilon_0 \Delta x} \quad (19)$$

$$E_{z,i,j,k}^{n+1} = E_{z,i,j,k}^n + (H_{y,i+0.5,j,k}^{n+0.5} - H_{y,i-0.5,j,k}^{n+0.5}) \frac{\Delta t}{\epsilon_0 \Delta x} + (H_{x,i,j-0.5,k}^{n+0.5} - H_{x,i,j+0.5,k}^{n+0.5}) \frac{\Delta t}{\epsilon_0 \Delta y} \quad (20)$$

where

Δt - time step,

- n - time step index,
 $\Delta x, \Delta y, \Delta z$ - Yee cell dimensions,
 (i, j, k) - Yee cell indices.

Due to the limitation of computer capacity, FDTD calculation can only be performed in a limited area. In order to simulate the electromagnetic scattering process in the open domain, absorbing boundary conditions need to be set at the cut-off boundary of the calculation area. Perfectly matched layer (PML) absorbing boundary is one of them. The PML was first proposed by Berenger (1994) [94], [95]. By setting a special dielectric layer at the truncation of the FDTD region, the wave impedance of this medium layer is completely matched with that of the adjacent medium, so the incident wave will pass through the decomposition surface and enter the PML without reflection. Since the PML is a dissipative substance, the transmitted wave entering the PML will be rapidly attenuated, so a PML with limited thickness can be used to obtain a good absorption effect.

3.2 Electron Beam Lithography

Electron beam lithography (EBL) refers to the process of using electron beams to transfer patterns on the surface, that is an extended application of photolithography. The accuracy of photolithography is affected by the scattering of photons on the wavelength scale. The shorter the light wavelength used, the higher the accuracy that can be achieved by photolithography. According to De Broglie's theory of matter waves, electrons are waves with extremely short wavelengths. In this way, the accuracy of EBL can reach the nanometer level, which provides a very useful tool for making nanowires and other nanostructures. EBL is widely used in the

semiconductor industry to explore the next generation of very large-scale integrated circuits.

The main processes of EBL are substrate surface pretreatment, photoresist coating, pre-baking, electron beam exposure, development, metal deposition or etching, and lift-off. The entire photolithography process is relatively complicated, and the correlation between every process is extremely critical, so each step of the process is very important. The schematic diagram of the process is as follows.

Fig. 3.2 Electron beam lithography process [96].

3.2.1 Substrate surface pretreatment

To ensure uniform photoresist coating, chemical solutions (such as acetone, isopropyl alcohol solution) need to be used to remove oxides and stains on the surface, and then rinsed with deionized water. In order to enhance the bonding force between the substrate and

photoresist film, the wafer needs to be baked for surface moisture removal.

3.2.2 Photoresist coating

Common coating methods include spin coating, spray coating and quantitative dispensing. Due to the high viscosity of ZEP520A and PMMA, the coating thickness is generally not more than 1 μm , and spin coating is usually used. The spin coating method is to drop the photoresist on the center of the wafer to rotate at a high speed (usually 3000-4000 r/min), and the photoresist evenly spreads the entire wafer by virtue of the centrifugal effect. The process is shown in the figure below.

Fig. 3.3 Stages of spin coating [97].

3.2.3 Pre-baking

The purposes of pre-baking are to make the solvent in the photoresist volatilize and

strengthens the bonding force between it and the wafer, and secondly promotes the self-levelling of the photoresist film and releases the internal stress of the film. Excessive pre-baking will cause the film to get harden or even peeled. The hardening of the film is not conducive to the elimination of its internal stress. Also, insufficient pre-baking will lead to incomplete solvent volatilization, resulting in defects in the film and floating resist phenomenon during development. Generally, the baking condition for ZEP520A is hot-plate baking at 95°C for 2 min.

3.2.4 Exposure

Exposure is a key process in the EBL process, and it is the most complicated step. The dimensional accuracy of the exposed pattern directly affects that of the processed samples. The exposure dose has the greatest impact on the exposure effect. If the exposure dose is insufficient, the polymer chains in the photoresist will not be fully broken, and the photoresist will remain on the sample surface during development, resulting in incomplete developed patterns, irregular shapes, and pattern depth lower than design requirements, etc., as shown in the figure below.

Fig. 3.4 Examples of (a) under-exposed, (b) good and (c) collapsed grating patterns in SEM images [98].

3.2.5 Development

The developing solvents are always required in the development process for selectively dissolving the unexposed (negative-tone resist) or exposed (positive-tone resist) part. For the commonly used AZ developer, the tri-sodium phosphate and disodium metasilicate solvents are mixed for generating fine-feature patterns [99]. The fixing process is to stop the development of the developer by using a fixing solution to avoid over-development. After that, the sample needs to be baked for volatilize the remaining developer and fixing solution in the photolithographic pattern, and to improve the bonding force between the photoresist and the substrate. The baking temperature and time depends on the type of photoresist and the thickness of the film after spin coating. If the baking condition is not in place, the pattern may collapse.

3.2.6 Metal deposition and lift-off

At present, the main methods for metal deposition are electroforming, magnetron sputtering, thermal evaporation and others. However, in micro-nano size electroforming, it is difficult to enter the photolithographic pattern due to the surface tension of the electroforming liquid. Therefore, magnetron sputtering and thermal evaporation are mainly used at present. Because resist is easy to dissolve in acetone and dimethylacetamide, which are always used as a resist remover to dissolve the photoresist under the metal layer or after etching process. After the resist is dissolved, the metal film is suspended. Ultrasonic vibration can be used to remove the suspended metal film, so that the designed metallic pattern is transferred on the sample, which is a typical lift-off process.

In conclusion, EBL is the lithography technology with the highest resolution so far. Because the direct writing method does not require expensive and time-consuming masks and the processing method is more flexible, it has attracted widespread attention. With the continuous improvement of industry requirements for semiconductor technology, EBL has gradually become a new pillar of semiconductor technology. With the advancement of science and technology, EBL technology has also obtained new applications, such as hybrid lithography technology combined with X-ray and ultraviolet light, nanoimprint technology, metal-assisted electrochemical etching technology, etc., EBL will have a place in the next generation of lithography.

3.3 Inductively Coupled Plasma - Reactive Ion Etching

The plasma etching process for semiconductor materials is an important technology in VLSI, ULSI and emerging MEMS processing. Reactive Ion Etching (RIE) is commonly used

in large-scale integrated circuit manufacturing, has reached its limit for processing wafers with a diameter of more than 200 mm and line widths and holes of 0.25 μm . Low-pressure high-density plasma etching equipment etc. can solve this problem and achieve low damage and high etching rate. Compared with electron cyclotron resonance (ECR), Inductively Coupled Plasma (ICP) etching technology has the characteristics of simple structure, highly cost effective, simple operation, larger ring-to-diameter ratio and smaller equipment. In recent years, it has been highly valued and developed rapidly. The ICP source also has the advantages of uniformity at least within a diameter of 20 cm, independent control of ion density and ion energy, which has currently become an ideal plasma source.

The ICP system has become the main tool for high-density plasma processing. ICP reaction can obtain high-density plasma greater than 10^{11} cm^{-3} , which can be used to realize advanced processing [100]. For example, deep etching of silicon wafers at room temperature can achieve high etching rate ($\sim 13 \mu\text{m}/\text{min}$), high aspect etching ratio, high selectivity, while keeping the sidewalls steep, the etching depth can be greater than 600 μm (etch through substrate), this etching process is widely used in various deep etching, such as MEMS production. By adding a de-passivation step between passivation and etching, or by controlling the thickness of the polymer thin layer, and reasonably adjusting other etching parameters, not only an anisotropic side surface can be etched, but also the inclination of side surface can be made change within a certain range [101], [102]. Using ICP etching technology to etch silicon-based materials and III-V compounds can also obtain good etching results.

Fig. 3.5 Schematic diagram of ICP-RIE [103].

Plasma is a mixture composed of electrons, positive and negative ions, and unionized neutral gas molecules. The total amount of positive and negative charges is equal, the net charge is zero, and the external appearance is neutral. The traditional method of generating plasma is to use direct-current glow discharge or high-frequency glow discharge, but the plasma produced by these two methods has high working pressure, low plasma density, and the applied voltage is too high, which cannot be adapted to the processing requirement for VLSI manufacturing. The emergence of ICP equipment can well solve the above problems.

Corresponding plasma can be generated in the ICP device by applying a coupled radio frequency electromagnetic field to the non-resonant induction coil. Generally, the frequency of the applied radio frequency electromagnetic field is 13.56 MHz. The ICP equipment was

originally a planar inductor invented by Keller [104]. The cavity of the ICP reaction equipment used for etching is usually cylindrical, and can be roughly divided into cylindrical helical antenna ICP, planar helical coil ICP and plug-in coil ICP according to the shape of existing radio frequency antennas [105]. The planar coil is invented by Lam Research, which is beneficial to uniformity, but the coupling technology is more difficult; the cylindrical spiral coil is also invented by Lam, that the coupling technology is less difficult. These two ICP reaction equipment are the most basic.

For the ICP-RIE, there are generally two sets of radio frequency sources controlled by automatic matching network. One of the ICP source controls the generation of plasma and adjusts the plasma density; the other RIE source controls the energy of ion bombardment and surface etching. ICP-RIE etching is a typical plasma-assisted etching that combines physical and chemical etching mechanisms. The role of the two mechanisms in etching is affected by factors such as the partial pressure ratio of reactant gas and inert gas, gas flow rate, reaction chamber pressure, applied voltage on substrates, and ICP coil power. Through the different combinations of the above various conditions, the etching mechanism can be divided into the following types [106]: (a) physical sputtering - the pure physical removal of the material by the energetic ions generated by gas molecules; (b) chemical plasma etching - neutral groups formed in the plasma react with the substrate to generate volatile products; (c) ion-enhanced chemical etching - energetic ions destroy the surface to enhance the surface chemical reaction rate or help enhance the removal of chemical reaction products from the surface; (d) pseudo-ion-controlled chemical etching - similar to (c) but the pseudo-preparation passivates the surface to make it less susceptible to ion bombardment. A basic reactive ion etching process is

based on (c) or (d), which combines chemical and physical etching mechanisms.

3.4 Electron Beam Evaporation

Electron beam (e-beam) evaporation is a method of vacuum evaporation, which is developed on the basis of tungsten filament evaporation. The e-beam is a high-speed flow of electrons. E-beam evaporation is a mature and main coating method in the current vacuum coating technology. It solves the problem that the film material and the evaporation source material are directly contacted and easily mixed in the resistance heating method. This method can evaporate high-melting-point materials and has higher density and faster evaporation speed than general beam currents. The produced film has high purity, good quality, and its thickness can be controlled more accurately, so that e-beam evaporation can be widely used to generate high-purity films, conductive glass and other optical material films. The characteristic of e-beam evaporation is that it does not or rarely covers sides of the three-dimensional samples, and usually only deposits on the target surface. This is the difference between electron beam evaporation and sputtering. It is commonly used in the fields of semiconductor scientific research industries. Use the accelerated electron energy to hit the material target, and make the material target evaporate, finally deposited on the target.

Fig. 3.6 E-beam evaporation schematic diagram [107].

The schematic diagram of e-beam evaporation is shown above. It is mainly composed of a control system, a vacuum system and an electron gun system. For the vacuum system, there are two mechanical pumps in the vacuum gas path, namely the front-stage mechanical pump and the high-vacuum cryopump. The cryopump is mainly used at a very low temperature to achieve vacuum based on the original cryogenic adsorption. purpose. During the startup of the high-vacuum cryopump, the front-stage mechanical pump will first make the pipeline in a vacuum state. When the vacuum of the pipeline reaches a certain level, the valve will open. So that the front-stage mechanical pump will continue to work, both the pipeline and cryopump have a vacuum state. The evaporation source of the e-beam is mainly composed of an electron gun and a crucible, and a set of mechanical equipment that can provide raw materials for the machine may be attached when necessary. In most cases, the design of the crucible and the control device for generating and controlling the electron beam will be integrated into the machine.

The working principle is that under high vacuum, the electron gun filament emits thermionic electrons after being heated, which is accelerated by the accelerated anode, and obtains a large amount of kinetic energy to bombard the evaporation material. The kinetic energy is converted into heat to vaporize the evaporation material, thereby realizing the coating. The e-beam evaporation source is composed of a hot cathode for emitting electrons, an electron accelerating electrode and a coating material as an anode. The energy of the e-beam evaporation source can be highly concentrated, so that the coating material reaches a high temperature locally and evaporates. By adjusting the power of the e-beam, the evaporation rate of the coating material can be conveniently controlled, which is especially beneficial for high melting point and high purity metal and compound materials.

3.5 Fourier transform infrared spectroscopy

The Fourier transform infrared (FTIR) equipment is mainly a Michelson interferometer, where the principle is shown in Fig. 3.7. The polychromatic light source inside the spectrometer is divided into two beams by the beam splitter in the interferometer, and then returns to the beam splitter through the reflection of the scanning mirror and fixed mirror to form interference. The interference light acts on the detector under test, as such, the photogenerated current is formed in the detector [108]. Due to the optical path difference between the scanning mirror and fixed mirror, the light intensity signal measured by the detector is a function of the optical path difference, and the photogenerated current is also a function of the optical path difference, as shown in the following equation:

$$I_L(x) = \int_{-\infty}^{\infty} P(v)R(v)\cos 2\pi vx dx \quad (21)$$

where $P(\nu)$ is the power distribution of the polychromatic light and ν is the frequency of the light. When measuring the spectral response of the detector, the power distribution of the polychromatic light should be a constant, and $R(\nu)$ is the spectral responsivity of the detector.

Fig. 3.7 The schematic diagram of FTIR operation principle [109].

The photogenerated current is amplified by the pre-amplification circuit built in the FTIR, and then sent to the computer for inverse Fourier transform, and the spectral response curve of the detector to be measured is obtained, as shown in the following formula:

$$R(\nu) = \frac{1}{P} \int_{-\infty}^{\infty} I(x) \cos 2\pi \nu x dx \quad (22)$$

The change of the optical path difference is realized by the movement of the scanning mirror of the interferometer. It can be seen from the formula that the integral of the optical path difference must be from $-\infty$ to $+\infty$. In the actual measurement, because the moving range of the scanning mirror is limited by space, the above-mentioned integral range cannot be infinite,

usually only tens of centimeters, which is bound to introduce the system error into the measurement [110]. Suppose the range of the optical path difference is $[-a/2, a/2]$, then the above integral formula is:

$$R'(v) = \frac{1}{P} \int_{-a/2}^{a/2} I(x) \cos 2\pi v x dx \quad (23)$$

Introduce the apodization function $g(x)$, the above transformation spectrum should be expressed as:

$$R'(v) = \frac{1}{P} \int_{-a/2}^{a/2} I(x) g(x) \cos 2\pi v x dx \quad (24)$$

The commonly used function types are rectangular apodization function:

$$g(x) = \begin{cases} 1 & |x| < \frac{a}{2} \\ 0 & \text{other range} \end{cases} \quad (25)$$

The right side of the above equation is the Fourier transform of the product of the two functions. In the calculation, the two functions are first subjected to Fourier transform, and then the transform result is convolved, so that the actual spectral distribution can be obtained from the interference pattern.

Assuming that the incident light is monochromatic light, the broadening of the corresponding output spectrum can be calculated Δu , which is expressed by the FWHM of the spectral peak:

$$\Delta u = \frac{2\pi}{a} \cdot \frac{65}{108} \cdot 2 \quad (26)$$

For the commonly used FTIR, set a to be 50 cm, the value of Δu can be obtained as 0.15 cm^{-1} by substituting the above formula. This has little effect on the characterization measurement of most material and common device spectra. For example, the wavelength of the spectrum of semiconductor materials is 1 μm to 10 μm , and the corresponding wave number

is 10000 to 1000. This error is only 10^{-3} to 10^{-4} and can be ignored.

For measuring the photoresponse spectrum, the detector to be measured replaces the detector in the system to detect the light output from the interferometer. After the signal is processed by the computer, the detector photocurrent to be measured is obtained as the response spectrum.

3.6 Photoresponse measurement

The schematic of photoresponse measurement system setup in our work is shown in Fig 3.8. A 1000-K blackbody radiation source is used to measure the detector responsivity in the IR range, where a chopper and an NIR (1-3 μm) or MIR (2.5-4.8 μm) bandpass filter are set before the radiation reaching the detectors under test. The measured photocurrent is converted into a photovoltage by a low-noise current preamplifier, and then read out by a lock-in amplifier. With the values of photocurrent (I_{PH}) and incident power (P_{inc}) obtained from a standard power meter, the blackbody responsivity (R_A) is thus derived from $R_A = I_{PH} / P_{inc}$.

Fig. 3.8 The schematic of photoresponse measurement setup.

For the response speed measurement, the detectors are illuminated by a 2.94 μm laser with a fixed rise and fall time of ~ 20 ns and the output power of the laser source for different modulation frequencies is calibrated by a standard powermeter. An oscilloscope after a preamplifier is used to record the response waveform. The rise time is then recorded in the time duration from 10% up to 90% of the maximum value, as well the amplitude-frequency waveform is documented by the amplitude difference in each frequency.

3.7 Summary

This chapter briefly introduces the key methods in the simulation, fabrication and characterization of detector. Before fabrication process, the FDTD method should be used to establish an accurate simulation model. Then, a set of the advanced fabrication equipment are used to realize the detector closest to the designed performance by simulation. For example,

use EBL to transfer nano- or micro-sized patterns to the substrate, use ICP-RIE to etch group III-V material for smooth surface and straight sidewall, and use e-beam evaporation to obtain high-quality metallic films. The fabricated detector is finally measured by FTIR to characterize the photoresponse performance. Only when the above-mentioned series of processes mentioned are designed very accurately, a high-performance detector can be ultimately obtained.

Chapter 4. Dark current analysis of InAsSb-based heterojunction photodiode

Among the infrared spectrum, middle infrared (3-5 μm) photodetection is of great significance for various important applications, such as remote-sensing, night-vision, security, and medical diagnosis. High-temperature operational focal plane arrays have always been pursued for this range. In this chapter, the dark current characteristics of InAsSb-based heterojunction photodiodes will be studied. Detailed study of dark current including surface leakage and bulk diffusion, SRH, and tunneling process in the photodiodes will be conducted based on dark current-voltage characteristics of square mesa devices with different sizes and under different temperatures.

4.1 Heterostructure design

The heterostructure was grown via a RIBER-32 MBE system. It was grown on an n-type GaSb substrate with a 1000 nm thick p-type GaSb buffer layer. The schematic of the device, shown in Fig. 4.1(a), includes a 30 nm thick p-type $\text{Al}_x\text{Ga}_{1-x}\text{Sb}$ layer with the x varying from 0.1 (p-GaSb side) to 0.42 (p-AlInAsSb side), a 40 nm thick p-type $\text{Al}_{0.42}\text{Ga}_{0.58}\text{Sb}$ layer, a 20 nm thick p-type $\text{Al}_{0.2}\text{In}_{0.8}\text{As}_{0.91}\text{Sb}_{0.09}$ layer, a 1500 nm thick unintentionally doped (u.i.d) $\text{InAs}_{0.91}\text{Sb}_{0.09}$ absorber layer, a 20 nm thick n-type $\text{Al}_{0.15}\text{In}_{0.85}\text{As}_{0.91}\text{Sb}_{0.09}$ layer, and a 50 nm thick n-type GaSb top contact layer from bottom to top. All the doped layers have a doping concentration of $2 \times 10^{18} \text{ cm}^{-3}$.

Fig. 4.1 (a) Structure of the heterostructure photodiode. (b) Schematic of energy band diagram of the photodiode. (c) PL spectrum at different temperatures. (d) Microscope images of photodiodes with different mesa sizes.

To obtain good high-temperature performance, we attempt to reduce the diffusion dark current originated from minority carriers in p- and n-side layers, which is usually the main contribution of bulk dark current at high temperature [2]. For this purpose, we inserted the large bandgap p-Al_{0.42}Ga_{0.58}Sb layer as a barrier layer to suppress the minority electron diffusion. To further decrease the minority carrier concentration, this p-Al_{0.42}Ga_{0.58}Sb layer was heavily doped but without obvious bandgap narrowing. For limiting transitions between the InAs_{0.91}Sb_{0.09} and its side layers, we inserted quaternary AlInAsSb layers on both n- and p-sides. This structure has high conduction band offset and nearly zero valence band offset in the p-side (see Fig. 4.1(b)), which makes it possible to block the diffused minority electrons from p-side

while easily collecting the photo-generated carriers, the same way in the n-side. High-resolution X-ray diffraction (HRXRD) results demonstrate the good interface quality in this heterostructure [111]. Photoluminescence (PL) measurements were performed for temperatures ranging from 13 K to 290 K, the corresponding results are shown in Fig. 4.1(c). With the temperature increasing, “red shift” for peak position is obvious and the FWHM of PL spectrum at 13 K is about 29 meV, indicating the good quality of this InAs_{0.91}Sb_{0.09} absorber layer [112]. The energy of the peak PL intensity fits well with the Varshni law $E_g(T)=E_g(0)-\alpha T^2/(\beta+T)$, where $E_g(0)$ is the band gap energy at 0 K, α and β are Varshni coefficients. The derived $E_g(0)$ is 0.3362 eV, corresponding to 3.688 μm in wavelength, α and β are 0.26 meV/K and 158 K, respectively, which are in good agreement with reported values [113], [114].

4.2 Device fabrication

Standard optical photolithography was used to define the square mesas with their sizes varying from 500 μm down to 20 μm . The mesas were etched down to the p-type GaSb buffer layer using high-temperature ICP-RIE, immediately followed by rinsing using H₂SO₄/H₂O₂/H₂O solution for chemical surface regeneration [115]. A 300-nm thick SiO₂ layer was deposited by chemical vapor deposition (CVD) to protect the mesa and isolate the electrodes. The absorption area was then defined by opening window on the SiO₂ layer using RIE. Meanwhile, a window was also opened for metal contact on the p-type buffer GaSb layer. Finally, Ti/Au (25/300 nm) was deposited by electron beam evaporation to form metallic contacts on the p-type buffer GaSb layer and n-type GaSb layer. Their good ohmic contact properties have been demonstrated separately by measuring the current-voltage characteristics

in metal-semiconductor-metal structures. Fig. 4.1(d) shows microscope images of devices with different mesa sizes.

4.3 Results and discussion

Dark current measurements were conducted under vacuum within liquid nitrogen cooled probe station in the range of 77 K to 293 K. For the mesa type devices, the dark current density can be expressed as $J=I/A=(I_B+I_S)/A=J_B+J_S\cdot P/A$, where I_B (J_B) is the bulk dark current (density), and I_S (J_S) is the surface dark current (density), P/A is the perimeter to cross-sectional area ratio. At room temperature (293 K), the dark current density J as a function of the P/A under applied bias from 0 V to -1.5 V and their linear fitting lines are shown in Fig. 4.2(a). Based on the derived fitting coefficients, the J_B and J_S at corresponding bias are shown in Fig 4.2(b). It can be seen that the J_S increases with the applied reverse bias, which can be attributed to the enhanced influence of the trap-assisted tunneling (TAT) as the electric field becomes stronger [12]. As for the J_B , we can also observe the rising trend with the reverse bias, which will be elucidated when later we discuss the bulk dark current contribution. In addition, the dark current density J as a function of P/A ratio and the linear fitting under applied bias of -0.1 V at temperatures from 77 K to 293 K are also conducted (Fig. 4.2(c)). The derived J_B and J_S at corresponding temperatures are shown in Fig. 4.2(d). We can observe a mild increasing trend of J_S with the increase of temperature, which is in agreement with normally observed characteristic [12]. Below 215 K, J_B slightly increases with the temperature; however, it will have a strong dependence on temperature above 215 K.

Fig. 4.2 (a) Dark current density (J) vs. perimeter to area (P/A) ratio for photodiodes with different mesa sizes measured at 293 K under applied bias from 0 V to -1.5 V. (b) The derived bulk dark current density (J_B) and surface leakage current density (J_S) vs. voltage bias at 293 K. (c) Dark current density (J) vs. perimeter to area (P/A) ratio for photodiodes with different mesa sizes measured under an applied bias of -0.1 V at different temperatures. (d) The derived bulk dark current density (J_B) and surface leakage current density (J_S) vs. temperatures under an applied bias of -0.1 V.

Fig. 4.3 The extracted bulk dark current (I_B) and surface leakage current (I_S) vs. mesa size under applied bias of (a) -0.1 V, (b) -0.3 V, (c) -0.5 V, and (d) -0.7 V.

Figures 4.3(a)-(d) show the extracted room-temperature I_B and I_S vs. mesa size under applied bias from -0.1 V to -0.7 V. It is clear to see both values increase with the mesa size, and over the region of mesa sizes from 20 μm to 500 μm , the I_B is always greater than the I_S when the magnitude of the reverse bias is smaller than 0.5 V. This reverse bias value is much larger than the operating bias of our photodiode, which is around zero bias. However, I_S becomes larger than I_B for small mesa devices when the magnitude of the reverse bias is 0.7 V (Fig. 4.3(d)). But for large mesa devices, I_S is still smaller than I_B . These results indicate that the effects of surface leakage on the photodiode will become more and more serious when the

magnitude of the reverse bias becomes larger. Meanwhile, this also demonstrates the significant effects of surface leakage current in small mesa devices [116].

To study the effects of temperature on I_B and I_S , Figs. 4.4(a)-(d) further present the extracted I_B and I_S vs. mesa size under applied bias of -0.1 V at temperatures from 255 K to 185 K (the results for 293 K has been shown in Fig. 4.4(a)). As shown, for small mesa devices, I_S is smaller than I_B when the temperature is larger than ~ 215 K. However, it becomes larger than I_B when the temperature is decreased to 185 K (Fig. 4.4(d)). It means that as the temperature decreases, the bulk current can be reduced much faster than the surface leakage, which is mainly attributed to the strong temperature dependence of diffusion and SRH current. Therefore, the effect of surface leakage will become more and more influential at low temperature, which is the limiting factor to the photodiode performance at low temperatures [117].

Fig. 4.4 The extracted bulk dark current (I_B) and surface leakage current (I_S) vs. mesa size under applied bias of -0.1 V at (a) 255 K, (b) 235 K, (c) 215 K, and (d) 185 K.

The surface leakage current originates mainly from physical damage caused in dry etching, non-ideal passivation, chemical clean-up process, gate effect from sidewalls, and the inherent issue of surface pinning of layers in the structure with high indium contents [118]. In our device fabrication, since we used the $H_2SO_4/H_2O_2/H_2O$ solution to rinse the device immediately after high-temperature ICP-RIE, the surface structural or optical damages are less than when only mechanical etching is used [115]. In our case, J_S is only about $8.18 \times 10^{-5} \text{ A} \cdot \text{cm}^{-1}$ at 293 K under applied bias of -0.1 V, which is smaller than the reported values of $1.55 \times 10^{-4} \text{ A} \cdot \text{cm}^{-1}$ for HgCdTe $p^+B_p n N^+$ barrier detectors [119], $2 \times 10^{-3} \text{ A} \cdot \text{cm}^{-1}$ for low-leakage InAsSb nanowire

photodetectors [120], and comparable with the reported values of $1.1 \times 10^{-5} \text{ A}\cdot\text{cm}^{-1}$ for the larger bandgap germanium-tin on silicon photodiode with surface passivation [121].

Table I. A summary of dark current density at room temperature under applied bias of -0.1 V of recently reported MIR photodetectors.

Detector type	Dark current density ($\text{A}\cdot\text{cm}^{-2}$)	Mesa diameter (μm)	Reference
InAsSb nBn diode	1.6	200	[5]
InAs _{0.7} Sb _{0.3} bulk photodiodes	450	195	[122]
InAsSb photovoltaic using barrier structure	20	500	[13]
Commercial InAsSb photovoltaic detector	1.9	1000	[123]
Type-II InAs/GaSb superlattice photodetectors	3.0	400	[43]
Hetero InAsSb photodiode	0.605	50	this work

In the following, we will study the bulk dark current of the hetero photodiode. Fig 4.6(a) shows the measured dark current density as a function of the voltage bias for temperatures ranging from 77 K to 293 K. We use the mesa size of $50 \mu\text{m}$ as the example, since it is very close to the pixel size for the focal plane array. As shown, good rectification characteristics of this heterostructure is observed. Under applied bias of -0.1 V , the dark current density is as small as $0.605 \text{ A}\cdot\text{cm}^{-2}$ at 293 K and it can be reduced to $6.6 \times 10^{-2} \text{ A}\cdot\text{cm}^{-2}$ and $1.16 \times 10^{-3} \text{ A}\cdot\text{cm}^{-2}$ at 255 K and 215 K, respectively. In Table I, we summarize the dark current density at room temperature under applied bias of -0.1 V of recently reported MIR photodetectors as well as the commercial products. Besides, the dark current density for the work of InAs_{0.91}Sb_{0.09}

photodiode without wide bandgap barrier layer, is above 40 A/cm^2 under the bias of -0.05 V [124]. Therefore, compared to the state-of-the-art photodetectors, owing to the special device design and lattice matched growth, our hetero photodetector, even with the smallest mesa size, has the lowest dark current density at room temperature. As such, it is demonstrated in Fig. 4.5(a) this heterojunction $n-i-p$ photodiode reaches a room-temperature blackbody detectivity of $1.5 \times 10^9 \text{ cm} \cdot \text{Hz}^{1/2} \text{ W}^{-1}$ under zero bias. Besides, the broadband spectral response behaviour is shown in Fig. 4.5(b).

Fig. 4.5 (a) Room-temperature blackbody detectivity under different voltage bias.
(b) Photocurrent spectra under zero bias measured at 300 K, 250 K and 180 K [111].

To gain the insight on the dominant dark current mechanism, Arrhenius plot of the dark current density ($\ln|J|$ vs. $1000/T$) under the applied bias of -0.1 V , -0.3 V and -0.5 V for the $50 \mu\text{m}$ square mesa is presented in Fig. 4.6(b). Normally, under the specific reverse bias, the plot can be fitted within a certain temperature range to extract the activation energy which determine the dominant mechanism by comparing with the temperature dependence of different types of dark currents, such as diffusion, SRH and tunnel current [125]. Diffusion

dark current mainly comes from the diffusion of minority carriers and the SRH process is usually very efficient in the depletion region of photodiodes, where the mid-gap traps are activated. It is usually the main source of dark current components in MIR photodiodes at relatively low temperature.

Fig. 4.6 (a) Dark current density vs. voltage bias for a $50\ \mu\text{m}$ square mesa photodiode at different temperatures from $77\ \text{K}$ to $293\ \text{K}$. (b) $\ln(|J|)$ vs. $1000/T$ for the $50\ \mu\text{m}$ square mesa photodiode under applied bias of $-0.1\ \text{V}$, $-0.3\ \text{V}$ and $-0.5\ \text{V}$, combined with linear fits for the activation energy at high temperatures. (c) Dark current density vs. voltage bias for photodiodes with different mesa sizes at $293\ \text{K}$. (d) $\ln(|J|)$ vs. $1000/T$ for the photodiodes with three typical mesa sizes under $-0.1\ \text{V}$. (e) Dark current activation energy vs. voltage bias for the $50\ \mu\text{m}$ square mesa photodiode at temperatures from $215\ \text{K}$ to $293\ \text{K}$. Horizontal dotted lines represents the bandgap from $215\ \text{K}$ to $293\ \text{K}$ derived from Fig 4.1(b).

For temperatures from 255 K to 293 K, the relation between the dark current density and temperature can be well fitted with the diffusion dark current equation $J_{\text{diff}} \sim T^3 \exp(-E_g/k_B T)$ as shown in the purple dashed line in Fig. 4.6(b). As the activation energy of E_a is ~ 0.3 eV which is quite close to the bandgap energy of the absorption layer, indicating that the diffusion current is dominant in this temperature range. For temperatures from 185 K to 215 K, the curve can be well fitted with the SRH recombination current equation $J_{\text{SRH}} \sim T^{3/2} \exp(-E_g/2k_B T)$, as shown in the green dashed line. As the activation energy E_a is ~ 0.155 eV which is close to half of the band gap energy of the absorption layer, indicating that the SRH current is dominant in this range. Below 170 K, the dark current has a very weak dependence on the temperature, indicating that the tunnel dark current is dominant in this region [126]. It is noted that the temperature dependence of the diffusion dark current is stronger than that of the SRH dark current. In other words, as the temperature decreases, the diffusion dark current can be reduced much faster than the SRH dark current. It has been reported that doping the active intrinsic layer slightly can help to reduce the generation-recombination process, therefore, reduce the dark current [2].

The dark current results of the photodiodes with different mesa sizes are presented in Fig. 4.6(c). As shown, the small mesa diodes have relatively large dark current density due to the large contribution of surface leakage (large P/A value). The extracted activation energies for the three photodiodes with typical mesa sizes of 50 μm , 300 μm and 450 μm show similar results (Fig. 4.6(d)).

Finally, the activation energy versus voltage bias at relatively high temperatures from 215 K to 293 K is shown in Fig. 4.6(e) for the 50 μm square mesa diode. The dashed lines exhibit

the E_g value at this temperatures range, indicating the diffusion limited region. The relation between E_a and E_g is well fitted with the result as shown in Fig. 4.6(b). It is observed that the activation energy at 293 K across an observable bias range is higher than the bandgap energy. The extra part of these activation energies may result from the accumulation at the interface between the InAs_{0.91}Sb_{0.09} absorber layer and large-bandgap p- Al_{0.42}Ga_{0.58}Sb layer [125]. It is noted that the activation energy decreases as the applied bias varying from -0.3 V to -1 V at different temperatures [125], this can be mainly due to the SRH and tunneling process in the photodiode.

4.4 Summary

The design, fabrication and characterization of an InAs_{0.91}Sb_{0.09}-based heterostructure photodiode are presented. A large bandgap p-AlGaSb layer is inserted to reduce the diffusion of minority electrons and two quaternary AlInAsSb layers are also used to limit type-II transitions between the InAs_{0.91}Sb_{0.09} and its side wide bandgap layers. The high-quality epitaxial layers were confirmed by HRXRD measurement and temperature-dependent PL spectra, which is important for achieving good detector performance. Detailed study of dark current including surface leakage and bulk diffusion, SRH, and tunneling process is conducted based on dark current-voltage characteristics of square mesa devices with different sizes and in different temperatures. For the 50 μm square mesa device under applied bias of -0.1 V, the dark current (density) is reduced to only 1.5×10^{-5} A ($0.6 \text{ A} \cdot \text{cm}^{-2}$) at room temperature (293 K), which is smaller than those recently reported nBn and photovoltaic detectors.

Chapter 5. Plasmonic Structures for Enhancement of MIR Photodetection

Current detection technologies are mainly based on excellent optoelectronic absorbers such as InGaAs in NIR [127], MCT in MIR [128], [129], and QWIP structures in LIR ranges [130]. The photodetection relying on the absorption by sensitive optoelectronic materials has been inherently limited by the absorption law $\exp(-\alpha d)$ [1], where α is the absorption coefficient and d is thickness of the absorption layers. For sufficient photon absorption, the detection structure on one hand, requires high α , and on the other hand, requires large d to give high quantum efficiency. However, for an optimized absorber, α is fixed, therefore, very large d is required to ensure that. Nevertheless, the large reflection loss still limits the maximum quantum efficiency. Besides, the large value of d will bring some realistic difficulties, such as large stress and high cost of products in material growth and complex process in device manufacturing [20].

The field of plasmonics studies the unique properties of light arising from the interaction between light and the metallic nanostructures at sub-wavelength scale [45]–[48]. Those nanostructures own the capability of supporting collective electron excitations, known as surface plasmons. When surface plasmon resonance occurs, the ability to concentrate light or produce large local field in extremely small volume enables significant absorption of electromagnetic waves in the optoelectrical absorbers. This kind of property has been widely utilized for improving the quantum efficiency of solar cells [49]. At IR range, metallic nanostructures are integrated with semiconductor detectors to enhance the absorption of photons, therefore, to improve the photoelectrical conversion efficiency. Thanks to the state-

of-the-art fabrication techniques such as EBL and FIB milling, as well as commercially available numerical design tools like FDTD, the design and fabrication of metallic nanostructures for infrared range now become very effective. Metallic nanostructures with different configurations and metals can be used to integrate with traditional detection structures such as heterojunction structure [16], [22], [111], [125], [131], [132], Schottky diode [23], quantum structures [24], and thermal detector [25]. Combined with these structures, the photoresponse of those detectors can be significantly improved.

Thus, in this chapter, the integrated devices with various plasmonic structures for MIR photodetection enhancement, including a U-SRR array and a rotated fourfold SRR array will be presented. The integrated plasmonic structures have the capability of confining IR light, accompanied with large optical field (power density) enhancement. We characterize the photocurrent spectra of the integrated devices, as well as reference ones at different applied voltage bias and temperatures. Obvious photocurrent enhancement is observed. Using this strategy, a maximum one order of magnitude of enhancement in middle infrared room-temperature detectivity (to about 2.0×10^{10} Jones) is achieved under zero bias without sacrificing the response speed.

5.1 U-SRR array enhanced MIR photodetector

In this section, we study the fundamental (m_0) and high order magnetic (m_1) and electric (e) modes of SRR array and present high order magnetic and electric modes enhanced photodetection performance of the integrated MIR photodetector consisting of a SRR array and an InAsSb-based heterojunction photodiode. Under zero bias, an uncooled detectivity of

$\sim 2.0 \times 10^{10}$ Jones is achieved without sacrificing response speed, which corresponds to about 10 times of enhancement. In addition, tunable enhancement by varying the spectral overlap between the two high-order modes and the absorption layer, and polarization-resolved photoresponse between the m_1 and e modes are also discussed.

5.1.1 Brief introduction of basic modes in U-SRR

Fig. 5.1 (a) Single SRR unit cell. (b-d) SRR mode characteristics for (b) m_0 mode under x polarized illumination, (c) e mode under y polarized illumination, and (d) m_1 mode under x polarized illumination.

In SRR, the magnetic and electric resonance modes are excited by different polarization-light (see Fig. 5.1(a)). The lowest order mode of an SRR is the fundamental magnetic resonance

(Fig. 5.1(b), m_0 mode) which is excited when the light is polarized along the SRR gap (x -polarization). In this situation, the accumulated electric charges at the SRR tips interact capacitively, giving rise to a circulating current along the SRR wire that produces localized magnetic fields perpendicular to the SRR plane (red arrow). This is also known as the “ LC ” resonance due to the strong resemblance of an SRR to an LC circuit. This resonance is associated with a strong horizontal electric dipole across the SRR gap. The strong radiation is thus generated from such an electric dipole, translating to reduced interaction between SRR and top contact layer due to radiative loss [133], [134]. The first high-order mode is the electric resonance (Fig. 5.1 (c), e mode) associated with plasmonic oscillations along the SRR vertical arms, which is excited when the light is polarized perpendicular to the SRR gap (y -polarization). The separated electric dipoles generated on each arm cannot generate circulating current, thus there is no magnetic dipoles generated in e mode [135]. In this way, the net dipole moments in e mode are not as large as in m_0 mode, leading to smaller radiation loss at the light-matter interaction. The second order mode is the higher-order magnetic mode (Fig. 5.1 (d), m_1 mode) associated with an electric dipole of the horizontal SRR bottom arm and anti-parallel electric dipole of the vertical SRR arms. This mode can be excited under y -polarized light at oblique incidence via exciting vertical dipoles with phase delays, or under x -polarization at normal incidence (in our case) via exciting the horizontal dipole [136] in SRR bottom arm which then leads to the generation of anti-parallel dipoles in SRR vertical arms due to the electric charge imbalance [137]. In this way, though there are three electric dipoles along the vertical and bottom arms, the radiation cancellation induced by the anti-parallel vertical dipoles can significantly reduce the loss, thus the electric field strength decays much slower than that of

the m_0 mode [135], [136], [138].

5.1.2 SRR-integrated photodetector design and fabrication

This section will present comparative investigation on the enhancement behavior of different resonant modes of the U-shape arrays. The design of the InAsSb-based heterostructure integrated with SRR array is presented in Fig. 5.2. The SRR array was integrated on top of GaSb contact layer in the p-type side. The InAsSb-based hetero photodiode was grown on n-type Te-doped GaSb substrate by MBE [131], which has the same heterostructure as the photodiode investigated in Chapter 4 except for the different layer sequence. Different from conventional homogeneous photovoltaic diode, a heterojunction with wide bandgap layers was used to reduce the dark current. The thicknesses of the p-type GaSb, AlGaSb and AlInAsSb layers were intentionally made much thinner (120 nm) so as to allow more interaction between the SRR arrays with the InAsSb absorption layer.

Fig. 5.2 Device schematic (not to scale) of the SRR-integrated InAsSb heterojunction photodiode.

Two kinds of devices with different SRR arrays on the identical InAsSb-based heterojunction photodiodes were first designed and fabricated for this study. The 390- μm sized square mesas were first defined by wet etching after standard photolithography, followed by deposition of 300 nm SiO_2 passivation layer (by PECVD) to reduce the surface leakage current and protect the mesas. The top and bottom contacts were then defined in the second photolithography step followed by lift-off of 20 nm thick titanium (as adhesion layer) and 200 nm thick gold (for ohmic contact). Using the alignment marks from the photolithography, the gold SRR arrays were then integrated onto the photodetector via EBL and standard lift-off process. The EBL process was based on 20 keV energy and 35pA beam current on 250 nm thick ZEP520A positive-tone resist on heterojunction InAsSb-based samples, where the SRR structures were patterned in a series of single pixel lines exposed at 200 pC/cm. The samples were developed for 20 s in ZED-N50 and rinsed for 20s in MIBK, both of which were done at room temperature. The gold thickness of the SRR was chosen to be 60 nm (with 3 nm titanium as adhesion layer) to avoid direct transmission through the metal film [139]. The skin depth of infrared wave in gold film (i.e., $\delta_s = \sqrt{\rho/(\pi f \mu)} \delta_s = \sqrt{\rho/(\pi f \mu)} \delta_s = \sqrt{\rho/(\pi f \mu)}$, where ρ is the resistivity, f is the frequency, and μ is the relative permeability) is found to be 6.15 – 9.72 nm for 2 – 5 μm wavelength range. The photodiodes without the SRR arrays were also fabricated as reference devices in measuring the photocurrent enhancement.

Fig. 5.3 (a) The SEM (false color) of SRR array on the heterojunction photodiode. (b)-(c) SEM images of fabricated (b) U-590 and (c) U-400 SRR arrays on the photodiode. All the scale bars represent 1 μm . (d)-(e) Simulated and measured reflection spectra of U-590 and U-400 under (d) x-polarized and (e) y-polarized illuminations. An Offset of 0.6 for U-590 was adopted.

The first SRR array (denoted here as U-590) was designed with the m_1 and e resonant modes overlapping with the photoresponse of InAsSb absorber (3-5 μm range), while the second SRR array (denoted here as U-400) was designed with the m_0 mode overlapping with it. Refer to Fig. 5.1(a), U-590 has the dimensions of $s=590$ nm, $w=160$ nm, $g=270$ nm, $t=60$ nm, and $p=900$ nm and U-400 has dimensions of $s=400$ nm, $w=150$ nm, $g=100$ nm, $t=60$ nm, and $p=600$ nm. The design of all the SRRs used in this work has been listed in Table V. The top view of the SRR photodetector is shown in Fig. 5.3(a). The fabricated U-590 and U-400 SRRs on top of the photodiodes are shown in Figs. 5.3(b) and (c).

Table II. Geometrical dimensions of the SRRs-arrays on heterostructure and Si

Sample	s (nm)	w (nm)	g (nm)	p (nm)	t (nm)
U-130	130	35	60	260	60
U-400	400	150	100	600	60
U-480	480	160	160	800	60
U-590	590	160	270	900	60
Si-U-520	520	160	160	1600	60
Si-U-320	320	130	60	480	60
Si-U-260	260	100	60	360	60

Figures 5.3(d) and (e) present the simulated and experimental reflection spectra of U-590 and U-400 under different polarizations. The polarization-resolved reflection measurements were carried out by FTIR coupled with Cassegrain-type objective lens and infrared polarizer. All measured spectra were normalized with respect to a gold mirror. For the reflection under x -polarization (R_x , Fig. 5.3(d)), the reflection peaks at longer and shorter wavelengths are identified as the m_0 and m_1 modes, respectively. The m_0 modes are found to be $6.75\ \mu\text{m}$ (for U-590) and $3.49\ \mu\text{m}$ (for U-400), in agreement with the linear dependence of LC resonance on SRR size [140]. The locations of m_1 modes are at $3.64\ \mu\text{m}$ for U-590 and $2.1\ \mu\text{m}$ for U-400. In general, the resonance modes from the experimentally measured spectra are less pronounced and broader than those from simulations. This might be attributed to the absorption of the photodiode, that introduces loss into the resonance modes. In order to verify this, we also fabricated similar SRR arrays on silicon substrate (whose dielectric constant is comparable to that of the InAsSb layer but with ignorable absorption) and observed more pronounced resonances in all modes (Fig. 5.4). The other cause for the difference between the simulated and measured reflection spectra at resonance modes, particularly for m_1 mode, is the weak excitation for normal incidence due to the anti-parallel vertical electric dipoles that cancel each

other²⁶. For the reflection under y-polarization (R_y , Fig. 5.3(e)), the e modes can be observed with their positions spectrally close to those of m_1 modes. This can be understood from the perspective of resonance-splitting in mutually-coupled plasmonic nanorods, where the e and m_1 modes are the symmetric and anti-symmetric modes resulting from mode hybridization [137]. It was thus found that the e and m_1 modes of U-590 overlapped with the spectra of InAsSb absorption layer as their resonant wavelengths reside near the bandgap of InAsSb at room temperature ($\sim 4.1 \mu\text{m}$). Meanwhile, the U-400 exhibits the overlap for its m_0 mode.

Fig. 5.4 Simulated and measured reflection spectra of SRR arrays on silicon substrate. (a) U-520, (b) U-320, and (c) U-260 under x-polarized and y-polarized illuminations. The SEM micrographs of each SRR are given in the insets, with all scale bars representing 1 μm .

5.1.3 Modes characterization in U-SRR array photodetectors

To gain insights on the field distribution of different resonant modes in the SRR arrays. We study the electric field enhancement (E/E_0 , E_0 is the electric field in bare photodiode) of the two SRR arrays integrated on the heterostructure photodiodes. All the simulations were performed using FDTD method, where round edges of 5 nm curvature were introduced to avoid numerical artefacts generated from the sharp edges. Periodic boundary conditions were used in the SRR unit cell and the mesh size was set to 1 nm in all simulations. The permittivity of gold was obtained from Palik [141], while the dielectric constant of the heterostructure photodiode was obtained from measured data and published literatures [142]. The dimensions of all the simulated SRRs on both heterojunction and silicon samples are presented in Table V.

In Fig. 5.5, we plot E/E_0 distribution for m_1 and e modes of U-590 and m_0 mode of U-400 as they locate in the photoresponse range of the photodiode. At the interfaces between the SRRs and top layer of the photodiode (GaSb contact layer, S1 group), all the modes exhibit strong light confinement expressed as significant field enhancement. The m_1 mode of U-590 offers the largest E/E_0 , followed by the e mode of U-590 and m_0 mode of U-400. The field distribution of the interface between SRR and top contact layer reflects the characteristic of different LSP modes in SRRs. As resonance occurs, the incident IR wave induced field would be concentrated around the interface. The enhanced optical electric field (power density) will excite more electron and hole pairs which become enhanced photocurrent after efficient collection by the electrodes. To study their contribution to performance improvement of photodiodes, we need to know the field enhancement in the absorber layer, that is, the InAsSb layer in our photodiodes. Therefore, we plot the distribution of E/E_0 in the upper surface of the InAsSb

absorber layer (S2 group). As shown, the E/E_0 at m_1 mode of U-590 is still the largest, followed by that at e mode of U-590, and at m_0 mode of U-400 which is drastically decreased. The distributions of E/E_0 in y-z (S3 group) cutting planes (from S1 group) offer clear expression on this. The horizontal dark dash lines represent the top surface of the absorber. As shown, E/E_0 at m_0 mode of U-400 decays very fast from the interface, as at the top surface of the absorber, E/E_0 has been already very close to the minimum. However, at m_1 and e modes of U-590, the E/E_0 still hold strong distribution tail in the absorber, especially for the m_1 mode.

Fig. 5.5 Analysis of resonant modes of U-590 and U-400 SRR arrays on InAsSb photodiodes. The m_1 and e modes of U-590 SRR array are at $3.64 \mu\text{m}$ and m_0 mode of U-400 SRR array is at $3.49 \mu\text{m}$. Rows S1, S2, and S3 show the E/E_0 images of the three modes at the interface between SRR and top contact layer, the upper surface of the InAsSb absorber, and y - z plane as denoted by the white line shown in S1, respectively. Row P1 represents the E/E_0 distributions along the cutting lines (depth) denoted in S3 of the 3 modes.

To have a direct qualitative expression for this variation trend, E/E_0 (P1 group) distributions along the cutting lines in z -direction as denoted in S3 are derived. The E/E_0 at m_0 mode of U-400 is the smallest in the absorber, and it reaches the minimum with the fastest speed. The E/E_0 has the largest overlap with the absorber for the m_1 mode of U-590, followed

by that for the e mode. This is consistent with the previous report that for lower-order modes (m_0 mode here), a greater portion of the E -field is strongly localized at the interface between the SRR structure and the overlaid dielectric layer, and on the other hand, higher-order modes would possess large penetration depth [143]. Thus, the m_1 and e modes play more important role than m_0 mode in enhancing the photodetector performances. In addition, the superimposing of e and m_1 modes would add up the enhancement. Therefore, the device with a U-590 SRR array integrated with an InAsSb-based photodiode (which is then called U-590-integrated device) should demonstrate larger enhancement of photoresponse compared to the U-400-integrated device.

5.1.4 Experimental verification

Spectral photocurrent measurements of the integrated photodetectors (which consist of a SRR array and an InAsSb-based heterostructure photodiode) and the reference (the same InAsSb-based photodiode without a SRR array) were performed by the same FTIR system used for reflection characterization, where the midwave light source was first passed through the Michelson interferometer inside the FTIR before being polarized and focused onto the sample. The collected photocurrent signals were first amplified by a low-noise current preamplifier before connected with the external port of the FTIR. Figure 5.6(a) plots the photocurrent spectra under zero bias ($V_b = 0$). As presented, an order of magnitude enhancement of photocurrent is observed for the U-590 integrated device. By contrast, the U-400 integrated device only shows $\sim 50\%$ enhancement. Such a modest enhancement is similar to the SRR or CSRR enhanced low-temperature operational QD in $5\text{-}8\text{ }\mu\text{m}$ by using m_0 mode [144], where

the optoelectrical absorber is around 400 nm below the SRR array, leading to strong attenuation for LSP and resulting in weak overlap. We also present the photocurrent spectra at -100 mV (Fig. 5.6(b)) and -200 mV (Fig. 5.6(c)), where the U-590 integrated device still shows obvious photocurrent enhancement. These results are consistent with the prediction from our mode study (Fig. 5.5). This is mainly because the U-590 integrated device exhibits strong overlapping of m_1 and e modes with the InAsSb absorption, while the U-400 integrated device has shown weak overlapping of m_0 mode with the absorption. To further distinguish the contributions of m_1 and e modes to the photoresponse improvement, we plot the polarization-resolved photocurrent spectra (under zero bias) for the reference (Fig. 5.6(d)) and U-590 integrated device (Fig. 5.6(e)), showing higher photocurrent enhancement under x polarization. Given that the e and m_1 modes are located around the same positions, we can therefore conclude that the m_1 mode (excited under x -polarization) provides more enhancement than the e mode (excited under y -polarization). This is because the m_1 mode offers more overlapping of LSP fields with the absorber compared to that of e mode as seen from Fig. 5.6(e).

Fig. 5.6 (a)-(c) Photocurrent spectra of SRR array-integrated devices and reference photodiode under (a) 0 mV, (b) -100 mV, and (c) -200 mV bias voltages. (d)-(e) Polarization-resolved photocurrent spectra of (d) the reference and (e) U-590 integrated device at zero bias. All measurements were done at room temperature.

To further verify the contribution of m_1 and e modes, we studied the role of the spectral overlap (for m_1 and e modes) in photocurrent enhancement by designing other SRR geometries (see Table V), namely the U-480 ($s=480$ nm, $w=160$ nm, $g=160$ nm, $t=60$ nm, $p=800$ nm), and U-130 ($s=130$ nm, $w=35$ nm, $g=60$ nm, $t=60$ nm, $p=260$ nm) with gradually blue-shifted m_1 and e resonance wavelength from that of U-590. The SEMs of fabricated U-590, U-480, and U-130 SRRs on top of heterostructure photodiode mesa are shown in Figs. 5.7(a)-(c). Figures. 5.7(d)-(e) present the simulated and experimental reflection spectra of U-590, U-480, and U-130 under different polarizations. For the reflection under x -polarization (R_x , Fig. 5.7(d)), the

locations of m_0 modes for decreasing SRR size are found to be $5.75\ \mu\text{m}$ (U-590), $5.31\ \mu\text{m}$ (U-480), and $2.0\ \mu\text{m}$ (U-130), in agreement with the linear dependence of LC resonance on SRR size. Here, we purposely make them out of the photoresponse wavelength range to avoid disturbances to investigation. The locations of m_1 modes are at $3.64\ \mu\text{m}$ (U-590), $3.04\ \mu\text{m}$ (U-480), and $1.19\ \mu\text{m}$ (U-130), gradually deviating from bandgap of the InAsSb absorber in the photodiode. For the reflection under y-polarization (R_y , Fig. 5.7(e)), the e modes can be observed with their positions spectrally close to those of m_1 modes. It was thus found that U-590 exhibits the most spectral overlap with the absorption in InAsSb layer as both the e and m_1 modes resides near the bandgap of InAsSb at room temperature ($\sim 4.1\ \mu\text{m}$).

Fig. 5.7 Optical responses of SRR arrays on InAsSb photodiode. (a-c) Fabricated (a) U-590, (b) U-480, and (c) U-130 SRR arrays on heterojunction samples. All the scalebars represent $1\ \mu\text{m}$. (d and e) Simulated and measured reflection spectra of U-590, U-480, and U-130 under (d) x-polarized and (e) y-polarized illuminations. Offset of 0.5 and 1 are applied for U-480 and U-590, respectively.

In order to relate the spectral overlap between the SRR resonance modes with InAsSb absorption, we study the electric field enhancement (E/E_0) of the SRR arrays on the heterostructure photodiode for the three SRRs at $3.64\ \mu\text{m}$ (m_1 and e modes of U-590). As shown in Fig. 5.8, by decreasing the SRR size from U-590, to U-480 and U-130, the field enhancement gradually decreases, offering an expectation that the photocurrent of the photodiode will also decrease from U-590 to U-480 and U-130.

Fig. 5.8 Field enhancement study of SRRs with different spectral overlap with the absorption of the photodiode.

Figure 5.9 plots the spectral photocurrent of these three integrated devices at different voltage bias. The highest enhancement occurs in the U-590 device, where an order of magnitude enhancement was observed. For U-130 which has the least spectral overlap, where no photocurrent enhancement was observed. It is noted here that all the photocurrent spectra show broadband enhancement character, which is mainly determined by the loss of the absorption dielectric and the non-ideal normal incidence in our photocurrent measurements, as well as the multiple reflection in the devices [60].

Fig. 5.9 Photocurrent spectra of integrated devices with different SRR arrays under (a) 0 mV, (b) -100 mV, and (c) -200 mV bias voltages.

5.1.5 Performance characterization

The performance of the U-590-integrated device accompanied by the reference one is presented in Fig. 5.10. The final sensitivity of a photodetector is evaluated by the detectivity D , which is defined as $D = R_A / (2q(J_d + J_b) + 4kT/(RA))^{1/2}$ for conventional mid-infrared photodiodes, where $R_A = I/P$ is the responsivity for the measured photocurrent I and incident power P , J_d is the dark current density, J_b is the background photocurrent noise, R is the

dynamic resistance, A is the detection area and q is the electronic charge. J_b can be deduced from the measured R_A and the total radiant exitance from the background defined as $M(T) = \int_{\lambda_1}^{\lambda_2} M(\lambda, T) d\lambda$. Here, 2π field-of-view is assumed in our case, and the integration is performed for the atmospheric window from $\lambda_1=2 \mu\text{m}$ to $\lambda_2=5 \mu\text{m}$. In this calculation, the $1/f$ noise is neglected as the devices are evaluated at high modulation frequency ($>2000 \text{ Hz}$). The broadband performance of the U-590 integrated and the reference devices were characterized with a 1000 K blackbody radiation source and a $2.5\text{-}4.8 \mu\text{m}$ filter. The measured photocurrent was converted into a photovoltage by a low-noise current preamplifier (Model SR570, Stanford Research Systems), and then read out by a Lock-in amplifier (SR810).

As shown in Fig. 5.10(a), the U-590 integrated device exhibits an order of magnitude higher R_A compared to the reference one, showing a responsivity of $\sim 0.5 \text{ A/W}$ under zero bias. By comparison, a reverse bias of -250 mV needs to be applied in order to achieve the same R_A for the reference device. This illustrates the capability of the U-590 integrated device in high responsivity MIR photodetection at low power consumption. Besides, it is observed that for the U-590 integrated device, its response saturation reaches first. It is mainly due to the plasmonic effect, as most electron-hole pairs are primarily generated in the absorber near the top metal-semiconductor interface. In this way, the photogenerated carriers can be faster collected by the electrode.

Fig. 5.10 (a) Responsivity as a function of voltage bias for reference and SRR-integrated photodetectors. (b) Typical I-V characteristic curve of the device. (c) Typical noise spectrum of the device. (d) Zero-bias detectivity of the U-590 integrated device at different temperatures.

In experiments, we observed very similar dark current characteristics for the reference and U-590-integrated devices. As an example, Fig. 5.10(b) plots the typical I-V characteristic curve of the U-590 integrated device. At zero bias, the dark current is around 1.16 nA and the derived resistance is around 15 K Ω . Thus, we can calculate the voltage noise level of the device through $(4k_B T R_0)^{1/2}$. At room temperature (293 K), the calculated value is about 15.57 nVHz $^{-1/2}$. To confirm the reliability of calculation, we measured the typical noise of the U-590 integrated device at zero bias. As shown in Fig. 5.10(c), at low frequency, the $1/f$ noise is dominant as expected. However, it tends to stable while increasing the frequency. At ~ 2000 Hz, the voltage

noise level is about $15.6 \text{ nV}\cdot\text{Hz}^{-1/2}$, which is very close to the calculation. The final D for the reference and U-590 integrated devices at different temperatures are presented in Fig. 5.10(d), where the samples were mounted in a cryostat with ZnSe window in the low-temperature measurements. A room temperature detectivity as high as 2×10^{10} Jones is achieved for the U-590 integrated device, which is an order of magnitude higher than that of the reference device. At the thermoelectric cooling (TEC) temperature (275 K and 255 K), which is practically achievable in low-cost cooling technology, U-590 integrated device exhibits detectivities of 3.4×10^{10} Jones and 4.2×10^{10} at 275 K and 255 K, respectively. These detectivity values still correspond to an order of magnitude higher than those of the reference one. The comparison of the recently reported MIR photodetectors (including those based on emerging 2D materials) with the SRR-integrated photodetector in this work is given in Table VI, showing that the U-590-integrated device exhibits excellent detectivity for both room temperature and TEC temperature operations. Moreover, the fact such high detectivities are achieved under zero bias also indicates the U-590 integrated device addresses the low-power consumption requirement for efficient detection.

Table III. Comparison of performance with commercial and reported MIR detectors.

Technology	Wavelength (μm)	Detectivity ($\text{cmHz}^{1/2}\text{W}^{-1}$)	Bias (V)	Reference
Commercial InAsSb PV	2-5.3	1×10^9 (293 K); 2.8×10^9 (243 K)	-1	[123]
Commercial InAs PV	1-3.65	4.5×10^9 (293 K); 3.2×10^{10} (243 K)	-0.5	[145]
Commercial PbSe PC	1.5-4.8	2.5×10^9	100	[146]
Commercial MCT PC	1-6	4×10^9 (293 K); 4×10^{10} (233 K)	-	[147]
InAsSb nBn	2-4.7	1.0×10^9 (293 K); 5×10^9 (250 K)	-1	[5]
HgTe colloidal QD	1.7-5	5×10^7 (293 K)	0.5	[148]
bP/MoS ₂ heterojunction	2-4	1.1×10^{10} (293 K)	0	[149]
HgTe/As ₂ S ₃ FET	0.5-3.5	$\sim 1.0 \times 10^9$ (293 K)	~ 5	[150]
black arsenic phosphorus	3-5	4.9×10^9 (293 K)	0	[151]
InP-based p-i- n	1.8-3.2	2.0×10^8 (293 K)	-0.5	[152]
2DSHA InAsSb n-i-p	2-5	8.0×10^9 (293 K)	-0.15	[60]
2DSHA InAsSb-GaSb heterojunction	2-5	1.4×10^9 (293 K)	-0.3	[66]
InAsSb nBn on GaAs	2-5	6×10^9 (220 K)	-0.1	[17]
InAs _{0.7} Sb _{0.3} Bulk Photodiodes	3.5-7.5	1.5×10^9 (275 K); 3×10^9 (255 K)	-0.1	[122]
SRR-array heterojunction InAsSb	2-5	2×10^{10} (293 K); 3.4×10^{10} (275 K); 4.2×10^{10} (255 K)	0	This work

Finally, the response speeds of the U-590 integrated device and the reference one was measured, where the photodiodes were illuminated by a 2.94 μm laser with a fixed rise and fall

time of ~ 20 ns and the output power of the laser source for different modulation frequencies was calibrated by a standard powermeter (Fig. 5.11(a)). As evident in Figs. 5.11(b) and (c), both the reference and U-590 integrated devices exhibit ~ 1 μ s rise and fall time, which is also comparable to those in commercial photodetectors. The results also confirm that the role of the LSP modes in improving infrared photodetection without sacrificing the response speed. The response speed was then verified by the amplitude-frequency response of the U-590 integrated device, as shown in Fig. 5.11(d). The f_{-3B} value of the U-590 integrated device is found to be 2.64×10^5 Hz, corresponding to a response time of ~ 1 μ s. This is in a good agreement with the results from time-domain measurements.

Fig. 5.11 (a) Reference signal of the 2.94 μm laser in response speed measurement. (b) Response waveform of the reference device. (c) Reference signal of the U-590 SRR-integrated device. (d) Amplitude-frequency response of the U-590 integrated devices.

5.1.6 Summary

This work studies field distributions of different resonant modes of U-shape SRR arrays and their enhancement for MIR photodetection in an integrated photodetector consisting of an InAsSb-based heterojunction photodiode and an SRR array. The higher order m_1 mode is found to contribute most to the enhancement, sequentially followed by the electric e mode and the fundamental m_0 mode. By superimposing m_1 and e modes in the designed SRR array, a room

temperature detectivity of 2.0×10^{10} Jones is achieved without supply of voltage bias. With a slightly thermoelectrical cooling, the detectivity can be increased to 3.4×10^{10} Jones and 4.2×10^{10} Jones at 275 K and 255 K, respectively. In addition, polarization-resolved photoresponse between m_1 and e modes and tunable enhancement through geometrical tailing SRR size are also observed.

5.2 Rotated fourfold U-shape array photodetector

In this section, a polarization-insensitive MIR photodetector which consists of a rotated fourfold SRR array and an InAsSb-based heterostructure photodiode will be presented. The resonant m_1 and e modes of the SRR array are designed to overlap with the absorption spectrum of the photodiode for enhancing photodetection. An order of magnitude enhancement on uncooled photosensitivity is demonstrated. Importantly, the enhancement is polarization-insensitive, which is very useful for robust photodetection.

5.2.1 Rotated fourfold U-SRR array photodetector design

The array integrated photodetector contains a rotated fourfold U-shape SRR array and a MIR heterojunction photodiode (see Fig. 5.12(a)). Under MIR illumination, the array can confine incident light around the interface between metal and semiconductor. This will lead to significant enhancement of optical field (power density), resulting in strong generation of EHPs in the optoelectrical absorber [66]. These photocarriers will then be collected by the electrodes, resulting in enhancement of photocurrent. The enhancement is expected to show polarization-independence, due to the invariant property of the rotated fourfold SRRs. Figure 5.12(b) shows the layer structure of the heterojunction photodetector. The unit cell (see Fig. 5.12(c)) of the

SRR array can be characterized with the parameters of wire height t , wire width w , wire length s (for both bottom and vertical side wires/arms), wire gap g , wire space d , and period p .

Fig. 5.12 (a) Schematic of the rotated fourfold U-shape SRR array integrated photodetector. The red and blue dots represent photoexcited electron-hole pairs. (b) Layer structure of the InAsSb-based photodiode. (c) Schematic of the rotated fourfold unit cell in the array.

5.2.2 Resonant mode analysis

The same as described in the previous section, high-order magnetic (m_1) and electric (e) resonant modes will be used to improve the photodetection performance owing to their large penetration depth. To make e and m_1 resonant modes overlap with the absorption spectrum of

InAsSb absorber, numerical FDTD was used to calculate the reflection spectra and distribution of optical field of the rotated fourfold U-shape SRR array. In simulation, the permittivity of gold was extracted from the book by Palik [141] and that of the heterojunction photodiode from measured data and published literatures [142], [153]. Following conventional rules [140], [154], to set the resonance positions at our interested wavelength range and avoid spectral complication arising from surface lattice resonance and resonance broadening, the unit of the rotated fourfold SRR array on the heterojunction photodiode had the geometrical dimension of $s=670$ nm, $w=150$ nm, $g=380$ nm, $t=60$ nm, $d=1350$ nm, and $p=3200$ nm. The SRR-arrays were fabricated by EBL and characterized by a FTIR incorporated with a microscope. The inset of Fig. 5.13(a) is the SEM of the array on the heterojunction photodiode.

Fig. 5.13 (a) Simulated and measured reflection spectra of the rotated fourfold SRR array on the heterojunction photodiode under X- and Y-polarized illuminations. The inset is the SEM image of the fabricated SRR array. The scale bar is 1 μm . (b) Simulated reflection spectra of the SRR-array under different polarization angles. (c-e) Simulated E (E/E_0), E_z , and H in X-Y interface between the SRR array and dielectric under X- and Y-polarized illuminations. (f) Simulated E in X-Z planes as denoted in (c) under X- and Y-polarized illuminations. All the field distributions were simulated at the resonant wavelength of ~4.20 μm .

Figure 5.13(a) presents the simulated and measured reflection spectra of the array in the wavelength range of 2-6 μm under different polarization. The resonance can be identified from the reflection peak [137]. With the m_0 mode purposely out of the absorption range of the InAsSb

absorber, the SRR array has its e and m_1 modes peaked at about $4.20\ \mu\text{m}$, which is located in the absorption range of the InAsSb absorber. The sharp peak at around $4.24\ \mu\text{m}$ is originated from the absorption disturbance of CO_2 in air. It is noted that the e and m_1 modes overlaps here. This can be understood from the perspective of resonant-splitting in mutually-coupled plasmonic nanorods, where e and m_1 modes are the symmetric and anti-symmetric modes resulting from mode hybridization [137]. The simulated reflection under X- and Y-polarizations are similar, reflecting good consistence with experimental results. To further demonstrate the polarization-independence of the rotated fourfold SRR array, we simulated the reflection spectra under different polarization angles from 0 to 90 degree and still observed the invariance (see Fig. 5.13(b)). We also simulated, fabricated and characterized the rotated fourfold SRR arrays on low-loss silicon substrates. As shown in Figs. 5.14(a)-(c), obvious resonant modes were observed with relatively good agreement between experiments and simulations, where the observed difference may come from the continually distributed incident angles in the FTIR measurements, which may lead to splitting and shifting for those lateral modes. They also demonstrated polarization-independence of the rotated fourfold SRR array to the incident light.

Fig. 5.14 Characterization of rotated fourfold U-shape SRR-array on Si with different geometrical dimensions (a) $s=300$ nm, $w=100$ nm, $g=100$ nm, $t=60$ nm, $d=180$ nm, and $p=960$ nm. (b) $s=370$ nm, $w=120$ nm, $g=130$ nm, $t=60$ nm, $d=230$ nm, and $p=1200$ nm. (c) $s=520$ nm, $w=160$ nm, $g=160$ nm, $t=60$ nm, $d=280$ nm, and $p=1600$ nm. All the scale bars represent $1\text{ }\mu\text{m}$.

To gain an insight into the resonant behaviour of this rotated fourfold SRR array, field distributions of the integrated photodetector are shown in Figs. 5.13(c)-(f). Figure 5.13(c) shows the distribution of E (E/E_0) at the array-semiconductor interface under X- and Y-polarized illuminations. Large optical field enhancement is observed under different polarization. From distribution of E_z at the interface (Fig. 5.13(d)), it is obvious that the resonance is dominated by a mixture of e and m_1 modes. When the gap is perpendicular to the electric field component of incident light, m_1 mode is excited with strong localization of magnetic field (H) in the inner bottom region (Fig. 5.13(e)) and in this situation, circulating current is generated owing to the bottom-arm charge imbalance [155]. Meanwhile, e mode is also excited when the gap is parallel to the light. In this situation, charge oscillations in vertical side arms lead to the same electric polarity for both terminals of the bottom-arm and thereafter, no magnetic dipole would be formed. The magnetic field is only localized in the vertical side arms rather than in bottom arm. The resonant behavior is always similar no matter it is under X- or Y- polarized illumination. It is different from that of the U-SRR array in which the m_1 and e modes can be clearly distinguished by varying polarization as they cannot be excited simultaneously [47].

Finally, field distributions in XZ-plane for the rotated fourfold SRRs are plotted to show the penetration of the resonance. As seen from Fig. 5.13(f), the field still shows strong enhancement in InAsSb absorber located 120 nm below the SRR. This enhancement can facilitate the generation of EHPs in the InAsSb absorber, resulting in more carriers to be collected.

5.2.3 Fabrication process

We then fabricated and characterized the integrated photodetector (referred as SRR) and reference detectors (referred as Ref). In the fabrication of the heterostructure photodiode, the 390- μm sized square mesas were defined by wet etching, followed by deposition of 300 nm SiO_2 passivation layer (by PECVD) to reduce the surface leakage current and protect the mesas. Windows for electrodes and absorption area were then opened by photolithorgraph and reactive-ion etching process. The bottom and top eletrodes were formed with 20 nm adhesion Ti and 200 nm Au. The fabricated photodiode is taken as reference. To make the integrated photodetector, the SRR array was fabricated on top of the such photodiode by EBL, followed by metal evaporation and a standard lift-off process. The array contains 3 nm adhesion Ti and 60 nm Au.

5.2.4 Results and discussions

Figure 5.15(a) shows the SEM (with false colour for better view) of the integrated photodetector. Figure 5.15(b) shows the photocurrent spectra of the integrated photodetector and the reference photodetector at different voltage bias from positive to negative. As shown, the integrated photodetector shows obviously enhanced photocurrent under typical applied voltage biases of 0.1 V, 0 V, -0.15 V and -0.3 V. However, under applied voltage biases of 0.2 V and -0.5 V, the enhancement decreases even disappears. This electrically controlled enhancement is consistent with our previous reports [156]. For the forward bias side, the smaller enhancement can be attributed to the modulation of overlap between surface plasmon and depletion region in the photodetector. Because the increased forward bias can decrease the

surface plasmon overlap with depletion, resulting in smaller absorption enhancement. For the larger reverse bias side, when it is over the fully depleted bias point, the saturation of velocity for carriers would prohibit further enhancement. And as the result of increased thermal oscillations of lattices (phonons) with further increasing reverse bias, the induced more photocarrier scattering can decrease the enhancement.

Fig. 5.15 (a) The SEM of the array photodetector (with false colour for better view). (b) Photocurrent spectra of SRR array and reference photodetectors under different applied voltage bias at room temperature.

To study the polarization-sensitivity of the detectors, we also characterized the spectral response of the two photodetectors under different polarization. As shown in Fig. 5.16(a), the SRR-array photodetector demonstrates large photocurrent enhancement under both polarizations and no obvious difference is observed, attributed to the rotationally symmetric property of the rotated fourfold SRR-array. Figure 5.16(b) plots photocurrents of the two

detectors at $4.2\ \mu\text{m}$ at different polarization angle, showing unpolarized photoresponse with negligible standard-error from measurement set-up. Therefore, by using rotated fourfold distribution of the SRR-array, enhancement of photocurrent with polarization-independence is achieved. This polarization-insensitive nature is based on the polarization-independent excitation of localized surface plasmon resonances in the rotated fourfold configuration, which is quite different from the propagating surface plasmon resonance in two dimensional nanohole array (2DSHA) [60]. The latter has a strong dependence on the phase-matching condition.

Fig. 5.16 (a) Photocurrent spectra under X- and Y-polarized illuminations of SRR array and reference photodetectors under 0 V bias. (b) Photocurrent of the two detectors for different polarization angle at $4.2\ \mu\text{m}$ at 0 V.

The final photosensitivity of the array and reference detectors were characterized with a 1000 K blackbody radiation source. In measurement, the radiation from the blackbody was chopped at 300 Hz and filtered by an MIR bandpass filter before reaching the detectors. The measured photocurrent was converted into photovoltage by a low-noise current preamplifier, and then read out by a lock-in amplifier. The photoelectric conversion of a photodetector is evaluated in terms of photosensitivity R_A which can be expressed as $R_A = I/P$ (I is the measured

photocurrent and P is the incident power on the active area. The incident power is the multiplication of incident power density and active area of the detector. A standard power meter (OPHIR PHOTONICS) was used to calibrate the incident power density. The size of the active area is $390\text{ }\mu\text{m}\times 390\text{ }\mu\text{m}$). Figure 5.17(a) shows the R_A of photodetectors under applied voltage bias from 0.5 V to -0.5 V. The SRR-array detector demonstrates obvious enhancement of R_A under different bias voltage. Specifically, a R_A of 1.12 A/W under -0.15 V is achieved, corresponding to ~ 7 -fold magnitude enhancement compared to the reference one (0.14 A/W). The final saturated R_A of the array detector is ~ 1.2 A/W, but for the reference one, it is only 0.9 A/W. In addition, the array detector achieves its saturation responsivity at a bias (~ -0.2 V) which is far smaller than that of the reference one (~ -0.5 V), indicating low power-consumption. The enhancement factor (Fig. 5.17(b)), defined as $\eta=R_A(\text{SRR})/R_A(\text{Ref})$, has a maximum value of ~ 11 at -0.1 V and it decreases under both positive and negative bias voltages, which is consistent with the variation trend of photocurrent spectra (see Fig. 5.15(b)). Therefore, order level of photosensitivity enhancement is observed for the rotated fourfold SRR-array integrated photodetector.

Fig. 5.17 (a) Photosensitivity of reference and SRR array photodetector under applied voltage bias from 0.5 V to -0.5 V. (b) The enhancement factor of the SRR-array photodetector to the reference.

5.2.5 Summary

The integrated MIR photodetector consisting of an InAsSb-based heterojunction photodiode and a rotated fourfold SRR array is investigated. High-order magnetic and electric resonant modes in SRR are used to enhance the photosensitivity. An order of magnitude enhancement on uncooled photosensitivity is achieved. Importantly, its enhancement has polarization-independent property, which is pursued for a host of practical applications where robust photodetection is required.

5.3 Conclusion

In this chapter, various plasmonic structures were selected for integration with the InAsSb-based heterojunction photodiode to realize enhancement on quantum efficiency. It is because the metallic nanostructures at sub-wavelength scale own the capability to concentrate light and produce strong electric field in the extremely small volume, thus facilitating the significant absorption of electromagnetic waves. By utilizing the plasmonic effect, a room

temperature detectivity of 2.0×10^{10} Jones is achieved without supply of voltage bias.

Chapter 6. Photon-trapping structures for photoresponse enhancement

In addition to the plasmonic structures mentioned in the previous chapter, the photon-trapping structure is regarded as a reliable solution to enhance the photoelectric conversion efficiency without compromising speed [157], as there are optical modes with group velocity close to zero, referred to as ‘slow Bloch modes’ [158], [159]. Such an exceptional phenomenon of slow light propagation can prolong light dwell time in the absorption layer. It serves as a light trap, leading to significantly enhanced absorption at slow mode resonance [160]. Besides, with the structure incorporated in the optoelectronic devices, the reflection at interface between air and dielectric is reduced due to altered light-matter interaction. Such dual effects of light trapping have been proved effective in applications of mode-locked lasers [161], waveguide modulators [162], [163], and solar cells [164]. In this chapter, we propose and demonstrate the InAsSb-based heterojunction photodetectors with the photon-trapping hole-array (PTHA) structure for polarization-independent photoresponse enhancement.

6.1 Photon-trapping for boosting MIR photoresponse

6.1.1 Device design

The schematic diagram of the InAsSb based heterostructure photodiode integrated with a PTHA is shown in Fig. 6.1(a), where the cylindrical hole array is in hexagonal lattice. The targeted device comprises a InAsSb-based heterojunction architecture grown on a GaSb substrate, where the absorption i-layer is $\text{InAs}_{0.912}\text{Sb}_{0.088}$ with a thickness of 1.5 μm . In a

conventional homojunction photodiode, large dark current is always the major obstacle for obtaining good performance. To improve on that, the basic device not only adopts the heterojunction architecture, but also includes a highly doped wide-bandgap p-AlGaSb layer between the GaSb contact layer and InAsSb absorption i-layer to prevent the minority carrier (electron) diffusion. The high doping in the p-type layer also facilitates low electron concentration without inducing obvious bandgap narrowing. The lattice-matched layers with different bandgaps are grown by RIBER-32 MBE system, where the specific layer parameters are indicated in Table. VII. HRXRD and PL spectra indicate high-quality interfaces and absorption layer [111].

Fig. 6.1 InAsSb based heterostructure photodiode with a PTHA. (a) Schematic diagram of the hetero photodiode with the PT structure (cylindrical hole array in hexagonal lattice) etched in the absorption layer. (b) Cross-section diagram of hetero photodiode with micro-structured holes.

The microscale holes are etched through the top contact layer to reach the absorber, aiming at promoting absorption efficiency and thus increasing the photoresponse capability. The corresponding cross-sectional diagram is shown in Fig. 6.1(b). To quantify the performance enhancement of the PTHA, we take the photodiode without PTHA as the reference (ref) and

the device integrated with the PTHA as “PT detector”, both having the same plane absorption area.

Table IV Layer Parameters of the InAsSb based Heterostructure Photodiode

Material	Composition	Thickness	Doping
GaSb		50 nm	$N_D \sim 2 \times 10^{18} \text{ cm}^{-3}$
$\text{Al}_x\text{In}_{1-x}\text{As}_y\text{Sb}_{1-y}$	$x=0.15;$ $y=0.009$	20 nm	$N_D \sim 2 \times 10^{18} \text{ cm}^{-3}$
$\text{InAs}_y\text{Sb}_{1-y}$	$y=0.912$	1500 nm	Intrinsic
$\text{Al}_x\text{In}_{1-x}\text{As}_y\text{Sb}_{1-y}$	$x=0.2;$ $y=0.912$	20 nm	$N_A \sim 2 \times 10^{18} \text{ cm}^{-3}$
$\text{Al}_x\text{Ga}_{1-x}\text{Sb}$	$x=0.42$	40 nm	$N_A \sim 2 \times 10^{18} \text{ cm}^{-3}$
$\text{Al}_x\text{Ga}_{1-x}\text{Sb}$	x from 0.42 to 0.1	30 nm	$N_A \sim 2 \times 10^{18} \text{ cm}^{-3}$
Buffer GaSb (Be)		1000 nm	$N_A \sim 2 \times 10^{18} \text{ cm}^{-3}$
Substrate GaSb (Te)		600 μm	$N_D \sim 7 \times 10^{17} \text{ cm}^{-3}$

6.1.2 Simulation results and analysis

FDTD method is used to analyze the light confinement capability and wave propagation condition in the PT detector. The periodic boundary conditions were used in the lateral direction of unit cell to simulate an infinite periodic array of the PT detector and the perfectly matched layer conditions were employed in the longitudinal z-direction. The mesh size was set to 5 nm in all simulations. The dielectric constant of the heterostructure photodiode was obtained from previously reported data [142]. The detector was illuminated with the plane waves and the absorption spectra were calculated by subtracting transmission and reflection, where the power monitors for reflection and transmission are positioned above the detector structure and below the substrate, respectively.

Firstly, to investigate the maximum light confinement capability of the PT structure,

geometrical parameters of the PT structure (hole array period p , the ratio of hole diameter to period (r_d), defined by d/p , and etched hole depth D) are scanned to obtain an optimal set of parameters that can achieve the maximum absorption spectra in the range of 2 to 5 μm .

Specifically, the absorption of heterostructure photodiode with the PT structure at $\lambda=3 \mu\text{m}$ is simulated by simultaneously scanning the hole array period (p) and ratio of hole diameter to period (r_d), defined by d/p , where the hole depth is initially set at 1 μm . The scanning range of p is set around the peak wavelength response of our InAsSb-based photodiode, and the r_d range is chosen between 0.4 and 0.7. The corresponding simulation results are shown in Fig. 6.2(a). Furthermore, Fig. 6.2(b) shows the range of hole depth (D) scanned from 0.5 μm to 1.3 μm at per step of 0.1 μm in the wavelength (λ) ranging from 2 μm to 5 μm under the previously simulated optimal p and r_d .

Those calculations are performed by selecting a set of optimal topological parameters of PT structure for obtaining a maximized absorption in the photodetector, which can then be used as the guideline for the PT hole array fabrication. The corresponding optimal parameters derived from the simulation results are $p = 3 \mu\text{m}$, r_d from 0.67-0.72, and $D \geq 1 \mu\text{m}$. Considering fabrication and effective absorption of light, we select 1 μm as the hole depth. Likewise, the optimal r_d is chosen with the smallest value in the selected range.

In addition, to verify the polarization independence of the PT structure, the absorption simulation is implemented by simultaneously scanning polarization angle (θ_{pol}) and λ , with optimized p , r_d and D values. As shown in Fig. 6.2(c), the PT structure possess the feature of polarization independence of the incident light due to the structure symmetry.

Fig. 6.2 Simulated absorption (A) results of the PT structure. (a) Simulated absorption at $\lambda=3$ μm by simultaneously scanning period (p) and ratio of hole diameter to period (r_d). (b) Simulated absorption by simultaneously scanning hole depth (D) and λ . (c) Simulated absorption at polarization angles from 0 to 90°.

Figure 6.3(a) illustrates the simulated absorption spectra of the PT detector in its optimal geometrical parameters, and the ref detector. It is observed that the absorption is obviously enhanced by making the PT structure, where the maximum enhancement rate of 55% is obtained at wavelength of 3 μm. The integrated absorption value, as an index to quantify the optical performance enhancement, is defined as the ratio of absorbed optical power to incident power over the wavelength range of 2 to 5 μm [165]. The simulation results indicate a maximal integrated absorption value of 56% for the PT detector. Compared with the 40% for the ref detector, a significant 38% absorption improvement is achieved. Meanwhile, the absorption value is quite robust with the change of geometrical parameters as a 5% variation in geometrical parameters only results in about 1% change in the integrated absorption. This characteristic is

helpful in facilitating large-scale production.

Fig. 6.3 Simulation results for the ref and PT detectors. Simulated (a) absorption spectra and (b) reflection spectra in 2 to 5 μm range. (c) The electric field distribution change with light propagation in PT detector at $\lambda=3 \mu\text{m}$, that is, the E_x component of the field with time increasing from left to right. Top row: x-z plane. Bottom row: x-y plane. Light illuminates the holes in the z direction. Time from left to right: $t=1.0, 4.0, 6.4, 8.7, 11.1$ fs. The field first goes into the hole and then spreads laterally into the photodetector as cylindrical waves. The top view of the unit cell for simulation is also shown on the right of (c), where “ p ” represents the period between the holes, and “ d ” represents the hole diameter.

To explore the light trapping mechanism in the PT structure, the simulated reflection spectra are presented in Fig. 6.3(b). It is observed that the reflection of PT detector is obviously lower than that of the ref detector, while the simulated transmission spectra are almost same. In this way, the reduction of reflection can almost directly reflect the absorption increase in the PT detector. The integrated reflection value between 2 to 5 μm for the PT detector is only 15%,

much smaller than the 34% of ref detector. Thus, one of the roles of the PT structure is to reduce reflection due to the increased air volume filling factor ($ff = \text{volume of air} / \text{volume of material}$) which is described as:

$$ff = \frac{\pi d^2}{2p^2 \tan(60^\circ)} \quad (27)$$

The corresponding effective refractive index (n_{eff}) of the PT hole array is thus reduced which is expressed in the following formula [166]:

$$n_{eff} = \sqrt{\varepsilon_b \frac{\varepsilon_i(1 + ff) + \varepsilon_b(1 - ff)}{\varepsilon_i(1 - ff) + \varepsilon_b(1 + ff)}} \quad (28)$$

where ε_i and ε_b are the dielectric constants of air and background material (InAsSb-based heterostructure, ~ 15 [167]), respectively. As a result, the reduced refractive indices will lead to a reduced reflection, as derived from the equation:

$$R = \frac{(n_i - n_{eff})^2}{(n_i + n_{eff})^2} \quad (29)$$

By taking the optimal parameters ($p = 3 \mu\text{m}$, $d = 0.67 p$) into the mathematic model, the calculated R is 21% with a n_{eff} of 2.67, which is consistent with the value of wavelengths below $2.5 \mu\text{m}$ and above $4.5 \mu\text{m}$ for the PT detector. The calculated R of the ref detector is 34% with a n_{eff} of $\sqrt{\varepsilon_b}$ equal to 3.88, which corresponds to that of wavelengths from 2 to $5 \mu\text{m}$ for the ref detector. Also, it is remarkable to note the effect of reflection reduction is more significant at wavelengths between 3 to $4 \mu\text{m}$, where the reflection value is around 10%.

Fig. 6.3(c) shows the E_x component of electric field distribution changing with time in the PT detector under a normal plane wave illumination. To better observe the light propagation, the unit cell in simulation contains 8 holes, whose area is expressed as: $2p \times 2p \times \tan 60^\circ$, since

the separate distance between two neighboring holes in y-direction of the hexagonal lattice is $p \tan 60^\circ$. The transient evolution of E_x distribution from $t = 1.0$ to 11.1 fs is depicted in the figure. The results show that the waves in lateral direction gradually appear around holes and form the collective lateral propagating modes. In order to clearly present the bending of light propagation direction, Poynting vector distribution is shown in Fig. 6.4, where the vector arrows are bent to lateral direction around the PT holes. This characteristic is almost the same at wavelengths between 3 to $4 \mu\text{m}$, but it never appears in the ref detector without the PT structure, suggesting that the laterally propagating modes are indeed generated by the PT hole array. These modes simultaneously move in downward and horizontal direction, indicating that the PT structure can support a set of modes with wavevectors in z direction (k_z) and in-plane direction ($k_{||}$). For the modes with large $k_{||}$, they are lateral propagating modes [168]. Since the photodiode dimension in x - y plane is much larger than the thickness of i -region, it leads to longer optical propagating path and longer dwell time before light exiting the absorption layer. In contrast to light propagating in z -direction only, the lateral propagating modes can result in more light absorption [160].

Fig. 6.4 Simulated lateral propagating modes in the detector with PT structure. (a) Poynting vector direction. (b) The corresponding E_x component of the field (top row: x-z plane. bottom row: x-y plane).

Besides, it is reported when the period of PT hole array is set close to the wavelength of the absorbed light, the group velocity of the modes can be treated as slow modes in photonic crystal, leading to more chances for stimulating laterally propagating modes [157], [169]. It thus explains why we can achieve an obviously enhanced absorption at wavelengths around $3\ \mu\text{m}$ with the period of PT structure set to $3\ \mu\text{m}$ [111]. In this way, the incident light propagating in PT hole arrays can obtain a large $k_{||}$ which makes light interaction in absorption layer more efficient [170].

Therefore, in the case of hetero detector assisted by the PT structure, the absorption enhancement can be attributed to the combination effects of lateral propagating modes around the resonant wavelengths and reduced reflection due to lower effective refractive index of the PT structure. In addition, the etched hole array also reduces the physical volume of the device. It can help to limit the bulk dark current which is the main obstacle for MIR detector operating at room temperature [171]. As such, the decreased bulk dark current can balance or even

overwhelm the increased surface leakage by extra exposed areas induced from the etched PT structure.

6.1.3 Device fabrication and characterization

The PT hole array in its simulated optimal geometrical parameters was fabricated on the InAsSb-based heterojunction photodiode. The corresponding SEM profile is shown in Fig. 6.5(a). The absorption spectra are then obtained by measuring the transmission and reflection via a FTIR, as shown in Fig. 6.5(b). Compared to the ref detector, it is demonstrated that a 38% absorption enhancement is obtained at 3 μm in the PT detector. Due to the continually distributed incident angles which are up to about 30 degrees mainly from the condenser in the FTIR experimental set-up (36 $\times$ objective lens ($\text{NA} = 0.5$)), the measured reflection spectra demonstrate broadband feature with a wider peak, compared with the simulation results under normal incident light [60]. Meanwhile, the absorption of the ref and PT detectors at different polarization angles were measured (Fig. 6.5(c)) and the results show the polarization-independent property of the PT structure, which is in consistent with the simulation result shown in Fig. 6.2(c).

Fig. 6.5 Fabricated PT structure and measured absorption spectra. (a) The SEM profile views of the PT hole array, parameterized by period p and hole diameter d , where the scale bar is $1\ \mu\text{m}$. (b) Measured absorption spectra of the ref and PT detectors in the wavelength range of 2 to $5\ \mu\text{m}$. (c) Measured absorption at $3\ \mu\text{m}$ of the ref and PT detectors for different polarization angles.

The detailed fabrication process schematic diagrams are described in Fig. 6.6. In order to check the effectiveness of PT structure, the heterostructure photodiode without the PT hole array is also fabricated as the reference device. The fabrication of reference device starts from the step of lithography for mesa patterning, followed by the same steps as PT devices.

A. PT Hole array pattern define & Surface passivation.

A 150-nm thick SiO_2 layer was deposited by CVD on the top of this InAsSb-based hetero material to serve as a hard mask during the etching of PT hole array structure, which would be later removed by buffered oxide etch (BOE). The material was then patterned by EBL, in which the 250-nm thick ZEP520A positive-tone photoresist was exposed under 20 keV electron gun

voltage and 35 pA beam current. After that, development in ZED-N50 for 20 s and rinsing in MIBK for 20 s were done at room temperature. The process parameters have been tuned in order to realize the designed optimal topological parameters of the PT pattern (hole array period p , ratio of hole diameter to period r_d). Following that, RIE was used to transfer the PT pattern on SiO₂ hard mask, with a 240 s process of 30 sccm CF₄ and 30 sccm CHF₃ flow at 15 mTorr and 170 W power. Then the patterned photoresist was removed by acetone and oxygen plasma. The device material was finally etched through the SiO₂ mask by the high-temperature ICP-RIE at 250 °C, using 8 sccm Ar, 2 sccm Cl₂ and 4 sccm BCl₃, at a DC bias of 125 V, with an ICP power of 400 W and a RF power of 140 W for 80 s. After etching, the exposed PT hole array surface was passivated by piranha solution, a mixture of sulfuric acid, deionized water, and hydrogen peroxide. The SiO₂ hard mask was then removed by buffered oxide etch (BOE). As shown in the SEM profile in Fig. 3(a), the vertical sidewalls of PT pattern, and the reasonable uniformity of the fabrication deviation error within 5% are obtained in device material.

B. Mesa etch & Surface passivation.

The mesa pattern on device material was defined by generic lithography process, using MJB4 mask aligner with the exposure wavelength of 365 nm and AZ5214 positive tone photoresist, spun after a hexamethyldisilazane adhesion promoter coating. Then the sample was developed in the diluted AZ developer (developer: water = 1: 2) for 2 mins and then rinsed in DI water. Following the mesa patterned on photoresist by development, the sample was etched through by wet etching method, with the etching solution mixed with phosphoric acid, citric acid, hydrogen peroxide and DI water. As a result, the mesa depth of 1800 nm was

obtained after photoresist removal. A 300-nm thick SiO₂ passivated layer was then deposited on top of the sample by CVD.

C. Window opening for light absorption & electrodes.

The windows opening for light absorption and electrodes in the passivated SiO₂ layer was done through standard lithography with the exposure wavelength of 365 nm and AZ2035 negative tone photoresist, spun after a hexamethyldisilazane adhesion promoter coating. The use of AZ2035 resist is well-suited for fully covering the top and bottom depth difference of mesa, as its thickness can be achieved up to around 3.5 μm through controlling the spin coating speed, and its resolution also fits for the critical dimension requirement of window opening. After pattern transferring to the photoresist, RIE was used to etch passivated SiO₂ layer for opening window, with a 480 s process of 30 sccm CF₄ and 30 sccm CHF₃ flow, at 15 mTorr and 170 W forward power. The patterned photoresist was then removed by acetone and oxygen plasma.

D. Electrode deposition.

Finally, the same standard lithography as the above window opening steps was adopted for defining top and bottom electrode pattern. The electrical contacts of 20-nm thick titanium (adhesion layer) and 280-nm thick gold on top and bottom GaSb layer were then formed by electron beam evaporator system and standard lift-off process.

Fig. 6.6 Schematic diagrams of fabrication process flow for heterostructure photodiode integrated with PT structure.

The corresponding SEM image of the fabricated device is shown in Fig. 6.7(a). The PT structure has covered about 70% of the light absorption area. The photocurrent spectra of the devices were measured at different temperatures and bias voltages. To gain clear insights into the enhancement from the PT structure, the enhancement factor (η) is defined as the ratio of measured values of PT detector to those of ref detector. As such, the η of photocurrent (I_{PH}) spectra, measured using a FTIR, is defined as $\eta = I_{PH, PT} / I_{PH, Ref}$. Figs. 6.7(b) and 6.7(c) show

the η of the PT detector measured at different biases and temperatures and the measured I_{PH} spectra for ref and PT detectors are shown in Fig. 6.8. The η values under zero bias at 293 K and 260 K, extracted from the black dash lines in Figs. 6.7(b) and 6.7(c) are shown in Figs. 6.7(d) and 6.7(e) respectively. The results indicate that the photoresponse enhancement becomes stronger with the decrease of temperature. To further quantify the enhancement at specific bias and temperature, we calculated the average value of the η integral from 2 to 5 μm at room temperature for different bias and under zero bias for different temperatures, as shown in Figs. 6.7(f) and 6.7(g), respectively. A 26% photocurrent enhancement is obtained under zero bias at room temperature, and the enhancement can reach to about 40% under the bias of -0.05 V. Meanwhile, it is observed that the zero-bias enhancement would be increased to 170% with the temperature decreasing to 243 K and become stable below 243 K. The observation will be explained in the following section. Besides, the polarization-independent character of the PT assisted photoresponse is confirmed by the I_{PH} at 3 μm of the two detectors measured under different polarization angles, as shown in Fig. 6.8(e).

Fig. 6.7 Photoresponse enhancement of PT detector relative to the ref detector. (a) SEM image of the fabricated PT detector. (b) Enhancement factor (η) of photocurrent (I_{PH}) spectra in the range of 2 to 5 μm measured under the bias from -0.3 V to 0.1 V measured at room temperature (293 K). (c) η of I_{PH} spectra at temperatures from 78 K to 293 K under zero bias. (d) Extracted room-temperature η of I_{PH} spectrum under 0 V. (e) Extracted η of I_{PH} spectrum under 0 V at 260 K. (f) The average value of the η integral from 2 to 5 μm at room temperature under the bias from -0.3 V to 0.1 V. (g) The average value of the η integral from 2 to 5 μm under zero bias at different temperatures.

Fig. 6.8 Comparison of photocurrent spectra for the ref and PT detector. Room temperature (293 K) photocurrent (I_{PH}) spectra measured under the bias from -0.3 V to 0.1 V for (a) ref and (b) PT detectors. Under zero bias, the I_{PH} spectra at temperatures from 78 K to 293 K for (c) ref and (d) PT detectors. (e) I_{PH} at $3 \mu\text{m}$ of two detectors for different polarization angles at room temperature under zero bias.

6.1.4 Experimental results and discussion

A 1000-K blackbody radiation source is used to measure the detector responsivity in the MIR range. The responsivity is defined as $R_A = I_s / P_{inc}$, where P_{inc} is the incident power radiated on detector and I_s is the signal current generated by the fabricated detectors. Figs. 6.9(a) and 6.9(b) shows the change of R_A under the bias from -0.3 V to 0.1 V at temperatures from 78 K to 293 K for the ref and PT detectors, respectively. The obvious enhancement is observed at

different temperatures and voltage biases. The extracted results at 293 K and 0 V are separately presented in Figs. 6.10(a) and 6.10(b), respectively. It is noted that a maximum room-temperature responsivity is obtained at -0.05 V for both the ref (0.39 A/W) and PT (0.48 A/W) detectors mainly due to the increased electric field. For the bias more negative than -0.05 V, the saturation effect suppresses the carrier velocity and increases the thermal recombination which lead to a decrease in responsivity [172]. Also, the response enhancement is not apparent at positive bias due to narrow depletion region and reduced electric field. As such, a 40% room-temperature response enhancement is obtained under the reverse bias of -0.05 V, which is in consistent with the measured result of photocurrent spectra. In addition, Fig. 6.10(b) shows an increased enhancement factor in responsivity with the decrease of temperature, due primarily to the reduced carrier density [156], [173]. In this way, the PT detector which owns more absorbed photons would expect a larger enhancement factor as observed. In the temperature region < 243 K, the response is saturated due to the limited light absorption and almost unchanged carrier density. The maximum enhancement of the zero-bias responsivity at temperatures below 240 K is about 170%.

For the noise (v_n) characteristic shown in see Figs. 6.9(c) and 6.9(d), it considers dark current shot noise, thermal noise and background noise as expressed in $v_n = (2q(J_d + J_b) + 4kT/(RA))^{1/2}$, where J_d and J_b are the dark current density and background noise current density, R is dynamic resistance and A is the mesa area [1]. It is noted that the noise near the zero-bias region is obviously reduced. Figs. 6.10(c) and 6.10(d) shows the extracted noise data at room temperature under different biases and under zero bias at different temperatures of the PT and ref devices, respectively. As shown in Fig. 6.10(c), a similar but

slightly lower noise is observed for PT detector at room temperature. It means that the reduced bulk dark current makes up for the potentially increased surface leakage, which also confirms the effectiveness of surface passivation we adopted in fabrication. It is noted that with the decrease of temperature (Fig. 6.10(d)), the noise of the PT detector owns a more significant reducing trend than that of the ref detector. It is mainly attributed to the stronger temperature dependence of the diffusion dark current, compared with the SRH recombination current [126], [132]. The detailed detectivity (D^*) data of the ref and PT detectors derived from $R_A/Noise$ are shown in Figs. 6.9(e) and 6.9(f), and Figs. 6.10(e) and 6.10(f) present the extracted data at 293 K and 0 V for the two devices, respectively. The room-temperature D^* of the PT detector is about 2.09×10^9 Jones under zero-bias, which is 29% higher than that of ref detector (1.62×10^9 Jones). When temperature decreases, the detectivity enhancement becomes more pronounced. At TEC temperatures of 260 K and 243 K, which are practically achievable in low-cost cooling technology, the detectivities of the PT detector are increased to 5.75×10^9 Jones and 7.97×10^9 Jones, respectively. These detectivity values correspond to about two and three times of those of the ref detector. In addition, it is remarkable that such high performances are all achieved under zero bias, indicating that the PT detector is suitable for the low-power-consumption detection.

Fig. 6.9 Comparison of responsivity, noise and detectivity for the ref and PT detectors. The responsivity (R_A) under the bias from -0.3 V to 0.1 V and at temperatures from 78 K to 293 K for (a) ref and (b) PT detectors. The noise (v_n) under the bias from negative to positive at temperatures from 78 K to 293 K for (c) ref and (d) PT detectors. The detectivity (D^*) under the bias from -0.3 V to 0.1 V and at temperatures from 78 K to 293 K for (e) ref and (f) PT detectors.

Fig. 6.10 Comparison of responsivity, noise and detectivity of the ref and PT detector. Responsivity (R_A) versus (a) bias and (b) temperature, Noise (v_n) versus (c) bias and (d) temperature. Detectivity (D^*) versus (e) bias and (f) temperature.

Finally, the response waveform in reaction to a 2.94 μm laser source is shown in Fig. 6.11(a), where the corresponding rise and fall time are around 1.4 μs and 1.2 μs for ref and PT detectors, respectively. Fig. 6.11(b) shows the amplitude-frequency response (f_{3dB}) values which are 2.4×10^5 Hz and 3×10^5 Hz for the ref and PT devices, respectively. The slightly better frequency response is mainly due to the faster collection of the photogenerated carriers as the physical holes shorten the transportation path for the carriers generated after absorbing the photons.

Fig. 6.11 Frequency response of the ref and PT detector. (a) Response waveform under zero bias. (b) Amplitude-frequency response.

6.1.5 Summary

The design and fabrication of PT detector which consists of an InAsSb-based heterostructure MIR photodiode with etched hole array structure is presented. With assistance of this polarization-independent PT structure, the resulted lateral propagating modes and reduced effective refractive index can enhance light absorption, leading to a broadband absorption improvement of 43% in the wavelength range from 2 to 5 μm . The PT hole array also reduces bulk dark current. A room-temperature detectivity of 2.09×10^9 Jones is obtained under zero bias, which is 29% higher than that of reference detector without PT structure. In addition, at thermoelectric cooling temperatures of 260 K and 243 K, the detectivities are about 5.75×10^9 Jones and 7.97×10^9 Jones without applied bias, which correspond to two- and three-times enhancement compared to that of the reference detector.

Compared with the rotated fourfold U-SRR structure, the detection performance enhancement of the PT structure is not so significant. But the PT detector does not require the additional metal, and the feature size is larger, facilitating the reliable fabrication. Therefore, PT structure can be more easily applied to large-scale integration and provide an effective

alternative for enhancing mid-infrared photodetection.

6.2 Hole Array Enhanced Dual-Band Infrared Photodetection

In this section, an InAsSb-GaSb heterostructure with a PTHA for polarization-independent dual-band photoresponse enhancement is presented. By incorporating a circular hole-array structure in hexagonal lattice with optimal topological parameters to the heterostructure, the absorption and photoresponse in the wavelength range of interest can be significantly enhanced. The achieved room-temperature responsivity enhancement rates in NIR and MIR under zero bias are 12% and 33%, respectively. Besides, the amplitude frequency response and speed are also slightly improved.

6.2.1 Device design

For the purpose of photon trapping, we consider a hexagonal lattice of circular hole array patterned in top dielectric layer, as depicted in Fig. 6.12(a). The basic heterostructure for photodetection comprises an 850-nm thick *nip* InAsSb structure grown on a GaSb substrate by MBE. The holes are formed by etching through the top *n*-InAsSb contact layer and part of the *i*-InAsSb layer, whose cross-sectional diagram is shown in Fig. 6.12(b) and basic information is listed in Table VIII.

Fig. 6.12 The InAsSb-GaSb heterostructure with PTHA structure. (a) Schematic of heterostructure with circular hole array in hexagonal lattice. (b) Cross-sectional diagram of the heterostructure with the holes etched into the InAsSb layer.

Table V. Basic information of the InAsSb-GaSb heterostructure

Material	Thickness	Doping (cm^{-3})
n-InAsSb	50 nm	$n \geq 1 \times 10^{18}$
u.i.d. InAsSb	700 nm	u.i.d. $\sim 1 \times 10^{18}$
p-InAsSb	100 nm	$p \geq 1 \times 10^{18}$
p-GaSb (buffer)	500 nm	u.i.d.
p-GaSb (Substrate)	$\sim 600 \mu\text{m}$	$p \sim 1 \times 10^{17}$

The basic heterostructure material, after epitaxial growth, was characterized by HRXRD scan with $1.54056 \text{ \AA}$ radiation, and the corresponding XRD spectra is shown in Fig. 6.13(a). It is found that the lattice mismatch between the InAsSb layer and GaSb substrate is about 300 ppm. According to Vegard's law, the derived component of Sb in InAsSb is 0.085. The optical property of the InAsSb layer was then characterized by PL from 7 K to 280 K, as shown in Fig. 6.13(b). The FWHM at 7 K is around 10 meV, demonstrating good optical quality of the InAsSb layer. The observed clear 'red shift' of peak energy with the temperature increasing follows well with the Varshni law $E_g(T) = E_g(0) - \alpha T^2/(\beta + T)$. The lower energy peak ($\sim 0.315 \text{ eV}$) shown in low-temperature PL spectra is likely due to the interband transition from the

conduction band of p-GaSb to valence band of p-InAsSb at the InAsSb-GaSb interface [174]–[176]. Figure 6.13(c) shows the corresponding fitting with α and β of 0.18 meV/K and 127 K, respectively, which are within the reasonable range for InAs_{0.915}Sb_{0.085}.

Fig. 6.13 Characterization of InAsSb-GaSb heterostructure. (a) HRXRD spectrum. (b) PL spectra from 7 K to 280 K. (c) PL peak energy positions and the corresponding Varshni fitting line.

Figure 6.14 demonstrates the SEMs of the hole array fabricated on the InAsSb-GaSb heterostructure. The smooth and straight sidewalls of the fabricated holes demonstrate the effectiveness of our etching processes. An enlarged view of the unit cell for PTHA with the lattice angle of 60° is also shown, parameterized by the lattice constant (a), hole diameter (d), hole depth (D).

Fig. 6.14 The SEMs of the fabricated InAsSb-GaSb photodetector with PTHA structure, with the unit cell parameterized by the lattice constant (a), hole diameter (d), hole depth (D) and lattice angle 60° .

6.2.2 Simulation results and analysis

To get a better PTHA structure, we firstly use FDTD method to perform simulations on absorption maximization. By solving Maxwell equations using this method, the reflection and transmission spectra of the PTHA structure in response to incident light as well as the electromagnetic field distribution in the heterostructure were calculated. The absorption spectra were extracted through subtracting transmission and reflection from one. The calculation included all layers of the heterostructure and the hole array was also taken into account. Periodic boundary conditions were used in the lateral dimensions of the FDTD region, and perfectly matched layers were set in vertical boundary. The structure was normally illuminated from the plane wave source, with the mesh size set in 5 nm. The dielectric constants of heterostructure materials were referred from the measured data and material database in the Lumerical software.

Fig. 6.15 Simulated spectra results of the InAsSb-GaSb heterostructure w/o PTHA structure. (a) Simulated absorption at $\lambda = 2.7 \mu\text{m}$ by simultaneously scanning lattice constant (a) and ratio of hole diameter to lattice constant (r_d). (b) Simulated absorption by simultaneously scanning hole depth (D) and wavelength (λ). (c) Simulated absorption by simultaneously scanning polarization angle (θ_{pol}) and λ . (d) and (e) Simulated absorption and reflection spectra with the optimal geometrical parameters, respectively.

Since the wavelength of $2.7 \mu\text{m}$ is roughly in the middle of peak photoresponses for GaSb and InAsSb, we select it as the center wavelength to simulate to obtain optimal hole-array parameters. Through simultaneously scanning the lattice constant a and r_d (the ratio of diameter d over a), the maximum absorption at $\lambda = 2.7 \mu\text{m}$ is achieved at the a and r_d of $3 \mu\text{m}$ and 0.65 , respectively, with the hole depth D initially set at 500 nm , as indicated in Fig. 6.15(a). Then with the optimized a and r_d , the hole depth is scanned from 100 to 1200 nm in the wavelengths (λ) from 1.5 to $5 \mu\text{m}$, and the results are shown in Fig. 6.15(b). It is found that when the holes

are deeper than 550 nm, there is only less than 1% absorption enhancement for an additional 100-nm depth. To save enough material for photogenerated carriers, the optimal D is selected as 550 nm. In this way, a set of geometrical parameters leading to maximum absorption with PTHA structure are obtained. Another key figure of merit for strong photodetection is the selectivity of photoresponse over a wide range of polarization angles. As indicated in Fig. 6.15(c), the absorption spectra of the PTHA is almost independent of polarization angles due to the structure symmetry. The corresponding absorption of the InAsSb-GaSb heterostructure with/without (w/o) the PTHA are illustrated in Fig. 6.15(d). Obvious enhancement in absorption is observed in the spectra from 1.5 to 5 μm for the heterostructure with the PTHA. The maximum enhancement occurs at about 2.7 μm , and corresponding enhancement rate is about 1.51.

The reflection spectra of the InAsSb-GaSb heterostructure w/o the PTHA are plotted in Fig. 6.15(e). In the wavelength range of interest, the heterostructure with the PTHA has a significant reduction in reflection compared to the reference material. There is a reflection valley around the position of $\lambda=2.7 \mu\text{m}$, where the reflection reduction is about 81%. It is due primarily to the reduced effective refractive index caused by the hole array. As the filling ratio of air hole (f) is represented by the volume fraction of air to dielectric, $\frac{\pi d^2}{2a^2 \tan(60^\circ)}$, a lower effective refractive index (n_{eff}) can be obtained from the following equation [177],

$$n_{eff} = \sqrt{\varepsilon_d \frac{\varepsilon_i(1+f) + \varepsilon_d(1-f)}{\varepsilon_i(1-f) + \varepsilon_d(1+f)}} \quad (30)$$

where ε_i is the dielectric constant of the air, and ε_d is that of background dielectric which can be regarded as an invariant value in the wavelengths of interest. According to the standard

grating theory, the calculated n_{eff} supports the wavelengths below the product of $\text{Re}(n_{eff})$ and a , which is fitted with our interest wavelength range [166]. As calculated, the lower n_{eff} can lead to almost 40% reflection reduction, corresponding to the flat part of reflection curve for PTHA.

Fig. 6.16 Simulated electric field (E_x) distributions with light propagating in the PTHA structure at (a) $\lambda=2.7 \mu\text{m}$, (b) $\lambda=1.7 \mu\text{m}$ and (c) $\lambda=3.9 \mu\text{m}$, respectively.

To find the reason for absorption enhancement around $2.7 \mu\text{m}$, we simulate the electric field distribution during light propagating in the PTHA, and the results are shown in Fig. 6.16. It is observed there is a lateral optical propagation mode between the holes, which does not exist in the reference, as indicated in Fig. 6.17. It is referred to as lateral optical slow bloch mode [157]. The resonance can effectively couple the incident waves to the absorption medium, leading to a low-group-velocity mode with large in-plane wave vector ($k_{||}$) [168]. Thus, a longer optical absorption path is generated in the PTHA, where the corresponding photon dwell time

in the structure is obviously longer at $2.7\ \mu\text{m}$ (8.2 fs), compared to those at $1.7\ \mu\text{m}$ (4.6 fs) and $3.9\ \mu\text{m}$ (5.4 fs). It is because such a resonant mode arises from coupling of the incident plane wave to the modes of hole array and occurs at the wavelength on a scale comparable to the lattice period of the structure [160]. The electric field distribution map demonstrates that the interferences at PTHA-air interface can simultaneously prolong the photon lifetime in the dielectric and maintain the shape of electric field. As such, the combination of prolonged photon lifetime and reduced effective refractive index facilitates the effective light confinement in the dielectric around the resonant wavelength, giving rise to prominent enhancement of absorption.

Fig. 6.17 Simulated electric field (E_x) distributions with light propagating in the reference design at $\lambda=2.7\ \mu\text{m}$.

6.2.3 Experimental verification

The InAsSb-GaSb heterostructures with the PTHA were fabricated based on the optimal geometrical parameters, defined by EBL and transferred pattern to InAsSb layers by Ar/Cl₂/BCl₃ based high-temperature ICP-RIE. FTIR integrated with a 36x objective, an

infrared polarizer and a KBr beam splitter was utilized to measure the reflection and transmission spectra. The absorption spectra presented were normalized with the results of gold pad. Figure 6.18(a) shows the measured absorption spectra, which are in good agreement with the simulation ones, except for a more broadband character in measured results due to the wide incident angle distribution in the measurement setup of FTIR [60]. The integrated absorption enhancement of the heterostructure with a PTHA is around 130 % in the wavelength range from 1.5 to 5 μm . The maximum enhancement at the resonance wavelength of 2.7 μm is about 150 % which agrees with the simulation result.

Fig. 6.18 Measured absorption and photocurrent (I_{PH}) for the devices w/o the PTHA. The device without the PTHA is taken as a reference. (a) Absorption spectra at room temperature. (b) Room-temperature I_{PH} spectra under zero bias. (c) I_{PH} at 2.7 μm at different polarization angles. (d-e) I_{PH} spectra of (d) reference and (e) PTHA detectors at temperatures from 220 K to 293 K under zero bias. (f-g) I_{PH} spectra of (f) reference and (g) PTHA detectors under the bias from -0.15 V to 0.15 V at room temperature (293 K).

We also made the InAsSb-GaSb heterostructures w/o a PTHA into devices for photodetection, where they were experienced same fabrication process. Firstly, standard lithography technology was used to define the square mesa. After that, the InAsSb and GaSb layers were etched with a citric acid-based etchant. Ti/Au (20 nm/280 nm) contacts were finally evaporated to form ohmic contacts on the top n -type InAsSb and bottom GaSb buffer layers,

with an active absorption area of $250\ \mu\text{m} \times 250\ \mu\text{m}$. To ensure the reliability of results, we fabricated multiple devices w/o a PTHA, where the characterization results were essentially the same.

The photocurrent spectra (I_{PH}) were measured using the same experimental setup as in the absorption measurements, except that the fabricated detectors were used to collect photocurrent signals instead of the internal MCT detector. In the measurement, the MIR light source was first introduced into the Michelson interferometer inside the FTIR. After that, it was focused on the fabricated devices. The photocurrent signals collected by the detector were amplified by a low-noise current preamplifier, and then connected to the FTIR external port. The measured photocurrent spectra of the devices with (red curve) and without (blue curve) PTHA at room temperature under zero bias are shown in Fig. 6.18(b). Remarkable enhancement in the device with the PTHA is clearly seen, especially in the 3 peak wavelengths of $1.7\ \mu\text{m}$, $2.4\ \mu\text{m}$ and $3.9\ \mu\text{m}$. The higher photocurrents at $1.7\ \mu\text{m}$ and $3.9\ \mu\text{m}$ are understandable as they correspond to the bandgap of GaSb and InAsSb, respectively. According to the absorption equation of $1 - e^{-\alpha d}$ [178], where the α and d are the absorption coefficient and the thickness of the InAsSb layer [179], respectively, about 55% of $1.7\ \mu\text{m}$ incident photons can pass through the whole InAsSb layers and 76% of such photons can pass the InAsSb layer in the holes to reach the GaSb layer, which leads to significant photocurrent at around $1.7\ \mu\text{m}$. The appearance of the peak at about $2.4\ \mu\text{m}$ is primarily due to the absorption of atmosphere [60], which causes reduction of photocurrent in the wavelengths between the 2.5 and $3.9\ \mu\text{m}$. The significant enhancement in photocurrent at about $2.4\ \mu\text{m}$ for the device with PTHA is due to the enhanced photon incorporation and longer dwell time.

To know the polarization dependence of spectra response, we characterized I_{PH} of both devices under different polarization states. As shown in Fig. 6.18(c), the enhancement factor for I_{PH} at 2.7 μm does not change significantly with polarization angles due to the structure symmetry of the PTHA. The photocurrent spectra measured at different temperatures and biases for both devices are exhibited in Figs. 6.18(d)-(g). It is demonstrated that the enhancement is always present in NIR and MIR bands, although the enhancement factor varies with temperature and bias. The corresponding mechanism for this phenomenon will be explained in the following section.

6.2.4 Performance characterization

In order to quantify the photoelectric conversion capability of the PTHA, a 1000 K blackbody radiation source was used to characterize the responsivities of the reference and PTHA detectors, where a 300 Hz chopper and an NIR (1-3 μm) or MIR (2.5-4.8 μm) bandpass filter were set before the radiation reaching the devices under test. The measured photocurrent was then read out through a low-noise current preamplifier and lock-in amplifier. With the values of photocurrent (I_{PH}) and incident power (P_{inc}) obtained from a standard power meter, the blackbody responsivity (R_A) is derived from $R_A = I_{PH} / P_{inc}$.

Fig. 6.19 Responsivity (R_A) of the devices w/o a PTHA. R_A for (a) NIR and (b) MIR at room temperature under the bias from -0.5 V to 0.5 V. (c-d) R_A for (c) NIR and (d) MIR under zero bias at temperatures from 220 K to 293 K. (e-f) R_A for NIR at temperatures from 220 K to 293 K and under biases from -0.5 V to 0.5 V of (e) reference and (f) PTHA detectors. (g-h) R_A for MIR at temperatures from 220 K to 293 K and under biases from -0.5 V to 0.5 V of (g) reference and (h) PTHA detectors.

Figures 6.19(a) and (b) shows the corresponding room-temperature R_A for NIR and MIR measured under biases from -0.5 V to 0.5 V for the device with (red dots) and without (blue dots) the PTHA. The R_A values of the PTHA detector for NIR and MIR at zero bias are enhanced to 0.73 A/W and 0.48 A/W, respectively, compared to the 0.65 A/W and 0.36 A/W for the reference. The R_A is increased when the bias becomes negative. It is due to the enlarged depletion region with the reverse bias to -0.8 V, as the width of depletion region (W) is proportional to $\sqrt{(V_{bi}-V_{bias})}$, where V_{bias} is the applied voltage bias, V_{bi} is built-in voltage [156]. Light absorption happens within the depletion region, therefore, the wider depletion leads to more photogenerated carriers and larger R_A [2]. In addition, the responsivities at different temperatures under zero bias are also characterized, and the results for NIR and MIR are exhibited in Figs. 6.19(c) and (d). Obvious enhancement occurs over the whole temperature range studied and the enhancement becomes more significant at lower temperature. The corresponding responsivity map measured at different temperatures and biases are shown in Figs. 6.19(e)-(h). Since the intrinsic carrier density is reduced when temperature decreases, it leads to the increased width of depletion region [173]. In this case, a larger responsivity enhancement can be expected in PTHA device, as the increased absorbed photons. The zero-bias enhancement factors for NIR and MIR at room temperature are 1.12 and 1.33 , respectively, and they are increased to 1.71 and 1.79 , respectively, when temperature drops to thermoelectric cooling (TEC) temperature of 220 K.

Fig. 6.20 Response speed. (a) Amplitude-frequency response of reference and PTHA detectors. The line of -3 dB is indicated by the black dash dot line. (b) Response waveform of the PTHA (left in red) and reference (right in blue) devices. The rise time (t_r) is defined as the time duration of amplitude from 10% to 90%.

Finally, to gain insights of the PTHA influence on response speed, the amplitude-frequency response was characterized by using a $2.94\ \mu\text{m}$ laser with 20 ns rise and fall time. As shown in Fig. 6.20(a), the $f_{-3\text{dB}}$ (the frequency when signal amplitude decreases to 70.7%) is slightly broader in the PTHA device [180], with the value around $2.2 \times 10^5\ \text{Hz}$. We also characterized it in time domain, as indicated in Fig. 6.20(b). The device with the PTHA shows a rise time (t_r) of $1.6\ \mu\text{s}$ which is shorter than the $1.9\ \mu\text{s}$ from the reference. This can be attributed to the fast collection of photocarriers associated with etched holes in the PTHA device, where the reduced structure volume may lead to lower junction capacitance and smaller RC delay, thus an enhanced response speed [181].

6.2.5 Summary

A dual-band enhanced infrared photodetector which is made by integrating a PTHA on the InAsSb-GaSb heterostructure is designed and characterized. Significant enhancements of

photoresponse, beneficial from the reduced effective refractive index and lateral propagating slow modes, are realized in both NIR and MIR without polarization selectivity. Photoresponse enhancement is observed at different temperatures and voltage biases, where the enhancement factor becomes greater at lower temperature. In addition, improvements in working frequency range and response speed are also observed.

Chapter 7. Conclusion and Recommendations

7.1 Conclusion

The PhD project mainly focuses on the high-operating-temperature infrared photodetection enhancement. The research involves two parts: reducing dark current density and increasing photoresponsivity. In the dark current reduction, the InAsSb-based heterostructure is carefully designed with a wide bandgap barrier layer to reduce the excessive dark current induced by diffusion of carriers. The characteristics of dark current density are investigated, including the detailed study of activation energy, to figure out the dominant dark current mechanism under different situations and to confirm the effectiveness of measures taken for decreasing dark current. For the photoresponse improvement, various plasmonic structures and photon-trapping structures are studied and they are integrated with the heterojunction photodiode. To gain an insight on light confinement by the photonic structures, the electric field distribution and reflection spectra are studied. The enhanced photodetectors are fabricated and characterized by appropriate techniques, and the measurement results demonstrate that the infrared photodetection performance is significantly improved. The remarkable enhancement makes infrared photodetection possible to operate at room temperature.

The conclusions of all the works are detailed as follows:

1. The design, fabrication and characterization of an $\text{InAs}_{0.91}\text{Sb}_{0.09}$ based heterostructure photodetector are presented. A large bandgap p-AlGaSb layer is inserted to reduce the diffusion of minority electrons and two quaternary AlInAsSb layers are also used to limit type-II

transitions between the $\text{InAs}_{0.91}\text{Sb}_{0.09}$ and its side wide bandgap layers. The high-quality epitaxial layers were confirmed by XRD measurement and temperature-dependent photoluminescence spectra, which is important for achieving good detector performance. Detailed study of dark current including surface leakage and bulk diffusion, SRH, and tunneling process is conducted based on dark current-voltage characteristics of square mesa devices with different sizes and in different temperatures. For the $50\text{ }\mu\text{m}$ square mesa device, under applied bias of -0.1 V , the dark current (density) is reduced to only $1.5\times 10^{-5}\text{ A}$ ($0.6\text{ A}\cdot\text{cm}^{-2}$) at room temperature (293 K), which is smaller than those recently reported nBn and photovoltaic detectors.

2. Tunable resonant behaviors of U-SRR and U4-SRR arrays with different U sizes are systematically studied by analyzing reflectance spectra, electric and magnetic field distribution and sensing performance. It is found that the polarization-invariant U4-SRR arrays show higher sensitivity and spectra contrast compared to the U-SRR arrays due to the larger interaction volume and stronger electric fields for the unpolarized incidence. Both the peak resonance wavelength and sensitivity increase with U size. The polarization-invariant high sensitivities at mid-infrared range, obtained in the U4-SRR arrays, provides an excellent alternative for mid-infrared sensing.

3. Field distributions of different resonant modes of U-shape SRR arrays and their enhancement for middle infrared photodetection in an integrated photodetector consisting of an InAsSb-based heterojunction photodiode and an SRR array are studied. The higher order m_1 mode is found to contribute most to the enhancement, sequentially followed by the electric e mode and the fundamental m_0 mode. By superimposing m_1 and e modes in the designed SRR

array, a room temperature detectivity of 2.0×10^{10} Jones is achieved without supply of voltage bias. With a slightly thermoelectrical cooling, the detectivity can be increased to 3.4×10^{10} Jones and 4.2×10^{10} Jones at 275 K and 255 K, respectively. In addition, polarization-resolved photoresponse between m_1 and e modes and tunable enhancement through geometrical tailing SRR size are also observed.

4. An integrated MIR photodetector consisting of an InAsSb-based heterojunction photodiode and a rotated fourfold SRR-array is designed and investigated. High-order electric and magnetic resonant modes in SRR are used to enhance the photosensitivity. An order of magnitude enhancement on uncooled photosensitivity is achieved. In addition, its enhancement has polarization-independent property, which is pursued for a host of practical applications where robust photodetection is required.

5. A zero-bias room-temperature detectivity enhancement of 29% higher than the reference detector without the PT structure is obtained, where the enhanced detectivity is increased to 2.09×10^9 Jones. When the temperature drops to thermoelectric cooling temperatures of 260 K and 243 K, the detectivity enhancement can be more than two- and three-times, respectively. A response speed as fast as that of the reference is also observed. To this end, the etched PT structure does realize the polarization-independent broadband photodetection improvement.

6. A dual-band enhanced infrared photodetector which is made by integrating a PTHA on the InAsSb-GaSb heterostructure is proposed and studied. Significant enhancements of photoresponse, beneficial from the reduced effective refractive index and lateral propagating slow modes, are realized in both NIR and MIR without polarization selectivity. Photoresponse

enhancement is observed at different temperatures and voltage biases, where the enhancement factor becomes greater at lower temperature. In addition, improvements in working frequency range and response speed are also observed. This work offers a feasible method for effectively enhancing polarization-independent photoelectric conversion in the multi-band of the electromagnetic spectrum.

7.2 Recommendations for further research

The uncooled high-performance high-operating-temperature IR photodetection and imaging system will remain to be pursued in the future. According to the presented work, surface plasmon and photon-trapping structures have proved their effectiveness in promoting infrared photodetection. Therefore, some future works which can be done are listed below:

1. Develop uncooled two-dimensional focal planar array infrared imaging systems. The system includes two-dimensional plasmon-enhanced InAsSb-based heterojunction photodetector array, readout integrated circuit, optics and electronics, while the plasmon-enhanced InAsSb-based heterojunction photodetector array is the heart of the system. The U-shape SRR array is used as the plasmonic structure to integrate with the InAsSb-based heterojunction photodetector array, due to the obtained largest photodetection enhancement among the photonic structures studied. The good uniformity of InAsSb-based III-V group materials allows the extension of the photodetector to large focal planar arrays and the final integrated system will have high enough detectivity for uncooled operation. The successful development of the high-sensitivity uncooled middle infrared imaging systems will boost the

manufacturing and engineering capability from material growth to device fabrication and holistic integration of the advanced systems.

2. Design a back-illumination approach to realize the plasmon enhanced photodetector with higher performance and easier integration, where the cross-sectional schematic is shown below. Because the 2D plasmonic array can partially absorb the incident optical signal when it comes from front surface of the photodetector. By adopting back illumination, the incident optical signal will go through the active layer first before reaching the top plasmonic array. Some of incident photons will be absorbed in the active region and converted into useful photocurrent. The unabsorbed photons of the incident signal will interact with the plasmonic array and be coupled back in plasmonic mode to the active region, which gives extra contribution to the photoresponse. On the other hand, back illumination configuration is compatible with standard flip-chip techniques while integrated with the ROIC. Further, by using backside illumination, the plasmonic resonance will be directly taken place around the interface between plasmonic array and active absorption layer, which will reduce its damping in air in case of front-side illumination.

Fig. 7.1 Cross-sectional schematic of the hetero photodiode for FPA based camera.

3. Design and fabricate the photon-trapping enhanced photodetector assisted with the deposited gold. At the metal-dielectric interface, the optical field can be enhanced by the SPR, with its penetration depth into the dielectric characterized by the SPP skin depth. The interaction between the SPP fields and the absorption area results in the increase of light-absorption, thereby enhancing detector photoresponse. This gives the motivation to utilize the plasmonic effect for further enhancing the light absorption in the heterostructure absorber layer with the previous optimal photon-trapping structure.

Fig. 7.2 The light energy propagation direction in the integrated photodetector with the PTHA structure w/o the deposited gold. (a) Schematics of cylindrical holes in hexagonal lattice pattern, showing the location of cross-section plane for simulation in (b) & (c) which consists of the bottom part of a cylindrical hole in the center. Cross sectional view of Poynting vector direction around the holes under vertical optical illumination at the wavelength of $3\ \mu\text{m}$ for the structure (b) without gold and (c) with the deposited gold in the thickness of $50\ \text{nm}$. The arrows represent the energy flux direction. Blue lines represent the edge of the hole bottom part, and yellow part represents the deposited gold.

FDTD simulation results for the electric field distribution of the integrated heterostructure photodetector with PTHA w/o the deposited gold are shown in Fig. 7.2. for a wavelength of $3\ \mu\text{m}$. Upon the interaction between the localized SPP fields and the absorption area, we can observe that the Poynting vector for the structure assisted with the deposited gold shows more propagation in lateral direction near the horizontal interface of the deposited gold and absorption area. It means that the light propagates in

the lateral (in-plane) direction in the InAsSb i-layer, where it is absorbed, besides, the direction of the Poynting vector below the horizontal interface is changed, which can increase the light propagation time inside the absorber layer, as indicated in Figs. 7.2 (b) and (c).

Fig. 7.3 Comparison of the simulated absorption spectra at $\lambda = 2$ to $5 \mu\text{m}$ for the heterostructure photodetectors without PT structure (grey line), with the PT structure (green line), with the PT structure and the deposited gold (blue line).

The absorption spectra for the plasma assisted heterostructure with the PT in the optimal parameters are shown in Fig. 7.3. It is seen that an extra of 10% absorption can be achieved by depositing a gold layer at the bottom of the photon trapping holes.

4. Design the plasmonic structure for dual-band enhancement on the InAsSb-GaSb heterostructure photodetector. Since the dual-band photodetection is of great importance in scientific and technological areas. Apply the plasmonic effect to promote the photodetection in

both NIR and MIR can be realized through carefully design the metallic structure.

Appendix. Comparative study of typical plasmonic structures in IR region

Metallic nanostructures (metasurfaces) can generate strong localized resonance modes, and by adjusting the geometry, flexible resonance spectral tunability can be achieved [21], [182], [183]. These advantages enable the manipulation of light at subwavelength scale. In this appendix, we investigate the resonance behaviour of several plasmonic structures in IR region, specifically, the U-SRR and U4-SRR arrays, and their sensing performance.

A.1 Introduction of SRR arrays

The split-ring resonators opened a new way for using sub-wavelength structures to obtain artificial materials with resonant magnetic and plasmonic properties [184]. A number of studies have been conducted on the optical response of the arrays with various SRR designs, such as simple SRR [47], [140], complementary SRR [185], double-layered SRR [186], and vertical SRR [187] structures. Each of them has its properties in terms of polarization dependence, spectral bandwidth, resonance condition and focusing properties. Such SRRs have been widely used for variety of applications, including superlens [188], optical absorbers [189], filters [190], invisibility cloak [191], fluorescence emission [155], and optical switching [192]. Among various designs, the U-shaped SRR has drawn intensive interests, due to their flexible geometry tunability, multiple resonance peaks and easy of fabrication [193]–[195]. A single U-SRR is usually regarded as an LC circuit, where the full length of “U” forms an inductor L , and the gap between the side arms forms a capacitor C [196]. An LC model can be used for physically describing the resonance behavior of U-SRRs [135].

SRR arrays have been used for sensing based on the local refractive index change, which is usually reflected by the shift of resonant peaks [143]. So far, such devices have been studied intensively in the visible region [137]. Recently, the biosensing capability for SRR array have been demonstrated in IR region and the molecular fingerprinting regime [197], [198]. Most of the SRR-based biosensors for increasing the sensitivity utilize the substrates with lower refractive index like transparent quartz, fused silica and polydimethylsiloxane [143], [198].

A.2 Fabrication and characterization methods of U- and U4-SRR arrays

Figure A.1 shows the examples of two kinds of the SRR arrays studied in this work. Figs A.1(a) and (b) are the SEM image and its schematic unit cell of a typical U-SRR array, while Figs A.1(c) and (d) show the SEM image and schematic unit cell of a typical U4-SRR array.

Fig. A.1 Illustration of U- and U4-SRR arrays. (a) SEM image and (b) Schematic unit cell of a typical U-SRR array. (c) SEM image and (d) Schematic unit cell of a typical U4-SRR array. The scale bars are 1 μm .

All our SRR arrays were fabricated on Si substrates which are 15 mm x 15 mm in dimensions. The substrates were first immersed in hydrofluoric acid solution to remove the top oxide layer. They were then consecutively cleaned in acetone and isopropanol, rinsed in deionized water, dried by nitrogen gas, and baked at 110 °C for 10 mins. Next, the ZEP520A resist was spin-coated to define the pattern using EBL. After development in standard *n*-amyl acetate (ZED-N50) and methyl isobutyl ketone (MIBK) solution, a 60-nm Au film with a 5-nm Ti film as an adhesion layer was deposited by the electron beam evaporation method. Finally, the gold resonator arrays are emerged via lift-off process.

Reflectance spectroscopy was adopted to characterize the resonance of SRR arrays, which were measured in the range of 1 μm to 9 μm by a FTIR equipped with an IR microscope (Bruker HYPERION 2000). A 36x magnification microscope objective (NA=0.5) was utilized to focus the light from FTIR on designed SRR array. After a KBr beam splitter (and an infrared polarizer), the reflected light signal was collected and recorded by a liquid-nitrogen cooled MCT detector. All the measured spectra were normalized with the reflectance spectra of a gold mirror through an 8 mm aperture. The frequency resolution is 32 cm^{-1} . All spectra were obtained via averaging the result of 128 scans.

FDTD was performed to interpret the nature of optical responses of the SRR-based arrays by simulating the reflectance spectra, local electric fields, and magnetic fields. In the simulation, plane wave was set to incident in the direction normal to array plane (*z*-direction). The periodic boundary conditions are applied in the plane propagation direction (*z*-direction) and perfectly matched layer conditions in the normal plane direction (*x* & *y*-direction). The dielectric functions of silicon and gold were taken from the book by Palik [141]. The mesh cell was set

to be 1 nm in each direction which is much smaller than the feature size of SRR. In order to match the actual structure size, the structures drawn in the simulation are in rounded corners, as caused by proximity effect in EBL process.

A.3 Investigation of U-SRR arrays

We start by considering the optical response of simple U-SRR arrays whose unit cell is shown in Fig. A.1(b) with resonator size (S), gap (g), line width (w) and period (p). Four U-SRR arrays with U sizes of $S = 170$ nm, 240 nm, 300 nm, and 400 nm were fabricated. Detailed geometrical dimensions are listed in Table II, where the periodicity is chosen to avoid spectral complications due to far-field coupling. Moreover, the inter-resonator spacing were not made too small to minimize resonance broadening due to near-field coupling loss.

Table VI. Detailed geometrical dimensions for the four U-SRR and four U4-SRR arrays.

	S (nm)	g (nm)	w (nm)	p (nm)
U-SRR170	170	90	80	340
U-SRR240	240	120	120	480
U-SRR300	300	160	140	600
USRR400	400	200	200	800
U4-SRR170	170	90	80	680
U4-SRR240	240	120	120	960
U4-SRR300	300	160	140	1200
U4-SRR400	400	200	100	1600

Figure A.2(a) shows the measured (black) and simulated (red) reflectance spectra of the four U-SRR arrays under unpolarized incidence. To determine the origins of the resonances, the electric and magnetic field distributions (normalized to the corresponding incident field) near the Si-metal interface is exhibited in Fig. A.3. The peak (labeled as 1) in MIR corresponds

to the fundamental magnetic resonance mode (m_0). It is typically attributed to the incident electric field in a direction perpendicular to gap edge (x-direction), which generates a magnetic-dipole moment normal to array plane by coupling to the capacitance between side arms [136]. The magnetic field is highly localized in the inner part of bottom arm (as shown in $|H|$ distributions), suggesting strong magnetic-dipole behavior. The electric field distribution indicates that the highest field is concentrated at inner edge on either side of the gap. This behavior is consistent with the plasmonic resonance nature of this mode [135]. The shorter-wavelength peak (labeled as 2) in NIR represents the combined effects of a high-order magnetic mode (m_1) and an electric mode (e_0). In order to illustrate the surface charge distribution, we plot E_z distribution at the surface of SRRs. As indicated in the E_z distribution, under the incident electric field in x-direction, two dipoles are generated on each corner of “U” and the two adjacent ones have opposite electric polarity. In this case, the electric dipole distribution resembles those of the quadrupolar mode [199], the magnetic field is not as strong as that in the m_0 mode, as shown in Fig. A.3. Therefore, this mode is also referred to as high-order magnetic mode m_1 . The other mode contributing to the peak is due to collective oscillation of free electrons in side arms under incident electric field in the direction parallel to gap edge (y-direction). Based on the E_z and $|H|$ profile, the field is symmetrically distributed in both side arms, and magnetic field is only localized in side arms. Therefore, no magnetic dipole can be generated at this resonance and this mode is called electric resonance e_0 [155]. The resonance wavelengths for the latter two modes are almost same, as these two modes are symmetric (e_0) and antisymmetric (m_1) modes originating from the hybridization of plasmonic modes [137]. As a verification, the reflection spectra of the U-SRR300 were measured at different

polarizations. As shown in Fig. A.3, the fundamental magnetic resonance peak ($\lambda=4.8\ \mu\text{m}$) of the sample occurs only in x -polarized incident light, while the peak at $\lambda=2.3\ \mu\text{m}$ occurs in both x - and y -polarizations [135]. The presented results also suggest good agreements between experiments and simulations, except the reflectance dip at the wavelength around $4.2\ \mu\text{m}$ in measured spectra, which is induced by carbon dioxide absorption. In the U-SRR400 which has a U size of $400\ \text{nm}$, a third peak appears at the short wavelength of about $1.4\ \mu\text{m}$ which is the high order electric resonance mode.

Fig. A.2 U-SRR array analysis. (a) Measured (black lines) and simulated (red lines) reflectance spectra of the U-SRR arrays with resonator sizes of 170 nm, 240 nm, 300 nm, and 400 nm, respectively. All the scale bars are 200 nm. (b) Resonant peak wavelengths as a function of S . The measured results are expressed as points and the simulated results as solid lines. (c) The measured (solid lines) and simulated (dash dot lines) reflectance spectra, R , R_x and R_y for U-SRR array of $S=300$ nm (US300).

Fig. A.3 Simulated distribution of electric field magnitude ($|E|$), z-component field (E_z) and magnetic field magnitude ($|H|$) at metal-dielectric interface for US300 array under x(y)-polarization at $\lambda=4.8 \mu\text{m}$ and $2.3 \mu\text{m}$, respectively.

Fig. A.2(b) shows the peak resonant wavelengths extracted from the reflection spectra as a function of U-shape size S . Both reflection peak wavelengths, λ_{p1} and λ_{p2} , exhibit positive proportional dependences on S in the studied range. λ_{p1} increases from $2.9 \mu\text{m}$ to $6.3 \mu\text{m}$, while λ_{p2} increases from $1.5 \mu\text{m}$ to $3.0 \mu\text{m}$ when the size of the U-SRRs increases from 170 nm to 400 nm . This observation can be quantitatively interpreted using the standing-wave plasmonic resonance (SWPR) model [200]:

$$FL = \frac{m(\lambda_m + \lambda_0)}{2n_{eff}} \quad (31)$$

where FL is the full length of single U-SRR, λ_m is the resonance wavelength at mode m , λ_0 is dependent on geometric size, and n_{eff} is the local effective refractive index determined by

substrate refractive index (n_{sub}) and surrounding medium (n_{sur}), as expressed below [143]:

$$n_{\text{eff}} = \alpha n_{\text{sub}} + (1 - \alpha)n_{\text{sur}} \quad (32)$$

where α is the weighting factor. The n_{sub} is chosen to be 3.42 which corresponds to the refractive index of Si in the range of 1 μm to 9 μm [201], and n_{sur} is set to be 1 as surrounding environment is air. Since the value of FL almost equals to three time of S , the slopes derived from Fig. A.2(b) at the mode of $m=1$ (m_0 mode) and 2 (m_1/e_0 mode) are in good accordance with the SWPR model, which gives α of 0.53.

A.4 Investigation of U4-SRR arrays

As a comparison, we also fabricated four U4-SRR arrays with the same U sizes as the four U-SRR arrays whose detailed dimensions are listed in Table II. U4 means there are four U-SRR in one unit cell with rotation design as shown in Fig. A.1(d). Fig. A.4(a) shows the reflectance spectra of the four array samples in the range of 1 to 9 μm under unpolarized incidence. There are three peaks in the reflection spectra of the U4-SRR arrays with U sizes of 170 nm, 240 nm and 300 nm, but four peaks in U4-SRR400. The three peaks, labeled as 1, 2 and 3, correspond to m_0 , e_0 and m_1 modes, respectively, and the fourth one in U4-SRR400 is the higher order electric resonance mode e_1 . They all shift to the longer wavelengths with the increased U size. For m_0 mode (labeled as 1) at $\lambda_{p1}=5.2$ μm of U4S300 SRR array, the highest electric field intensity is as almost three times as that of the US300 SRR array, and a much larger contrast (37% for U4S300) is realized. The observed phenomenon in U4-SRR array may be attributed to the fact that the adjacent SRRs do not interact with each other because they are orthogonal each other. This reduced effective near-field coupling leads to narrower resonance

line width. The main reason for the increased contrast is due to polarization-invariant property induced by its rotational symmetry design. For a unit cell of U-SRR array, the magnetic and electric modes cannot be simultaneously excited in one polarization, leading to their weak resonance behavior under unpolarized light. However, in U4-SRR, due to its rotational symmetry configuration, the incident light in any one polarization direction can simultaneously excite different modes in one unit cell. The same electric field distribution and same reflectance spectra under x- and y- polarization also help verify the polarization independence character of this structure. The strong resonance behavior of U4-SRR array thus makes the reflection spectra peak narrower and the m_1 and e_0 modes separated.

Fig. A.4 U4-SRR array analysis. (a) Measured (black lines) and simulated (red lines) reflectance spectra of U4-SRR arrays with resonator sizes of 170 nm, 240 nm, 300 nm, and 400 nm, respectively, for unpolarized incidence. All the scale bars are 200 nm. (b) Resonant peak wavelengths as a function of S . The measured results are expressed as points and the simulated results as solid lines. (c) The measured (solid lines) and simulated (dash dot lines), R , R_x and R_y for U4-SRR array of $S=300$ nm (U4S300).

Fig. A.5 Simulated distribution of electric field magnitude ($|E|$), z-component field (E_z) and magnetic field magnitude ($|H|$) for U4S300 array under x- (y-) polarization at $\lambda=5.2 \mu\text{m}$, $3.0 \mu\text{m}$ and $2.3 \mu\text{m}$, respectively.

As can be seen from the electric field distributions in Fig. A.5, for magnetic resonance, adjacent SRRs with perpendicular orientations cannot be excited simultaneously, yet those with opposite orientations can be excited to produce magnetic dipoles in opposite directions. In terms of inter-resonator coupling, this has wide implication. The electric and magnetic coupling in planar SRR arrays have been studied in detail [202], [203]. The magnetic coupling between SRR occurs via transverse dipole coupling, which gives blue shift as the inter-resonator distance is decreased. Meanwhile, the electric coupling between SRRs comprises of transverse and longitudinal coupling, with their proportionality determined by the x and y periodicities [202]. In contrast to the regular square lattice, there are opposite magnetic dipoles excited within a unit cell of a fourfold rotationally symmetric lattice, giving rise to a negative transverse magnetic coupling and therefore a resonance red shift. The existence of such magnetic coupling

is also supported by the fact of a strong SRR magnetic response in the infrared, which is far from the interband transition of gold at 539 nm. This agrees with the observed red shift of m_0 resonance from 4.8 μm (in US300-SRR) to 5.2 μm (in U4S300-SRR) for the two arrays with the same U size. In terms of electric dipole, as there is no electric coupling between adjacent SRRs due to their perpendicular orientations, the periodicity of the U4-SRR is effectively twice that of the U-SRR and the electric coupling in U4-SRR is much smaller compared to that in U-SRR. For the magnetic resonance (m_0 mode), this means that the inter-resonator coupling is dominated by the magnetic coupling. For higher order modes, the much smaller electric coupling among the SRRs translates to narrower resonance widths, leading to spectral distinguishability of electric mode and higher order magnetic modes at $\lambda=3\ \mu\text{m}$ and $2.3\ \mu\text{m}$, respectively, under unpolarized excitation.

For the size effect on resonant wavelength, the SWPR model for U-SRR arrays can also be applicable to the U4-SRR arrays. Fig. A.4(b) shows the peak reflection wavelengths, λ_{p1} of fundamental magnetic resonance m_0 , λ_{p2} of electrical resonance e_0 , and λ_{p3} of high order magnetic resonance m_1 , as a function of U size. The three peak wavelengths, λ_{p1} , λ_{p2} , and λ_{p3} increase from 3.2 μm , 1.9 μm and 1.5 μm to 7.0 μm , 4.0 μm and 3.0 μm when the U size is increased from 170 nm to 400 nm. Compared to the U-SRR arrays, in addition to the obvious splitting of e_0 and m_1 modes, all resonance modes of the U4-SRR arrays with the same U size occur at longer wavelength.

A.5 Sensing performance

As the local refractive-index environment has a significant effect on resonance positions

[204], it provides great possibility for the application in sensing. High sensing performance requires higher sensitivity and larger spectra contrast, which are expressed in the following equation:

$$\begin{aligned} \text{Sensitivity} &= \frac{\Delta\lambda}{\Delta n} \\ \text{Spectra contrast (\%)} &= R_{\max} - R_{\min} \end{aligned} \quad (33)$$

where $\Delta\lambda$ is the change of resonance wavelength and Δn is the variation of local refractive index, $R_{\max}$ and $R_{\min}$ are the peak reflectance values at resonance and adjacent higher reflectance valley, respectively. The sensitivity is determined by various factors, notably the E -field enhancement, plasmonic field localization, plasmonic decay length, and the interaction volume between the plasmonic mode and the analyte [54], [187].

To study the differences in sensing performance for U- and U4-SRR arrays, a 100-nm thick PMMA layer was spin-coated atop. We found that 100 nm is sufficient as it is larger than the plasmonic decay lengths of all the SRR modes considered in this work. This is also confirmed in ref. [205], where the resonance shift saturates at analyte thickness below 100 nm in terahertz SRR. Its refractive index is around 1.48 for the wavelengths of interest [206]. Then we determined the sensitivity of each sample by measuring the difference of peak resonance wavelengths with and without PMMA coating. The sensing spectra of the U-SRR and U4-SRR arrays with $S=300$ nm are illustrated in Fig. A.6(a). Red shifts in all resonant peaks were observed and they are consistent with the simulation results. It is noted that the wavelength shift is larger in the U4-SRR array than that in the U-SRR array. Based on the peak wavelength shifts, the corresponding sensitivity values at each peak resonance wavelength for the U-SRR and U4-SRR arrays are calculated and they are illustrated in Figs. A.6(b) and (c), respectively.

The sensitivities of m_0 mode in all arrays are obviously greater than that of other modes because the antenna radiation induced higher localized electric fields at the dielectric- metallic interface. Take the U4-SRR with $S=300$ nm as an example, the sensitivities at m_0 , e_0 and m_1 modes are 443 nm/RIU, 142 nm/RIU, and 142 nm/RIU, respectively. In addition, the sensitivities for all resonance modes are positively proportional to the resonator size. For clarity, the sensitivities at m_0 mode for the U-SRR and U4-SRR arrays as a function of U size are shown in Fig. A.6(d). It is seen that the sensitivity value is increased from 201 nm/RIU to 642 nm/RIU when the U size is increase from 170 nm to 400 nm for the U4-SRR arrays.

Fig. A.6 (a) The reflectance spectra with and without PMMA coating in US300 and U4S300 arrays. The sensitivities at each peak resonance wavelength for (b) U-SRR and (c) U4-SRR arrays as a function of resonator size S . (d) The comparison of sensitivities in m_0 mode of U- and U4-SRRs.

It can be seen that the sensitivities of U4-SRR arrays are higher than those of U-SRR arrays. This is attributed to the larger interaction volume in the U4-SRR arrays. In order to verify this, we investigated the sensing characteristics of m_0 mode in U-SRR and U4-SRR arrays for different cladding layer thickness. The plasmonic decay lengths are ~ 100 nm for U4-SRR and ~ 80 nm for U-SRR arrays, respectively. The longer plasmonic decay length in the U4-SRR arrays translates to a larger interaction volume, which results in higher sensitivity. As a comparison, we list the sensing capabilities of related platforms in Table III. To the best of our knowledge, the 642 nm/RIU achieved is higher than those reported IR sensors fabricated on silicon substrates.

Table VII. Sensitivity of planar structures on silicon substrate in infrared range.

Devices	Sensitivity (nm/RIU)	Wavelength (μm)	Reference
gold dipole-antenna array	300	7	[207]
photonic crystal resonator	400	1.5	[208]
ring resonators based on sub-wavelength grating	490	1.6	[209]
suspended microracetrack resonator with lateral subwavelength-grating metamaterial cladding	337.5	2	[210]
slot-waveguide ring resonator	298	1.3	[211], [212]
U-SRR array	533	6.4	Our work
U4-SRR array	642	6.9	Our work

A.6 Summary

In this work, tunable resonant behaviors of U-SRR and U4-SRR arrays with different U sizes are systematically studied by analyzing reflectance spectra, electric and magnetic field distribution and sensing performance. It is found that the polarization-invariant U4-SRR arrays

show higher sensitivity and spectra contrast compared to the U-SRR arrays due to the larger interaction volume and stronger electric fields for the unpolarized incidence. Both the peak resonance wavelength and sensitivity increase with U size. The polarization-invariant high sensitivities at mid-infrared range, obtained in the U4-SRR arrays, provides an excellent alternative for mid-infrared sensing.

Publications

1. **Fei Suo**, Jinchao Tong, Li Qian, and Dao Hua Zhang. “Study of Dark Current in Mid-Infrared InAsSb-Based Hetero $n-i-p$ Photodiode.” July 2018, *Journal of Physics D: Applied Physics* 51 (27). DOI: 10.1088/1361-6463/aac8d0.
2. **Fei Suo**, Jinchao Tong, and Dao Hua Zhang. “Dark Current Analysis of InAsSb-Based Hetero- $p-i-n$ Mid-Infrared Photodiode.” February 2020, *IEEE Journal of Quantum Electronics* 56 (1). DOI:10.1109/JQE.2019.2952388.
3. **Fei Suo**, Jinchao Tong, Landobasa Y M Tobing, Weijun Fan, Zhengji Xu, and Dao Hua Zhang. “Comparative Study of U- and U4-Split-Ring Resonator-Based Metasurfaces for Sensing in Near- and Mid-Infrared Region.” December 2020, *Journal of Optics* 22 (12). DOI: 10.1088/2040-8986/abc785.
4. **Fei Suo**, Jinchao Tong, Xiren Chen, Zhengji Xu, and Dao Hua Zhang. “Hole array enhanced dual-band infrared photodetection.” February 2021, *Optics Express* 29(5). DOI: 10.1364/OE.415987.
5. **Fei Suo**, Jinchao Tong, and Dao Hua Zhang. “Photon-trapping array for enhanced midwave infrared photoresponse.” September 2021, *Journal of Physics D: Applied Physics* 54 (50). DOI: 10.1088/1361-6463/ac25b1.
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