Mid-wavelength infrared photodetection and surface plasmon enhancement

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**NANYANG
TECHNOLOGICAL
UNIVERSITY**

**MID-WAVELENGTH INFRARED
PHOTODETECTION AND SURFACE PLASMON
ENHANCEMENT**

**QIU SHUPENG
SCHOOL OF ELECTRICAL & ELECTRONIC ENGINEERING
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SCHOOL OF ELECTRICAL & ELECTRONIC ENGINEERING

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Abstract

Infrared (IR) photodetectors with peak sensitivity wavelength in mid-wavelength infrared (MWIR) spectral window (3-5 μm) have attracted extensive interests due to the highest atmospheric transmission in this range. Traditional photodetectors operating in this wavelength range are mainly based on HgCdTe, PbSnTe and InSb, which either have difficulties in repeatable growth of uniform composition bulk crystals and epitaxial layers or need low temperature environment, which lead to the development of alternative material systems, such as InAs/GaSb type-II superlattice (SL) and InAsSb based material system.

To improve high temperature performance of photodetectors, a concept of surface plasmon polariton (SPP) enhancement has been proposed in recent years. By placing a plasmonic structure which has strong light focusing capability in sub-wavelength regime, close to absorption region of a detector, tight spatial confinement and high local field intensity of surface plasmons enable to enhance light-matter interaction and thus to improve the performance of light detection. A practical and efficient way is to integrate a sub-wavelength metallic two-dimensional hole array (2DHA) and an absorption structure.

In this thesis, the author will present his works on simulation and analysis of plasmonic enhanced photodetection via metallic 2DHA, investigation of InAs/GaSb type-II superlattice and InAsSb based infrared photodetectors, and plasmonic enhanced room temperature GaSb/InAsSb heterostructure photodiode. The details are summarized as follows:

Simulation and analysis of extraordinary optical transmission (EOT) through sub-wavelength metallic 2DHA, the underlying physics and mechanism of plasmonic enhanced photodetection have been studied. Possible variables and parameters which may affect the transmission and enhancement of photodetector

performance have been analyzed. These include periodicity of hole array, hole diameter, refractive index of substrate, thickness of metal film, hole shape and light incident direction. The simulation results provide a good guide for design of 2DHA photodetectors.

The origin of Wood's anomaly in optical transmission through metallic hole array has been analyzed. Here, the contradiction of the existence of Wood's anomaly in EOT and the generally observed broadband performance enhancement of photodetector via 2DHA is successfully explained. It is interpreted that at Wood's anomaly wavelength, the extremely low transmission results from excitation of incident light as SPP, which has a low efficiency of being decoupled from the metal-dielectric interface and doesn't contribute to transmission. Also, how this theory can be applied to illustrate the broadband photoresponse enhancement of integrated structure of photodetector and metallic hole array is described.

A n-i-p based mid-infrared InAs/GaSb type-II superlattice (SL) photodetector working at 220 K has been designed and fabricated. According to characterization results, the grown SL structure has very high quality. At 220 K, the 50% cutoff wavelength of the photoresponse is about 4.66 μm , the R_0A is as high as 14.9 $\Omega\cdot\text{cm}^2$, and the dark current is very low. The peak detectivity of the photodetector is $2.23 \times 10^{10} \text{ cm}\cdot\text{Hz}^{1/2}/\text{W}$ at 3.0 μm under zero bias, which is the highest for the InAs/GaSb SL photodetector operating at 220 K.

High performance InAsSb based photodetector operating at room temperature has been fabricated and investigated. The InAsSb material is grown on the GaSb substrate by molecular beam epitaxy (MBE) and photoconductive detector is made by them. The grown materials show high quality and slight lattice mismatch to the substrate. The photoconductors fabricated based on the InAsSb/GaSb structure show spectral response ranging from near infrared (NIR) to MWIR range. They can work

well at low voltage bias and the measured blackbody detectivities are $\sim 2.4 \times 10^7$ $\text{cm} \cdot \text{Hz}^{1/2} / \text{W}$ and $\sim 6.1 \times 10^9$ $\text{cm} \cdot \text{Hz}^{1/2} / \text{W}$ at room temperature and 77 K, respectively.

Photodetection performance of n-GaSb/n-InAsSb heterostructure at different temperatures and biases has been investigated. The devices were found to be capable of dual color photodetection at fixed large forward biases at different temperatures and the maximum responsivity occurs at room temperature. As the forward bias decreases, a turning bias exists at which the photocurrent changes its direction and the voltage value varies with temperature. At reverse biases, the absorption of GaSb dominates the photocurrent and the maximum photocurrent occurs at about 205 K. All the observation can be explained by the proposed model.

Plasmonic enhanced infrared photodetection based on n-GaSb/n-InAsSb heterostructure is realized and investigated. By integrating properly designed sub-wavelength metallic 2DHA on top, the room temperature photocurrent and detectivity of the photodiode is enhanced by ~ 2 times. Besides, the dark current of the heterostructure is not adversely affected by 2DHA fabricated on top. The performance enhancement is due to higher quantum efficiency of the 2DHA-heterostructure, resulting from electric field concentration at the metal-dielectric interface.

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List of abbreviations

Abbreviations	Full expressions
IR	infrared
MWIR	middle wavelength infrared
LWIR	long wavelength infrared
SWIR	short wavelength infrared
VLWIR	very long wavelength infrared
SL	superlattice
SPP	surface plasmon polariton
2DHA	two-dimensional hole array
EOT	extraordinary optical transmission
FIB	focused ion beam
EBL	electron beam lithography
MBE	molecular beam epitaxy
NIR	near infrared
SP	surface plasmon
EM	electromagnetic
TM	transverse magnetic
TE	transverse electric
EHP	electron-hole pair

SRH	Shockley-Read-Hall
NEP	noise equivalent power
PC	photoconductive
PV	photovoltaic
PEM	photoelectromagnetic
HOT	high-operating-temperature
QWIP	quantum well infrared photodetector
FDTD	finite-difference time-domain
FTIR	Fourier transform infrared spectroscopy
SEM	scanned electron microscope
LSP	localized surface plasmon
FWHM	full width at half maximum
RA	Rayleigh anomaly
ML	monolayer
RIE	reactive-ion etching
ICP-RIE	inductively coupled plasma reactive-ion etching
HRXRD	high resolution x-ray diffraction
PL	photoluminescence
AR	antireflection
SNR	signal to noise ratio
CW	continuous wave

2DEG	two-dimensional electron gas
ME	melt epitaxy
MOCVD	metalorganic chemical vapour deposition
OMVPE	organometallic vapour phase epitaxy

Chapter 1. Introduction

1.1 Motivation

Infrared (IR) photodetectors have been studied extensively in the past decades [1]–[9], due to a wide range of applications in civilian, medical, military and astronomy fields. Special interest has been focused on the wavelengths of the two atmospheric windows which are in 3–5 μm [middle wavelength infrared (MWIR)] and 8–12 μm [long wavelength infrared (LWIR)], respectively, due to the highest transmission in these two bands [10]–[12], as shown in Figure 1.1.

Figure 1.1 Transmission of energy through the atmosphere as a function of wavelength. Wavelength regions of high transmittance are atmospheric windows. Gases and their absorption wavelengths are noted [10], [11].

The MWIR photodetectors could be used for monitoring gases such as CH₄, CO₂, N₂O and O₃ quickly. Nowadays, most of the MWIR photodetectors are fabricated with narrow-gap semiconductor materials, such as HgCdTe, PbSnTe, and

InSb [1], [7]. These narrow-gap semiconductor materials exhibit high electron mobility, high optical absorption coefficient and low thermal generation rate [2], [3]. In addition, these alloys allow the band gap of the semiconductors and thus the spectrum response of the detectors to be customized for specific applications.

To obtain high performance, most semiconductor IR photodetectors need to operate at temperatures much lower than 300 K (typically 77 - 200 K) [2]. This is for suppressing the thermal generation rate to the lowest level possible. But cooling requirements render semiconductor IR photodetectors to be heavy, bulky, expensive and inconvenient to use, which prevent them from being more widely spread. Thus, one of the major research objectives is to increase the operating temperature of semiconductor IR photodetectors [13].

In the past years, the performance of HgCdTe photodetectors near room temperature was significantly improved [14]–[17]. HgCdTe alloy has large optical coefficients which enable high quantum efficiency. Besides, favorable inherent recombination mechanisms lead to longer carrier lifetime and higher working temperature. The bandgap tunability of HgCdTe alloy makes it suitable for usage from short wavelength infrared (SWIR) range to very long wavelength infrared (VLWIR) range. These superior features make the HgCdTe ternary alloy close to an ideal infrared detector material system, especially for high temperature operation. Nevertheless, there are some disadvantages HgCdTe still suffers from. They are some technological problems resulting from a weak Hg-Te bond, such as high mercury vapor pressure over melts, health hazard due to the highly toxic compounds, and serious difficulties in repeatable growth of uniform composition bulk crystals and epitaxial layers [2], [13], [14]. In addition, the high cost of commonly used lattice-matched CdZnTe substrate remains to be a big issue to be solved. These problems encouraged the development of alternative materials in the past forty years. Among them, the most important alternative materials are the InAs/GaSb type-II superlattice (SL) [18]–[37] and the III-V InAsSb ternary alloy [38]–[46].

As a promising alternative of HgCdTe, the InAs/GaSb type-II SL material system was theoretically proposed by Tsu et al. in 1977 and then demonstrated a decade later by Smith and Mailhot that the optical absorption coefficient of this SL material can be as good as that of the HgCdTe alloy with the same bandgap [18], [19]. This InAs/GaSb type-II SL material system is characterized by a “broken-gap” type-II alignment, in which the conduction band bottom of InAs is slightly lower than valence band top of GaSb. Because of this unusual bandgap lineup, the bandgap of the SL system can be tuned in a wide wavelength range. Specifically, this synthesized SL material can have a bandgap smaller than either of these two constituent materials, making the material system ideal for fabricating small band gap detector. By varying the thickness of InAs and GaSb layer, the cutoff wavelength of the SL material can be tuned from 3 to 40 μm . Also as a result of this unusual bandgap alignment, the holes and electrons are localized in different layers, the holes in the GaSb layer and electrons in the InAs layer [19]. This spatial separation of holes and electrons contributes to suppression of Auger recombination. Compared with HgCdTe alloy with same bandgap, the electron effective mass of the SL material is much larger, and it is not dependent on the bandgap size as in the case in bulk semiconductor material. This large electron effective mass significantly reduces diode tunneling current. Therefore, combined with the reasonably large optical matrix elements, the optical absorption coefficient of InAs/GaSb SL material can be as good as that of HgCdTe alloy with the same bandgap [19]. However, despite the plenty of theoretical predicted and technological advantages InAs/GaSb SL material system offers, these predictions haven’t been confirmed by experiment results. Currently, the dark current of SL detectors is still much larger than that of HgCdTe detectors, particularly in MWIR range [47]–[49]. Thus, the performance of InAs/GaSb SL detector is still far from being superior to that of HgCdTe detectors.

As another attractive alternative of HgCdTe, the InAsSb ternary alloy also receives a lot of attention [38], [39], [41], [42]. Compared with HgCdTe, this III-V alloy is much more stable and has a fairly weak dependence of band edge on

composition. Different with ionic bonding in HgCdTe, the stronger chemical bonds available in the low atomic number III-V family and the larger covalent bonding contribution make InAsSb a very stable material. Other better properties of InAsSb include low dielectric constant and small room temperature self-diffusion efficient. In addition, growth of the InAsSb alloy with high uniformity and repeatability is much easier. More importantly, the InAsSb based infrared photodetectors are expected to have high performance when operating either close to or at room temperature [38], [39], [41]. Therefore, there is vast interest on development of InAsSb based photodetector operating near room temperature.

For further improving high temperature performance of semiconductor MWIR photodetectors, a concept of surface plasmon polariton (SPP) enhancement has been proposed in recent years [50]. By placing plasmonic structure, which has strong light focusing capability at sub-wavelength regime, near to absorption region of the detector, performance enhancement of photodetector can be achieved [51]. Tight spatial confinement and high local field intensity of surface plasmon enable it to be particularly attractive for enhancing light-matter interaction and thus for improving the performance of light detection [52]. But conventional SPP excitation techniques, such as prism coupling and highly focus ion beam, are obviously not practical for this purpose. A much simpler scheme of integrating plasmonic structure and photodetector is required. Thus, people turned to the sub-wavelength, metallic two-dimensional hole array (2DHA) structure. This idea arose from the extraordinary optical transmission (EOT) through metallic 2DHA, which was first observed and discussed in 1998 [53]. The EOT is attributed to 2DHA's capability of sustaining the plasmonic modes and facilitating light coupling through Bragg scattering at the same time. In addition, due to the advances in nanotechnology, it is now possible to fabricate very high quality 2DHAs using available techniques such as focused ion beam (FIB) and electron beam lithography (EBL). Nowadays, the most widely used technique for SPP enhanced photodetection is placing

sub-wavelength metallic 2DHA structure near photodetector absorption region, as shown in Figure 1.2.

Figure 1.2 Schematic of integrated structure of photodetector and sub-wavelength metallic 2DHA.

In 2010, the first time that surface plasmon enhanced infrared photodetector based on InAs quantum dots was achieved [54]. By fabricating metallic 2DHA on top, the photoresponse enhancement as high as 130% was observed at resonance wavelength. Since then, extensive theoretical and experimental work has been done in this research field [55]–[59]. However, to the best of the author’s knowledge, the dependence of transmission and transmission efficiency through 2DHA on various variables is not fully understood. And the quantitative relation between extraordinary transmission through metallic 2DHA and performance enhancement of photodetector is not revealed yet. More importantly, the mechanism behind this performance enhancement of surface plasmon photodetector is still not very clear.

Much work remains to be done before people can fully understand of the SPP enhancement.

One particular point needs to be mentioned here is the apparent contradiction between small bandwidth of transmission peak and the observed broadband SP performance enhancement of photodetector. According to experimental and simulation results, the peak of transmission through metallic 2DHA is extremely sharp. So, theoretically, the performance enhancement should only be possible in a very narrow range close to transmission peak wavelength. However, as shown by available experiment results, the performance enhancement is usually broad [54], [56], [57]. The enhancement can even occur at Wood's anomaly wavelength, at which the transmission is extremely small. Thus, in order to have a more clear understanding of the mechanism of SP performance enhancement, a new interpretation to this contradiction is required.

1.2 Objectives

Grounded on above motivations, the major objectives of this thesis are described as below:

1. To simulate and investigate the extraordinary transmission through metallic 2DHA, strong light concentration at metal-dielectric interface, and mechanism of plasmon enhanced photodetection. The author wants to have a clear understanding of effects of all possible variables which may affect the plasmonic enhancement. Also, the author wants to study the underlying physics behind the plasmonic enhancement phenomenon and apply these simulation results and understanding of underlying mechanism as a guide for design of metallic 2DHA structure on top of photodetectors.

2. To study and explain the apparent contradiction between narrow transmission peak resulting from Wood's anomaly and broadband plasmonic performance enhancement. The author wants to have a detailed analysis of this contradiction and propose a reasonable interpretation to it. This is essential if people want to grasp full understanding of the SPP enhanced photodetection effect and apply it in practical applications.
3. To design and study InAs/GaSb type-II SL photodetectors which can have high performance near room temperature. This promising material system is expected to have better performance than HgCdTe photodetector. But currently the dark current of InAs/GaSb type-II SL photodetector is still too large when compared with HgCdTe photodetector, especially in MWIR range. So the author hopes to improve the design of n-i-p based mid-infrared InAs/GaSb type-II superlattice photodetector, reduce its dark current, and increase its operating temperature to near room temperature.
4. To design and fabricate InAsSb based photodetector operating near room temperature. The InAsSb alloy is an attractive material which has better properties than HgCdTe in many aspects. The author wants to study InAsSb based photoconductors and n-GaSb/n-InAsSb heterostructure photodiode for MWIR detection.
5. To experimentally realize the plasmonic enhanced photodetection. By integrating sub-wavelength metallic 2DHA on top, it is expected that the photoresponse will be enhanced due to coupling of incident light as SPP. The author will compare the experimental observations with simulation results.

1.3 Major achievements

The major contributions are listed below:

1. Completed simulation and analysis of EOT through 2DHA, the underlying physics and mechanism of SPP enhancement of photodetection. The author has analyzed possible variables and parameters which may affect EOT and the enhancement of photodetector performance. They are periodicity of hole array, hole diameter, refractive index of substrate, thickness of metal film, hole shape and light incident direction [60].
2. Analyzed the origin of Wood's anomaly in optical transmission through metallic 2DHA. The author successfully explained the contradiction of the Wood's anomaly and the generally observed broadband performance enhancement of photodetector via 2DHA. A new interpretation to this phenomenon is proposed: at Wood's anomaly wavelength, the extremely low transmission results from excitation of incident light as SPP, which has a low efficiency of being decoupled from the metal-dielectric interface and doesn't contribute to transmission. And the author also demonstrated how this theory can be applied to illustrate the broadband photoresponse enhancement of integrated structure of photodetector and metallic hole array.
3. Investigated a high performance n-i-p based mid-infrared InAs/GaSb type-II superlattice photodetector working well at 220 K. According to characterization result, the grown SL structure has very high quality. The thickness of each period of SLs is very close to the author's design thickness. At 220 K, the 50% cutoff wavelength of the photoresponse is 4.66 μm . The R_0A of the detector is as high as $14.9 \Omega \cdot \text{cm}^2$. And the peak detectivity of the photodetector is $2.23 \times 10^{10} \text{ cm} \cdot \text{Hz}^{1/2} / \text{W}$ at 3.0 μm under zero bias. This is the

highest reported detectivity of InAs/GaSb SL photodetector operating at 220 K.

4. Studied high performance InAsSb based photodetector capable of operating at room temperature. The InAsSb materials grown on GaSb substrate by molecular beam epitaxy (MBE) and photoconductive detectors made by them were investigated. The grown materials show high quality and slight lattice mismatch to the substrate. The photoconductors fabricated based on the InAsSb/GaSb structure show spectral response ranging from near infrared (NIR) to MWIR range. They can work well at low voltage bias and the measured blackbody detectivities are $\sim 2.4 \times 10^7 \text{ cm} \cdot \text{Hz}^{1/2}/\text{W}$ and $\sim 6.1 \times 10^9 \text{ cm} \cdot \text{Hz}^{1/2}/\text{W}$ at room temperature and 77 K, respectively.
5. Investigated photodetection of n-GaSb/n-InAsSb heterostructure at different temperatures and biases. The devices were found to be capable of dual color photodetection at fixed large forward biases at different temperatures and the maximum responsivity occurs at room temperature. As the forward bias decreases, a turning bias exists at which the photocurrent changes its direction and the voltage value varies with temperature. At reverse biases, the absorption of GaSb dominates the photocurrent and the maximum photocurrent occurs at about 205 K. All the observation can be explained by the proposed model.
6. Plasmonic enhanced infrared photodetection based on n-GaSb/n-InAsSb heterostructure is realized and studied. By integrating properly designed sub-wavelength metallic 2DHA on top, the room temperature photocurrent and detectivity of the photodiode is enhanced by ~ 2 times. Besides, the dark current of the heterostructure is not adversely affected by 2DHA fabricated on top. It is pointed out that the performance enhancement is because of higher quantum efficiency of the 2DHA-heterostructure,

resulting from electric field concentration at the metal-dielectric interface. The author also has explained the origin of broadband plasmonic performance enhancement.

1.4 Organization of the thesis

This dissertation includes eight chapters, which are organized as follows:

Chapter 1 is the introductory chapter. It introduces the motivation, objectives, major achievements during the author's Ph.D. program and organization of this thesis.

Chapter 2 covers the background of research work introduced in this thesis. In this chapter, the author first presents fundamental knowledge of SPP, including unique properties of SPP, dispersion relation of SPP, excitation techniques of SPP and a discussion of the length scales of SPP. Then, the author introduces basics of infrared photodetectors, especially about InAs/GaSb type-II superlattice and InAsSb based photodetectors. Last, the author briefly discusses the simulation technique used to calculate transmission through metallic 2DHA and field distribution at the metal-dielectric interface, experimental methods used to fabricating metallic 2DHA and characterizing photodetector performance.

Chapter 3 presents the author's simulation work and theoretical analysis of metallic 2DHA for enhancement of mid-wavelength infrared photodetection. It contains comprehensive simulation and analysis of transmission through 2DHA and field distribution at the metal-dielectric interface. The author has analyzed the underlying physics of EOT and how this can be used for enhancing performance of photodetectors. These conclusions can be a good guide for designing 2DHA structure for SPP enhanced photodetection.

Chapter 4 describes the author's analysis of the origin of Wood's anomaly in optical transmission through sub-wavelength metallic 2DHA. First, the background of Wood's anomaly is introduced. And the well-known Wood's anomaly phenomenon emerges at wavelength very close to main resonance wavelength of 2DHA. This seems to be contradictory to the generally observed broadband performance enhancement of photodetector via 2DHA. Then the author will present analysis and interpretation of origin of Wood's anomaly in EOT. Last, the author will demonstrate how this theory can be utilized to understand the broadband photoresponse enhancement of integrated structure of photodetector and metallic hole array.

Chapter 5 describes the author's work on designing and fabricating a high performance InAs/GaSb SL mid-wavelength infrared photodetector using n-i-p design. In this chapter, the author will first give a brief introduction of the basics of InAs/GaSb type-II SL. Then the author will introduce the design and fabrication process of InAs/GaSb type-II SL photodetector. Last, the author will present the characterization results and analysis. The peak detectivity of the photodetector is $2.23 \times 10^{10} \text{ cm} \cdot \text{Hz}^{1/2} / \text{W}$ at $3.0 \text{ } \mu\text{m}$ under zero bias. This is the highest reported detectivity of InAs/GaSb SL photodetector operating at 220 K.

Chapter 6 presents the work on the structural and optical properties and photodetection performance of an InAsSb layer grown on a GaSb substrate by MBE. The photoconductors fabricated based on the InAsSb/GaSb structure show spectral response ranging from NIR to MWIR range. They can work well at low voltage bias and the measured blackbody detectivities are $\sim 2.4 \times 10^7 \text{ cm} \cdot \text{Hz}^{1/2} / \text{W}$ and $\sim 6.1 \times 10^9 \text{ cm} \cdot \text{Hz}^{1/2} / \text{W}$ at room temperature and 77 K, respectively.

Chapter 7 presents the investigation of n-GaSb/n-InAsSb heterostructure photodetectors for infrared photodetection and experiment work of plasmonic enhanced infrared photodetection. First, the author will first present work on

n-GaSb/n-InAsSb heterostructure, which is found to have capability of dual color photodetection at fixed large forward biases at different temperatures and the maximum responsivity occurs at room temperature. A model has been proposed to explain the observations. Then, the author will demonstrate the experiment work of plasmonic enhanced infrared photodetection. By integrating properly designed sub-wavelength metallic 2DHA on top of n-GaSb/n-InAsSb heterostructure, the room temperature photocurrent and detectivity of the photodiode can be enhanced by ~2 times. A detailed analysis of the enhancement mechanism and origin of broadband performance enhancement will be presented.

Chapter 8 concludes the major contributions of this Ph.D. project. This chapter summarizes the conclusions of this thesis and provides recommendations for future work.

Chapter 2. Background

Before presenting the author's work in details in following chapters, theoretical background of surface plasmon (SP) and mid-wavelength infrared photodetector need to be introduced first. In this chapter, the author first reviews theoretical basis of SPP, including unique properties of SPP, dispersion relation, SPP excitation techniques and length scales of SPP. Then, the author will introduce basics of infrared photodetectors, especially about InAs/GaSb type-II SL photodetector and InAsSb based photodetector. Last, the author will have a brief discussion of the simulation technique used to calculate transmission through 2DHA and field distribution at the metal-dielectric interface, experimental methods used to fabricate sub-wavelength 2DHA and characterize performance of photodetector.

2.1 Surface plasmon polariton fundamentals

Surface plasmon is coherent oscillation of electrons at an interface between any two materials where the real part of the dielectric function changes sign across the interface, e.g. a metal-dielectric interface. It has been studied extensively since the pioneering work of Ritchie in 1957 [61]. Although surface electromagnetic (EM) waves were previously discussed by Zenneck and Sommerfeld [62]–[64], Ritchie was the first one to introduce the term “surface plasmon”. The existence of SP was theoretically investigated by Ritchie in the context of loss spectra of low-energy beams undergoing diffraction at thin metallic films [61], [65]. Apart from the expected bulk plasmon excitation of energy $\hbar\omega_p$, Ritchie's investigation predicted an additional loss at a lower energy $\hbar\omega_p/\sqrt{2}$, subsequently termed low-lying energy loss. Ritchie's prediction was later confirmed by Powell and Swan, who observed the additional peak in electron energy loss spectra of aluminum and magnesium in reflection [66], as shown in Figure 2.1. The peak gradually shifted to lower energies during oxidation of the metal films, suggesting it being connected with an EM

excitation at the metal-air surface, which during the experiment was slowly evolving into a metal-oxide interface.

Figure 2.1 Electron energy loss spectra of a thin magnesium film in progressive stages of oxidation [66].

The charge motion in a surface will excite EM field that propagates along the interface. To describe the charge motion and the associated EM field as an entity, a more accurate term named surface plasmon polaritons is needed. SPPs are a type of surface wave, guided along the interface, evanescently confined in the perpendicular direction, as illustrated by Figure 2.2. By coupling the EM fields to oscillations of the conductor's electron plasma, these EM surface waves are generated. Taking the wave equation as a starting point, this section describes the fundamentals of SPPs,

including unique properties of SPPs, dispersion relation of SPPs, common techniques of SPPs excitation and the length scales of SPP.

Figure 2.2 Schematic representation of an electron density wave propagating along a metal–dielectric interface [52]. The details of relevant length scales indicated in the plot will be discussed in section 2.1.4.

2.1.1 Wave equation

For the purpose of analyzing physical characteristics of SPPs, Maxwell's equations are applied to the flat interface between a dielectric and a conductor. For simplicity, the dielectric material discussed here will be limited to linear, isotropic, and nonmagnetic medium here. Due to the absence of external charge and current densities, Maxwell's equations can be rewritten in the following form:

$$\nabla \cdot \mathbf{D} = 0 \quad (2.1a)$$

$$\nabla \cdot \mathbf{B} = 0 \quad (2.1b)$$

$$\nabla \times \mathbf{E} = - \frac{\partial \mathbf{B}}{\partial t} \quad (2.1c)$$

$$\nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t} \quad (2.1d)$$

In order to solve above equations and find solutions in a form suitable for the description of confined propagating waves, the derivation will be proceed in two steps here. First, assume a harmonic time dependence of the electric and magnetic field, which implies $\mathbf{E}(\mathbf{r}, t) = \mathbf{E}(\mathbf{r})e^{-i\omega t}$, $\mathbf{H}(\mathbf{r}, t) = \mathbf{H}(\mathbf{r})e^{-i\omega t}$. ω is the harmonic angular frequency of the EM waves. Second, define the propagation geometry as shown in Figure 2.3. For simplicity, assume a one-dimensional problem in the Cartesian coordinate system. Specifically, ϵ depends only on coordinate z , implying that $\epsilon = \epsilon(z)$. The waves travel along the x -direction, and show no spatial variation in y -direction. The plane $z = 0$ coincides with the interface sustaining the propagating EM waves, which can be described as $\mathbf{E}(x, y, z) = \mathbf{E}(z)e^{-i\beta x}$, $\mathbf{H}(x, y, z) = \mathbf{H}(z)e^{-i\beta x}$. The complex valued $\beta = k_x$ is named the propagation constant of the propagating waves and corresponds to the component of the wavevector in the direction of propagation.

Figure 2.3 Definition of planar waveguide geometry. The EM wave travels along the x -direction.

For harmonic time independence ($\frac{\partial}{\partial t} = -i\omega$), propagation along the x -direction ($\frac{\partial}{\partial x} = i\beta$) and homogeneity in the y -direction ($\frac{\partial}{\partial y} = 0$), from the curl equations (2.1c, 2.1d), the following set of coupled equations are derived

$$\frac{\partial E_y}{\partial z} = -i\omega\mu_0 H_x \quad (2.2a)$$

$$\frac{\partial E_x}{\partial z} - i\beta E_z = i\omega\mu_0 H_y \quad (2.2b)$$

$$i\beta E_y = i\omega\mu_0 H_z \quad (2.2c)$$

$$\frac{\partial H_y}{\partial z} = i\omega\epsilon_0 \epsilon E_x \quad (2.2d)$$

$$\frac{\partial H_x}{\partial z} - i\beta H_z = -i\omega\epsilon_0 \epsilon E_y \quad (2.2e)$$

$$i\beta H_y = -i\omega\epsilon_0 \epsilon E_z \quad (2.2f)$$

It can be clearly seen that this system has two sets of self-consistent solutions with different polarization properties for propagating waves. The first set solution is the transverse magnetic (TM) modes, where only the field components E_x , E_z and H_y are nonzero, and the second set the transverse electric (TE) modes, with only H_x , H_z and E_y being nonzero.

For TM modes, the set of solution reduces to

$$E_x = -i \frac{1}{\omega\epsilon_0 \epsilon} \frac{\partial H_y}{\partial z} \quad (2.3a)$$

$$E_z = - \frac{\beta}{\omega\epsilon_0 \epsilon} H_y \quad (2.3b)$$

and the TM mode wave equation is

$$\frac{\partial^2 H_y}{\partial z^2} + (\omega_0^2 \mu_0 \epsilon_0 \epsilon - \beta^2) H_y = 0 \quad (2.3c)$$

For TE modes the analogous set is

$$H_x = i \frac{1}{\omega \mu_0} \frac{\partial E_y}{\partial z} \quad (2.4a)$$

$$H_z = \frac{\beta}{\omega \mu_0} E_y \quad (2.4b)$$

with the TE mode wave equation

$$\frac{\partial^2 E_y}{\partial z^2} + (\omega_0^2 \mu_0 \epsilon_0 \epsilon - \beta^2) E_y = 0 \quad (2.4c)$$

2.1.2 Dispersion relation of SPP

Here, the discussion will focus on the simplest geometry sustaining SPPs, namely a single, flat interface (see Figure 2.4) between a conducting half space ($z < 0$) described by a dielectric function $\epsilon_1(\omega)$ and an adjacent dielectric, non-absorbing half space ($z > 0$) with positive real dielectric constant ϵ_2 . The metallic character implies $\text{Re}[\epsilon_1] < 0$. The author hopes to find out propagating wave solutions confined to the interface and evanescently decaying in the perpendicular z -direction.

Figure 2.4 Definition of geometry of SPP propagation along an interface between a dielectric material and a metal. The surface wave propagates along x-direction and decays in z-direction.

First, take a look at TM solution. Using the equation set (2.3) in both half spaces, following equations are derived

$$H_y(z) = A e^{i\beta x} e^{k_1 z} \quad (2.5a)$$

$$E_x(z) = -iA \frac{1}{\omega \epsilon_0 \epsilon_1} k_1 e^{i\beta x} e^{k_1 z} \quad (2.5b)$$

$$E_z(z) = -iA \frac{\beta}{\omega \epsilon_0 \epsilon_1} e^{i\beta x} e^{k_1 z} \quad (2.5c)$$

for $z < 0$ and

$$H_y(z) = B e^{i\beta x} e^{-k_2 z} \quad (2.6a)$$

$$E_x(z) = iB \frac{1}{\omega \epsilon_0 \epsilon_2} k_2 e^{i\beta x} e^{-k_2 z} \quad (2.6b)$$

$$E_z(z) = -iB \frac{\beta}{\omega \epsilon_0 \epsilon_2} e^{i\beta x} e^{-k_2 z} \quad (2.6c)$$

for $z > 0$. $k_i = k_{z,i}$ ($i = 1, 2$) is the component of the wavevector perpendicular to the interface between the two media. Its reciprocal value, $z_i = 1 / |k_i|$, defines the evanescent decay length of the fields perpendicular to the interface, which quantifies the tight confinement of the wave.

Continuity of H_y and E_x at the interface requires that $A = B$ and

$$\frac{k_2}{k_1} = - \frac{\epsilon_2}{\epsilon_1} \quad (2.7)$$

Confinement to the interface means $\text{Re}[k_1] > 0$ and $\text{Re}[k_2] > 0$. As the author has stated in the beginning of this section, the dielectric medium has a positive real dielectric constant, i. e. $\epsilon_2 > 0$. So, from equation (2.7), it is known that confinement to the surface requires $\text{Re}[\epsilon_1] < 0$. This indicates that EM surface waves exist only at the interfaces between materials with opposite signs of the real part of their dielectric constants, such as a conductor and an insulator or semiconductor. For metals, $\text{Re}[\epsilon_1] < 0$ is fulfilled at frequencies below the bulk plasmon frequency ω_p .

In addition, the expression for H_y needs to fulfill the wave equation, yielding

$$k_1^2 = \beta^2 - k_0^2 \epsilon_1 \quad (2.8a)$$

$$k_2^2 = \beta^2 - k_0^2 \epsilon_2 \quad (2.8b)$$

where $k_0 = \omega_0 \sqrt{\mu_0 \epsilon_0} = \frac{\omega}{c}$ is defined as the wavevector of propagating wave in vacuum. Combining above equations with (2.7), the central equation of this section, i.e., the dispersion relation of SPPs propagating at the interface of two media, is derived,

$$\beta = k_0 \sqrt{\frac{\epsilon_1 \epsilon_2}{\epsilon_1 + \epsilon_2}} \quad (2.9)$$

The above expression is valid for both complex and real ϵ_1 , i. e. for conductors with and without attenuation.

Before analyzing more detailed properties of the dispersion relation, the possibility of TE modes existing at the interface will be briefly investigated. From equation (2.6), the respective expressions for the electric and magnetic field components are

$$E_y(z) = A e^{i\beta x} e^{k_1 z} \quad (2.10a)$$

$$H_x(z) = iA \frac{1}{\omega \mu_0} k_1 e^{i\beta x} e^{k_1 z} \quad (2.10b)$$

$$H_z(z) = iA \frac{\beta}{\omega \mu_0} e^{i\beta x} e^{k_1 z} \quad (2.10c)$$

for $z < 0$ and

$$E_y(z) = B e^{i\beta x} e^{-k_2 z} \quad (2.11a)$$

$$H_x(z) = -iB \frac{1}{\omega \mu_0} k_2 e^{i\beta x} e^{-k_2 z} \quad (2.11b)$$

$$H_z(z) = iB \frac{\beta}{\omega \mu_0} e^{i\beta x} e^{-k_2 z} \quad (2.11c)$$

for $z > 0$. Continuity of E_y and H_x at the interface requires that $A = B$ and $Ak_1 = -Bk_2$. So for TE modes, the following result are derived

$$A(k_1 + k_2) = 0 \quad (2.12)$$

Since confinement to surface demands that $\text{Re}[k_1] > 0$ and $\text{Re}[k_2] > 0$, this condition is only satisfied only when $A = 0$, so that also $A = B = 0$. Therefore, no surface modes exist for TE polarization. Surface plasmons only exist for TM polarization waves.

Now, the characteristics of SPPs will be analyzed by taking a closer look at the dispersion relation. Figure 2.5 shows plots of equation (2.9) for a metal with negligible damping described by the real Drude dielectric function ($\epsilon_1(\omega) = 1 - \frac{\omega_p^2}{\omega^2}$) for an air ($\epsilon_2 = 1$) and a fused silica ($\epsilon_2 = 2.25$) interface [65]. Negligible damping of electron oscillation implies that $\text{Im}[\epsilon_1(\omega)] = 0$ here. Surface plasmon frequency is defined as the frequency when β goes to infinity. From equation (2.9), it is known this is achieved only when

$$\epsilon_1(\omega) + \epsilon_2 = 0 \quad (2.13)$$

Insert the Drude dielectric function, and then the relation for surface plasmon frequency is expressed as

$$\omega_{\text{sp}} = \frac{\omega_p}{\sqrt{1+\epsilon_2}} \quad (2.14)$$

Infinite β indicates that group velocity $v_g \rightarrow 0$. Thus the mode acquires electrostatic characteristic, and it is known as the surface plasmon.

Figure 2.5 Dispersion relation of SPPs at the interface between Drude metal with negligible damping and air (gray curves) and silica (black curves) [65].

When $\epsilon_2 = 1$, namely for a metal-air interface, $\omega_{sp} = \omega_p / \sqrt{2}$. This reminds people of the low-lying loss frequency predicated by Ritchie. Besides, as ϵ_2 increases, ω_{sp} shifts to lower frequency. The shift of peak in electron energy loss spectra to lower frequency was exactly the phenomenon observed by Powell and Swan in experiment.

From Figure 2.5, it is found that the SPP excitations correspond to the part of the dispersion curves lying to the right of the respective light lines of air and silica. Thus, a free-space photon incident to a metal smooth surface cannot excite an SPP at the metal-dielectric interface. Special phase matching techniques such as grating or prism coupling are necessary for their excitation, which will be discussed in next section.

Before discussing the techniques for SPP excitation, take a look at SPP at real metals. The above discussions is based on an ideal assumption with $\text{Im}[\epsilon_1(\omega)] = 0$. In real metals, however, the SPP suffers both from free-electron and interband damping. This indicates that $\epsilon_1(\omega)$ is complex, and along with it also the propagation constant β . Here β approaches a finite value at the surface plasmon frequency, as shown in Figure 2.6 [65].

Figure 2.6 Dispersion relation of SPPs at a silver/air (gray curve) and silver/silica (black curve) interface. Due to the damping, β approaches a finite value at the surface plasmon frequency [65].

2.1.3 SPP excitation techniques

Surface plasmon polaritons can be excited by electrons or photons. Excitation by electrons is created via electron bombardment into the bulk of metal. As the electrons scatter, fast electrons lose energy to the conduction electrons in the metal. The component of the scattering vector parallel to the surface results in the formation

of a surface plasmon polariton. And this is the context in which existence of surface plasmon was first predicted theoretically by Ritchie.

Another common technique is optical excitation. However, as mentioned in last section, SPPs on a planar metal-dielectric interface cannot be excited directly by incident light. Hence, various optical techniques for phasing matching are employed, including prism coupling (Figure 2.7) [67], [68], highly focused optical beams (Figure 2.8) [69] and grating coupling (Figure 2.9).

For prism coupling, a beam is reflected at the interface between the insulator of higher dielectric constant ε and the metal, having an in-plane momentum $k_x = k\sqrt{\varepsilon}\sin\theta$, where θ is the incident angle. This momentum is sufficient to excite SPPs at the interface between the metal and the lower-index dielectric. As for excitation using highly focused optical beams, it is a variant of prism coupling. The author will not discuss details of SPP excitation by electrons, highly focused optical beams and prism coupling here. Instead, the author will concentrate on grating coupling, which is most widely used nowadays.

Figure 2.7 (a) Kretschmann and (b) Otto configuration of an Attenuated Total Reflection setup for coupling surface plasmons. In both cases, the surface plasmon propagates along the metal-dielectric interface [67], [68].

Figure 2.8 Schematic of the excitation of a white-light continuum of SPPs and their observation via detection of the leakage radiation using an index-matched oil immersion lens [69].

Figure 2.9 Phase-matching of light to SPPs using a grating. θ is the angle of incidence, k is the wavevector of light in vacuum.

As shown in Figure 2.9, light beam impinges the metal surface under an angle θ to the surface normal. By patterning the metal surface with a shallow grating of grooves or holes with lattice constant p , the mismatch in wavevector between the in-plane momentum $k_x = k \sin \theta$ of incident photons and surface plasmon wavevector

β can be overcome. For the simplest one-dimensional grating of grooves shown above, phase matching occurs when the condition

$$\beta = k \sin\theta \pm iG \quad (2.15)$$

is fulfilled, where $G = \frac{2\pi}{p}$ is the reciprocal vector of the grating, and $i = 1, 2, 3, \dots$

Obviously, the minimum reflection appears when SPP is excited here.

Next, the discussion is expanded to two-dimensional hole arrays, as shown in Figure 2.10. According to the momentum conservation law, the following expression is derived

$$\mathbf{k}_{sp} = \mathbf{k}_x \pm i\mathbf{G}_x \pm j\mathbf{G}_y \quad (2.16)$$

where $\mathbf{G}_x$ and $\mathbf{G}_y$ are the reciprocal lattice vectors and $|\mathbf{G}_x| = |\mathbf{G}_y| = \frac{2\pi}{p}$ for square lattice, $i, j = 1, 2, 3, \dots$. For normal incident light, $\mathbf{k}_x = \mathbf{0}$. Equation (2.16) reduces to

$$\mathbf{k}_{sp} = \pm i\mathbf{G}_x \pm j\mathbf{G}_y \quad (2.17)$$

Apparently, from equation (2.17), it is known that only by patterning optically thick metal film with hole arrays of specific periodicity, SPP can be excited at the metal surface. Besides, by adjusting the parameters of metal film and hole array, SPP of desired wavelength can be excited.

Figure 2.10 Two dimensional hole array of periodicity p perforated in thin metal film.

However, conventional theory predicted that the transmission through sub-wavelength hole is extremely small, which seems to imply that the above technique of SPP excitation is not suitable for practical applications, such as enhancing the response of photodetector by exciting SPPs at the interface. What is indeed the transmission through sub-wavelength hole? The author will discuss this in details in Chapter 3.

2.1.4 SPP length scales

Now, the author will briefly discuss the length scales associated with the SPP modes at the planar metal-dielectric interface [70]. The author is interested in SPP wavelength, λ_{SPP} , the penetration depth of the field associated with SPP mode into the metal, δ_{m} , and the penetration depth of the field into the dielectric medium, δ_{d} . These length scales are indicated in Figure 2.2. Since what the author is interested in is the field enhancement at the metal-dielectric interface, instead of how far SPP can propagate along the planar interface, the author is not going to discuss the SPP propagation length scale.

Start from dispersion relation of SPP, expressed by equation (2.9), which is rewritten here

$$k_{\text{SPP}} = \frac{2\pi}{\lambda_0} \sqrt{\frac{\epsilon_m \epsilon_d}{\epsilon_m + \epsilon_d}} \quad (2.18)$$

where λ_0 is wavelength of free space light, ϵ_m and ϵ_d are relative dielectric function (constant) of the metal and dielectric medium respectively.

In infrared regime, the dielectric function of metal is usually a complex function with real part and imaginary part, which can be written as

$$\epsilon_m = \epsilon'_m + i\epsilon''_m \quad (2.19)$$

For the infrared range the author is interested in, normally $|\epsilon'_m| \gg |\epsilon''_m|$. Thus, the real part of SPP wavevector is

$$k'_{\text{SPP}} = \frac{2\pi}{\lambda_0} \sqrt{\frac{\epsilon'_m \epsilon_d}{\epsilon'_m + \epsilon_d}} \quad (2.20)$$

Therefore, the wavelength of SPP, λ_{SPP} , calculated by $2\pi/k'_{\text{SPP}}$, is

$$\lambda_{\text{SPP}} = \lambda_0 \sqrt{\frac{\epsilon'_m + \epsilon_d}{\epsilon'_m \epsilon_d}} \quad (2.21)$$

Next, consider the SPP penetration depth, into metal and dielectric medium. Remember that $k_i = k_{z,i}$ ($i = 1, 2$) is the component of the wavevector perpendicular to the interface between these two media. And its reciprocal value, $\delta_i = 1 / |k_i|$, defines the evanescent decay length of the fields perpendicular to the interface, which quantifies the tight confinement of the wave. Thus, combining dispersion

relation and equation (2.8), and considering that $|\epsilon'_m| \gg |\epsilon''_m|$, the following expressions are derived

$$\delta_m = \frac{\lambda_0}{2\pi} \sqrt{\left| \frac{\epsilon'_m + \epsilon_d}{\epsilon_m'^2} \right|} \quad (2.22)$$

$$\delta_d = \frac{\lambda_0}{2\pi} \sqrt{\left| \frac{\epsilon'_m + \epsilon_d}{\epsilon_d^2} \right|} \quad (2.23)$$

To have a rough comparison with the simulation results to be shown in Chapter 3, consider SPP mode at metal-dielectric interface bounded by gold and a dielectric medium having a dielectric constant of 16.0. The dielectric function data of gold is retrieved from Handbook of Optical Constants of Solids [71]. The author plots length scales of λ_{SPP} , δ_m , and δ_d versus wavelength, in Figure 2.11.

As can be seen from Figure 2.11, the λ_{SPP} is almost linearly dependent on free-space wavelength. In fact, this can be inferred from equation (2.21). In the wavelength range considered here (1.5 μm - 6.5 μm), $|\epsilon'_m| \gg |\epsilon_d|$, thus $\lambda_{\text{SPP}} \sim \frac{\lambda_0}{\sqrt{\epsilon_d}}$. For the dielectric medium considered here ($\epsilon_d = 16$), $\lambda_{\text{SPP}} \sim \lambda_0/4$. And it will be shown in Chapter 3 that the periodicity of 2DHA should be very close to λ_{SPP} .

Figure 2.11 Plot of SPP wavelength (curve with diamond markers), the SPP penetration depth of the field into gold (curve with circle markers), and the penetration depth of the field into the dielectric medium (curve with square markers) versus free-space wavelength.

For the SPP penetration depth into gold, it is almost a constant of ~ 25 nm. And the SPP penetration depth into dielectric medium, which the author is particular interested in, is 0.5 $\sim$ 1.5 times of wavelength. Remember that this is only applicable for planar smooth metal-dielectric interface. As it will be shown in Chapter 3, the penetration depth of SPP mode excited by metallic 2DHA, into dielectric medium is around 300 nm, which is much smaller than the value calculated here. This is mainly because of the presence of hole array milled in metal film, causing the penetration depth to decrease significantly. The reason that the author is particular interested in SPP penetration depth into dielectric medium, is that this value determines how far away the photodetector absorption region can be from the plasmonic structure. If the distance between active region and

plasmonic structure is too large, apparently there will be no enhancement. In fact, the action region of photodetector should be as close to plasmonic structure as possible.

2.2 Infrared photodetector fundamentals

Photodetectors are sensors of light or other electromagnetic energy. An infrared photodetector reacts to infrared radiation, whose wavelength is shorter than microwaves, but longer than visible light, as classified in the electromagnetic spectrum shown in Figure 2.12.

Figure 2.12 Classification of infrared in the electromagnetic spectrum.

During the development of infrared detectors in past several decades, they have already been used in many fields (see Figure 2.13), including medical, earth resources, industry and energy conservation applications [8]. Medical applications include infrared thermography in which infrared scans of the body detect cancers or other trauma which increases surface temperature of the body. Earth resource determinations are done by using infrared images from satellites in conjunction

with field observation for calibration (in this way, e.g., the area and content of forests and fields can be determined). In some cases, even the health state of a crop can be determined from space. Energy conservation in industry and homes has been aided by the use of infrared scans to determine the points of maximum heat loss. Demands for these technologies are quickly growing due to their effective applications, for example, in IR thermography in medical diagnostics, IR astronomy, car driving, longtime prognoses of agriculture crop yield, chemical process monitoring, global monitoring of climate changes and environmental pollution, and so on.

Figure 2.13 Applications of infrared photodetectors [8].

Many materials have been investigated in the IR detector field. In fact, a simple theorem, after Norton, is stated: “All physical phenomenon the range of about 0.1 – 1 eV can be proposed for IR detectors” [72]. Compared with thermal detectors, photodetectors have a wavelength selective photoresponse, as illustrated by Figure 2.14. The incident radiation is absorbed within the photodetector material, by

interaction with electrons either bound to lattice atoms or to impurity atoms or with free electrons [1], [8]. Also, they exhibit high signal-to-noise ratio and very fast response. However, to achieve this, the photodetectors usually need cryogenic cooling. This is to suppress thermal generation of charge carriers. The thermal transition competes with optical ones, which makes the non-cooled photodetectors very noisy.

Figure 2.14 Relative spectral response of photodetector and thermal detector.

The most attractive materials used for photodetectors are narrow bandgap semiconductors. In fact, progress in IR photodetector technology is mainly connected to semiconductor IR photodetectors. In semiconductor photodetectors, the observed electrical output signal arises from the changed electronic energy distribution. Figure 2.15 demonstrates the fundamental optical excitation processes in semiconductors, including intrinsic absorption, extrinsic absorption and free carrier absorption [73].

The photodetection in semiconductors is based on the general principle of the generation of electron-hole pairs (EHPs) under the illumination of light. If a

semiconductor material is illuminated by photons of an energy equals to or larger than the bandgap, the absorbed photons stimulate electrons from valence band into the excited states in the conduction band, where the electrons behave like the free electrons capable of traveling long distances across the crystal structure, under the effects of an intrinsic or externally-applied electric field. In this way, the holes left in the valence band contribute to electrical conduction by moving from one atomic site to another under the influence of the electric field. The separation of EHPs created by the absorption of light gives rise to a photocurrent, which refers to the fraction of the photogenerated free charge carriers collected at the edges of the material by the electrodes of the photodetecting structure.

Figure 2.15 Fundamental optical excitation processes in semiconductors. (a) intrinsic absorption, (b) extrinsic absorption, (c) free carrier absorption [73].

Based on the nature of interaction, the type of photodetectors can be divided into different groups, as shown in Table I. Among them, the most important ones are intrinsic photodetectors, extrinsic photodetectors, photoemissive photodetectors and quantum well photodetectors.

Table I Comparison of IR photodetectors [8].

Type		Advantages	Disadvantages
Intrinsic	IV-VI (PbS, PbSe, PbSnTe)	Easier to prepare More stable materials	Very high thermal expansion coefficient Large permittivity
	II-VI (HgCdTe)	Easy bandgap tailoring Well-developed theory & experience Multicolor detectors	Nonuniformity over large area High cost in growth and processing Surface instability
	III-V (InGaAs, InAs, InSb, InAsSb)	Good material & dopants Advanced technology Possible monolithic integration	Heteroepitaxy with large lattice mismatch Long wavelength cutoff limited to 7 μm (at 77 K)
Extrinsic (Si:Ga, Si:As, Ge:Cu, Ge:Hg)		Very long wavelength operation Relatively simple technology	High thermal generation Extremely low temperature operation
Free carriers (PtSi, Pt₂Si, TrSi)		Low-cost, high yields Large & close packed 2-D arrays	Low quantum efficiency Low temperature operation
Quantum wells	Type I (GaAs/AlGaAs, InGaAs/AlGaAs)	Matured material growth Good uniformity over large area Multicolor detectors	High thermal generation Complicated design and growth
	Type II (InAs/InGaSb, InAs/InAsSb)	Low Auger recombination rate Easy wavelength control Multicolor detectors	Complicated design and growth Sensitive to the interfaces
Quantum dots	InAs/GaAs, InGaAs/InGaP, Ge/Si	Normal incidence of light Low thermal generation	Complicated design and growth

In this section, the author is going to introduce basics of photodetector and several attractive semiconductor materials used for fabricating high performance IR photodetectors.

2.2.1 Infrared photodetector figures of merit

Characterizing the performance characteristics of infrared photodetector is complex, due to the large number of experimental variables involved. Various electrical, radiometric and environmental parameters need to be taken into account and controlled.

Here, to characterize the performance of photodetector, several quantities will be introduced. They are mainly quantum efficiency (η), spectral current responsivity (R_i), dark current (I_d), and detectivity (D^*). These quantities are related with each other, which will be explained in details.

Quantum efficiency describes the number of EHPs generated per incident photon. It is related to spectral current responsivity by

$$R_i = \frac{\lambda \eta}{hc} qg \quad (2.24)$$

where λ is the wavelength, h is Plank's constant, c is velocity of light, and q is the electron charge, g is photoelectric gain. The photoconductive gain, g , is put forward as a simplifying concept for the understanding of photoconductive phenomenon. It characterizes how well the excited EHPs can be collected to generate current response of the photodetector.

Dark current is the relatively small electric current that flows through the photodetector even when no photons are entering the device; it consists of the charges generated in the detector when no outside radiation is entering the detector.

There are many possible mechanisms for dark current, which may also be different for different types of photodetectors. Usually, dark current in narrow bandgap semiconductor photodetectors are differentiated into bulk and surface components [74]. Take type-II InAs/GaSb SL photodetector as an example, the most important bulk components are thermally generated diffusion current, generation-recombination current associated with Shockley-Read-Hall (SRH) process, Zener tunneling current and trap-assisted tunneling current. The surface component is associated with the surface states in the junction. During the isolation process of individual pixel, the periodic crystal structure interrupts abruptly, resulting in formation of the dangling chemical bonds at the semiconductor-air interface. These unsatisfied bonds generate surface states within the bandgap. Besides, differential etching, etch by-products and surface contaminant associated with the fabrication process all may create extra interfacial states contributing to dark current. To improve the performance of a photodetector and increase photodetector operating temperature, an efficient way of reducing the dark current is necessary.

Detectivity (D^*) is the most important parameter utilized to characterize a photodetector, which directly compares photodetector performance using methods and technologies of operation which are distinctly different at first glance. It is used to characterize normalized signal to noise performance of photodetector. The spectral detectivity is given by

$$D^* = \frac{\sqrt{A\Delta f}}{NEP} \quad (2.25)$$

where A is the photosensitive area of the photodetector, Δf is the frequency bandwidth, NEP is the noise equivalent power. Depending on the main dark current components of a photodetector, the detectivity may have different expressions. Again, take type-II InAs/GaSb SL as an example, the shot noise limited D^* can be calculated using

$$D^* = \frac{R_i}{\sqrt{2qJ + (4kT)/(R_d A_d)}} \quad (2.26)$$

where J is the dark current density, k is the Boltzmann constant, T is the temperature of the device, R_d is dynamic resistance, A_d is photodetector area. A comparison of detectivity of various commercially available infrared detectors is shown in Figure 2.16.

Figure 2.16 Comparison of the D^* of various commercially available infrared detectors when operated at the indicated temperature. Chopping frequency is 1000 Hz for all detectors except the thermopile (10 Hz), thermocouple (10 Hz), thermistor bolometer (10 Hz), Golay cell (10 Hz) and pyroelectric detector (10 Hz). Each detector is assumed to view a hemispherical surrounding at a temperature of 300 K. Theoretical curves for the background-limited D^* (dashed lines) for ideal photovoltaic and photoconductive detectors and thermal detectors are also shown. PC, photoconductive detector; PV, photovoltaic detector; and PEM, photoelectromagnetic detector [8].

2.2.2 High-operating-temperature infrared photodetectors

As mentioned earlier, IR photodetectors usually work at low temperatures to suppress the noise of the detector, generated from various mechanisms associated with the narrow bandgap. The cooling requirement is the major obstacle to the more widespread use of semiconductor IR photodetector systems. Currently, major efforts are devoted to reduce system cost, weight, size and power consumption to increase the working temperature in high-operating-temperature (HOT) photodetectors. The most important of them are HgCdTe, InAs/GaSb type-II SL and InAsSb ternary alloys.

HgCdTe is almost an ideal IR detector material, which is conditioned by three important features: tunable energy band gap range from SWIR to VLWIR, large absorption coefficient enabling high quantum efficiency, and favorable intrinsic recombination mechanism leading to high operating temperature [15]. Besides, other favorable properties of HgCdTe include the ability to obtain both high and low carrier concentrations, high electron mobility and low dielectric constant.

Nevertheless, HgCdTe still suffers from some problems. For instance, there are some technological problems resulting from a weak Hg-Te bond, including health hazard due to the highly toxic compounds, high mercury vapor pressure over melts, and serious difficulties in repeatable growth of uniform composition bulk crystals and epitaxial layers [2], [13], [14]. Moreover, commonly used lattice-matched CdZnTe substrate remains to be a big issue to be solved due to its high cost. These problems encouraged the development of alternative materials in the past forty years. Among them, the most important ones are the InAs/GaSb type-II superlattice [18]–[23] and the III-V InAsSb ternary alloy [38]–[46].

In 1977, Tsu et al. first theoretically studied the InAs/GaSb type-II superlattice, in which the conduction band bottom of InAs is slightly lower than valence band top

of GaSb [18]. They pointed out that this usual bandgap alignment offers new intriguing features and make superlattice devices useful. Besides, it was found that the energy gap is strongly dependent on thickness or period of each layer. By tuning the thickness of each layer, the bandgap can be tuned in a wide wavelength range. A decade later, Smith and Mailhiot proposed that the optical absorption coefficient of this SL material can be as good as that of the HgCdTe alloy with the same bandgap, as shown in Figure 2.17. Since then, the SL material has generated extensive interest in IR detection [32], [75]. As a result of “broken-gap” type-II alignment of InAs/GaSb SL material system, the holes and electrons are localized in different layers, the holes in the GaSb layer and electrons in the InAs layer. This spatial separation of holes and electrons contributes to suppression of Auger recombination. Compared with HgCdTe alloy with same bandgap, the electron effective mass of the SL material is much larger, which significantly reduces diode tunneling current. Therefore, combined with the reasonably large optical matrix elements, the optical absorption coefficient of InAs/GaSb SL material is comparable to that of HgCdTe alloy with the same bandgap [76]. In addition, in contrast with quantum well infrared photodetectors (QWIPs), the normal incidence absorption is allowed in SL photodetector, resulting in much higher quantum efficiency [77]. These superiorities have made InAs/GaSb SL photodetector a competitive alternative to state-of-the-art HgCdTe detector [78], [79].

Figure 2.17 Absorption coefficient as a function of photon energy for InAs-Ga_{0.6}In_{0.4}Sb SL and Hg_{1-x}Cd_xTe, $x = 0.212$ alloy [19].

As another attractive alternative of HgCdTe, the InAsSb ternary alloy also receives a lot of attention [38], [39], [41], [42]. Compared with HgCdTe, this III-V alloy is much more stable and has a fairly weak dependence of band edge on composition. Different with ionic bonding in HgCdTe, the stronger chemical bonds available in the low atomic number III-V family and the larger covalent bonding contribution make InAsSb a very stable material. Other better properties of InAsSb include low dielectric constant and small room temperature self-diffusion efficient. In addition, growing of the InAsSb alloy with high uniformity and repeatability is much easier. More importantly, the InAsSb based infrared photodetectors are expected to have high performance when operating either close to or at room temperature [38], [39], [41]. Therefore, there is extensive interest on development of InAsSb based photodetector operating near room temperature.

2.3 Simulation and experiment methods

To study the underlying physics behind EOT and mechanism of SPP enhancement, an accurate simulation of the transmission through 2DHA and field distribution at the metal-dielectric interface is required. Also, an advanced technique of fabricating sub-wavelength 2DHA is very important. In this section, the author will introduce three-dimensional finite-difference time-domain (FDTD) simulation method and EBL technique for fabricating 2DHA. Besides, the author will introduce Fourier transform infrared spectroscopy (FTIR) technique used for characterizing photodetector response.

2.3.1 FDTD simulation method

The FDTD method is a state-of-the-art approach for solving Maxwell's equations in complex geometries [80]–[82]. It is a fully vectorial method that naturally gives both time domain, and frequency domain information to the user, offering unique insight into all types of problems in electromagnetics and photonics. Thus, a wide range of useful quantities can be calculated, including the transmission, reflection of light and the complex Poynting vector.

This method is discrete in both time and space. It is a grid-based differential numerical modeling method. The EM fields and structural materials of interest are described on a discrete mesh made up of so-called Yee cells [83], as shown in Figure 2.18. Maxwell's equations are solved discretely in time, where the time step used is related to the mesh size via the speed of light. This method is an exact representation of Maxwell's equations in the limit that the mesh cell size goes to zero.

Figure 2.18 Illustration of a standard Cartesian Yee cell used for FDTD.

The resulting finite-difference equations are solved in either hardware or software in a leapfrog manner: the electric field vector components in a volume of space are solved at a given instant in time; then the magnetic field vector components in the same spatial volume are solved at the next instant in time; and the process is repeated over and over again until the desired transient or steady-state electromagnetic field behavior is fully evolved.

In this work, the author uses commercially available software Lumerical FDTD for simulation, as shown in Figure 2.19. When necessary, the author exports the data to Matlab for further processing and drawing figures.

Figure 2.19 Lumerical FDTD Solutions Graphical User Interface.

Structures to be simulated may have a wide variety of EM material properties. Various light sources can be added to the simulation. The software calculates how the EM fields propagate from the source through the structure. Subsequent iteration results in the electromagnetic field propagation in time. Typically, the simulation is run until there are essentially no electromagnetic fields left in the simulation region.

Using Lumerical, time domain information can be recorded at any spatial point (or group of points). This data can either be recorded for the duration of the simulation, or it can be recorded only as a series of "snapshots" at times pre-defined by the user. Frequency domain information at any spatial point (or group of points) may be obtained through the Fourier transform of the time domain information at same point. Thus, the frequency dependence of power flow and modal profiles may be obtained over a wide range of frequencies from a single simulation. Besides, results obtained in the near field using the FDTD technique

can be transformed to the far field, in applications where scattering patterns are crucial.

2.3.2 Electron beam lithography

To fabricate 2DHA, there are mainly three techniques, photolithography, FIB and EBL [84]. In this work, the author uses EBL for fabricating 2DHA, and only discusses this technique here.

EBL is a high-resolution lithographic technique for nanostructure patterning. It is the practice of scanning a focused beam of electrons to draw customized shapes on a surface covered with an electron sensitive film called a resist. As the electrons can be treated as the de-Broglie wave, the wavelength of the electron can be calculated by equation $\lambda = h/p$, where h is the plank constant and p is the momentum of the electron. The wavelength of the electron beam can reach sub-10 nm scale, depending on the acceleration voltage. Besides the acceleration voltage, the resolution of EBL is much dependent on the electron scattering, proximity effect and resists sensitivity. The electron beam writing system was proposed in 1955 based on the scanning electron microscope [50]. It uses the scanning electron beam to write directly on the photoresist and removes or remains the region of exposure. It can be widely used in photolithography mask fabrication, semiconductor research and nanotechnology.

The process flow of EBL operation is shown in Figure 2.20. The burning point step is to ensure that the electron beam was focused well and no much astigmatism for the beam. The ideal burning point should be less than 30 nm in diameter and the shape is perfect circle. The resolution is dependent on how small the point can be. The diameter of the point represents the single line width or the pixel size of area exposure. If the burning point is not round enough, one needs to repeat the focusing and adjust the step until the perfect round shape is reached.

Figure 2.20 Process flow of Raith E-line EBL operation.

For fabricating metallic hole array, the author needs to do E-Beam deposition and lift-off after the exposure process. Figure 2.21 shows a scanned electron microscope (SEM) image of metallic 2DHA the author has fabricated.

2.3.3 Fourier transform infrared spectroscopy

FTIR is a technique used to obtain an infrared spectrum of emission or absorption or of a solid, liquid or gas [85]. A FTIR spectrometer can collect high spectral resolution data over a broad spectral range simultaneously. This advantage makes it superior to a dispersive spectrometer which only measures intensity over a narrow spectral range at a time. The term Fourier transform infrared spectroscopy arises from the fact that Fourier transform is utilized to convert the raw data into the actual spectrum.

Figure 2.21 SEM image of metallic 2DHA on silicon, fabricated using EBL.

Instead of shining a monochromatic beam of light at the sample, this technique shines a beam containing a wide range of frequencies of light at once, and measures how much of that beam is absorbed by the sample. Next, the beam is modified to contain a different combination of frequencies, giving another data point. This process is repeated many times. Afterwards, a computer takes all these data and works backwards to infer what the absorption is at each wavelength [85]. The beam described above is generated by starting with a broadband light source—one containing the full spectrum of wavelengths to be measured. The light shines into a Michelson interferometer—a certain configuration of mirrors, one of which is moved by a motor. As this mirror moves, each wavelength of light in the beam is periodically blocked, transmitted, blocked, transmitted, by the interferometer, due to wave interference. Different wavelengths are modulated at different rates, so that at each moment, the beam coming out of the interferometer has a different spectrum. As mentioned above, computer processing is required to turn the raw data (light absorption for each mirror position) into the desired result (light absorption for each

wavelength). The processing use is a common algorithm called the Fourier transform (hence the name, "Fourier transform spectroscopy").

In this work, the author mainly uses FTIR for measuring the response spectra of the fabricated photodetectors. The FTIR used by the author and its optics layout is shown in Figure 2.22. By integrating the FTIR with liquid nitrogen cooled Dewar, temperature control accessory and preamplifier, the author can measure spectral response at different temperatures and bias voltages. Note that it is very important to normalize the spectrum to a standard pyroelectric detector's response, which is almost flat in the mid-infrared wavelength range. Only in this way can the author get relative photoresponse of the detector.

Figure 2.22 (a) The VERTEX 70 FTIR in Photonics Lab I and (b) the optics layout of VERTEX 70.

Chapter 3. Two-dimensional metallic hole array for enhancement of mid-wavelength infrared photodetection

A hole in a metal film is perhaps the simplest optical element, which has been studied for several centuries. However, despite its apparent simplicity, an accurate description of its optical properties turned out to be extremely difficult, especially when the radius of hole is significantly smaller than the wavelength of impinging radiation ($r \ll \lambda_0$). Starting from conventional theory of diffraction by a sub-wavelength hole, this chapter subsequently describes extraordinary transmission through a sub-wavelength hole and hole array. Then, the author reports simulation and analysis of extraordinary transmission through metallic 2DHA. Based on the simulation results, the author will discuss the mechanism of SPP enhancement of photodetection in details. These results will be a good guide for designing metallic 2DHA for plasmonic enhanced photodetection.

3.1 Conventional theory of diffraction by a small hole

Figure 3.1 shows a single sub-wavelength hole perforated in a thin metal film. Since the hole radius is much smaller than wavelength of incident light, the problem can't be treated using the Huygens-Fresnel principle and the scalar diffraction theory by Kirchhoff [86]. When analyzing this system, Bethe and Bouwkamp assumed that the metal was a perfect conductor and the film was infinitely thin [87], [88]. With the assumption that impinging light intensity is constant over the area of the hole, they derived a precise analytical expression for light transmission through sub-wavelength hole. For normal incidence, the hole can be described as a small magnetic dipole located in the plane of the aperture [65], [87]. According to their theory, the transmission efficiency (normalized to the aperture area) is given by

$$T = \frac{64}{27\pi^2} (kr)^4 \propto \left(\frac{r}{\lambda}\right)^4 \quad (3.1)$$

where r is the radius of the aperture, $k = 2\pi/\lambda$ is the norm of wavevector of impinging radiation of wavelength λ . The scaling with $(r/\lambda)^4$ indicates very weak total transmission and rapidly dropping transmission as λ becomes larger than r . Besides, A. Roberts pointed out that the transmission efficiency is further attenuated if real depth of the hole is taken into account [89].

Figure 3.1 Transmission of light through a circular hole of radius r in an infinitely thin metal film.

3.2 Extraordinary transmission through a sub-wavelength hole and hole array

Bethe and Bouwkamp's theory of diffraction by a small hole was challenged by later theoretical and experimental studies. Their theory relies on two major assumptions, the metal film is infinitely thin, yet the screen is still perfectly opaque due to infinite conductivity. Obviously, this assumption is just an idealized case.

In 1998, the extraordinary transmission through sub-wavelength metallic hole array was first observed and demonstrated by Ebbesen [53]. This has triggered extensive interest of research in EOT [90]–[93]. Soon, advances in technology have made it even possible to measure the diffraction and transmission from a single hole

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in a metallic film directly [94], [95]. Measurements indicate that light diffraction is much less than that predicted by previous theory proposed by Bethe and Bouwkamp. In fact, due to localized surface plasmon excitation (LSP), the transmission through a single sub-wavelength hole is much larger than predicted by conventional theory, and it doesn't decrease monotonically with increasing wavelength, as shown in Figure 3.2. As introduced in Chapter 2, SPPs are propagating, dispersive electromagnetic waves coupled to the electron plasma of a conductor at a dielectric interface. On the other hand, Localized surface plasmons are non-propagating excitations of the conduction electrons of metallic nanostructures coupled to the electromagnetic field. The author will not go through details of LSP here, since the author is only interested in sub-wavelength metallic hole array, and LSP only plays a minor role in this system [96]–[98].

Figure 3.2 Transmission properties of a cylindrical holes milled in optical thick suspended Ag films. (a) SEM micrograph image of a single sub-wavelength hole in a suspended Ag film. (b) Transmission spectra at normal incidence for cylindrical holes of diameter $d = 270$ nm, for a range of hole depths h [95].

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Now, turn back to the EOT through sub-wavelength metallic hole array. It was found that the maximum transmission is orders of magnitude larger than the prediction of conventional theory, as shown in Figure 3.3. The EOT is attributed to excitation of SPP at the metal-dielectric interface [53], [99], [100]. Incident radiation is mediated by SPP and then transmitted through hole array [100]. This effect significantly increases transmission. L. Mart ín-Moreno et al. presented theoretical study of this phenomenon [101]. But the calculation is very complicated. Later, crucial role of metal surface in enhanced transmission through sub-wavelength hole was discussed [102], [103] and the effects of hole depth on enhanced light transmission through sub-wavelength hole arrays was also theoretically and numerically studied [101], [104]. A review of different aspects of this phenomenon can be found in [52], [84].

Figure 3.3 Zero-order transmission spectrum for a square array of 150 nm holes with a period a_0 of 0.9 μm in a 200 nm thick Ag film. [53].

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This extraordinary transmission discovery makes the use and control of photons in a manner analogous to that of electrons in solids possible. Since the fundamental limit in controlling light is its extremely low transmission through sub-wavelength holes [53]. The extraordinary transmission phenomenon has stimulated vast theoretical and experimental research since then. Among them, the most important one is the enhancement of performance of photodetectors [54]–[59], [105]–[113].

However, previous studies have not revealed clearly effects of various variables and parameters of the system on transmission and transmission efficiency through metallic 2DHA. Besides, some of the parameters discussed in previous studies are not good enough for real applications. For example, the hole depth discussed in [104] is large, thus the transmission is small for practical application. To understand more about the transmission through metallic 2DHA and physics behind this extraordinary transmission phenomenon, then apply hole array for surface plasmon enhanced photodetection, the author has done more detailed simulation and analysis, as discussed in next section.

3.3 Simulation results and analysis

As shown in Figure 3.4, metallic array of circular holes is fabricated above a dielectric substrate. Here, the upside-down view of the system is shown for better illustration. Transmission through this sub-wavelength hole array and field distribution in sub-wavelength regime are simulated using FDTD method. The author has investigated all possible variables and parameters that may affect the transmission spectrum and field distribution of the sub-wavelength hole array. They are periodicity of hole array (p), hole diameter (d), refractive index of substrate ($n_d = \sqrt{\epsilon_d}$, where ϵ_d is dielectric constant), thickness of metal film (t), hole shape and light incident direction. Since the author is interested in MWIR range, the author will mainly consider the transmission peak wavelength located in this range,

neglecting higher SPP modes at shorter wavelengths. The author will show simulation results and present detailed analysis of these variables and parameters in following sections respectively.

Figure 3.4 A schematic of 2DHA structure in which p is the periodicity of hole array, d is the hole diameter, t is the thickness of metal film, and ϵ_d is the dielectric constant of substrate.

3.3.1 Effects of periodicity and diameter of hole array

To begin with, first take a look at transmission through metallic 2DHAs with different periodicities. The diameter d of circular hole is fixed at $0.46 \mu\text{m}$, and the metal film is made of gold, with thickness of $t = 20 \text{ nm}$. The refractive index of substrate is $n_d = \sqrt{\epsilon_d} = 4.0$. The periodicity is varied between $0.72 - 1.12 \mu\text{m}$, with other parameters remain unchanged. The wave source used here is normally incident along positive z direction, polarized in x -direction, with wavelength range from $1.50 \mu\text{m}$ to $6.50 \mu\text{m}$. The simulated transmission percentages for different periodicities as a function of wavelength are shown in Figure 3.5.

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As shown in Figure 3.5, transmission percentages through 2DHA is much larger than those predicted by Bethe and Bouwkamp's theory, which in this case is in the order of 10^{-3} if calculated using their theory. Besides, the transmission spectra exhibit sharp peaks in the wavelengths, i.e., the main resonance wavelengths in spectra, which are as much as 8-10 times of diameter of circular hole. These wavelengths are far beyond the diffraction limit. In this wavelength range, there are no propagating waveguide modes transmitting through the hole. At the same time, the transmission through un-patterned gold film of same thickness is less than 5%, which would be even smaller at those main resonance wavelengths shown in Figure 3.5.

Figure 3.5 Transmission spectra of gold 2DHAs with different periodicities ($d = 0.46 \mu\text{m}$, $t = 20 \text{ nm}$, $n_d = 4.0$). The periodicity increases from $0.72 \mu\text{m}$ to $1.12 \mu\text{m}$.

Coupling of incident radiation as SPP at the interface is why these peaks appear [53]. The incident light excites SPPs, which then travel through hole array. These main resonance wavelengths correspond to the lowest surface plasmon

modes. There are also some peaks at shorter wavelengths, which correspond to higher plasmonic modes.

If these transmission curves are compared with each other, it will be found that position of spectra peaks shift to longer wavelength with increasing periodicity of hole array. In fact, the peak wavelength is linearly dependent on periodicity of hole array, as shown in Figure 3.6. For simplicity, the author only plot main resonance wavelength here. This linear dependence of resonance wavelength on periodicity can be verified by theoretical calculation, which will be discussed in details later.

Figure 3.6 Main resonance wavelength as a function of periodicity of hole array.

Next, consider 2DHAs with different hole diameters. The circular hole diameter d changes from 0.30 to 0.60 μm , and the periodicity of hole array is set as 0.92 μm . Other parameters are the same with those when comparing periodicities. The simulation results are shown in Figure 3.7.

As shown in Figure 3.7, when periodicity is fixed, the positions of peak wavelengths is almost the same for different hole diameters. But the transmission

percentage at the main resonance wavelength is increased for larger hole diameters. The position main resonance wavelength versus hole diameter is shown in Figure 3.8.

Using momentum conservation law, the peak wavelengths can be calculated theoretically. Rewrite the momentum conservation law equation for normal incidence here

$$\mathbf{k}_{sp} = \pm i\mathbf{G}_x \pm j\mathbf{G}_y \quad (3.2)$$

Figure 3.7 Transmission spectra of gold 2DHAs with different hole diameters ($p = 0.92 \mu\text{m}$, $t = 20 \text{ nm}$, $n_d = 4.0$). The hole diameters are varied from $0.30 \mu\text{m}$ to $0.60 \mu\text{m}$.

Figure 3.8 Main resonance wavelength as a function of hole diameter of hole array.

where $\mathbf{G}_x$ and $\mathbf{G}_y$ are the reciprocal lattice vectors and $|\mathbf{G}_x| = |\mathbf{G}_y| = \frac{2\pi}{p}$ for square lattice, $i, j = 1, 2, 3, \dots$. From dispersion relation equation (2.9), the following equation is derived

$$\beta = \frac{2\pi}{\lambda} \sqrt{\frac{\epsilon_m \epsilon_d}{\epsilon_m + \epsilon_d}} \quad (3.3)$$

where ϵ_m and ϵ_d are the dielectric constants of the metal and substrate, respectively.

Combine equation (3.2) with (3.3), the following resonance wavelength equation is derived

$$\lambda_{i,j} = \frac{p}{\sqrt{i^2 + j^2}} \sqrt{\frac{\epsilon_m \epsilon_d}{\epsilon_m + \epsilon_d}} \quad (3.4)$$

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Equation (3.4) clearly demonstrates that resonance wavelength is linearly dependent on periodicity of hole array, and it is not affected by varying hole diameters. Besides, comparison between theoretical calculation of resonance wavelength and simulation result is made here. Take the transmission spectrum of hole array with $p = 0.92 \mu\text{m}$ and $d = 0.46 \mu\text{m}$ as an example, as shown in Figure 3.9, there is a main peak at wavelength of $3.85 \mu\text{m}$, and three higher order peaks at shorter wavelength of $2.70 \mu\text{m}$, $1.95 \mu\text{m}$ and $1.65 \mu\text{m}$ respectively.

Theoretical calculation results using equation (3.4) are shown in following Table II. It is clearly shown in Table II that peak wavelength of simulation matches that of theoretical calculation very well as the differences between resonance wavelength by theoretical calculation and simulation results are rather small.

Figure 3.9 Transmission spectrum of gold 2DHA with $p = 0.92 \mu\text{m}$ and $d = 0.46 \mu\text{m}$. The wavelengths of surface plasmon modes are indicated by arrows.

Table II Comparison of peak wavelengths by theoretical calculation and simulation results.

$\sqrt{i^2 + j^2}$	1	$\sqrt{2}$	2	$\sqrt{5}$
calculation (μm)	3.73	2.68	1.93	1.76
simulation (μm)	3.85	2.70	1.95	1.65
difference	3.2%	0.7%	1.0%	6.25%

From above discussion, it is known that the periodicity of hole array is easily determined when a peak wavelength for specific application is requested. But how about the hole diameter? Taking a closer look at Figure 3.7, it is found that although transmission percentage increases when hole diameter is larger, the full width at half maximum (FWHM) of main resonance also increases, as shown in Figure 3.10.

Figure 3.10 FWHM of main resonance as a function of diameter of hole array.

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In fact, if the hole diameter is larger, the simulation shows an even larger FWHM. This reminds people of the flat transmission through non-absorbing dielectric material, i.e. the substrate here. Thus, it can be imagined that when hole diameter is too large, a large portion of incident light transmits through the hole array directly, without being excited as SPP first. This is absolutely not what the author wants. At the same time, the hole diameter can't be too small, or else the transmission would be too low for practical application.

To determine optimal diameter of sub-wavelength hole array, transmission efficiency is defined here, using below equation

$$\eta = \frac{T}{T_0 * F} \quad (3.5)$$

where T denotes transmission through metallic 2DHA, F is filling fraction of hole area in metal film, T_0 is transmission through bare substrate with no metal film on top, calculated by

$$T_0 = 1 - R_0 = 1 - \left(\frac{n_d - 1}{n_d + 1} \right)^2 \quad (3.6)$$

Here the refractive index of substrate is $n_d = 4.0$, thus $T_0 = 0.64$. Without SPP generation effect, the transmission through hole array is limited by $T_0 * F$, since the area covered by metal is expected to block incident light and only through the hole can incident light transmit. For circular hole in square array, filling fraction is

$$F = \frac{\frac{\pi}{4}d^2}{p^2} \quad (3.7)$$

Therefore, equation (3.5) reduces to

$$\eta = \frac{T}{T_0 \cdot \frac{\pi d^2}{p^2}} = \frac{4}{\pi} \left(\frac{p}{d} \right)^2 \frac{T}{T_0} \quad (3.8)$$

Using equation (3.8), transmission efficiencies are calculated at main resonance wavelength when for two cases. One is for hole diameter being fixed at $d = 0.46 \mu\text{m}$, and the other is the periodicity being fixed at $p = 0.92 \mu\text{m}$. The results are shown in the following Figure 3.11.

Figure 3.11 A plot of transmission efficiency as a function of (a) the periodicity p ($d = 0.46 \mu\text{m}$) and (b) hole diameter d ($p = 0.92 \mu\text{m}$).

As shown in Figure 3.11, at the resonance wavelengths, the highest transmission efficiency is around 3.85, which indicates much more light than that is directly impinging into the hole area is transmitted. In fact, the radiation which is incident to metal area is excited as SPP. This surface wave is channeled to the hole rim and then transmitted through hole array. Besides, from these two figures, it can be found that transmission efficiency reaches a maximum value when hole diameter is approximately half of periodicity.

The optimal geometry parameters for achieving highest transmission efficiency are very important. Higher transmission can be achieved by increasing

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hole diameter, but a large fraction of incident light would be transmitted directly through the holes, rather than in the form of excited SPPs. Thus, optimal geometry parameters for highest transmission efficiency have significant influence on practical applications.

Now, look at the near-field distribution of electric field and Poynting vector. One thing needs to be mentioned here is that the electric field amplitude of incident light is set as 1 V/m in all simulation. Besides, if not specified, the units of the colorbar in the figures showing electric field and Poynting vector distribution are V/m and W/m^2 , respectively.

First, the vector graph of electric field in the x-z plane at resonance wavelength $3.85 \mu\text{m}$ is shown in Figure 3.12, where $z = 0$ plane is at the metal-dielectric interface. From Figure 3.12, the oscillation of electric field near metal surface can be seen and the electric field decays rapidly in the perpendicular direction, namely z direction here. In addition the penetration depth in metal side is much smaller than that in dielectric side, similar to what are seen in section 2.1.4. Besides, the SPP wavelength equals to periodicity of 2DHA exactly, which is also mentioned in section 2.1.4.

To look at the electric field distribution more clearly, surface graph of electric field in the same x-z plane is shown in Figure 3.13. It is obvious that the electric field penetrates into the substrate of $\sim 0.4 \mu\text{m}$. For SPP excited at the planar metal-dielectric interface, if the free-space wavelength of incident light is $3.85 \mu\text{m}$, the penetration depth into dielectric medium is around $3.60 \mu\text{m}$. This means the capability of concentrating light is much stronger for metallic 2DHA, compared with planar metal surface. Also because of this tight concentration of light, if people want to use metallic 2DHA to enhance the performance of photodetector, the active region should be as close to the metal film as possible [54].

Figure 3.12 Vector graph of electric field in the x-z plane at resonance wavelength. Dashed line denotes $z = 0$ plane, i.e., metal-dielectric interface.

Next, take a look at the electric field distribution in the planes perpendicular to z direction, i.e., $z = 30$ nm and $z = -50$ nm plane, which are 30 nm above and below the two surface plane of gold. Figure 3.14 shows x and z component of electric field (E_x and E_z) in $z = 30$ nm plane. Note that y -component (E_y) is relatively small and negligible here. It is clearly shown that electric field is concentrated along the rim of circular hole. Inside the hole, there is no E_z of electric field, while outside of hole no E_x . This agrees very well with boundary conditions of metal surface. Similar conclusion goes for electric field in reflected plane $z = -50$ nm, as shown in Figure 3.15.

Figure 3.13 A cross-sectional view of the electric field in the vicinity of hole array. Dashed line denotes $z = 0$ plane, i.e., metal-dielectric interface.

Figure 3.14 Simulated near field distribution of (a) x-component (E_x) and (b) z-component (E_z) of electric field in plane $z = 30$ nm. Dashed line denotes rim of circular hole.

Figure 3.15 Simulated near field distribution of (a) x-component (E_x) and (b) z-component (E_z) of electric field in plane $z = -50$ nm. Dashed line denotes rim of circular hole.

For comparison, the author also simulated near-field distribution of electric field at wavelength of 4.00 μm , 3.85 μm , 3.70 μm and 2.70 μm (corresponding to the second mode of SPP), as shown in Figure 3.16.

As shown in Figure 3.16, resonance at wavelength 3.85 μm is the strongest. While for wavelength at 4.00 μm , confined electric field is much smaller. As it has been observed in transmission spectra, transmission at 3.70 μm is extremely small, thus there is almost no field concentration at this wavelength. In fact, this conclusion is not very accurate. A more detailed discussion of the scenario is presented in Chapter 4. For wavelength at 2.70 μm , this corresponds to the second mode of SPP. Compared with main resonance at 3.85 μm , resonance at this wavelength is smaller yet distinguishable. Besides, an interesting phenomenon of second mode is, apart from the resonance at the center area around rim of hole, there is also small resonance in the edge of unit. It is believed this is from the fundamental nature of second order of SPP.

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Figure 3.16 Near-field distribution of electric field in x-z plane and $z = 30$ nm plane at wavelength of (a) $4.00 \mu\text{m}$, (b) $3.85 \mu\text{m}$, (c) $3.70 \mu\text{m}$ and (d) $2.70 \mu\text{m}$.

Now, consider Poynting vector in the vicinity of hole array. Figure 3.17 shows x and z components of Poynting vector, P_x and P_z , in the x-z plane, respectively. It is obvious that P_z only exists inside the hole and always propagates along positive z direction. And P_x exists both inside and outside the hole, always propagates along metal-dielectric interfaces in opposite direction in two sides of the hole. Besides, P_x inside and outside the hole both propagates to the hole rim, which makes light concentration around hole rim possible. In conclusion, metallic hole array excites the incident wave source as SPP, and then channel this surface wave to the rim of hole. Since the structure is period in x direction, the power flow between neighboring holes can be imagined.

The P_x and P_z in transmitted surface ($z = 30$ nm) and reflected surface ($z = -50$ nm) are shown in Figure 3.18 and 3.19, respectively. As shown in these figures, P_x propagates along opposite direction, while P_z propagates in positive z direction. These results confirm the author's thinking of power flow.

Figure 3.17 (a) x component (P_x) and (b) z component (P_z) of Poynting vector at resonance wavelength $3.85 \mu\text{m}$ in the x-z plane. Dashed line denotes $z = 0$ plane, i.e., metal-dielectric interface.

Figure 3.18 (a) x component (P_x) and (b) z component (P_z) of Poynting vector at resonance wavelength $3.85 \mu\text{m}$ in $z = 30 \text{ nm}$ plane. Dashed line denotes rim of circular hole.

Figure 3.19 (a) x component (P_x) and (b) z component (P_z) of Poynting vector at resonance wavelength $3.85 \mu\text{m}$ in $z = -50 \text{ nm}$ plane. Dashed line denotes rim of circular hole.

From Figure 3.18 and 3.19, the power flow along the metal surfaces and inside the holes can be imagined, as plotted in Figure 3.20. This matches the simulation result shown in Figure 3.21. The EM wave is concentrated at the surface, and it propagates along the metal surface and oscillates around the metal-dielectric interface. This oscillation process will enhance the interaction of light and matter in active region of photodetector. This will then increase quantum efficiency of photodetector, thus the performance of it. It is believed this is why SPP can be used for enhancing performance of photodetector.

Figure 3.20 Schematic of power flow of SPPs. p is the periodicity of the hole array, d is the hole diameter, t is thickness of the metal film.

Figure 3.21 Simulated x component (P_x) of Poynting vector in the vicinity of hole array. Dashed line denotes contour of gold hole array.

3.3.2 Refractive index of substrate

Then, the author investigates dependence of transmission on refractive index of substrate. The periodicity and circular hole diameter are fixed at $0.92 \mu\text{m}$ and $0.46 \mu\text{m}$ respectively. The gold film thickness is set as $t = 20 \text{ nm}$. The refractive index of substrate increases from 3.6 to 4.4, and the transmission spectra are shown in Figure 3.22.

As shown in Figure 3.22, the shapes of the transmission spectra are almost the same for different values of n_d . And it shows that the resonance wavelength increases monotonically with increasing n_d . This can be reflected from the resonance wavelength equation (3.4). Since in the mid-infrared wavelength range the author is interested in, $\epsilon_m < 0$, $\text{Re}[-\epsilon_m] \gg \text{Im}[\epsilon_m]$ and $\text{Re}[-\epsilon_m] \gg \epsilon_d$, the equation (3.4) can be approximately reduced to

Figure 3.22 Transmission spectra of gold 2DHA with different refractive indexes of substrate. The 2DHA have $p = 0.92 \mu\text{m}$, $d = 0.46 \mu\text{m}$, $t = 20 \text{ nm}$. The refractive index n_d is varied from 3.6 to 4.4.

$$\lambda_{i,j} = \frac{p}{\sqrt{i^2 + j^2}} (\epsilon_d)^{\frac{1}{2}} = \frac{p}{\sqrt{i^2 + j^2}} n_d \quad (3.9)$$

Equation (3.9) indicates that the resonance wavelength is approximately linearly dependent on refractive index of substrate. It is seen that once the interested wavelength is known by the application, the refractive index of the substrate will determine the periodicity of the metallic 2DHA.

3.3.3 Thickness of metal film

Now, the author analyzes the effect of metal film thickness on transmission. Before presenting simulation results, the author first considers this effect from theoretical perspective. Apparently, in the process of exciting SPPs by the incident

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light, the metal film performs an important role. Since the author hopes the light being only transmitted in the form of SPPs, the metal film should be as thick as possible. However, thicker metal film also means higher reflection, thus lower transmission. In other words, if the film is too thick, although almost all of the transmitted light can be converted as SPPs, the transmission is extremely small. This is not expected in practical applications. Hence, there should be a trade-off for the metal film thickness.

Now, look at the simulated transmission spectra shown in Figure 3.23. Here, the circular hole array has period $p = 0.92 \mu\text{m}$ and diameter $d = 0.46 \mu\text{m}$. The refractive index of substrate is 4.0. The thickness of gold film is varied from 20 nm to 60 nm.

Figure 3.23 Transmission spectra of gold 2DHA with different metal film thicknesses ($p = 0.92 \mu\text{m}$, $d = 0.46 \mu\text{m}$, $n_d = 4.0$, and t changes from 20 nm to 60 nm).

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It is clearly shown in the figure that there is a red shift of resonance wavelengths when the metal film becomes thinner and thinner. To understand the shift, we can refer to equation (3.4), which indicates that $\lambda_{i,j}$ is linearly proportional to $[\varepsilon_m \varepsilon_d / (\varepsilon_m + \varepsilon_d)]^{1/2}$. Notice that in the real-world situation, the metallic film is not semi-infinite. Thus, ε_m is averaged by background material (air in this case) index, implying that the metal film is less “metallic”. One can define the dielectric constant of “combined” medium of metal and air as ε_c . When t decreases, the averaging effect plays a more important role for “combined” medium, which is less and less “metallic”. As $\text{Re}[\varepsilon_c]$ is negative and $\text{abs}(\text{Re}[\varepsilon_c])$ decreases as t decreases, the peak wavelength $\lambda_{i,j}$ shows a red shift when the metal film become thinner. Apart from this, as t decreases, transmission intensity increases. This means in order to achieve high transmission, a thin metal film should be used. In addition, there is a sharp increase of transmission at resonance wavelength when t decreases from 30 nm to 20 nm. It is because $t = 20$ nm is approaching skin depth of SPP sustained at gold-dielectric interface. As being discussed in section 2.1.4, SPPs penetrate a depth δ_m in the metal which is called skin depth (or penetration depth) of surface plasmon into metal. The skin depth of SPP can be calculated using equation (2.23). For clarity, the author rewrites the equation as following

$$\delta_m = \frac{1}{k_0} \sqrt{\frac{\varepsilon'_m + \varepsilon_d}{\varepsilon_m'^2}} \quad (3.10)$$

where ε'_m is real component of dielectric function of metal. In the wavelength range the author considers here, the skin depth of SPPs is almost a constant of ~25 nm. This means in the 25 nm thick metal film, the intensity of electric field decays to $1/e$. When the thickness becomes smaller, the significant SPPs would pass through the other surface to the dielectric, instead of being trapped at the metal surface. When the thickness of metal film is too small, this portion of un-trapped SPP cannot be neglected any more.

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It is obvious there is a trade-off when selecting the thickness of metal film. The optimal thickness should be approximately skin depth of SPP in metal.

It should be mentioned here that this optimal metal film thickness is related to incident direction of light. As it will be discussed in section 3.3.5, the optimal metal film thickness for illumination from back of the substrate is distinctly different from that for illumination from front.

3.3.4 Hole shape

Next, the author discusses effect of hole shape on transmission and transmission efficiency. For comparison with circular hole array, the author simulated two square hole arrays. One of them has the square hole area the same as circular holes, while the other has the side length of the square holes equal to the diameter of the circular holes. The simulation results are shown in Figure 3.24.

As shown in Figure 3.24, when circular hole and square hole have same area, the maximum transmission is almost the same with circular hole. Thus the transmission efficiency is the same. Besides, the width of transmission peak is larger for the square hole array. When they have same width, transmission through square hole is larger than circular. This is quite obvious because same width implies larger area for square hole. Besides, from the transmission spectra, it is found that square hole corresponds to larger FWHM than circular hole.

The near-field distribution of electric field in the x-y plane of $z = 30$ nm and Poynting vector in x-z plane are shown in Figure 3.25 and 3.26, respectively. From Figure 3.25, it can be found that the electric field concentrates around the rim of square hole in two sides. This is expected and similar to what has been seen for circular hole array. And the x and z component of Poynting vector in the x-z plane

shown in Figure 3.26 also confirms the author's thinking of power flow in hole array.

Figure 3.24 Transmission spectra of two square hole arrays and one circular hole array. The blue curve denotes the transmission of the square hole array in which the square holes have the same area as the circular holes, while red curve shows the transmission of the square hole array in which the side length of the square holes is equal to the diameter of the circular holes.

Figure 3.25 Simulated near field distribution of (a) x-component (E_x) and (b) z-component (E_z) of electric field in the plane of $z = 30$ nm. Dashed line denotes rim of the square hole.

Figure 3.26 (a) x component (P_x) and (b) z component (P_z) of Poynting vector at resonance wavelength $4.00 \mu\text{m}$ in the x-z plane. Dashed line denotes $z = 0$ plane, i.e., metal-dielectric interface.

However, when looking at the electrical field distribution in x-z plane, as shown in Figure 3.27, the electrical field can only penetrate into the substrate around $\sim 0.2 \mu\text{m}$. This is only half of that in circular hole array.

Figure 3.27 A cross-sectional view of the electric field in the vicinity of square hole array. Dashed line denotes $z = 0$ plane, i.e., metal-dielectric interface.

3.3.5 Backside illumination scheme

In previous sections, the author always considers front-side illumination scheme, in which light penetrates through sub-wavelength hole array first. By integrating this metallic 2DHA near the active region of a photodetector, enhanced photoresponse is expected. But the enhancement is usually very limited, due to low coupling efficiency. This results from the frequency difference between the SPP modes on the two sides of the metal film. Because normally light is incident from air, and the dielectric constants of air and substrate are distinctly different. So there is a large difference between the frequencies of SPPs on different surfaces.

In order to overcome this limitation, there are mainly two solutions. One is using refractive index matching liquid, which has a close or same dielectric with the substrate. Apparently, this is not applicable for real applications. The author is not going to discuss this one in details. The other solution is illumination from back. Compared with illumination from front, research on back illumination is much less. For back illumination, light is incident directly onto the metal-substrate interface, instead of penetrating through the sub-wavelength hole in the front illumination scheme. So the coupling efficiency of incident radiation is expected to be much higher.

The schematic of backside illumination is shown in Figure 3.28. The parameters are $p = 1.2 \mu\text{m}$, $d = 0.6 \mu\text{m}$. The thickness of gold film is $t = 40 \text{ nm}$. The refractive index of substrate is set as 3.6 to model III-V alloy. Figure 3.29 shows simulated transmission and reflection spectra. For front and backside illumination, the transmission around the lowest order is almost the same. The lowest order means $i^2 + j^2 = 1$, as the author has mentioned in previous section. But if looking at the reflection, it would be found that the reflection for front and backside illumination is distinctly different. At peak transmission wavelength, for front illumination, reflection is a bit larger than 0.5. While for backside illumination, the reflection is

almost zero. It means that much more is coupled as SPP, instead of being reflected. Stronger light concentration should be expected at the metal-dielectric interface, which will be shown later. One thing needs to be mentioned here is the peak wavelength. The author has derived the peak wavelength expression in previous section (equation 3.4), and the expression can be used for calculation here. The calculated value with the expression is $4.356 \mu\text{m}$. It is different from the peak wavelength $4.66 \mu\text{m}$ shown in Figure 3.29 and the difference will be explained later.

Figure 3.28 (a) Cross-sectional view and (b) top view of sub-wavelength gold hole array. The periodicity of hole array is p , hole diameter is d . The refractive index of substrate is n_d . The thickness of metal film is t .

The electric field distributions at the metal-dielectric interface of peak wavelength are shown in Figure 3.30. As can be seen, light is strongly concentrated along the rim of circular hole, which is denoted by dashed curve. Compared with front illumination, electric field strength is 3 ~ 4 times larger for backside illumination. In terms of power or intensity, it is about 10 times larger. This indeed confirms stronger light concentration for backside illumination. Is it possible to further increase the light intensity? Well, as shown in Figure 3.29, the peak transmission for both front and back illumination is about 25%, and the reflection is almost zero. It is known from front illumination that when metal film gets thicker, transmission decreases. For backside illumination, the transmission may also

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decreases as metal film thickness increases. Could more light and higher coupling efficiency of SPPs be achieved with increasing metal film thickness?

Figure 3.29 Comparison of front and backside illumination scheme. The green and red curves are transmission and reflection spectrum for front illumination respectively. The blue and purple curves are transmission and reflection spectrum for back illumination respectively. The vertical arrow marks the lowest SPP mode.

Figure 3.30 Electric field ($\ln|E|$) distribution at the metal-dielectric interface for (a) front-side and (b) back-side illumination. Dashed line denotes the contour of hole.

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Figure 3.31 shows the electric field distributions for different film thickness, 100, 300 and 500 nm. First, for all these film thickness, it is clearly shown that the amplitude of electric field for backside illumination is much larger than front illumination. What the author is more interested in is comparison of different thicknesses of metal film for backside illumination. The electric field amplitude increases from 16 for 40 nm, to 21 for 100 nm, and 34 for 300 nm, and it then decreases when metal thickness becomes 500 nm. The highest electrical field with the metal thickness of around 300 nm should also mean the highest coupling efficiency. An explanation of this optimal thickness will be given below.

Figure 3.31 Comparison of electric field ($\ln|E|$) distribution at the metal-dielectric interface in metal hole array of different thickness, 100 nm for (a) and (d), 300 nm for (b) and (e), 500 nm for (c) and (f). The first row is for front side illumination and the second row is for backside illumination.

The transmission data through hole array with different thicknesses for both incident directions are shown in Figure 3.32. As can be seen here, the transmissions

for front and backside illuminations are almost the same. When t decreases from 500 nm to 100 nm, the transmission increases exponentially ($T \propto e^{-t/t_0}$). When t is even smaller, the transmission gradually levels off. This is probably because when the metal film is very thin, light can directly penetrate through it. From this figure, t_0 can be found to be ~92 nm. Utilizing below expression of calculating the intensity through a cylindrical waveguide in metal [104]

$$I(t, \lambda_p, d) \propto \exp\left[-\frac{4\pi t}{\lambda_p} \sqrt{\left(\frac{\lambda_p}{1.7d}\right)^2 - 1}\right] \quad (3.11)$$

it will be found that t_0 is around ~81 nm. This is very close to the author's simulation result.

Figure 3.32 Transmission through metallic hole array with varied film thickness. The red line corresponds to front illumination while green line corresponds to backside illumination.

Besides, as can be seen in Figure 3.33, when metal film thickness increases, peak transmission wavelength decreases sharply first and then becomes almost unchanged. This is because for thin metal film, the direct transmission can't be neglected. This together with the SPP portion, leads to a peak wavelength longer than that of optically thick metal film. For thicker metal film, the direct transmission through the hole can be ignored, and the peak transmission wavelength is mainly determined by the generated SPPs. This constant value is $4.39\text{ }\mu\text{m}$, which is very close the calculated $4.36\text{ }\mu\text{m}$ earlier.

Figure 3.33 Blue shift of peak transmission wavelength as metal film thickness increases.

To find the optimized metal film thickness for backside illumination scheme, transmission and reflection for different metal thicknesses were simulated. As shown in Figure 3.34, when metal film becomes thicker, different with the case of 40 nm thick metal film, the reflection is not extremely small any more. It increases very fast as metal film thickness increases, indicating that the coupling efficiency is greatly influenced. So it is known that when t increases, transmission decreases, and

reflections increases. There should be a specific thickness at which the absorption (1-T-R) has a maximum value. As shown in Figure 3.35, when metal film is 270 nm thick, the absorption can be as high as 0.88. Thus the coupling efficiency should be highest for this thickness. This thickness is quite different from the generally used about 30 nm metal for front illumination..

Figure 3.34 Reflection of metallic hole array versus film thickness for backside illumination.

Figure 3.35 Absorption of metallic hole array as a function of thickness of metal film for backside illumination.

According to simulation, backside illumination has higher efficiency in coupling incident light as SPPs than front illumination. The amplitude of electric field confined at the interface can be much larger. This makes backside illumination a better configuration for device applications, such as plasmon enhanced photodetectors. Also, the author has considered the dependence of coupling efficiency on metal film thickness. It is found that highest coupling efficiency (~88%) can be achieved when metallic hole arrays has an optimal film thickness of ~270 nm.

3.4 Chapter summary

In this chapter, the author has done a complete simulation and analysis on the EOT of sub-wavelength metallic 2DHA and field distribution at the metal-dielectric interface. The author first described conventional theory of diffraction by a small hole, which turned out to have greatly underestimated the transmission because of

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the assumptions made. Then the discovery of EOT phenomenon is briefly introduced. After that, the author analyzed the effects of all possible variables and parameters which include periodicity of hole array, hole diameter, refractive index of substrate, thickness of metal film, hole shape and light incident direction.

The peak transmission wavelength is linearly dependent on periodicity of hole array, and is not influenced by hole diameter. From the simulation, the best SPP coupling efficiency is achieved when hole diameter is about half of periodicity of hole array. In addition, the electric field and Poynting vector distributions are also simulated, which can help visualizing the interaction of incident light with the metallic 2DHA.

In the MWIR range, the transmission peak wavelength is linearly dependent on refractive index of substrate. In fact, below equation is a good approximation

$$\lambda_{i,j} = \frac{p}{\sqrt{i^2+j^2}} \sqrt{\frac{\epsilon_m \epsilon_d}{\epsilon_m + \epsilon_d}} \quad (3.12)$$

Thus, when the wavelength for a specific application is chosen, and the substrate material is selected, the periodicity and hole diameter of hole array can be determined. For front illumination, the optimal thickness of gold film should be of skin depth or slightly larger than it, i.e. ~25 nm. For hole shape, it is found that the SPP penetration depth into dielectric medium generated by square hole is only half of that in circular hole array.

Lastly, front and backside illumination is compared. According to simulation, backside illumination has higher efficiency in coupling incident light as SPPs than front illumination. The amplitude of electric field confined at the interface is much larger. This makes backside illumination a better configuration for practical applications, such as plasmonic enhanced photodetector. In addition, the dependence of coupling efficiency on metal film thickness is also studied. It is found that highest

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coupling efficiency (~88%) can be achieved when metallic hole arrays has an optimal film thickness of ~270 nm.

Chapter 4. Analysis of the origin of Wood's anomaly in optical transmission through sub-wavelength metallic hole array

In last chapter, the author has a detailed discussion of extraordinary transmission through metallic 2DHAs at specific wavelength, determined by various parameters of 2DHA. However, as shown by current experiment data and simulation results, the transmission through metallic 2DHA is extremely small at the wavelength close to transmission peak wavelength [53], [114]. Within a very narrow wavelength range, the transmission rapidly decreases from maximum to an extremely small value. This phenomenon is also known as Wood's anomaly [115]. However, this seems to be contradictory to the broadband performance enhancement of plasmonic photodetector [54], [56], [57]. Thus, an appropriate explanation is required for this contradiction. In this chapter, a brief introduction of Wood's anomaly will be presented first, followed by analysis of origin of Wood's anomaly in EOT. Finally, the author will clarify how the proposed theory can be used to explain the unexpected enhancement of response of photodetector integrated with metallic 2DHA at Wood's anomaly wavelength.

4.1 Introduction of Wood's anomaly

Since EOT through sub-wavelength metallic hole arrays was reported in 1998 [53], there has been extensive interest for clarifying this phenomenon theoretically and experimentally [52], [84], [116]. However, most of the efforts have been concentrated on studying the mechanism of transmission enhancement at peak wavelengths, leaving the extremely low transmission at slightly shorter wavelengths being rarely investigated from the perspective of SPP. Within a small wavelength range, the transmission rapidly decreases from maximum to a value close to zero. Similar phenomenon has been observed in metallic diffraction grating, known as

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Wood's anomaly [115]. This grating anomaly phenomenon has attracted vast attention since it was discovered by Wood in 1902 [115], [117]. When observing the spectrum of a continuous light source given by an optical metallic diffraction grating, Wood noticed an astonishing phenomenon: Under certain conditions, the drop from maximum illumination to minimum, a drop of 10 to 1, occurred within a range of wavelengths not greater than the distance between the sodium lines [115]. He pointed out an important aspect that this phenomenon was present only for p-polarized light. This reminds people of the SPPs at metal-dielectric interface, which only exist for TM polarization waves. However, the SPP notion appeared many years later. So Wood was unable to provide any explanation to this phenomenon.

Soon after Wood's discovery, Rayleigh presented the first interpretation to this phenomenon: the anomaly appears when scattered wave emerges tangentially to the plane of the grating [117]. This can be expressed by famous grating formula

$$\sin(\theta_n) = \sin(\theta_i) + n\lambda/d \quad (4.1)$$

where θ_i is incident angle, θ_n is diffraction angle, λ is wavelength in free space, d is grating period and n is scattered order. The anomaly occurs when $\sin(\theta_n) = \pm 1$. Thus, the Wood's anomaly wavelengths are given by

$$n\lambda/d = \sin(\theta_i) \pm 1 \quad (4.2)$$

However, there is a discrepancy of about 5% between Rayleigh's theoretic prediction and Wood's experimental results. In addition, the grating formula used in Rayleigh's explanation is merely geometrical, treating metal only as a passive geometrical object in the path of the incident light, having no influence on the shape of the anomaly [117]. A theoretical breakthrough was accomplished by Fano, who pointed out that there are two sets of anomalies: a sharp anomaly predicted by

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Rayleigh's theory and a diffuse anomaly attributed to superficial wave propagating along the surface of grating and exponentially damped in the normal direction [118], which was found out to be SPPs some years later. The Rayleigh anomaly and SPP resonances (RA-SPP) together affect the transmission through metallic hole array, which is commonly accepted explanation nowadays [91], [99], [119]–[121].

Nevertheless, the RA-SPP theory still can't fully explain the phenomenon observed in the optical transmission through metallic hole arrays. First, for optically thick metal film, the portion of light which penetrates into the hole and then emerges parallel to the interface is extremely small at the Wood's anomaly wavelength. Thus, the RA effect can only have a minor influence on the extremely low transmission. Also, this theory is unable to explain the backside illumination scenario. For illumination from backside, the transmission through the hole array is the same as that in front illumination. Furthermore, this theory also cannot fully justify the unexpected response enhancement of photodetector with metallic hole array on top at Wood's anomaly wavelength [54]. If RA effect plays a major role and light diffracts parallel to the grating surface, it is unlikely that the photoresponse can be enhanced. Here, a new interpretation to this phenomenon is proposed: at Wood's anomaly wavelength, the extremely low transmission results from excitation of incident light as SPPs, which have a low efficiency of being decoupled from the metal-dielectric interface and don't contribute to transmission. And it will be demonstrated how this theory can be applied to illustrate the broadband photoresponse enhancement of integrated structure of photodetector and metallic hole array.

4.2 Analysis of origin of Wood's anomaly in EOT

The author has done simulation of transmission and reflection through a two-dimensional sub-wavelength gold hole array structure, as shown in Figure 4.1. The simulation is done using FDTD method. The period and hole diameter of gold

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hole array are selected as 1.2 μm and 0.6 μm , respectively. The thickness of gold layer is assumed to be 40 nm, and the dielectric constant of the beneath substrate be 12.96. Figure 4.1(c) shows the transmission and reflection spectra from 3.00 to 7.00 μm . For simplicity, only the lowest order of transmission peak and Wood's anomaly is considered here. The transmission peaks at $\lambda_{\text{SPP}} = 4.66 \mu\text{m}$, having an absolute value of around 26.5%. At this wavelength, the transmission efficiency (normalized to filling fraction of hole area) exceeds unity, known as extraordinary optical transmission. This implies that not only the light incident to the hole area, but also light incident to the metal surface area is transmitted. However, what the author is really interested in is the transmission minimum, which is as low as 0.37% at $\lambda_{\text{RA}} = 4.43 \mu\text{m}$. The transmission changes over 70 times within a 0.23 μm wavelength range.

The conventional RA-SPP theory attributes this extremely low transmission to light diffraction in the direction parallel to grating surface [91], [117], [118]. More specifically, at Wood's anomaly wavelength, light diffracts at the exit side of a hole array as a radiate wave traveling parallel to the metal-substrate interface and vanishes eventually, instead of contributing to transmission. However, as the author has mentioned earlier, for the optical metallic hole array, the portion of light which can tunnel through the hole and then diffract is extremely small. So, it is believed that grazing light only has a minor effect on this extreme low transmission and can't fully explain the Wood's anomaly.

Figure 4.1 (a) Cross-sectional view and (b) top view of a gold hole array structure. The period and circular hole diameter are set as 1.2 μm and 0.6 μm , respectively. The thickness of gold film is chosen as 40 nm. The dielectric constant of substrate is set as 12.96. (c) Simulated transmission and reflection spectra through the gold hole array structure. The lowest order of transmission peak is at 4.66 μm , marked by a vertical solid arrow. The transmission minimum is at 4.43 μm , marked by a vertical dashed arrow.

In order to investigate the origin of Wood's anomaly, the author first examined the electric field (E_z) distribution in the vicinity of gold hole array. The reason to purposely choose E_z is that the electric field perpendicular to the metal surface

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characterizes the strength of coupling incident light as SPPs. Figure 4.2 shows the cross-section view of E-field (E_z) distribution in the plane cutting through the hole center at three different wavelengths. Within expectation, at peak transmission wavelength λ_{SPP} , strong concentration of incident wave in the vicinity of metal-dielectric interface can be clearly seen. But what astonishes the author is the enhancement of electric field at $4.43 \mu\text{m}$, since the transmission is extremely low at this wavelength. The high concentration of electric field at λ_{RA} indicates appreciable efficiency of coupling incident light as SPPs. Although the field concentration strength is not as high as that at $4.66 \mu\text{m}$, it is still incredibly high when compared with $7.00 \mu\text{m}$ at which there is almost no SPPs being excited.

At Wood's anomaly wavelength, the appreciable electric field concentration seems to be contradictory to the extremely low transmission. The transmission through the gold hole array is usually ascribed to incident light being excited as SPPs, propagating through hole and then being decoupled from the metal surface and radiated from the interface [52], [53]. However, at λ_{RA} , the strength of interaction of incident light and surface plasmon is considerable, while the transmission is almost zero. This implies that high efficiency of exciting SPP may not always lead to large transmission. In other words, transmission alone may not be able to well characterize the coupling efficiency of SPP at the interface.

As a confirmation, the Poynting vector distribution in cross-sectional plane is investigated, as Poynting vector distribution can provide information on how the energy flows and the path of light when it encounters the metallic hole array. It is clearly seen in Figure 4.3(a) that, at λ_{SPP} , there is strong oscillation of energy in the metal surface. Also, a substantial portion of energy radiates away from metal surface, contributing as transmission. Thus, both the coupling efficiency of SPP and transmission through the hole array are very high at this wavelength. Interestingly, at $\lambda = 4.43 \mu\text{m}$ shown in Figure 4.3(b), there is considerable energy resonance at the interface, while the overall energy flowing away from the metal surface can be

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neglected. These observations should be able to verify the above speculation that transmission alone can't be used to well characterize the coupling efficiency of incidence to SPPs.

Figure 4.2 Cross-section view of electric field (E_z) distribution in the vicinity of metallic hole array at various wavelengths: (a) $\lambda = 4.66 \mu\text{m}$, (b) $\lambda = 4.43 \mu\text{m}$ and (c) $\lambda = 7.00 \mu\text{m}$. The hole is centered in x direction and the frame of metal film is outlined by white dashed lines.

Figure 4.3 Simulated Poynting vector distribution in cross-section plane at (a) $\lambda = 4.66 \mu\text{m}$ and (b) $\lambda = 4.43 \mu\text{m}$. The cut plane is at center of the hole while $Z=0$ represents the metal-dielectric interface.

Furthermore, it is suggested that the absorption, instead of transmission, should be applied to describe the resonance strength of light at the interface. In the mid-infrared wavelength range, the absorption of gold film is neglected. Based on the transmission and reflection spectra in Figure 4.1(c), the absorption of incident light can be extracted. For comparison, plots of transmission, absorption and integrated intensity ($\int_s |E_z|^2 ds$) are shown in Figure 4.4. The integrated intensity is

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used to characterize the strength of the coupling light to SPPs. As can be seen in the figure, the absorption spectrum is in good agreement with the integrated intensity spectrum, and the shapes of the two spectra are very different from transmission spectrum. As mentioned earlier in the section, the absolute value of peak transmission is about 70 times of that at λ_{RA} . For absorption and integrated intensity, however, the peak values are only 3.1 and 3.5 times of that at λ_{RA} , respectively. This difference is even smaller if the value at λ_{SPP} and λ_{RA} are compared. Thus, although the transmission at Wood's anomaly wavelength is extremely small, the resonance strength at this wavelength is comparable with that at peak transmission wavelength. The difference is that, at λ_{RA} , the excited SPPs are more tightly confined to the interface and the decoupling efficiency is very low, leading to a very low transmission.

Figure 4.4 Comparison of transmission and absorption of the sub-wavelength hole array with integrated electric field intensity ($\int_s |E_z|^2 ds$) in the vicinity of hole array, i.e. $z = -0.3 \mu m$ plane. The red dashed arrow marks the Wood's anomaly wavelength.

4.3 Explanation of the contradiction

Now, take a look at the scenario of enhancing photoresponse of photodetector using metallic hole array. The enhancement of photoresponse at λ_{SPP} is attributed to electric field concentration and resonance at the interface [51], [54]. For the photodetector configuration without metallic 2DHA, when the incident light enters the absorption region of a photodetector, some photons will be absorbed and converted into current while those photons which cannot be absorbed will transmit through and leave the active region. It means that the incident photons have only one chance of being absorbed. If incident light can be localized in sub-wavelength regime, however, then the chance for being absorbed will be greatly enhanced. At λ_{SPP} , the highly focused electric field enhances quantum efficiency of photodetector [108]. A number of experimental results show that the metallic hole array also has photoresponse enhancement at Wood's anomaly wavelength [54], [56], [122]. This is contradictory to what would be expected if the Wood's anomaly results merely from light grazing at the exit surface, a non-resonant feature. The contradictory can be explained as follows: at Wood's anomaly wavelength, the coupling efficiency is actually still considerable. Instead of emerging parallel with the metal-dielectric interface, the incident photons are converted as SPPs which are confined near the interface. Thus, the enhancement at this wavelength is still appreciable. This will explain the considerable performance enhancement at λ_{RA} , although the transmission is extremely small..

4.4 Chapter summary

In this chapter, the investigation of the origin of Wood's anomaly in optical transmission through a sub-wavelength metallic hole array is investigated and discussed. The electric field (E_z) distribution at Wood's anomaly wavelength shows considerable concentration of electric field and resonant excitation of SPPs at the metal-substrate interface. Unlike at peak transmission wavelength, the efficiency of

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SPPs being decoupled from the metal surface at λ_{RA} has little contribute to transmission. So the author concludes that the transmission can't characterize the strength of coupling to SPPs, and proposes that absorption is more appropriate to describe the efficiency of coupling incidence to SPPs. This proposed theory can be used to clarify the enhanced photoresponse of the photodetector integrated with a metallic hole array at λ_{RA} . At Wood's anomaly wavelength, the excited SPPs can penetrate to the action region of photodetector at a certain extent and enhance response, although the transmission is extremely low.

Chapter 5. High performance n-i-p based mid-infrared InAs/GaSb type-II superlattice photodetector

As mentioned in previous chapter, the dominating technologies of IR detector market are based on HgCdTe, InSb and QWIPs [2]. However, although HgCdTe detectors have high detectivity and quantum efficiency, they still suffer from difficulties in uniform growth, technical problems in mass production for large focal plane arrays and high cost of commonly used lattice-matched CdZnTe substrate [2], [20]. While for InSb based photodetector, the wavelength response is not tailorable due to a fixed bandgap in mid-infrared wavelength range. For QWIPs, they are suffering from problems such as large dark current and low quantum efficiency, resulting from intraband transition, small volume of absorption region and forbidden normal incidence absorption [15], [21]. This has encouraged development of alternative materials, among which InAs/GaSb type-II superlattice is the most promising one. In this chapter, the basics of InAs/GaSb type-II superlattice material system will be first introduced and then the growth and fabrication of superlattice photodetector, followed by characterization results and detailed discussion of the the performance of the photodetectors.

5.1 Introduction of InAs/GaSb type-II superlattice

In 1977, Tsu et al. first theoretically studied the InAs/GaSb type-II superlattice, in which the conduction band bottom of InAs is slightly lower than valence band top of GaSb [18], as shown in Figure 5.1. They pointed out that this usual bandgap alignment offers new intriguing features and make superlattice devices useful. Besides, it was found that the energy gap is strongly dependent on thickness or period of each layer. By tuning the thickness of each layer, the bandgap can be tuned in a wide wavelength range. A decade later, Smith and Mailhiot proposed that the optical absorption coefficient of this SL material can be as good as that of the HgCdTe alloy with the same bandgap. Since then, the SL material has generated

extensive interest in IR detection [32], [75]. As a result of “broken-gap” type-II alignment of InAs/GaSb SL material system, the holes and electrons are localized in different layers, the holes in the GaSb layer and electrons in the InAs layer. This spatial separation of holes and electrons contributes to suppression of Auger recombination. Compared with HgCdTe alloy with same bandgap, the electron effective mass of the SL material is much larger, which significantly reduces diode tunneling current. Therefore, combined with the reasonably large optical matrix elements, the optical absorption coefficient of InAs/GaSb SL material is comparable to that of HgCdTe alloy with the same bandgap [76]. In addition, in contrast with QWIPs, the normal incidence absorption is allowed in SL photodetector, resulting in much higher quantum efficiency [77]. These superiorities have made InAs/GaSb SL photodetector a competitive alternative to state-of-the-art HgCdTe detector [78], [79].

Figure 5.1 Type-II bandgap alignment of InAs/GaSb T2SL system [74].

However, despite of the plenty of theoretically predicted advantages that the InAs/GaSb SL material system offers, the dark current of SL detectors is still much

larger than that of HgCdTe detectors, particularly in mid-infrared wavelength range. Thus, the performance of InAs/GaSb SL detector is still far from being superior to that of HgCdTe detectors [47], [48].

In this chapter, a high performance InAs/GaSb SL mid-wavelength infrared photodetector using n-i-p design, operating at 220 K will be presented and discussed [13], [123], [124]. At this temperature, the 50% cutoff wavelength of the photoresponse is 4.66 μm . The R_0A of the detector is as high as $14.9 \Omega \cdot \text{cm}^2$, and the peak detectivity of the photodetector is $2.23 \times 10^{10} \text{ cm} \cdot \text{Hz}^{1/2} / \text{W}$ at 3.0 μm under zero bias.

5.2 Growth and fabrication of superlattice photodetector

The InAs/GaSb SL structure presented in this study was grown on a Te-doped GaSb (001) substrate by solid source MBE. Figure 5.2 shows the schematic drawing of the photodetector. It has a n-i-p structure, which consists of 487 nm thick n-type SLs with InAs layer doped to $3 \times 10^{18} \text{ cm}^{-3}$ by Si, 1948 nm thick unintentionally doped SLs and 487 nm thick p-type SLs with GaSb layer doped to $2 \times 10^{18} \text{ cm}^{-3}$ by Be. All the SLs consist of 8 monolayer (ML) InAs and 8 ML GaSb in each period. A 12 nm thick InAs cap layer doped to $3 \times 10^{18} \text{ cm}^{-3}$ using Si and a 800 nm thick GaSb layer doped to an order of 10^{18} cm^{-3} using Be are above and below the n-i-p structure respectively, as contact layers [22], [23], [125]–[127].

Figure 5.2 Cross-sectional profile of SL photodetector structure and microscope image of the fabricated device. The SL structure consists of 8 ML InAs and 8 ML GaSb in each period. A 300 nm thick SiO₂ layer on the device is deposited for passivation.

The device fabrication process is shown in Figure 5.3.

Figure 5.3 Process flow of fabrication of the SL photodetector. The first deposition of SiO₂ is used as a hard mask.

After cleaning wafer, a SiO₂ layer was deposited on top, and then contact photolithography was done. After that, the exposed SiO₂ was etched using reactive-ion etching (RIE). The recipe used was RF power 170 W, pressure 150 mTorr, 30.0 sccm CF₄ and 30.0 sccm CHF₃. Then, after removing photoresist, the remaining SiO₂ acted as a hard mask during dry etching of wafer. The inductively coupled plasma reactive-ion etching (ICP-RIE) was used for dry etching. The recipe was 2.0 sccm Cl₂, 4.0 sccm BCl₃, 8.0 sccm Ar at 250 °C, and the average etching rate was ~10 nm/s. The etching went through the entire SL structure and stopped in the GaSb buffer layer. After etching wafer and removal of remaining SiO₂, the mesas were defined. The sidewalls of the mesas were protected by depositing a 300 nm thick SiO₂ layer. After that and following photolithography, ICP-RIE was again used for etching SiO₂ to open contact windows on top and bottom. The purpose for using

ICP-RIE instead of buffered oxide etching solution is to avoid unwanted lateral undercut effect, which has adverse effect on sidewall passivation. Then the photoresist was removed, another photolithography was done, and a composite layer of 20 nm thick Ti and 500 nm thick Au was deposited using electron-beam evaporation, for both top and bottom Ohmic contacts. Single element devices of different photosensitive areas varying from $40 \times 40 \mu\text{m}^2$ to $440 \times 440 \mu\text{m}^2$ were fabricated. After fabrication, the devices with $300 \times 300 \mu\text{m}^2$ square mesas were wire bonded to a chip carrier for further characterization.

5.3 Device characterization and discussion

The quality of SL layers was investigated by high resolution x-ray diffraction (HRXRD). Figure 5.4 shows the HRXRD curve of the ω - 2θ scan around the GaSb (004) reflection for the as-grown n-i-p sample. The XRD curve demonstrates that satellite peaks due to the SL periodic structure up to the third order were clearly observed. The GaSb substrate peak and SL 0th order peak are too close each other to be discerned. From the spacing between the satellite peaks, the thickness of each period of SLs was extracted being 47.6 Å, which is extremely close to the designed thickness (48.7 Å). These results indicate that a high quality SL structure was grown.

Figure 5.4 HRXRD curve of the ω - 2θ scan around the GaSb (004) reflection for the as-grown n-i-p sample. Satellite peaks of the SL periodic structure up to the third order are shown.

After fabrication and wire-bonding, the devices were then mounted onto a liquid nitrogen cooled Dewar for characterization of spectral photoresponse, dark current density and current responsivity. Spectral response at different temperatures and bias voltages was measured using FTIR and then normalized to a standard pyroelectric detector's response. Figure 5.5 shows the normalized zero-bias photoresponse spectrum at 77 K, 160K, 220 K and 297 K, together with normalized photoluminescence (PL) spectrum at 77 K.

Figure 5.5 Measured zero-bias photoresponse spectra and PL spectrum. Photoresponse spectra at 77 K (solid curve), 160K (dotted curve), 220 K (dashed curve) and 297 K (dashed-dotted curve) are shown. Short-dashed curve is PL spectrum at 77 K. For comparison, the photoresponse value at 160 K (220 K, 297 K) is multiplied by a factor equaling to ratio of response maximum value at 77 K to that at 160 K (220 K, 297 K). The 50% cutoff wavelength of photoresponse is 4.39 μm at 77 K, in agreement with PL spectrum peak wavelength. Note that the PL spectrum dip at 4.24 μm is because of the absorption of CO_2 in the measurement path. A red-shift of 50% cutoff wavelength of photoresponse is clearly observed when temperature increases.

It is clearly demonstrated that the photoresponse peaks around 1.94 μm and the 50% cutoff wavelength determined from photoresponse spectrum, around 4.39 μm at 77 K, is in good agreement with the PL spectrum peak wavelength. Figure 5.5 also displays the zero-bias photoresponse spectra at 160 K, 220 K and 297 K, which clearly exhibit a red-shift of 50% cutoff wavelength from 4.39 μm at 77 K to 4.49

μm at 160 K, 4.66 μm at 220 K and 4.91 μm at 297 K, respectively. At 220 K, the device photoresponse covers the entire atmosphere window of 3 - 5 μm range. In fact, the fabricated device has a very good performance at 220 K, which will be discussed in details later.

Figure 5.6(a) shows the measured dark current densities of the device at 77 K, 160 K, 220 K and 297 K, respectively. Under zero bias, the dark current density at 77 K and 220 K are $1.05 \times 10^{-7} \text{ A/cm}^2$ and $3.02 \times 10^{-5} \text{ A/cm}^2$, respectively. The resistance area product under zero bias is as high as $14.9 \text{ } \Omega \cdot \text{cm}^2$ at 220K. The dark current density at 77 K is comparable to similar type II superlattice photodetectors reported previously by others, while the dark current density at 220 K is much better [20]. For InAs/GaSb type-II SL photodetector, the dark current mainly consists of four components: thermal diffusion component, generation-recombination current, trap-assisted-tunneling current and surface leakage current [128], which is depicted by equation (5.1)

$$J_{\text{dark}} = J_{\text{diff}} + J_{\text{gr}} + J_{\text{tat}} + J_{\text{sc}} \quad (5.1)$$

For temperature around 77 K, the generation-recombination component and trap-assisted-tunneling component dominate the dark current [129]. As temperature increase to around 200 K, the surface leakage component begins to play a major role [130]. Thus, to suppress the dark current around 200 K, an effective way of reducing surface leakage current must be exploited. In most of the previous work done by others, the way used to etch and define mesa is wet chemical etching with a mixed solution of citric acid, phosphoric acid, and hydrogen peroxide [20], [22], [128]. This can create numerous defects in the sidewall of the fabricated device, resulting in large dark current. In contrast, as described in section 5.2, the etching method used here is dry etching with ICP-RIE. The defects and dangling bond created during etching process are much less. Therefore, the surface leakage current can be significantly suppressed.

Figure 5.6 Dark current density and detectivity of the device with a mesa of $300 \times 300 \mu\text{m}^2$. (a) Dark current densities at 77 K, 160 K, 220 K and 297 K. At 220 K, The resistance area product under zero bias is $14.9 \Omega \cdot \text{cm}^2$ which is a surprisingly high value at 220 K. (b) Calculated detectivity at different temperatures under different bias voltages. At 220 K, the detectivity is 2.23×10^{10} Jones under zero bias.

Using blackbody radiation, the current responsivities of the device at 77 K, 160 K, 220 K and 297 K under different bias voltages were measured. Then, specific detectivity (D^*) can be estimated using the following equation [131]

$$D^* = R_\lambda / \sqrt{2qJ + (4kT)/(R_d A_d)} \quad (5.2)$$

where R_λ is the current responsivity, q is electron charge, J is dark current density, K is Boltzmann constant, T is the temperature of the device, R_d and A_d are dynamic resistance and diode area respectively. Figure 5(b) shows the calculated detectivity at different temperatures and under different bias voltages.

The detectivity verse bias voltage curves show similar shape at different temperatures. From reverse bias to forward bias, the detectivity first increases gradually, then peaks around zero bias and finally decreases rapidly under forward bias. At 77 K, the peak detectivity is calculated being $1.82 \times 10^{12} \text{ cm} \cdot \text{Hz}^{1/2}/\text{W}$ under zero bias. At 220 K, the detectivity is $2.23 \times 10^{10} \text{ cm} \cdot \text{Hz}^{1/2}/\text{W}$ under zero bias. This is the highest obtained value for InAs/GaSb SL photodetector at this temperature to the best of our knowledge [20]. The detectivity only decreases less than two orders of magnitude when temperature increases from 77 K to 220 K. This is distinctly different from the generally observed three orders of magnitude decrease of detectivity in this temperature range. Apparently, this small decrease of detectivity should be attributed to the relatively small increase of dark current when temperature increases from 77 K to 220 K. At 220 K, the responsivity is 0.59 A/W under zero bias at 3.0 μm . The external quantum efficiency (η) can be calculated using following equation:

$$\eta = R_\lambda hc / (q\lambda) \quad (5.3)$$

where h is Planck's constant, c is the light velocity, λ is the wavelength. At 220 K, η is calculated being 24.6% at 3.0 μm . If antireflection (AR) coating is applied to the device, the present D^* and η here can be multiplied by ~ 1.3 .

5.4 Chapter summary

In this chapter, n-i-p based InAs/GaSb type-II SL photodetector was fabricated and characterized. First, the background of InAs/GaSb type-II SL is introduced, followed by the growth and device fabrication details. After that, characterization results are presented. The fabricated device has an unexpected high detectivity at 220 K. At this temperature, this detector has a 50% cutoff wavelength of the photoresponse at 4.66 μm and the R_0A of the device is as high as 14.9 $\Omega\cdot\text{cm}^2$. Measured from blackbody radiation, the current responsivity is 0.59 A/W. Due to low dark current achieved, the photodetector has a peak detectivity of $2.23 \times 10^{10} \text{ cm}\cdot\text{Hz}^{1/2}/\text{W}$ under zero bias at 220 K. This is the highest obtained detectivity of InAs/GaSb SL operating at this temperature. The surprisingly high detectivity of the device makes it a promising mid-infrared photodetector operating at high temperature.

Chapter 6. Study of InAs_{0.91}Sb_{0.09} photoconductor for near and middle infrared photodetection

Antimonide based III–V materials have been attracting great attention as they have wide applications covering photodetection, light source, photovoltaics and electronic devices. As an important alternative of HgCdTe, the III-V ternary alloy InAsSb has received extensive attention [38], [39], [41], [42]. In this chapter, the structural and optical properties and photodetection performance of an InAsSb layer grown on a GaSb substrate by MBE will be presented. The photoconductive InAsSb films grown on GaSb structure show spectral response ranging from NIR to MWIR range. They can work well at low voltage bias as detector and the measured blackbody detectivities are $\sim 2.4 \times 10^7 \text{ cm} \cdot \text{Hz}^{1/2} / \text{W}$ and $\sim 6.1 \times 10^9 \text{ cm} \cdot \text{Hz}^{1/2} / \text{W}$ at room temperature and 77 K, respectively. Starting from brief introduction of background of InAsSb based photodetector, this chapter will then describe device fabrication procedures and characterization. After that, measured results and analysis will be presented.

6.1 Introduction

Photodetectors operating in the near, middle, and long infrared wavelength ranges are of great importance as they have applications in many areas, including optical communication and imaging [8], [132]–[135]. Room temperature InGaAs photodetectors are usually used in the NIR region [132], and cooled InSb and HgCdTe based photodetectors are dominant in middle and long wavelength infrared ranges. However, for InGaAs, even though the composition of Ga can be adjusted to extend its cutoff wavelength to longer wavelength, it still can't cover the MWIR region. For HgCdTe material, due to the high Hg vapor pressure during material growth, it suffers from non-uniformity and instability. Antimony based III-V semiconductors have shown great potential for infrared photodetection [126], [136]–

[144]. Among them, $\text{InAs}_{1-x}\text{Sb}_x$ based photoconductors can cover broadband response wavelength ranges as the bandgap of this material can vary from 0.35 to 0.1 eV (corresponding cut off wavelength from 3.4 to 12.4 μm) at room temperature by changing the composition of element Sb from $x = 0$ to $x = 1$ [145]. The work on $\text{InAs}_{0.2}\text{Sb}_{0.8}$ photoconductors with cutoff wavelength of 3.65 μm grown on patterned Si substrates by MBE was the first demonstration of the feasibility of a technology suitable for monolithic integration of InAsSb-based IR detectors and Si-based electronic devices [146]. Later, the same group reported an $\text{InAs}_{0.05}\text{Sb}_{0.95}$ photoconductor showing a voltage responsivity of 420 V/W at 77 K and 4.1 μm . An $\text{InAs}_{0.04}\text{Sb}_{0.96}$ immersion photoconductor with a response wavelength range of 2 - 9 μm has also been reported at room temperature [147].

In this chapter, InAsSb layer grown on GaSb substrate by MBE will be investigated. The material has limited lattice mismatch to the substrate, high quality and capable of photodetection from NIR to MWIR.

6.2 Device fabrication and characterization

The $\text{InAs}_{1-x}\text{Sb}_x$ epilayers were grown by MBE on GaSb substrate. The epitaxial layers were characterized by XRD and PL. Photoconductors were processed by standard photolithography as circular mesas with radius of 300 μm . Citric acid based chemical solution was used to form the photoconductor. Ti/Au (50/300 nm) double layers were evaporated to form two Ohmic contacts. A cross-sectional view and a real optical microscope image of the device are shown in Figure 6.1. In experiments, the performance of the detector with illumination from front and back was evaluated.

Figure 6.1 (a) Cross-sectional schematic of the photoconductor. (b) The optical microscope image of the InAsSb/GaSb photoconductor.

Figure 6.2(a) and (b) show the XRD spectrum and color map of the InAsSb/GaSb sample, respectively. Lattice mismatch between GaSb substrate and the InAsSb layer can be observed and the layer quality is good as its XRD intensity is similar to that of the substrate. The lattice mismatch is about 0.17% and the composition of Sb extracted from the XRD results is about 0.0903 which is almost the same as planned. Figure 6.2(c) shows the experimental PL spectra of the InAsSb layer measured at temperatures of 10 – 150 K. Clear redshift of the peak position with the increasing temperature was observed, indicating that the band gap of the InAsSb material decreases due to the increased interatomic distance. Both Varshni law [148] and Bose-Einstein relation [149] were used to fit the plot for PL peak versus temperature. As shown in Figure 6.2(d), most of the experimental data points locate on the latter fitting curve, indicating that Bose–Einstein relation can better describe the results due to smaller standard errors. The $E_g(0)$ value obtained from both fittings is 0.332 eV, corresponding to $\sim 3.76 \mu\text{m}$ in wavelength.

Figure 6.2 (a) XRD spectrum obtained from (004) diffraction of the sample. (b) (224) color map of XRD data. (c) PL spectra of the InAsSb layer measured at different temperatures. (d) PL peak positions at different temperatures, compared to the fittings with Varshni law and Bose–Einstein relation. The Varshni law is expressed as $E_g(T) = E_g(0) - \alpha T^2 / (\beta + T)$, where $E_g(0)$ is the band gap at $T = 0$ K while α and β are Varshni coefficients. The Bose-Einstein relation is described by $E_g(T) = E_{gBE}(0) - 2\alpha_B / (e^{\theta_{BE}/T} - 1)$, where α_B is the strength of the electron-average phonon interaction and θ_{BE} is the average phonon temperature.

6.3 Measurement results and analysis

The devices were mounted to a chip holder by wire bonding. A helium-based Cryogenics cooling system and a Lakeshore 330 temperature controller were used to change and stabilize the operating temperature of the device. The photoconductors were measured with illumination from front and back of the

sample. A preamplifier and a lock-in amplifier were used to record the photocurrent response. Current–Voltage (I–V) curves were first measured using a Semiconductor Device Analyzer (B1500A, Agilent). Figure 6.3(a) shows typical I–V curves of the photoconductor at 293 K from –1 V to 1 V. The curve shows excellent Ohmic-contact and symmetry characters. And the measured resistance of the device is $\sim 30 \Omega$.

The performance of InAsSb photoconductors was characterized using a blackbody source at a temperature of 1000 K and a modulation frequency of 300 Hz under applied voltages from 0 to ~ 120 mV. In experiments, a narrow optical band pass filter (2.5 – 4.8 μm) was used to block the unwanted radiation. Figure 6.3(b) shows the linear relationship between the photocurrent and the applied bias voltage. It is in agreement with the theoretical expectation [8],

$$I_{\text{ph}} = q\eta A\Phi_s g = q\eta A\Phi_s \tau/t_t = q\eta A\Phi_s V_b \tau \mu_e / l^2 \quad (6.1)$$

where, q is the element charge, η is the quantum efficiency, A is the area of the sensitive element, Φ_s is the incident photos flux, g is the photoconductive gain, V_b is the bias voltage, τ is the lifetime of the carriers, μ_e is the mobility of the electrons, t_t is the transit time of electrons and l is the distance between metal contact. The blackbody responsivity R_{bb} can be expressed as $R_{\text{bb}} = I_{\text{ph}}/P$ (P is incident radiation power on the detector). To determine P , the following expression can be used

$$P = \sigma(T_b^4 - T_0^4)A_b \times A / (2\sqrt{2}\pi L^2) \quad (6.2)$$

Figure 6.3 (a) Current-Voltage (I–V) characteristic curves of the InAsSb photoconductor at 293 K and 77 K. (b) Photocurrent and responsivity of the detector with respect to voltage bias at 293 K for front and back illumination. (c) Photocurrent and responsivity of the detector with respect to voltage bias at 77 K with other conditions remaining the same.

where, σ is the Stefan constant, T_b and T_0 are the temperature of blackbody and background, respectively, A_b is the area of the exit window of the blackbody source and L is the distance between the detector and the exit window. A standard power meter (OPHIR Photonics) is also used to calibrate the irradiance of the blackbody source. The blackbody responsivity under different voltages was obtained as shown in Figure 6.3 (b). Specifically, under the voltage of ~90 mV and front illumination, the blackbody responsivity is ~0.27 A/W at room temperature, and by decreasing the temperature to 77 K, the corresponding value becomes ~15.82 A/W (Figure 6.3(c)), which shows an approximate ~60 times enhancement. Theoretically, the responsivity of the photoconductor can be expressed as

$$R_I = q\eta\tau V_b \mu_e / (l^2 h\nu) \quad (6.3)$$

The large blackbody responsivity improvement at 77 K should be attributed to the prolonged lifetime and enlarged mobility. On the other hand, even though the photocurrents under illumination from the front and back are very close each other, the responsivity shows large difference due to the different active absorption area. When the photodetector is illuminated from the front, the active absorption area is between the two metallic contacts. When it is illuminated from the back, the active area is that of the mesa. Therefore, the detector shows much higher productivity in photodetection when it is illuminated from the front. This can be attributed to the large reflection loss on the GaSb surface (34.5% compared to 31.1%), as well as the large recombination of carriers before they are collected by electrodes when illuminated from the back. The blackbody detectivity D_{bb}^* can be calculated as

$$D_{bb}^* = R_{bb} (A\Delta f)^{1/2} / I_N = (A\Delta f)^{1/2} SNR / P \quad (6.4)$$

Chapter 6. Study of InAs_{0.91}Sb_{0.09} photoconductor for near and middle infrared photodetection

where, Δf is the equivalent noise bandwidth, I_N is the noise current, and SNR is the signal to noise ratio. Under the voltage of 90 mV and with illumination from front, the measured SNR are ~ 200 and $\sim 5 \times 10^4$ at 293 K and 77 K, respectively. And the equivalent noise bandwidth is ~ 100 Hz. Therefore, the blackbody detectivities are $\sim 2.4 \times 10^7 \text{ cm} \cdot \text{Hz}^{1/2} \cdot \text{W}^{-1}$ and $\sim 6.1 \times 10^9 \text{ cm} \cdot \text{Hz}^{1/2} \cdot \text{W}^{-1}$ at 293 K and 77 K, respectively.

The relative response spectra at different temperatures were measured by using a photocurrent system with a monochromator (Triax 320, Instruments SA). The continuous wave (CW) light source used in the photocurrent system is a Ceramic Element infrared source. It was mechanically chopped before it entered into the monochromator. A low noise current preamplifier (Model SR570, Stanford Research Systems) was used to bias the device, amplify the photocurrent signals and transfer it to voltage signals. And then, a Lock-in amplifier (Model SR810, Stanford Research Systems) was used to read out both the amplitude and the phase (polarity) of the signals. A commercial 1000 VW^{-1} pyroelectric detector was utilized to obtain the relative power spectrum of the source. Figure 6.4 shows the relative spectral response of the InAsSb photoconductor at temperatures of 77 K, 180 K, and 293 K under the voltage of 80 mV. As shown in the figure, the device has a broadband response in wavelengths ranging from $\sim 1 \text{ } \mu\text{m}$ to $\sim 4 \text{ } \mu\text{m}$. By decreasing temperature, the responsivity can be largely improved.

Figure 6.4 Relative spectral response of the photoconductor under front illumination at temperatures of 77 K, 180 K and 293 K under a bias of 80 mV.

As a comparison, Table III shows a summary of the analogous InAsSb detectors reported. As shown in the table, it is difficult to compare as the conditions such as growth technique, substrate, Sb composition, and device dimension are different. In the case here, the InAsSb material with a Sb composition of 0.09, grown on GaSb substrate, can perform well in the planned near to middle infrared range. In particular, such photodetectors can work well at lower bias.

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Table III Summary of analogous InAsSb photoconductors.

Characters	This work	Ref. [146]	Ref. [150]	Ref. [151]	Ref. [147]
Growth technique	MBE	MBE	MBE	ME ^a	ME
Substrate	GaSb	Si	Si	InAs	InAs
Sample	InAs _{0.91} Sb _{0.09}	InAs _{0.2} Sb _{0.8}	InAs _{0.05} Sb _{0.95}	InAs _{0.051} Sb _{0.949}	InAs _{0.023} Sb _{0.977}
Bias(mA)	3	15	15	10	10
Blackbody Resp. (V/W)	293 K: 8.1 77 K: 475	-	-	293 K: < 158.4	293 K: 20 - 168
Wavelength (μm)	1 - 4	~3.65	8 - 12	2 - 9	2 - 9
Detectivity (cm·Hz ^{1/2} /W)	293 K: ~2.4×10 ⁷ 77 K: ~6.1×10 ⁹ (1000 K, 300 Hz, 2.5 - 4.8 μm)	-	-	293 K: 1.5×10 ⁸ (500 K, 1200 Hz, 8 μm)	293 K: 2 - 6×10 ⁸ (500 K, 800 Hz)

^aMelt epitaxy

6.4 Chapter summary

In this chapter, the work on the structural and optical properties and photodetection performance of an InAsSb layer grown on a GaSb substrate by MBE was presented. An XRD study shows that the Lattice-mismatch between the GaSb substrate and the InAsSb epitaxial layer is about 0.17% and the derived composition of Sb is about 0.09. PL measurements at varied temperatures reveal that the energy band gap of the InAsSb material is about 0.33 eV and the luminescence peaks follow Bose–Einstein relation. The photoconductors fabricated based on the InAsSb/GaSb structure show spectral response ranging from NIR to MWIR range. They can work well at low voltage bias and the measured blackbody detectivities are $\sim 2.4 \times 10^7$ cm·Hz^{1/2}/W and $\sim 6.1 \times 10^9$ cm·Hz^{1/2}/W at room temperature and 77 K, respectively.

Chapter 7. GaSb/n-InAsSb heterostructure photodetector and surface plasmon enhanced photodetection

In this chapter, the work on n-GaSb/n-InAsSb heterostructure photodetectors for infrared photodetection and experiment work of plasmonic enhanced infrared photodetection will be presented. First, the n-GaSb/n-InAsSb heterostructure, which is found to have capability of dual color photodetection at fixed large forward biases at different temperatures and the maximum responsivity occurs at room temperature will be introduced. A model has been proposed to explain the observations. Second, the experiment work of plasmonic enhanced infrared photodetection will be discussed. By integrating properly designed sub-wavelength metallic 2DHA on top of n-GaSb/n-InAsSb heterostructure, the room temperature photocurrent and detectivity of the photodiode can be enhanced by ~2 times. Analysis of the enhancement mechanism and explanation of broadband plasmonic enhancement will be presented.

7.1 Dual color photodetection from n-GaSb/n-InAsSb heterostructure

7.1.1 Introduction

InAs_{1-x}Sb_x alloys have a widely tunable band gap while changing the composition x of Sb [152]–[154]. It will be lattice matched to GaSb substrate when the composition is about 0.09 [8], [145]. Over last two decades or so, great efforts were dedicated to the investigation of InAsSb/GaSb diodes both in physics and applications [42], [136], [139], [140], [142], [144], [155]–[157]. Due to the broken-bandgap alignment between the InAsSb epitaxial layer and GaSb substrate, the InAsSb/GaSb heterostructure exhibits unusual properties under different conditions [158], [159]. The earlier work mainly focused on the electrical properties

and the band alignment of this kind of structures [160], [161]. Thereafter, Sharabani et al. investigated an n-GaSb/n-InAsSb heterostructure which showed high zero-bias resistance area product R_0A of $2.5 \Omega \cdot \text{cm}^2$ at room temperature and dual color detections with the same polarity of photocurrent under different biases [40], [46]. Later, Lackner et al. investigated similar GaSb/InAsSb heterostructure which also showed dual color detections but at opposite polarity although the bias was the same [162]. Till now, the observed photodetection and the mechanism behind in the heterostructure photodetectors remain controversial.

In this section, detailed investigation of n-GaSb/n-InAsSb heterostructure photodetectors for infrared photodetection at different temperatures and biases will be presented. The results show that the heterostructure photodetectors are capable of dual color photodetection at a fixed forward bias with its highest responsivity occurred at room temperature; With the decrease of the forward bias, a turning point, at which the photocurrent changes its direction, exist and the corresponding voltage values increases with the decrease of temperature; At all reverse biases, the photocurrents flow in the same direction but the maximum current occurs at about 205 K. A new model is proposed, which can well explain all the observations.

7.1.2 Fabrication process and device characterization

The heterostructure is fabricated by epitaxial growth of an $\text{InAs}_{0.91}\text{Sb}_{0.09}$ epitaxial layer on an n-type GaSb substrate with an electron concentration of $2 \times 10^{17} \text{ cm}^{-3}$ by MBE. The un-doped InAsSb layer is n-type with a concentration of $6 \times 10^{16} \text{ cm}^{-3}$ and the lattice mismatch between the epitaxial layer and GaSb substrate is about 0.17%, corresponding a composition x of 0.09. More detailed description can be found in Ref. [127]. Photodetectors were fabricated by standard photolithography and citric acid based chemical solution into circular mesas with a radius of 250 μm . No passivation layer was deposited for protection of the devices.

Ti/Au (50/300 nm) double layers were evaporated on the structure for Ohmic contacts, as shown in Figure 7.1.

Figure 7.1 (a) Schematic cross-section view of the heterojunction detector. The forward bias is defined as the circumstances when the positive potential is applied to the InAsSb contact. (b) The optical microscope image of the n-GaSb/n-InAsSb heterostructure.

To characterize the devices, they were mounted to a chip holder by wire bonding. A liquid helium compressor and a Lakeshore 330 temperature controller were used to change and stabilize the temperature of the devices. I-V characteristic curves at different temperatures were measured by a Semiconductor Device Analyzer (B1500A, Agilent). The forward bias is defined when the positive potential is applied to the InAsSb contact (see Figure 6.1). The relative spectral response of the device at different temperatures and different biases were measured using a home-made photocurrent system [133], [138]. The continuous wave light source used in the photocurrent system is a Ceramic Element infrared source. It is mechanically chopped before entering into the monochromator. A low noise current preamplifier (Model SR570, Stanford Research Systems) was used to obtain the output signal. And then, a Lock-in amplifier (Model SR810, Stanford Research System) was used to read out both the amplitude and the phase (polarity)

of the signals. The software automatically acquires the relative spectral responses. A commercial 1000 V/W pyroelectric detector was utilized for calibration.

7.1.3 Measurement results and discussion

Figure 7.2(a) shows the measured dark currents with respect to the applied bias in the temperature range of 45 K - 300 K, which are slightly asymmetrical and are greater when the device is positively biased. The measured R_0A products as a function of $1000/T$ obtained from Figure 7.2(a) are plotted in Figure 7.2(b). The product is found to increase with the decrease of temperature first and then saturate at the temperature of nearly 50 K due mainly to the surface leakage current. The measured R_0A value is about $1 \text{ } \Omega \cdot \text{cm}^2$ at room temperature (300 K), and it increases to about $1500 \text{ } \Omega \cdot \text{cm}^2$ when the temperature decreases to 45 K, which are in agreement with those previously reported [155], [163].

Figure 7.2 (a) Dark current with respect to voltage at temperatures from 45 K to 300 K of a typical device. (b) Temperature dependence of R_0A .

The performance of the heterostructure was characterized using a blackbody source (MIKRON M360) at a temperature of 1000 K and a modulation frequency of 300 Hz. By using bandpass 2.5 - 4.8 μm and 1 - 3 μm filters, respectively, dual color detections were observed at room temperature at fixed forward biases. As the photocurrents are generated from the absorption over a specific wavelength range, the spectral responses at different temperatures and different biases were then

measured. Figure 7.3(a) shows the calibrated spectral responsivity at temperatures of 145, 200 and 300 K under a forward bias of 690 mV. It is found that the dual-color detection ranges originated from the absorption of InAsSb and GaSb indeed exist, and the photocurrents in both ranges flow in the same direction. For the detection originated from the GaSb substrate, the cut-off wavelength is about 2.2 μm at room temperature and it shifts to approximately 2 μm at 145 K. Meanwhile, for the InAsSb dominating detection, the cut-off wavelength is about 4.2 μm at room temperature and it also shows ‘blue shift’ at low temperatures. The responsivity at room temperature is about 0.15 A/W and 0.13 A/W at 1.5 μm and 3.2 μm , respectively. It is interesting to note that with the testing temperature decreases, the responsivity value is also decreased. According to the expression of $D_{\lambda}^* = R_i \sqrt{RA/4kT}$ where R_i is the current responsivity with a unit of A/W, and RA is the resistance area product. The measured Johnson noise limited detectivity at room temperature is $2.3 \times 10^9 \text{ cm} \cdot \text{Hz}^{1/2}/\text{W}$ and $2.1 \times 10^9 \text{ cm} \cdot \text{Hz}^{1/2}/\text{W}$ at the wavelengths of 1.5 μm and 3.2 μm , respectively.

Figure 7.3(b) shows the photocurrent spectra of the device at 100 K under forward biases of 430 mV and 510 mV, respectively. As observed from the figure, when the forward bias is at 510 mV, the photocurrent flows in the direction consistent with the forward bias, although the photocurrent is not as strong as that at a forward bias of 690 mV. However, it is interesting to note that when the forward bias is reduced to 430 mV, the direction of the photocurrent becomes opposite, and the photocurrent generated from the absorption of InAsSb layer becomes not as significant as before. These observations imply that there must be a critical forward bias value at which the photocurrent becomes zero and then changes the flow direction when the forward bias becomes smaller. To better understand the phenomena, the photocurrent spectra at different temperatures and at different forward biases were then measured. It is found that at each temperature, there is a corresponding forward bias which is defined as a ‘turning bias’ as at which the photocurrent starts to change its flow direction. The ‘turning bias’, as a

function of temperature is presented in Figure 7.3(c) and it decreases monotonically with the increase of temperature.

Figure 7.3 (a) Spectral responsivity of the heterojunction photodetector at temperatures of 145, 250 and 300 K under a forward bias of 690 mV. (b) Spectral photocurrents of the photodetector measured at 100 K under forward biases of 430 and 510 mV, respectively. (c) ‘Turning point’ voltage values at different temperatures. (d) Spectral photocurrents of the photodetector at temperatures of 45, 115, 155, 205, 235, and 300 K under reverse bias of 200 mV. Inset is the absolute value of photocurrents at different temperatures at 1.5 μm, which is to show the trend of the photocurrent with temperature.

The photocurrent spectra of the device at temperatures of 45 - 300 K under a reverse bias of 200 mV are shown in Figure 7.3(d). Firstly, the photocurrents measured at all the temperatures are mainly contributed by the GaSb part while the

contribution by the InAsSb part is not significant. Secondly, the photocurrent value increases first and then decreases as the temperature decreases from 300 K to 45 K. The inset in Figure 7.3(d) shows the photocurrent values at 1.5 μm measured at different temperatures where the maximum photocurrent occurs at about 205 K. Thirdly, the ‘blue shift’ of the cut-off wavelength with the decreasing temperature is also observed.

To explain the findings, the properties and the energy band offsets between the two materials, N-GaSb and n-InAsSb, which form the heterojunction need to be considered [40], [46], [152], [160], [162]. When the two materials have intimate contact, electrons will transfer from the GaSb layer to the InAsSb across the interface due to the difference in electron’s affinities between them. However, as the InAsSb layer is also n type, electrons will accumulate on the InAsSb side to form two-dimensional electron gas (2DEG). The depletion region of the heterostructure will then be formed mainly on the GaSb side and an internal built-in electrical field is also built up which points from the n-GaSb to the n-InAsSb side. The schematic energy band diagram of the heterojunction at thermal equilibrium is shown in Figure 7.4(a) [164], in which the band-gap energy of GaSb and InAsSb are 0.726 eV and 0.332 eV, respectively, and the conduction band and valence-band offsets at the interface are $\Delta E_c = 0.82$ eV and $\Delta E_v = 0.36$ eV, respectively.

When a reverse bias is applied to the heterojunction, the depletion region, mainly on GaSb side, will be wider, as shown in Figure 7.4(b). Under illumination, EHPs on the GaSb side will be generated and they can be easily separated by the strong internal electric field, resulting in a photocurrent which is in the same direction as the reverse bias. On the InAsSb side, there are also EHPs generated in the narrow depletion region near the interface. However, due to the high barrier related to the band offset ΔE_c , only limited number of electrons can turn through

and contribute to photocurrent, which can well explain the experimental results shown in Figure 7.3(d).

When the heterojunction is at forward bias but not strong enough, the effective electrical field in the depletion region will be weaker as the applied field is in the direction opposite to that of the built-in field, and the depletion region becomes narrower. In this case, the photon-generated EHPs in the depletion region on the GaSb side still dominate the photocurrent and the current flows in the direction the same as those at reverse bias (but opposite to the applied forward bias), as shown in Figure 7.4(b) with a forward bias of 430 mV.

Figure 7.4 Schematics of energy band diagrams of the heterojunction at different situations. (a) At thermal equilibrium at 300K and low temperature. (b) At reverse bias. (c) At forward bias with $V_b < V_{bi}$. (d) At forward bias with $V_b > V_{bi}$.

When the forward bias is equal to the built-in voltage, a zero net voltage across the heterojunction will occur. In this case, there should be a zero photocurrent and the corresponding forward bias is defined as the ‘turning bias’ as the photocurrent will change its flow direction when the forward bias is more than it. This implies that by measuring the bias of zero photocurrent one can estimate the built-in potential. Note that the ‘turning bias’ is a function of temperature as the built-in voltage decreases with the increase of temperature due primarily to the increase of intrinsic carrier concentration, as shown in Figure 7.3(c) [152], [165].

When the forward bias is greater than the turning bias (or built-in voltage in value) of the heterojunction, the direction of the net voltage across the heterojunction will be the same as the forward bias. In this case, the depletion region becomes negligible and the heterojunction is more like a nonhomogeneous resistor, as shown in Figure 7.4(d). Under illumination, the EHPs generated in the GaSb and InAsSb will all flow in the same direction without barrier, which can explain the two range photocurrent spectra shown in Figure 7.3(a).

With the model discussed above, the photocurrent spectra measured at different temperatures can also be explained. As shown in Figure 7.3(a), the photocurrent spectrum is the highest at room temperature when the heterojunction is under high forward bias, and it becomes lower when the temperature is decreased. This is mainly due to the decrease of the effective voltage across the heterostructure as the internal built-in potential is increased with the decrease of temperature while the total forward bias is fixed.

To explain the results shown in inset of Figure 7.3(d), where the photocurrents were measured at a reverse bias at different temperatures, two main factors should be considered. On one hand, with the decrease of temperature, the internal built-in potential in the heterojunction will be increased. As a result, the net potential drop across the depletion region will be increased due to the fixed reverse bias and the depletion region will also be widened. This will cause an increase of EHPs and

thus the photocurrents. On the other hand, when the temperature is low enough, the carrier concentration will be reduced with the decreasing temperature, leading to the increase in the resistance of the bulk GaSb and InAsSb materials. As a result, the net voltage across the heterojunction will be less and the photocurrent will also be smaller due to the decrease of the EHPs. The two opposite competitive mechanisms, thus, lead to a temperature at which the photocurrent reaches its maximum value. It occurred at about 205 K in the studied heterojunction, as indicated in the inset of Figure 7.3(d).

In conclusion, photodetection of n-GaSb/n-InAsSb heterostructure were systematically investigated at different temperatures and biases. The devices are found capable of dual color photodetection at fixed large forward biases at different temperatures and the maximum responsivity occurs at room temperature. With decreasing forward bias, a turning bias exists at which the photocurrent changes its direction and the voltage value varies with temperature. At reverse biases, the absorption of GaSb dominates the photocurrent and the maximum photocurrent occurs at about 205 K. All the observation can be well explained..

7.2 SPP enhanced photodetection in the GaSb/InAsSb heterostructure photodiode

In this section, the experiment work of surface plasmon enhanced room temperature n-GaSb/n-InAsSb heterostructure photodiode will be introduced. By integrating properly designed sub-wavelength metallic 2DHA to the top of the n-GaSb/n-InAsSb heterostructure, the room temperature photocurrent and detectivity of the photodiode can be enhanced. The enhancement mechanism and broadband performance enhancement will be discussed.

7.2.1 Device fabrication procedures

The photodetector investigated here is n-GaSb/n-InAsSb heterostructure photodiode which has similar configuration to the one studied in section 7.1. In order to observe plasmonic enhanced performance, the thickness of InAsSb layer is reduced to $\sim 1\ \mu\text{m}$. Besides, the fabrication procedures for the device are a bit different, as shown in Figure 7.5. Here, dry etching and ICP-RIE were used for mesa definition to avoid undercut effect, which may be induced by wet etching. Besides, the heterostructure is passivated by a 300-nm thick SiO_2 during fabrication. The sub-wavelength 2DHA on top is fabricated by EBL exposure, followed by electron-beam deposition and lift-off process. The fabricated 2DHA is square hole array and consists of 5 nm thick Ti and 60 nm thick Au. Figure 7.6(a) shows the schematic of integrated structure of GaSb/InAsSb heterostructure and gold 2DHA. Here, only front illumination is considered. The SEM image of fabricated hole array is shown in Figure 7.6(b).

Figure 7.5 Fabrication process flow of integrated structure of gold 2DHA and n-GaSb/n-InAsSb heterostructure.

Besides, the hole array has a periodicity of 900 nm and hold width of $\sim 450\ \text{nm}$. The periodicity of 900 nm is chosen to enhance the photoresponse at $\sim 3.4\ \mu\text{m}$. In

chapter 3, the effects of different parameters and variables on plasmonic enhanced photodetection have been discussed. Thus, the optimal designed parameters and relevant simulation results will be used here. One thing needs to be mentioned is that the refractive indexes of Ti, Au and InAsSb used in simulation are extracted from Handbook of Optical Constants of Solids [71]. For comparison, the gold 2DHA with periodicity of 550 nm and 1280 nm were also fabricated. The hole width of 2DHA is always selected as half of periodicity for optimized SPP coupling efficiency and performance enhancement.

Figure 7.6 (a) Schematic of integrated structure of GaSb/InAsSb heterostructure and gold 2DHA. The thickness of InAsSb layer is $\sim 1 \mu\text{m}$. (b) SEM image of gold 2DHA with periodicity of 900 nm and hole diameter of $\sim 450 \text{ nm}$.

7.2.2 Device characterization and simulation results

After device processing is completed, the devices were wire-boned to a chip carrier for optical and electrical characterization. Figure 7.7 shows measured room temperature photocurrent spectra, taken from three 2DHA-heterostructure devices with $p = 550, 900$ and 1280 nm , respectively. Besides, a heterostructure photodiode without gold DHA on top was also fabricated as a reference, of which the corresponding photocurrent spectrum is also shown in the figure for comparison. As shown in Figure 7.7, the photocurrent spectrum of 2DHA-heterostructure has a similar shape to the reference heterostructure. Besides, for all 3 gold

2DHA-heterostructure devices, the photocurrent spectrum all show enhancement in wide wavelength range around $\sim 4.0 \mu\text{m}$ and $\sim 1.7 \mu\text{m}$. This unexpected wide wavelength enhancement seems to be contradictory to the mechanism of plasmonic enhancement. SPP resonance only exists in a narrow range of wavelengths, as shown by transmission spectra in the inset of Figure 7.7. Thus, theoretically speaking, only narrow band performance enhancement due to SPP excitation should be observed. This phenomenon is also shown in other people's work [54], [56], [166]. A detailed explanation of this phenomenon will be provided in section 7.2.3. Specially, for the sample with a DHA and periodicity of 900 nm, the highest enhancement is ~ 2.3 times at $\sim 3.4 \mu\text{m}$. This matches very well with the initial design of best performance enhancement around $3.5 \mu\text{m}$ and the simulation result shown in the inset of Figure 7.7 (b). In chapter 3, the mechanism of plasmonic enhancement of photoresponse has been discussed in details. In short, when light is incident onto gold 2DHA, the light is excited as SPPs, which are highly concentrated and tightly confined at the interface. As a result, the quantum efficiency of 2DHA-heterostructure is enhanced.

Figure 7.7 Comparison of measured photocurrent spectra of heterostructure photodiodes under voltage bias of 800mV without (red line) and with (blue lines) a gold 2DHA, (a) $p = 550 \text{ nm}$, (b) $p = 900 \text{ nm}$ and (c) $p = 1280 \text{ nm}$. The corresponding transmission spectra of 2DHA with different periodicities are shown in the insets.

Before presenting the explanation, the impact of gold 2DHA on dark current needs to be mentioned. The detectivity of a photodetector is closely related to the dark current, which can be expressed by

$$D^* = \frac{R_i}{\sqrt{2qJ + (4kT)/(R_d A_d)}} \quad (7.1)$$

where J is the dark current density, k is the Boltzmann constant, T is the temperature of the device, R_d is dynamic resistance, A_d is photodetector area. Thus, to have a high detectivity, the dark current should be as small as possible. The dark current for samples without and with 2DHA is shown in Figure 7.8. The data demonstrates that the dark current is almost the same for samples without and with a 2DHA in the low bias voltage range. This is extremely important when sub-wavelength metallic 2DHA is used for enhancing photodetector performance.

Figure 7.8 Dark current of the heterostructure photodiode without gold 2DHA and with 2DHA of different periodicities. As can be seen, the gold 2DHA does not have an adverse effect on the dark current of heterostructure photodiode.

7.2.3 Analysis of the broadband performance enhancement

The sample with a 2DHA with periodicity of 900 nm will be analyzed here. As shown in Figure 7.7(b), the transmission through 2DHA is highest at 3.38 μm , and rapidly decreases to 0 at 3.26 μm . This extremely low transmission effect is also called Wood's anomaly, which is introduced and analyzed in details in chapter 4. According to the theory proposed in chapter 4, although the transmission at Wood's anomaly wavelength is extremely small, the efficiency of coupling incident light as SPP at this wavelength is not as low as it seems to be. For clarity, the normalized electric field magnitude in the vicinity of 2DHA at $\lambda = 3.38 \mu\text{m}$, 3.26 μm and 2.52 μm is shown in Figure 7.9.

Figure 7.9(a) shows that, at the main resonance wavelength, the electric field is highly concentrated at the metal-dielectric interface. This is within expectation. The second SPP mode occurs at 2.52 μm , and there is also tight confining of electric field at this wavelength. However, at 3.26 μm shown in Figure 7.9(b), the electric field concentration is also considerable, although transmission is almost zero. To explain the broadband plasmonic performance enhancement, the theory proposed in chapter 4 can be utilized here. At Wood's anomaly wavelength, instead of emerging parallel with the metal-dielectric interface, SPPs are excited and confined near the surface. Different from the SPPs at main resonance wavelength, the SPPs excited at Wood's anomaly wavelength are more confined to the region close to the interface, leading to very low transmission.

Figure 7.9 Cross-sectional view of the electric field in the vicinity of hole array at (a) $\lambda = 3.38 \mu\text{m}$, (b) $\lambda = 3.26 \mu\text{m}$ and (c) $\lambda = 2.52 \mu\text{m}$, respectively. The light is incident along z direction, and the electric field is linearly polarized along the x axis. The color bar denotes the normalized electric field magnitude.

The integrated intensity of the electric field ($\int_s |E_z|^2 dS$) at the interface is a more precise parameter for characterizing SPP coupling efficiency than transmission [166]. The integrated intensity, together with photocurrent and transmission spectrum, is shown in Figure 7.10. It is clearly seen from Figure 7.10(b) that the integrated intensity of electric field for the incidence of $3.26 \mu\text{m}$ is still significant, compared to that at incidence of $3.38 \mu\text{m}$ although the transmission is the lowest. This is distinctly different with the extremely small ratio of transmission at λ_{RA} to that at main resonance wavelength. Thus, it is reasonable to believe that the tightly concentrated light at λ_{RA} leads to performance enhancement of photodetector. And the broadband plasmonic performance enhancement can be explained.

Figure 7.10 (a) Measured photocurrent spectra of heterostructure photodiodes without and with a 2DHA on top. (b) Integrated intensity of electric field ($\int_s |E_z|^2 dS$) in the vicinity of hole array. (c) Transmission spectrum of the gold 2DHA. The Wood's anomaly wavelength is denoted as λ_{RA} . For better illustration, the data here is in 2.60 - 5.50 μm range.

7.3 Chapter summary

In this chapter, two major works based on n-GaSb/n-InAsSb heterostructure are presented.

First, the work on photodetection of n-GaSb/n-InAsSb heterostructure, at different temperatures and biases is presented. The devices are found to have dual color photodetection at fixed large forward biases at different temperatures and the maximum responsivity occurs at room temperature. As the forward bias decreases, a turning bias exists at which the photocurrent changes its direction and the voltage value varies with temperature. At reverse biases, the absorption of GaSb dominates the photocurrent and the maximum photocurrent occurs at about 205 K. The model proposed can explain all the observations.

Second, the experiment work of plasmonic enhanced infrared photodetection is presented. By integrating properly designed sub-wavelength metallic 2DHA on top of n-GaSb/n-InAsSb heterostructure, the room temperature photocurrent and detectivity of the photodiode is enhanced by ~2 times. And the dark current of the heterostructure is not adversely affected by gold 2DHA fabricated on top for low bias. It is believed that the performance enhancement is because of higher quantum efficiency of the 2DHA-heterostructure, resulting from tight concentration of electric field at the metal-dielectric interface. The reason of broadband plasmonic performance enhancement is also discussed.

Chapter 8. Conclusions and future works

In this chapter, the works done in the author's Ph.D. project are summarized, and some recommendations for future work are proposed.

8.1 Conclusions

The Ph.D. project is on mid-wavelength infrared photodetection and surface plasmon enhancement. The mechanism of plasmonic enhanced photodetection via metallic 2DHA and demonstrated plasmonic enhanced photodiode based on n-GaSb/n-InAsSb heterostructure are studied and photodetectors based InAs/GaSb type-II SL system and InAsSb photoconductor are investigated. The conclusions of the works are summarized below:

1. Completed a comprehensive simulation and analysis of EOT through 2DHAs, and the underlying physics and mechanism of SPP enhancement of photodetection. All possible variables and parameters which may affect EOT and the enhancement of photodetector performance are considered. These variables include periodicity of hole array, hole diameter, refractive index of substrate, thickness of metal film and hole shape. These simulation results and analysis would be a good guidance in designing 2DHA for enhancing photodetector performance.
2. Analyzed the origin of Wood's anomaly in optical transmission through a metallic 2DHA. The contradiction of the Wood's anomaly and the generally observed broadband performance enhancement of photodetector via 2DHA is discussed. A new interpretation to this phenomenon is proposed: at Wood's anomaly wavelength, the extremely low transmission results from excitation of SPPs by the incident light, which has a low efficiency of being decoupled from the metal-dielectric interface and doesn't contribute to

transmission. The new interpretation can be used to explain the broadband photoresponse enhancement of integrated structure of photodetector and metallic hole array.

3. Designed and fabricated a high performance n-i-p based mid-infrared InAs/GaSb type-II superlattice photodetector. According to characterization result, the grown SL structure has very high quality. The thickness of each period of SLs is very close to the designed thickness. At 220 K, the 50% cutoff wavelength of the photoresponse is 4.66 μm . The R_0A of the detector is as high as $14.9 \Omega \cdot \text{cm}^2$. And the peak detectivity of the photodetector is $2.23 \times 10^{10} \text{ cm} \cdot \text{Hz}^{1/2}/\text{W}$ at 3.0 μm under zero bias. This is the highest reported detectivity of InAs/GaSb SL photodetector operating at 220 K.
4. Fabricated InAsSb based photodetector operating at room temperature. The InAsSb materials grown on the GaSb substrate by MBE and photoconductive detectors made by them were investigated. The grown materials show high quality and slight lattice mismatch to the substrate. The photoconductors fabricated based on the InAsSb/GaSb structure show spectral response ranging from NIR to MWIR range. They can work well at low voltage bias and the measured blackbody detectivities are $\sim 2.4 \times 10^7 \text{ cm} \cdot \text{Hz}^{1/2}/\text{W}$ and $\sim 6.1 \times 10^9 \text{ cm} \cdot \text{Hz}^{1/2}/\text{W}$ at room temperature and 77 K, respectively.
5. Photodetection of n-GaSb/n-InAsSb heterostructure at different temperatures and biases is studied. The devices were found to be capable of dual color photodetection at fixed large forward biases at different temperatures, and the maximum responsivity occurs at room temperature. As the forward bias decreases, a turning bias exists at which the photocurrent changes its direction and the voltage value varies with temperature. At reverse biases, the absorption of GaSb dominates the

photocurrent and the maximum photocurrent occurs at about 205 K. All the observation can be explained by the proposed model.

6. Surface plasmon enhanced infrared photodetection based on n-GaSb/n-InAsSb heterostructure is investigated. By integrating properly designed sub-wavelength metallic 2DHA on top, the room temperature photocurrent and detectivity of the photodiode is enhanced by ~2 times. Besides, the dark current of the heterostructure is not adversely affected by 2DHA fabricated on top when the bias is low. The performance enhancement is because of higher quantum efficiency of the 2DHA-heterostructure, resulting from electric field concentration at the metal-dielectric interface. The author also has explained the origin of broadband plasmonic performance enhancement.

8.2 Future works

Surface plasmon enhanced infrared photodetection and HOT MWIR photodetector will remain to be hot research topics in the future, due to more and more possible applications and higher performance requirements. To further improve the high operate temperature performance, the followings should be done in the future.

1. A more efficient technique for fabricating sub-wavelength metallic 2DHA is required. For research purpose, researchers only need to fabricate hole array in a very small area. And it is done by EBL technique. But if it is going to be used for industry, which needs mass production, a much faster and more efficient exposure technique is needed. Interference lithography, an attractive tool for fabricating periodic structures, has received a lot of attention these years [167]–[171]. This technique is emerging as one of the most powerful yet relatively inexpensive methodology for fabricating large

area patterns with micron- to sub-micron periodicities [171]. A schematic of interference lithography is shown in Figure 8.1. Different from the technique of scanning a focused beam of electrons to draw custom shapes used in EBL, interference lithography is very similar to photolithography. It can expose the hole area at the same time, which saves a lot of time. Thus, this will be a practical way for fabricating large area metallic 2DHA, and more work should be done to study this technique.

Figure 8.1 Schematic for two-beam and four-beam interference [167].

2. Try using metallic 2DHA for other kinds of photodetectors. Since the mechanism of plasmonic enhancement using 2DHA is already analyzed and illustrated, it can be applied to other photodetectors. Due to enhanced quantum efficiency effect of SPPs, this will be especially inspiring for those photodetectors which can only have thin absorption layer and low quantum efficiency. The plasmonic photoresponse enhancement of these photodetectors can be even as high as ~40 times [56].
3. More experimental work on back configured plasmonic structure needs to be done. As shown by the simulation results in section 3.3.5, the back illumination schematic has much higher light concentration than front side illumination. Thus, performance enhancement is expected to be even larger. But relevant experimental work is very few. In order to grasp a full

understanding of plasmonic enhanced photodetection, more research work about back illumination schematic can be done.

4. A more efficient way of suppressing dark current of InAs/GaSb type-II SL material is required. As shown by the experiment results, the photodetector has a high performance at 220 K. At this temperature, the dark current is small enough, and the detectivity of the detector is comparable with other high performance photodetector. But at room temperature, the dark current is still much larger than HgCdTe photodetector. So the detectivity is much smaller. For further increasing the operating temperature of SL photodetector, a better passivation technique. SU-8 is a choice. As reported by others, SU-8 can have a good suppression of dark current of the photodetector [172].

Author's Publications

1. **S. Qiu**, L. Y. M. Tobing, J. Tong, Y. Xie, Z. Xu, P. Ni and D.-H. Zhang, "Two-dimensional metallic square-hole array for enhancement of mid-wavelength infrared photodetection." *Optical and Quantum Electronics* 48.3 (2016): 1-8.
2. **S. Qiu**, L. Y. M. Tobing, Z. Xu, J. Tong, P. Ni and D.-H. Zhang, "Surface Plasmon Enhancement on Infrared Photodetection." *Procedia Engineering* 140 (2016): 152-158.
3. **S. Qiu**, J. Tong, Y. Xie, P. Ni and D.-H. Zhang, "High performance n-i-p based mid-infrared InAs/GaSb type-II superlattice photodetector operating at 220 K", to be submitted.
4. **S. Qiu**, L. Y. M. Tobing, J. Tong and D.-H. Zhang, "Analysis of the origin of Wood's anomaly in optical transmission through sub-wavelength metallic hole arrays", to be submitted.
5. **S. Qiu**, L. Y. M. Tobing, J. Tong and D.-H. Zhang, "Direction-dependent light concentration through sub-wavelength metallic hole array", in preparation.
6. **S. Qiu**, L. Y. M. Tobing, Y. Xie, Z. Xu, J. Tong, P. Ni and D.-H. Zhang, "Design and Simulation of Two Dimensional Hole Array for Surface Plasmon Enhancement of InAsSb Based Infrared Photodetectors", *Numerical Simulation of Optoelectronic Devices* (2015)
7. **S. Qiu**, J. Tong P. Ni, W. J. Wang and D.-H. Zhang, "Antimonide based semiconductors and metallic structures for enhanced infrared

- photodetection", International Conference on Advanced Functional Materials (2015)
8. J. Tong, Y. Xie, Z. Xu, **S. Qiu**, P. Ni, L. Y. M. Tobing and D.-H. Zhang, "Study of dual color infrared photodetection from n-GaSb/n-InAsSb heterostructures." AIP Advances 6.2 (2016): 025120.
 9. J. Tong, Y. Xie, Z. Xu, P. Ni, **S. Qiu**, L. Y. M. Tobing and D.-H. Zhang, "InAs_{0.91}Sb_{0.09} photoconductor for near and middle infrared photodetection." Physica Scripta 91.11 (2016): 115801.
 10. P. Ni, J. Tong, L. Y. M. Tobing, Z. Xu, **S. Qiu**, X. H. Tang and D.-H. Zhang, "A buffer-free method for growth of InAsSb films on GaAs (001) substrates using MOCVD." Journal of Crystal Growth (2016).
 11. Z. Xu, L. Y. M. Tobing, Y. Xie, J. Tong, P. Ni, **S. Qiu**, T. Yu and D.-H. Zhang, "Aluminum based structures for manipulating short visible wavelength in-plane surface plasmon polariton propagation." Optics Express 23.17 (2015): 22883-22889.

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