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Elliptical Cylinder Metallic Array for Enhancing Room-temperature Midwave Infrared Photodetection

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Abstract

Metasurface, from periodical and artificial structures of “meta-atoms” constructed by subwavelength-sized metallic resonators, has been incorporated with optoelectronic devices to realize improved and multifunctional performance. Here, we report a fourfold rotationally-symmetric elliptical cylinder metasurface for enhancing photodetection in midwave infrared (2-5 μm) range. This metasurface has the capability to confine light within small volume and polarization-independence property. Enhanced photodetector consisting of this metasurface and an InAsSb-based heterojunction photodiode is fabricated and evaluated in detail. Polarization-independent improvement for performance is achieved. A 4-fold specific detectivity (D^*) improvement (to 3.3×10^9 Jones) compared to that of a reference photodiode is achieved for room-temperature operation. Electrically controlled enhancement for the enhanced device is observed with a maximum enhancement factor of 6 (600%) for photocurrent (or responsivity). The enhanced photodiode has response speed similar to that of the reference.

Keywords: Elliptical cylinder metasurface, unpolarized enhancement, rotationally-symmetric, midwave infrared photodetection.

Introduction

High performance midwave infrared (2-5 μm) photodetectors for room-temperature operation have been pursued for low-cost and compact infrared systems. Over the last decades, mercury cadmium telluride (HgCdTe) photodetectors have taken a dominant position in midwave infrared range [1], but they usually suffer from weak bond strengths, non-uniformity, and expensive epitaxial substrates. Lead selenide (PbSe) photoconductors own fine performance at room temperature but usually operate under larger voltage bias and have slow response. Antimonide (Sb) based III-V materials have shown great promise for midwave infrared applications owing to their superior bond strengths and material stability, well-behaved dopants, and high-quality III-V substrates [2-7]. However, due to low absorption coefficient in the 2-5 μm range, these photodetectors typically possess thick absorption layer, this in turn, will enlarge the bulk dark current (decrease the specific detectivity) and prolong the transit time of photocarriers (slow down the response speed).

Metallic subwavelength structures that can support surface plasmon polaritons (SPPs) have multitudinous applications, depending on their geometrical dimension and operation frequency [8-9]. The exceptional ability of plasmonic structures to confine light in extremely small volume has proved useful in improving the performances of photodetectors [10-15]. By using these structures, the thickness of the absorption layer can be reduced significantly. This will simultaneously reduce the bulk dark current. Various structures have been integrated on midwave infrared detectors for enhancing the detection performance. Notably, the metallic two-dimensional subwavelength hole arrays (2DSHAs) [4], have been previously used in photovoltaic *n-i-p* photodiodes [16], dual-band heterostructures [17], nBn detectors [15] and low-temperature quantum dots [18] for enhancing the performance. However, the SPP modes in

2DSHAs are associated with the phase matching conditions related to the lattice arrangement and periodicity [19], resulting in strong dependence of the SPP mode excitation on the angle of incidence. By contrast, the excitation of localized surface plasmons (LSP) is comparatively more robust as the LSP modes depend mainly on the geometrical parameters of the individual plasmonic nanoantenna.

In this work, we integrate a subwavelength elliptical cylinder array on an InAsSb-based heterojunction photodiode for enhanced room-temperature midwave infrared photodetection. The elliptical cylinder metasurface is arranged with a fourfold rotationally-symmetric configuration to couple incident light without any polarization-dependence. In this way, unpolarized enhancement of photodetection is achieved for room-temperature operation. The LSP excitation mainly from electric-dipole resonance in this metallic structure and the gap effect between elliptical cylinders can confine incident light in the vicinity of the metal-semiconductor interface. The fourfold rotationally-symmetric array on the photodiode launches a 4-fold specific detectivity improvement (to 3.3×10^9 Jones) compared to reference device without patterned metasurface. Electrically controlled enhancement with a maximum enhancement factor of 6 for photocurrent (or responsivity) is observed. The enhanced device demonstrates a response speed similar to that of the reference one.

Results and discussion

The enhanced photodetector contains an InAsSb-based *p-i-n* heterojunction and a fourfold rotationally-symmetric elliptical cylinder array integrated atop it. This metallic array is designed with strong midwave infrared confinement at the metal-semiconductor interface to facilitate light absorption in the optoelectrical semiconductors. In this way, the excitation of electron-hole pairs (EHPs) in InAsSb absorber will be intensified, resulting in enhanced photocurrent after prompt

collection of EHPs by electrodes. The InAsSb-based *p-i-n* heterojunction is grown on n-type Te-doped GaSb substrate by molecular beam epitaxy (MBE). Different from typical homogeneous photovoltaic *p-i-n* diode, we use hetero-semiconductor layers with band offsets from the *i* layer to form a heterojunction to reduce the dark diffusion of carriers (Fig. 1a) [20-21]. A 1000 nm thick n-type GaSb buffer layer is first grown on the n-type (Te: $1.5 \times 10^{18} \text{ cm}^{-3}$) GaSb substrate as a contact layer for the n-type electrode. Afterwards, 20 nm n-type quaternary AlInAsSb layer, 1500 nm non-intentionally doped $\text{InAs}_{0.912}\text{Sb}_{0.088}$ layer, 20 nm p-type AlInAsSb layer, 40 nm p-type AlGaSb layer, and 30 nm p-type AlGaSb layer with graded Al composition are grown subsequently to reduce diffusion movement of dark electrons. Finally, 30 nm p-type GaSb layer is grown as the contact layer for the p-type electrode. The thinner p-type GaSb and AlGaSb layers with total thickness of 120 nm aims to increase the interaction between metallic array and InAsSb absorbers, where photon absorption would be mainly taken place. The unit cell (Fig. 1b) of the metasurface can be characterized with height t , gap g , length a , b , angle θ , and period p .

Figure 1. (a) Structure of the InAsSb-based *p-i-n* heterojunction. (b) Schematic of the subwavelength fourfold rotationally symmetric elliptical cylinder unit cell. (c) SEM of the fabricated metasurface atop the heterojunction. The scale bar represents 1200 nm.

To study the capability of the metallic array to confine light in the vicinity of the metal-semiconductor interface, numerical FDTD (v8.13, Lumerical) is used to monitor the distributional pattern of optical electric fields. The permittivity of gold is extracted from Palik [22]. The dielectric constant of the heterojunction p - i - n is from measured data and literatures [2,23]. The final determined unit cell has the geometrical size of $t=60$ nm, $g=180$ nm, $a=600$ nm, $b=350$ nm, $\theta=45$ degree, and $p=1100$ nm. Here, we also define factor r (the ratio between size of other unit cells to the finally determined one) for other unit cell with different size but fixed angle $\theta=45$ degree (to ensure invariance under different polarizations).

Figure 2. (a) Simulated reflectance of unit metallic cell with gradually varied geometrical dimension. (b) Simulated reflectance of the unite cell with $r=1$ at different polarization angles.

As shown in Fig. 2a, the resonance wavelength (denoted as valleys and peaks) of the unit metallic structure exhibits red-shifting while increasing r from 0.626 to 1.469. Here, we choose

the case when the factor equals to one as the final determined structure, which has the resonance peak and valley at $3.51 \mu\text{m}$ and $3.15 \mu\text{m}$, respectively, right located in the response range of the heterojunction. Fig. 2b demonstrates the invariance of reflectance of this metallic structure under different polarized angles owing to the rotationally-symmetric character of the metasurface. This will ensure unpolarized enhancement for final performance of the enhanced device, which is very useful in robust and uniform photodetection.

Figure 3. (a-f) Distribution of electric field in X-Y and X-Z planes under different polarizations. (g-h) Electric field along the cutting lines in (a) and (b), respectively.

To gain an insight on light confinement by the metallic structure, we study the electric field enhancement $|E/E_0|$ (E_0 is the electric field in bare heterojunction) and E_z of the enhanced photodetector (Fig. 3a-3f) at the resonance valley as an example. As shown from the cutting line l_1 (Fig. 3g) at the interface, the optical field is significantly enhanced under both light-

polarizations. A maximum field enhancement of 10 is achieved, corresponding to a 100-fold enhancement of power density, indicating strong light-confinement at around the interface. The field enhancement at the upper interface of the InAsSb absorber (denoted as white dash lines in Fig. 3c and 3f) is still large. The light-confinement in the device would facilitate the generation of EHPs, therefore resulting in enhanced photoresponse. It is noted that rigorous analysis for the overall field enhancement in the photodiode requires a double integration in the whole absorber over the whole response wavelength range, which is rather difficult to be realized. Besides, even the optical electric field in the bare heterojunction is small, it shows slightly decreasing trend in z direction depending on the intrinsic absorption coefficient, which hints the final performance improvement is comprehensively determined by the field enhancement and the overall enhanced volume in the device. The distribution of E_z exhibits invariance after rotating a 90 degree between X-pol (Fig. 3b) and Y-pol (Fig. 3e), further demonstrating the unpolarized property of this metasurface. We can also find strong electric-dipole resonance modes parallel to the light-polarization in these two distributional patterns of E_z . Fig. 3h plots the typical light confinement in z -direction by the metallic structure (cutting line l_2 from Fig. 3c). The intensity reduces gradually from the metal-semiconductor interface. It is also noted here that except the contribution from LSP (due to electric-dipole resonance) to the field enhancement, the gap between the four elongated cylinders would also contribute to the enhancement due to the coupling among those cylinders. This can be identified from the mild field enhancement in the gaps.

In enhanced device fabrication, 390- μm sized square mesas are defined by wet etching after normal photolithography, followed by deposition of 300 nm SiO_2 passivation layer. Windows for electrodes and absorption area are then opened. The bottom and top electrodes are formed with

20 nm adhesion Ti and 200 nm Au. The fabrication of the elliptical cylinder array is carried out using electron-beam lithography (EBL) on 250 nm ZEP520A positive tone resist on heterojunction samples. The metasurface consists of 3 nm thick Ti adhesion layer and 60 nm thick Au. Reference photodiode without metallic patterns accompany with the enhanced device is also fabricated. In fabrication, the metallic and reference devices have undergone the same technical process except for the final step where metals are kept for the patterned device. The photocurrent spectra are characterized by using a Fourier-transform infrared spectrometer (FTIR) with a KBr beam splitter and a midwave infrared source. The performance is characterized with a 1000 K blackbody with midwave infrared filters. In response time measurement, a 2.94 μm laser source with rise and fall time of 20 ns is utilized.

Figure 4. (a) Room-temperature spectral photocurrent of the enhanced and reference devices under voltage bias from -0.5 V to 0.2 V. (b) Polarization dependence of the peak photocurrent of the devices under zero bias voltage.

Fig. 4a plots the spectral photocurrent of the enhanced and reference devices at different voltage bias from -0.5 V to 0.2 V. Obvious photocurrent enhancement depending on the applied voltage bias is observed. At -0.2 V, a maximum enhancement factor η (defined as the ratio between photocurrent of the enhanced device to that of the reference one) of ~ 6 is achieved. At -0.5 V and 0.2 V, the enhancement for the photocurrent decreases and the enhancement factor tends to unit. This electrically controlled enhancement is relevant to the property of the bare heterojunction, which will be discussed below. It is also noted that the photocurrent of the respective device increases and finally tends to saturation as increasing of their reverse voltage bias, attributed to the gradually enlarged and finally saturated depletion volume, which is typical for photovoltaic *p-i-n* devices [1-2]. Fig. 4b plots the peak photocurrent of the devices at different polarization angles under zero bias. As shown, both devices exhibit invariance while changing the polarization angle, demonstrating unpolarized enhancement for the photoresponse. This is consistent with the simulations. Therefore, the rotationally-symmetric cylinder array helps to achieve polarization-independent improvement of photoresponse.

Before evaluating the final blackbody responsivity R_A and specific detectivity D^* improvements by the metasurface, we measure the dark current-voltage (I-V) characteristics of the photodiodes and extract their dark current density J_d under applied voltage from -0.4 V to 0.4 V (Fig. 5a). The two devices show comparable dark current level from the heterojunction itself, demonstrating the stability and repeatability in fabrication. Fig. 5b shows the R_A of photodiodes under applied voltage bias from -0.6 V to 0.6 V. Both the devices exhibit typical photoreponse characteristics for photovoltaic *p-i-n* diodes, where the responsivity increases with increasing applied reverse bias and finally tends to saturation owing to the saturation of carrier velocity. At forward voltage bias, the depletion or absorption volume in the device will be reduced significantly, resulting in

extremely small photocurrent or responsivity. The electrically controlled enhancement, expressed as η , is also derived as presented in Fig. 5c. Similar to the results shown in the spectral photocurrent, the enhanced photodetector exhibits a maximum enhancement factor of ~ 6 at -0.2 V and it gradually decreases to both positive and negative sides. This is mainly determined by the overlapping between the localized surface plasmon and the depletion volume of the heterojunction, as well as the transit property of the photocarriers, which has been reported previously by our group [24].

Figure 5. (a) Current-Voltage characteristic curves of the enhanced and reference devices. (b) Responsivities of the devices. (c) The enhancement factor at different voltage biases. (d) Detectivities of the devices. Response speed of the (e) reference and (f) enhanced devices.

With the determined R_A and J_d , we can finally obtain D^* . Here, we only consider the typical reverse bias range for photovoltaic devices. Noise contributions from dark current, thermal disturbance and background radiations are considered as $D^* = R_A / (2q(J_d + J_b) + 4kT/(RA))^{1/2}$ (q is the electronic charge, J_b is the background photocurrent noise, R is the dynamic resistance, and A is the area. J_b can be derived from the measured R_A and the total radiant exitance from background $M(T) = \int_{\lambda_1}^{\lambda_2} M(\lambda, T) d\lambda$, 2π field of view is assumed in our case, $\lambda_1 = 2 \mu\text{m}$, and $\lambda_2 = 5 \mu\text{m}$). As shown in Fig. 5d, the enhanced photodetector shows obvious improvement of D^* at different voltage biases. Specifically, a D^* value of 3.3×10^9 Jones is achieved under -0.2 V bias, corresponding to 4-fold enhancement. For the reference device, a maximum D^* of only 1.4×10^9 Jones is achieved under -0.4 V bias. To achieve the same performance, the enhanced device only needs a voltage bias of -0.05 V , indicating lower power supply consumption for the enhanced device. The achieved room-temperature performance is superior to those reported bare devices without integration of metallic patterns [20, 25-30].

We finally evaluate the typical response speed of the devices using a $2.94 \mu\text{m}$ square wave source with a rise and fall time of 20 ns . The rise and fall time are defined as the time period between 10% to 90% of the maximum response amplitude. The reference photodetector shows a rise time of $1.848 \mu\text{s}$ and a fall time of $1.241 \mu\text{s}$ (Fig. 5e). The corresponding value for the enhanced device is $0.781 \mu\text{s}$ and $0.732 \mu\text{s}$ (Fig. 5f), which are a little faster than those of the reference one. This might be the result of different situation of photocarriers generation and collection, As for enhanced device, it mainly occurs in the vicinity of the interface and therefore, it can be collected fast than that in reference device. This point needs to be further studied in future. Therefore, the performance improvement of the enhanced device is achieved without sacrificing the response speed of the photodetector.

Conclusion

We have designed an enhanced midwave infrared photodetector consisting of an InAsSb-based *p-i-n* heterojunction and an integrated fourfold rotationally-symmetric elliptical cylinder array. This metasurface shows large optical field enhancement in vicinity of the metal-semiconductor interface and possesses invariance under different light-polarizations. The enhanced device demonstrates a 4-fold specific detectivity improvement (to 3.3×10^9 Jones) compared to the reference one without sacrificing of response speed. It also exhibits unpolarized performance improvement, attributed to polarization-independence of the fourfold rotationally symmetric metasurface. Electrically controlled enhancement is achieved with a maximum enhancement factor of 6. We believe this enhanced photodiode would benefit current infrared technologies in thermal imaging, communication, and molecular spectroscopy.

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