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Wide spectrum responsivity detectors from visible to mid-infrared based on antimonide

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\textbf{ABSTRACT}

A kind of wide spectrum infrared detectors based on InAs/GaSb type-II superlattices (T2SLs) operating from 0.5 μm to 5 μm wavelength range is reported. The materials were grown by Molecular Beam Epitaxy (MBE) on GaSb substrates. Diverse types and sizes microstructure are fabricated on the surface of the detector to form the photon traps (PTs) array. PTs decrease the reflectivity and increase the light absorption of epitaxial material. Compared with the planar mesa detectors without antireflection (AR) film, detectors with PTs array exhibits a high responsivity of 0.86 A/W at 1160 nm and maximum D* reaches to 10^9 cm Hz^1/2/W in visible wavelength. Also, the PTs processed on detector augment spectral response and QE in infrared wavelength. The peak responsivity of the detector with PTs is 1.35 A/W and QE can exceed to 0.76 in the infrared wavelength. The infrared detector with PTs is attractive for numerous applications.

1. Introduction

Recently, visible extended infrared detectors have drawn great attention as they are widely used in imaging [1], gas sensing [2], remote sensing [3], space-based earth observation [4], defense applications [5], spectrum measurements [6,7], and missile warning systems [8]. So far, there are plenty of techniques to achieve wide spectrum detectors, for instance, single-photon, nanowire, and optical thin films. The superconducting single-photon detector (SSPD), based on ultrathin, sub-micron-width NbN structures are ultrafast and sensitive to ultraviolet, visible, and infrared (IR) photons. It can be applied to detect the wavelength range between 0.5 μm and 5.6 μm [9]. One method for nanostructured devices was already demonstrated. It contacted the meander-shaped NbN stripe to the shorter sections parallelly [10]. Also, the nanowire has been developed to realize high-sensitivity and broadband response photodetectors. Two of the most well-known tools for uniformly ordered nanowire array are nanoimprint lithography and RIE/ICP dry etching [11]. Different methods have been proposed that compositing graded CdSSe nanowire on mica, shown a highest light-to-dark ratio to 10^6, can response the spectrum from 405 nm to 800 nm [12]. Among all the methods, coating films are widely used for the detection of broadband spectrum. The use of pulsed laser deposition (PLD) technique is a well-established approach in thin films [13]. However, the limitation of common planar detectors is that they response relative narrow wavelength by making films. The planar Si detectors with SiO\textsubscript{2} antireflection films just response spectrum from 360 nm to 1000 nm and it exhibits a responsivity of up to 0.27 A/W near 500 nm, while below 400 nm it reduces to below 0.1 A/W [14]. To detect visible and infrared wavelength simultaneously, optical components such as lenses, prisms, and gratings can be used in the fabrication of detectors [3]. These optical structures can increase light absorption.

Metamaterials [15], semiconductor 2-dimensions (2D) materials and superlattices are broadly available and has been used in the studies of wide spectrum detection. Molecular beam epitaxy (MBE) [16] has been developed and introduced to semiconductor materials technology diffusely few years ago [17]. In most recent studies, a kind of 2D materials that GaSe on GaSb substrates fabricated by MBE technique were investigated for broadband detectors. The results show these devices reveal a broadband detectivity from 400 to 1800 nm and superior response from 20 to 30 μs [18]. Since the 1990 s, Fraunhofer IAF firstly explicitly dedicated InAs/GaSb type-II superlattices (T2SLs) material development for antimony-based superlattices detectors [19,20].
InAs/GaSb T2SLs photodiodes suffer from a comparatively low minority carrier lifetime that gives rise to an increased dark current. Meanwhile, InAs/GaSb T2SLs infrared (IR) detectors allow realizing high-performance single element and array detectors for the 3–20 μm regime [21]. These superlattices have prominent performances. Compared with HgCdTe, it has high absorption coefficients. In addition, the properties of broad-band detection capability, suppressed Auger recombination rates [22], flexible energy band design and high material uniformity has attracted a lot of attentions [23-28].

Here, this paper presents a visible extended midwave infrared photodetector based on InAs/GaSb T2SLs that exhibits a response in the wavelength from 0.5 μm to 5 μm. In this letter, detector structures were successfully grown on GaSb substrates by MBE. The key characteristic of this detector is combining the microstructure photon traps (PTs) and InAs/GaSb T2SL materials to make wide spectrum detectors. Besides, the influences of different geometric sizes of PTs are presented.

2. Materials and fabrications

The materials of this detector were grown with a solid source GenII MBE (molecular beam epitaxy) system on 2-inch Te-doped n-type GaSb (0 0 1) substrates. The structure is composed of MWIR InAs/GaSb MBE (molecular beam epitaxy) system on 2-inch Te-doped n-type GaSb material. The key characteristic of this detector is combining the microstructure photon traps (PTs) and InAs/GaSb T2SL materials to make wide spectrum detectors. Besides, the influences of different geometric sizes of PTs are presented.

The materials of this detector were grown with a solid source GenII MBE (molecular beam epitaxy) system on 2-inch Te-doped n-type GaSb (0 0 1) substrates. The structure is composed of MWIR InAs/GaSb T2SLs. This started to grow with a GaSb Te-doped (5 × 10^17 cm^-3) buffer. Then, it followed by 800 nm thickness 10 monolayers (ML) InAs/1 ML GaSb/5 ML AlSb/1 ML GaSb as the bottom contact. After that, a 400 nm thickness 10 ML InAs/1 ML GaSb/5 ML AlSb/1 ML GaSb undoped layer serves as the barrier inserted to block the majority carriers while allowing unimpeded transport of the minority carriers [29]. Whereafter, the absorption layer consists of a 2 μm thickness (10^16 cm^-3) 8 ML InAs/8 ML GaSb. And a 400 nm thickness 8 ML InAs/8 ML GaSb acts as a top contact layer. An 18 nm thickness doped GaSb is the final cap layer. Reflection high energy electron diffraction (RHEED) was used to calibrate sources during the device epitaxy and high-resolution X-ray diffraction (HRXRD) represented the constituents of materials [30]. Also, atomic force microscopy (AFM) was conducted to characterize the quality and uniformity of the material [31]. Fig. 1(a) is the experimental high-resolution (0 0 4) X-ray diffraction rocking curve of the devices, which HRXRD scan of InAs/GaSb/AlSb/GaSb (10/1/5/1) and InAs/GaSb (8/8) SLs. It exhibits many intense satellite peaks with a full width at half-maximum (FWHM) of the first-order peak equal to 43.2 arcsec of InAs/GaSb/AlSb/GaSb (10/1/5/1) and 50.4 arcsec of InAs/GaSb (8/8). Fig. 1(b) shows the AFM image of a 10 × 10 μm scan area of the surface of the device. The measured root mean square (RMS) surface roughness is equal to 0.14 nm. Atomic steps with several micron width are clearly visible. These results attest the good crystalline quality of the layers in the SL periods.

As Fig. 2 delineates the structure schematic of the wide spectrum detector, (a) with quadrangular prism PTs and (b) with hole prism PTs. Single element detectors were manufactured with circle mesa of the diameter of 50 μm, 100 μm, 150 μm, 200 μm, 300 μm, 500 μm. The devices were fabricated inside a class 1000 cleanroom. However, the photolithography experiments took place in a cleanroom which is class 100. The detector fabrication was carried out by the following processes. Firstly, it’s the definition of two kinds of PTs arrays, quadrangular and hole prism. SiO2 hard etching mask was deposited by Plasma Enhanced Chemical Vapor Deposition (PECVD) on superlattice wafer to define PTs array after UV photolithography. Subsequently, Inductively Coupled Plasma (ICP) dry etching was of utilization to form an about 1.7–1.8 μm thick cap and absorption layer of materials with the combination gases of 4.5sccm Cl2/11.7sccm CH2/8.6sccm Ar. To ensure 90° inclination of PTs, the RF power, ICP power, and vacuum pressure should be set suitable enough. Next, the mesa was defined after removing residual SiO2. Similar with PTs array definition, PECVD, traditional UV photolithography and ICP are also performed for mesa. Since, anodic sulfide and a 200 nm SiO2 dielectric layer deposited by ion-beam sputtering deposition (IBSD) were used as chemical passivation and physical protection respectively for the sidewalls to minimize the ambient influences. Finally, the formation of Ohmic contact [32] was conducted. Windows through the passivation layers of sulfide and SiO2 to allow access to the mental electrodes were opened using Cl2 and CH4 plasma etch. Then, Ti (50 nm)/Pt (50 nm)/Au (300 nm) were deposited by electron beam evaporation from the top to the bottom contact as the metal electrodes simultaneously. Single pixel photo-detectors were then encapsulated and wire bonded for further characterization.

In this report, three sizes PTs with different edge lengths (L), L1 = 3 μm, L2 = 4 μm, and L3 = 5 μm, and with the gaps of the same lengths (2 μm), were fabricated on the surface of detectors. Meanwhile, two types of geometrical structures, quadrangular and hole prism PTs arrays, were presented. Fig. 3 illustrates the three-dimensional views of the unit quadrangular prism PTs (a) (c), and hole prism PTs array (b) (d) used for the device.

3. Results and discussion

According to Fig. 4, which is the scanning electron microscopy (SEM) image of the quadrangular prism PTs unit cell (a) and prism array (b), L = 3 μm, PTs on the surface of detectors are well prepared. To increase the absorption of photons for detectors, ICP needs to be accurately controlled to guarantee the vertical inclination of PTs and favorable morphology. In addition, PTs array is required to be manufactured orderly on the optical aperture of detectors. The average refractive index (n_ave) for prism PTs is:

Fig. 1. (a) HRXRD scan of InAs/GaSb/AlSb/GaSb (10/1/5/1) and InAs/GaSb (8/8) SLs; (b) AFM image of a 10 × 10 μm scan area of the surface of the device.
Where $n$ is the refractive index density of the PTs structure, $\Omega$ represents the region of the calculated structure and $dV$ refer to the volume differentiation of this region. According to equation*, minimizing the average refractive index can reduce the reflection rate and increase the light absorption, which can lead to significant improvement of the spectral response of the detector.

The relationship between reflectivity ($R$) and refractive index ($n$) is

$$R(\lambda) = \frac{(n_{\text{ave}} - n_{\text{air}})^2}{(n_{\text{ave}} + n_{\text{air}})^2}$$

Fig. 5 performs the calculated tendency of reflectivity of the quadrangular prism (red circle) and hole (blue cross) prism changing with an edge length of ranging from 1.5 $\mu$m to 6 $\mu$m. It can be found that, when the edge length is less than 4.8 $\mu$m, detectors with little edge length quadrangular prism array have smaller reflectivity than the hole one. Minimized micro-structure quadrangular prism on detector surface can significantly improve light absorption. However, it is obvious that $R$ of quadrangular prism array is nearly equal to that of hole prism array at one point. That means different types of PTs influence devices analogously of this square geometrical size. But after that, a detector with hole prism array absorbs more incident illumination than a detector with quadrangular prism array. The photon absorption of the active area is relevant to the spectral response of the detector.

For optical characterization, the epitaxial material is processed into single pixel photodetectors with circle mesa geometry. We compared detectors with an edge length of PTs of $L = 3 \mu m$, $4 \mu m$, $5 \mu m$ quadrangular and hole prism pillar arrays separately with the values obtained for the planar device without PTs. Detectivity ($D^*$) is used to describe the degree of photo-generated current and noise of detectors. It can be expressed as follows [34]:

$$D^* = R(\lambda) \frac{R_0 A}{4kT}$$

where $A$ is the active area of the device, $k$ is the Boltzmann constant and $R(\lambda)$ is responsivity given in A/W. $R_0$ is resistance at zero bias.

To determine how diverse types and geometric dimensions of PTs affect the performances of devices, measurements were conducted at a 500 mV bias voltage, in the temperature of 77 K. The spectral responsivity $R_i$ in A/W is the output signal response per monochromatic incident radiation. Fig. 6 depicts the spectral response $R_i(\lambda)$ measured by grating spectrometer and computational $D^*$ of different geometric dimension wide spectrum detectors at 77 K, 500 mV, which (a) (c) is for the detectors with quadrangular prism array and (b) (d) is for the ones with holes. For detectors with quadrangular prism array, responsivity rises with the reduction of geometric size. At the wavelength of 1160 nm, the responsivity of detectors with quadrangular prism array reaches the peak, with a value of 0.86 A/W. On the contrary, detectors response more radiation with smaller hole prism array, when the edge
The length of PTs is smaller than 5 \( \mu m \). The peak value is 0.68 A/W at 1160 nm. And this peak responsivity is about equivalent to the detectors with \( L = 5 \mu m \) quadrangular prism array PTs. Additionally, the responsivity of detectors with PTs significantly exceeds that of the planar detectors without PTs and antireflection (AR) coating films. The experimental results are in accordance with the calculated tendency. Consequently, the ideal light trapping array structures can increase the absorption of light extremely, which results in a high efficiency in the visible spectrum.

However, for the \( D^* \) in the wavelength of 500 nm to 2000 nm, the maximum value of detectors with prism PTs is \( 10^9 \text{cmHz}^{1/2}/\text{W} \), which is of the same order for both quadrangular and hole prism array. PTs fabricated on the surface of detector increase the area of etching, even \( R_0A \) of devices is reduced.

Spectral response measurements are conducted at 500 mV in the temperature of 77 K using a Fourier transform infrared (FTIR) spectrometer and a calibrated blackbody source. The measurement of the responsivity in the wavelength of 2–5 \( \mu m \) consists of two portions. Those are the spectral response and calibrated integrated response [35]. Quantum efficiency (QE) denotes the fraction of the incident photon on the optical area of the detector and the number of induced electron-hole pairs that these photons create [36,37]. QE is limited by the number of incident photons that enter the material, the photon absorption forming electron-hole pairs within the thickness of the photon detector and the ability of the photo-generated carriers reaching the electrical contacts. The quantum efficiency is expressed by the following equation [38]:

\[
\eta(\lambda) = \frac{hc}{\lambda q R(\lambda)}
\]

Where \( h \) is Planck's constant, \( c \) is the velocity of light in vacuum, \( q \) is the electron charge. The responsivity in (A/W) is presented in Fig. 7(a) (b) and (c) (d) for QE from 2 \( \mu m \) to 5 \( \mu m \), under the condition of 77 K, 500 mV bias voltage. The results indicate that distinct micro-structure PTs array influences the devices differently. Ignoring the effects of absorption peaks, a detector with an \( L_1 = 3 \mu m \) quadrangular prism can improve the responsivity to 1.35 A/W at 2.2 \( \mu m \) maximally. As well, the peak value of QE is 0.76 at 2.2 \( \mu m \). In addition, a detector with \( L_1 = 5 \mu m \) hole prism arrays enhances the peak responsivity to 0.5 A/W and the maximum QE to 0.3 at least.

4. Conclusion

In summary, a wide spectrum detector ranging from 0.5 to 5 \( \mu m \) with various prism pillar PTs based on InAs/GaSb type-II superlattice (T2SLs) was demonstrated. The details of fabrication, the performance characterization of micro-structure PTs and devices are introduced precisely. The visible spectral response \( R(\lambda) \) has been identified by gratings spectrometer and \( D^* \) was gained by further calculations and analysis. Compared with the planar detector without AR coating films, detectors with quadrangular prism array can response the light in the visible spectrum. The maximal responsivity of wide spectrum detector can reach to 0.86 A/W and the maximal detectivity (\( D^* \)) is up to \( 10^9 \text{cmHz}^{1/2}/\text{W} \) at 1160 nm under the condition of 77 K, 500 mV bias voltage. Also, FTIR spectrometer and a calibrated blackbody source were used to measure the spectral response in the wavelength from 2 \( \mu m \) to 5 \( \mu m \). The various micro-structure PTs improve the peak responsivity and QE in 2–5 \( \mu m \) spectrum diversely. The quadrangular prism (\( L = 3 \) \mu m) array can increase the peak responsivity to 1.35 A/W and QE to 0.76 at 2.2 \( \mu m \), 77 K, 500 mV bias voltage. The results manifest the PTs on the surface of the detector can increase the absorption of photons. These performance enhancements attest to the fact that the wide spectrum detectors with PTs based on T2SLs are able to response the wavelength from 0.5 to 5 \( \mu m \), which can be seen as a promising option for color imaging systems, military, biological and other potential application.
Fig. 6. Spectral response of detector with prism arrays, quadrangular (a) and hole (b) and D* for quadrangular (c) and hole (d) varies with wavelength from 500 nm to 2000 nm, in the temperature of 77 K, 500 mV bias voltage.

Fig. 7. Spectral response of detector with prism arrays, quadrangular (a) and hole (b) and QE for quadrangular (c) and hole (d) varies with wavelength from 2 μm-5 μm, in the temperature of 77 K, 500 mV bias voltage.
Conflict of interests

The authors have no conflict of interests.

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