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High quality InAsSb-based heterostructure *n-i-p* mid-wavelength infrared photodiode

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Abstract

We present the effect of interface quality on the performance of InAsSb based hetero *n-i-p* middle wavelength infrared (MWIR) photodiodes. By adopting heavily doping wide bandgap p- and n-type layers and inserting a thin layer between the two doped layers and the absorbing InAsSb region, the interface quality can be improved. We also employed proper fabrication processes in device fabrication to improve surface quality. It is found that the improved interface and surface quality can reduce the noise current and enhance detection performance. A detectivity of $\sim 1.5 \times 10^9$ cmHz^{1/2}W⁻¹ can be achieved at room temperature, and it can be increased to $\sim 4.0 \times 10^9$ cmHz^{1/2}W⁻¹ at 250 K.

Introduction

High-sensitivity infrared detection is of great interest for the development of non-cryogenic focal planar cameras¹. In recent years, thermal pyroelectric and microbolometers have been widely used for room-temperature (293 K) imaging, but their respond speed is inherently limited by the thermal response mechanisms. It is thus interesting to explore high temperature quantum detectors with high detectivity at

room temperature. Mercury cadmium telluride (MCT) based photodetectors are dominant in the middle wavelength infrared (MWIR) range. However, For MCT material, due to the high Hg vapor pressure during material growth, it suffers from non-uniformity and instability. Antimony (Sb) based III-V semiconductors are considered as viable alternatives for the state-of-the-art technology²⁻¹². Among them, InAs_{1-x}Sb_x alloy has gained much interest due to their wide bandgap tunability by changing Sb composition¹³⁻¹⁶, with lattice matched condition to GaSb substrate when Sb composition is ~9%^{1,17}. Over last decades, great efforts were devoted to the investigation of InAsSb based photodiode both in physics and applications. To obtain high detection performance, it is essential to reduce the noise current in these photodiodes.

In this article, we report a photovoltaic InAsSb-based hetero *n-i-p* diode for MWIR detection. Specially designed highly doped p- and n-type wide bandgap barrier layers are used to form a hetero *n-i-p* structure, which can reduce diffusion dark current. A thin layer is also inserted between the doped layer and the undoped InAsSb layer to improve interface quality. In device-fabrication, proper processes were also implemented to reduce surface leakage current. At room temperature, a detectivity of $\sim 1.5 \times 10^9 \text{ cmHz}^{1/2} \text{W}^{-1}$ is demonstrated.

The InAsSb based *n-i-p* heterostructure was grown on n-GaSb substrate by RIBER-32 molecular beam epitaxy (MBE) system¹⁸. The cross-sectional diagram of

heterostructures and the corresponding energy band diagram are shown in Fig.1. A p-GaSb layer of 1000 nm was first grown. It was then followed by a p-AlGaSb:Be layer of 30 nm with Al composition varied from 10% to 42%, a p-Al_{0.42}Ga_{0.58}Sb layer of 40 nm, a p-Al_{0.2}In_{0.8}As_{0.912}Sb_{0.088} layer of 20 nm, an undoped InAs_{0.912}Sb_{0.088} layer of 1500 nm, an n-Al_{0.15}In_{0.85}As_{0.909}Sb_{0.091} layer of 20 nm, and an n-GaSb contact layer. All the doped layers have a doping concentration of $2 \times 10^{18} \text{ cm}^{-3}$. In the heterostructure, the unintentionally doped InAs_{0.912}Sb_{0.088} with a thickness of 1500 nm is the active absorption layer for MWIR. To obtain a high detection performance, it is essential to reduce dark current resulting from the diffusion of electrons and holes respectively from *p*- and *n*-type layers. In conventional homojunction photodiode, this kind of dark current is expected to be large as no barrier exists to block those diffusion carriers. Therefore, we used highly doped wide bandgap layers to form the barriers for low dark current. Such doping concentrations can reduce the minority carrier concentrations but with negligible bandgap narrowing¹⁹. The p-Al_{0.2}In_{0.8}As_{0.912}Sb_{0.088} layer of 20 nm inserted between active InAs_{0.912}Sb_{0.088} and p-Al_{0.42}Ga_{0.58}Sb is to limit type II electron-hole transitions at the interface.²⁰

FIG. 1. (a) Cross-section schematic of the photodiode (not to real scale). The right inset is the microscope image of the device, AB represents the cross-section line. The scale bar represents 100 μm . (b) Schematic energy band diagram of the photodiode.

Figure 2 shows the high resolution X-ray diffraction (HRXRD) spectrum of the heterostructure $n-i-p$ sample. It is found that the $\text{InAs}_{0.912}\text{Sb}_{0.088}$ active layer is almost latticed match to the GaSb substrate which gives high quality interface between them. The lattice mismatch between the wide bandgap AlGaSb and GaSb is about 3500 ppm., which is very small. Since the wide bandgap layer is only 30 nm thick, and there is also a 20 nm $p\text{-Al}_{0.2}\text{InAsSb}_{0.088}$ layer between the AlGaSb and the $\text{InAs}_{0.912}\text{Sb}_{0.088}$, which can keep the good interface quality.

FIG. 2. XRD data of the InAsSb based *n-i-p* sample.

The quality of the heterostructure is also characterized by photoluminescence (PL) technique. Figure 3 presents the experimental PL spectra of the sample measured at the temperature range of 10 K -170 K. The clear and normal “red shift” of peak position with the increasing temperature was observed. It is found that the peak energy follows well with the Varshni law $E_g(T) = E_g(0) - \frac{\alpha T^2}{\beta + T}$, where $E_g(0)$ is the band gap at $T = 0$ K while α and β are Varshni coefficients. The derived $E_g(0)$ is about 0.322 eV. At 13 K, the FWHM for the PL spectrum is ~ 29 meV, showing the high quality of the absorption layer.

FIG. 3. Photoluminescence spectra of the sample measured at different temperatures. Inset: Photoluminescence peak positions at different temperatures, compared to the fittings with Varshni law.

Photovoltaic photodiodes made of the heterostructure consist of $\sim 1.8 \mu\text{m}$ deep mesa with pixel sizes ranging from $40 \mu\text{m}$ to $400 \mu\text{m}$. They were obtained by wet chemical solution based on $\text{H}_2\text{SO}_4:\text{H}_2\text{O}_2:\text{H}_2\text{O}$, followed by high-temperature **inductively coupled plasma - reactive ion etching (ICP-RIE)**. The absorption areas were obtained by opening windows in the passivated 300 nm SiO_2 layer which is deposited to reduce the surface leakage current and protect the mesa surface. Ti/Au ($50/300 \text{ nm}$) was used both for n and p ohmic contacts, formed on 1000 nm GaSb buffer layer and 50 nm n -type GaSb top contact layer, respectively. A microscope image of the device with size of $350 \times 350 \mu\text{m}^2$ is shown in the inset of Fig. 1(a). The photodiodes were mounted and wire-bonded to a ceramic chip carrier.

The Current-Voltage (I-V) characteristics of photodiodes with different pixel sizes were performed at different temperatures (Fig. 4). For a mesa-type photodiode, the dark current density can be expressed as

$$J = I / A = I_B + I_s \cdot P / A, \quad (1)$$

where, I_B is the bulk dark current and I_s is the perimeter dark current mainly owing to surface leakage. Fig. 4(a) shows the dark current density of the photodiode at zero bias voltage as a function of the perimeter to area (P/A) ratio at room temperature. It is seen that the dark current density increases slightly when the P/A ratio increases. This implies that I_s is much smaller than I_B , indicating a negligible surface leakage current.

FIG. 4. (a) Dark current versus perimeter to area (P/A) ratio for photodiodes with different active areas measured at 293 K under zero bias. (b) R_0A characteristics as a function of $1000/T$ for $350 \times 350 \text{ }\mu\text{m}^2$ photodiode, derived from current-voltage (I-V) measurements at different temperatures. The inset shows the typical I-V curves at 293, 220 and 77 K. The ideality factor at 293 K is ~ 1.3 .

We then studied the R_0A products of the $350 \times 350 \text{ }\mu\text{m}^2$ photodiode at different temperatures. Rectifying characteristics were achieved for all temperatures. The R_0A values derived from I-V characteristics as a function of temperature are presented in

Fig. 4(b) and the typical I-V curves measured at 293 K, 220 K, and 77 K are also shown in the figure as inset. The R_0A product is $0.25 \Omega\text{cm}^2$ at room temperature. At lower temperature, the R_0A value will increase rapidly, and it becomes $1.33 \Omega\text{cm}^2$ at 250 K and $1.3 \times 10^4 \Omega\text{cm}^2$ at 77 K. Large R_0A product implies a small dark current of the device. In order to understand the dominating transport mechanism for the dark current, we deduce the activation energy from the slope of $\ln(R_0A)$ versus $1/T$. Conventionally, the activation energy is expected to be equal to the band gap when diffusion is the dominant mechanism. However, when Shockley-Read-Hall (SRH) generation-recombination is the dominant mechanism, the characteristic value is expected to be half of the bandgap¹. By fitting the experimental results shown in Fig. 4 (a), the deduced activation energy is found to be 0.249 ± 0.02 eV. After being multiplied by the ideality factor ~ 1.3 , the activation energy is consistent with band gap of $\text{InAs}_{0.912}\text{Sb}_{0.088}$. Thus, above 130 K, the dark current is diffusion dominated due to the strong diffusion of carriers at high temperatures.

The responsivity and detectivity were measured by using 1000 K blackbody radiation source under different voltages and temperatures. The blackbody responsivity R_{bb} can be expressed as $R_{bb} = I_{ph} / P$, where P is incident radiation power on the detector.

To determine P , we can use the expression¹

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

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. We also used a standard power meter (OPHIR Photonics) to calibrate and confirm the irradiance of the blackbody source. The blackbody responsivity under different voltages was obtained as shown in the inset of Fig. 5(a). The responsivity is 0.03 A/W at zero bias and is significantly increased at reverse bias. The responsivity shows a saturated value of ~ 1.1 A/W under reversed bias voltage higher than 600 meV. The thermal noise limited detectivity D_{bb}^* can then be obtained as

$$D^* = R_{bb} / \sqrt{4kT / (RA) + 2eI}, \quad (3)$$

where, k is the Boltzmann constant, e is the charge element, I is the dark current density and RA is the resistance-area product at different bias. As shown in Fig. 5, a detectivity as high as $\sim 1.5 \times 10^9$ cmHz^{1/2}W⁻¹ is achieved at zero bias, which is higher than the previous reports and comparable to the recently developed InAsSb-based nBn photodetectors.^{21,22} Under reverse bias, as shown in the insets of Fig. 5(a), the detectivity drops very fast mainly due to the increased dark current compared to that at zero bias condition. To show the dependence of the detectivity on temperature variation, we then measured the performance of the photodiode at different temperatures under zero voltage bias, as shown in inset of Fig. 5(b). The increase in responsivity with the decreasing temperature results mainly from the decrease of noise current. Correspondingly, the detectivity of the photodiode at 180 K, 220 K, 250 K, 270 K, and 293 K are also presented. Indeed, the detectivity increases in the same fashion as the responsivity with the decreasing temperature, where the detectivity of $\sim 4.0 \times 10^9$ cmHz^{1/2}W⁻¹ was obtained at 250 K. This operating temperature can be

practically achieved by simple thermoelectric cooling.

FIG. 5. (a) Blackbody detectivity of the $350 \times 350 \mu\text{m}^2$ photodiode at different bias voltages at room temperature, obtained from the corresponding responsivity as shown in inset. (b) Blackbody detectivity of the $350 \times 350 \mu\text{m}^2$ photodiode at different temperatures, obtained from the corresponding responsivity as shown in inset.

A **fourier transform infrared spectroscopy** (FTIR) system with mid-infrared source and KBr **beamsplitter** (BMS) was used to characterize the photocurrent spectrum of the photodiode at zero bias. Fig. 6 shows the relative spectral photocurrent response at

293 K, 250 K and 180 K. The photodiode exhibits a broadband photocurrent response from $\sim 2 \mu\text{m}$ to $\sim 5 \mu\text{m}$ at room temperature. With the temperature being decreased to 250 K, the cut-off wavelength blue shifts and the photocurrent spectrum becomes narrower, i.e., from $\sim 2 \mu\text{m}$ to $\sim 4.7 \mu\text{m}$. Larger blue shift at lower temperature is to be expected due to the widened bandgap in $\text{InAs}_{0.912}\text{Sb}_{0.088}$. At 180 K temperature, we observed a blue shift of cut-off wavelength from $5 \mu\text{m}$ to $4.2 \mu\text{m}$.

FIG. 6. Relative spectral photocurrent response of $350 \times 350 \mu\text{m}^2$ photodiode under zero bias voltage at 293 K, 250 K, and 180 K

In summary, we have designed and fabricated InAsSb -based heterostructure n - i - p photodiode for MWIR photodetection with high sensitivity at high temperatures. The dark current has been significantly reduced by adopting heavily doped n -type and p -type barrier layers into the n - i - p structure for reducing diffusion holes and electrons, and by inserting a thin quaternary layer between the doped layers and the active InAsSb region to improve interface quality and reducing electron flow due to the type II band edge lineup. The detectivity as high as $\sim 1.5 \times 10^9 \text{ cmHz}^{1/2}\text{W}^{-1}$ has been

achieved at room temperature, which can be enhanced by $\sim 2.6\times$ ($\sim 4.0\times 10^9$ cmHz^{1/2}W⁻¹) when the temperature is slightly decreased to 250 K. This performance has potential for future room temperature imaging and applications.

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