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Study of dual color infrared photodetection from n-GaSb/n-InAsSb heterostructures

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We report detailed investigation of n-GaSb/n-InAsSb heterostructure photodetectors for infrared photodetection at different temperatures and biases. Our results show that the heterostructure photodetectors are capable of dual color photodetections 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.

I. INTRODUCTION

InAs$_{1-x}$Sb$_x$ alloy has been attracting great interest due to its widely tuntable band gap while changing the composition $x$ of Sb.\textsuperscript{1-3} It will be lattice matched to GaSb substrate when the composition is about 0.09.\textsuperscript{4,5} Over last two decades or so, great efforts were dedicated to the investigation of InAsSb/GaSb diodes both in physics and applications.\textsuperscript{6-14} Due to the broken-bandgap alignment between the InAsSb epitaxial layer and GaSb substrate, the InAsSb/GaSb heterostructures exhibit unusual properties under different conditions.\textsuperscript{15,16} The earlier work was mainly focused on electrical properties and band alignment of this kind of structures.\textsuperscript{17,18} Thereafter, Sharabani et al\textsuperscript{19,20} investigated n-GaSb/n-InAsSb heterostructures which showed high zero-bias resistance area product $R_0A$ of 2.5 $\Omega$ cm$^2$ at room temperature and dual color detections with the same polarity of photocurrent under different biases. Later, Lackner et al\textsuperscript{21} investigated similar GaSb/InAsSb heterostructures which also showed dual color detections but at opposite polarity although the bias was the same. Till now, the observed photodetection and the mechanism behind in the heterostructure photodetectors remain controversial. In this article, we report detailed studies of the photodetection in the n-GaSb/n-InAsSb heterostructures under a wide range of biases and temperatures, and propose a new model which can well explain all observations.

II. EXPERIMENTAL

The heterostructure is fabricated by epitaxial growth of an InAs$_{0.91}$Sb$_{0.09}$ epitaxial layer on an n-type GaSb substrate with an electron concentration of $2\times10^{17}$ cm$^{-3}$ by molecular beam epitaxy. The undoped InAsSb layer is n-type with a concentration of $6\times10^{16}$ cm$^{-3}$ and the lattice mismatch between the epitaxial layer and GaSb substrate is about 0.17%, corresponding a composition $x$ of 0.09. The detailed description is published in a separate paper.\textsuperscript{22} Photodetectors were fabricated by standard photolithography and citric acid based chemical solution into circular mesas with a radius

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FIG. 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.

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 (see Fig. 1).

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 as the case when the positive potential is applied to the InAsSb contact (see Fig. 1). The relative spectral response of the device at different temperatures and different biases were measured using a home made photocurrent system.23,24 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.

III. RESULTS AND DISCUSSION

Figure 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 they are greater when the device is positively biased. The measured $R_0 A$ products as a function of $1000/T$ obtained from Fig. 2(a) are plotted in Fig. 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 $R_0 A$ value is about 1 Ω·cm$^2$ at room temperature (300 K), and it increases to about 1500 Ω·cm$^2$ when the temperature decreases to 45 K, which are in agreement with those previously reported.7,25

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, we observed dual color detections at room temperature at fixed forward biases. As the photocurrents generated from the absorption over a specific wavelength range, we further measured the spectral responses at different temperatures and different biases. Figure 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 responsivities at room temperature are
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 $D^* = R_i/\sqrt{RA/(4kT)}$ where $R_i$ is the current responsivity with a unit of A/W, and $RA$ the resistance area product. the measured Johnson noise limited detectivity at room temperature is about $2.3 \times 10^9$ cm-Hz$^{1/2}$/W and $2.1 \times 10^9$ cm-Hz$^{1/2}$/W at the wavelengths of 1.5 µm and 3.2 µm, respectively.

Figure 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, we measured photocurrent spectra at different temperatures and at different forward biases. It is found that at each temperature, there is a corresponding forward bias which we define 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 Fig. 3(c) and it decreases monotonically with the increase of temperature.

We then measured the photocurrent spectra of the device at temperatures range of 45-300 K under a reverse bias of 200 mV and the results are shown in Fig. 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
FIG. 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.

decreases as the temperature decreases from 300 K to 45 K. The inset in Fig. 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 our findings, the properties and the energy band offsets between the two materials, N-GaSb and n-InAsSb, which form the heterojunction needs to be considered.\textsuperscript{1,17,19–21} 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 Fig. 4(a),\textsuperscript{1,17,19,27} 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 Fig. 4(b). Under illumination, electron – hole pairs (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 $\Delta E_C$, only limited number of electrons can turn through and contribute to photocurrent, which can well explain the experimental results shown in Fig. 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
FIG. 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 $V_b > V_{bi}$.

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 it flows in the direction the same as those at reverse bias (but opposite to the applied forward bias), as shown in Fig. 4(b) with a forward bias of 430 mV.

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 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 Fig. 3(c).

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 Fig. 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 Fig. 3(a).

With the model discussed above, we can also explain the photocurrent spectra measured at different temperatures. As shown in Fig. 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 Fig. 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
TABLE I. Summary of reported n-GaSb/n-InAsSb heterostructures for photodetection.

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<tr>
<th>Sample</th>
<th>This work</th>
<th>Ref. 19, 20</th>
<th>Ref. 21</th>
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<tr>
<td>Growth technique</td>
<td>MBE</td>
<td>MOCVD</td>
<td>OMVPE</td>
</tr>
<tr>
<td>Device behavior</td>
<td>Forward: dual color detection with the same photocurrent phase; bias turn-point. Reverse: Temperature turn-point.</td>
<td>Forward: bias adjustable dual color detection with the same photocurrent phase.</td>
<td>Forward: dual color detection with the opposite photocurrent phase.</td>
</tr>
<tr>
<td>GaSb doping (cm⁻³)</td>
<td>2 × 10¹⁷</td>
<td>1.1 × 10¹⁸</td>
<td>8 × 10¹⁶</td>
</tr>
<tr>
<td>InAsSb (cm⁻³)</td>
<td>6 × 10¹⁸</td>
<td>1 × 10¹⁶</td>
<td>5 × 10¹⁵</td>
</tr>
<tr>
<td>V_b for dual color detection</td>
<td>690 mV (293 K)</td>
<td>50 mV for GaSb; 150 mV for InAsSb (180 K)</td>
<td>400-600 mV (77 K)</td>
</tr>
<tr>
<td>R_oA (Ω cm²)</td>
<td>1 (300K), 1500 (45 K)</td>
<td>2.5 (room temperature)</td>
<td>4540 (77K), 143 (300K)</td>
</tr>
<tr>
<td>Detectivity (10⁹ cm Hz¹/² W⁻¹)</td>
<td>300 K: 2.3 (1.5 µm); 2.1 (3.2 µm)</td>
<td>300 K: 4.9 (InAsSb absorption)</td>
<td>-</td>
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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 Fig. 3(d).

Due to the differences in the fabrication techniques, materials parameters and device process in the reported works on InAsSb/GaSb heterostructures, as summarized in Table I, it may not be possible to get the same observations. Our model, however, can also qualitatively explain the reported observations. In the work of Lackner et al, dual color detection was observed at different polarities at the same bias. In their structure, the carrier concentration of the InAsSb layer is 5 × 10¹⁵ cm⁻³ which is much less than that of the GaSb layer they used. It is likely that the resistance of the InAsSb layer becomes comparable with that of the junction depletion region which is mainly in the GaSb layer, and therefore part of the forward bias is applied to the InAsSb layer. As a result, the photocurrent generated in the InAsSb layer at longer wavelength spectrum flows in the direction consists with the forward bias. For the photocurrent generated in the depletion at shorter wavelength spectrum, due to the existence of built-in electrical field, if flows in the direction opposite the forward bias. For the work of Sharabani et al, the dual color detection was observed with the same polarity. In their case, the photocurrent observed at 150 mV also shows two spectra, similar to what we observed at high forward bias although the intensity at short wavelength spectrum is lesser.

IV. CONCLUSIONS

In conclusion, photodetection of n-GaSb/n-InAsSb heterostructure were systematically investigated at different temperatures and biases. The devices are found capable of duel color photodetection at fixed large forward biases at different temperatures and the maximum responsivity occurs at room temperature. With 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.

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