Resistance Control by Doping Concentration in PV InSb Detector

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Abstract

Dynamic resistance and its correlation to impurity concentration were investigated by fabricating InSb diodes with different impurity concentration on both sides of the junction. It shows that at 77 K the resistance at zero bias, which is the least of current in I-V curve, has a maximum value (1.5×10^5 Ω-cm^2) for p^+-n diode structure (impurity concentration of 2×10^{15} cm^{-3} for n-type and 1×10^{18} cm^{-3} for p-type). Increasing the impurity beyond these values causes resistance peak to decrease at zero bias and decreasing impurity causes peak resistance to shift to a higher reverse bias.

Keywords: InSb photodiode, dynamic resistance, dark current, impurity concentration.

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1. Introduction

Indium antimonide (InSb) is an important III-V compound semiconductor that is conventionally used to detect middle wave (3–5 μm) infrared radiation [1]. It has the highest intrinsic electron mobility and the smallest band gap (0.227 eV at 77 K) of all binary III-V compounds [2]. InSb photodiodes are generally fabricated by impurity diffusion [3], molecular beam epitaxy [4], and ion implantation [5]. InSb photodetector arrays have existed since the late 1970s for thermal sensing and night-vision applications. In the photovoltaic devices, to achieve the highest possible detectivity; the value of the dynamic resistance should be maximized and
increasing the zero-bias resistance improves the overall device performance [6].

\[ D^* \propto \sqrt{R_0 A} \]  

(1)

Where \( R_0 \) is the zero bias resistance and \( A \) is the sensitive area. In order to big resistance the p-n photodetector are operated under reverse bias condition. In many applications, the InSb photodiode is operated near zero bias voltage with the minimum leakage current, so it's desirable to have maximum resistance in reverse bias, close to the zero [7]. To calculate dynamic resistance we should derivate dark currents with respect to voltages. The dark current consists of the diffusion current, Generation-recombination current, shunt current and Tunneling current.

Diffusion current is the results from the diffusion of thermally generated minority carriers. Generation-Recombination current (g-r) is concluded from the traps in the depletion region, the g-r current in an InSb photodiode is given by the relation (2) [8].

\[ J_{gen} \propto T^{3/2} \exp \left( -\frac{E_g}{2kT} (V_{bi} - V)^{1/2} \right) \]  

(2)

Shunt current is shunt-leakage behavior in junction performance and surface leakage current and can be modeled as an ohmic resistance component \( R_{sh} \) that is the diode shunt resistance. Tunneling current is the fourth type of dark current component that can exist in a tunneling current caused by electrons directly tunneling across the junction from the valance to the conduction band. The tunneling current in InSb is given by Equation (3) [8]:

\[ I_T = K_1 (V_{bi} - V)^{1/2} \left( \frac{V^2}{T} \right) \exp \left( -\frac{K_2}{(V_{bi} - V)^{1/2}} \right) \]  

(3)

Where \( K_1 \) and \( K_2 \) are constants with respect to \( V \) and \( T \).

Impurity concentration selection is one of the factors that must be taken into account to have a minimum leakage current and maximum dynamic resistance. In this article, the fabrication method of the InSb detector, the resistance–voltage curves of it as a function of concentration, and the optimum concentration are described.

2. Experimental method

The substrates used for photo diode fabrication are (111) oriented, n-type A InSb substrates with concentrations of \( 2 \times 10^{15} \) cm\(^{-3} \) and \( 3 \times 10^{18} \) cm\(^{-3} \). A large number of authors have emphasized the effect of InSb wafers cleaning on final device performance and defined many different cleaning methods to achieve an \( \text{In}_x\text{O}_y \) and \( \text{Sb}_x\text{O}_y \) native oxide free surface [9-10]. In this experiment, the wafers were cut to the dimensions of 1×1 cm. A side of the InSb substrate were cleaned using organic solvents for 15 min and etched using CP4A (HNO\(_3\): CH\(_3\)-COOH: HF: H\(_2\)O at 2:1:1:10) etchant [11]. Further cleaning was done by buffer HF followed by a long rinse in DI water and dried using nitrogen gun [12]. On A face of the InSb substrates surfaces, 1µm of p and p+ layers was implanted on substrate using Be+ implantation and RTA annealing [13]. A mesa structure diode was carried out
Resistance control by doping concentration

using photolithography process and etching in (HF:H₂O₂:H₂O at 1:1:4) solution [14]. The etched region was anodized in 0.1N KOH solution by a constant current source and then a 1µm SiO layer was evaporated to improve the stability of the anode oxide. Pt/Cr/Au and Cr/Au was deposited by heat evaporation with thickness of 500Å Pt, 300 Å Cr and 3000 Å Au as an ohmic contact on p- and n-type respectively. After this process, the fabricated devices were diced into individual pieces. Finally, the processed chip was mounted on cooled head of a LN₂ Dewar. I-V and R-V characteristics were measured using a KEITHLEY instrument. Typical detector geometry is shown in figure 1.

![Figure 1: Schematic of fabricated InSb diode structure](image)

3. Results and discussion

Three InSb diodes with different impurity concentration on both sides of the junction were fabricated as table 1.

<table>
<thead>
<tr>
<th></th>
<th>N_D (cm⁻²)</th>
<th>N_A (cm⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>p⁺⁻n⁻</td>
<td>3×10¹⁸</td>
<td>2×10¹⁹</td>
</tr>
<tr>
<td>p⁺⁻n</td>
<td>2×10¹⁵</td>
<td>1×10¹⁸</td>
</tr>
<tr>
<td>p⁻⁻n</td>
<td>2×10¹⁵</td>
<td>5×10¹⁶</td>
</tr>
</tbody>
</table>

![Table 1. Parameters used to fabricate InSb Photodiodes.](table)

Fig. 2 shows the resistance-voltage (R-V) curves of the InSb detectors with an area of 1 mm². The R-V curves were measured at fixed temperatures of 77 K. In the p⁺⁻n⁻ diode, resistance peak is very low and appears in very small positive bias. But in both p⁻⁻n and p⁺⁻n diodes the resistance peaks appear in reverse bias with approximately high value than p⁺⁻n⁻. The p⁺⁻n structure has maximum of resistance in zero bias with approximately 10⁵ Ω-cm² peak so R-V characterization of p⁺⁻n InSb photodiode is optimum compare with another concentration and has best condition in the peak value and peak position.
In order to investigate the effect of currents change on dynamic resistance we simulate the currents and resistance change by voltage of p+-n InSb photodiode. Figure 3 show the theoretical superposition and individual currents for p+-n InSb photodiode. Relevant parameters are listed in Table 2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>( L_{pn} ) (( \mu )m)</td>
<td>50</td>
</tr>
<tr>
<td>( A_d ) (cm²)</td>
<td>( 1 \times 10^{-2} )</td>
</tr>
<tr>
<td>( \tau_{pn} ) (s)</td>
<td>( 8 \times 10^{-7} )</td>
</tr>
<tr>
<td>( n_i ) (cm⁻³)</td>
<td>( 1 \times 10^9 )</td>
</tr>
<tr>
<td>( N_D )</td>
<td>( \approx 2 \times 10^5 )</td>
</tr>
<tr>
<td>( N_A )</td>
<td>( \approx 1 \times 10^8 )</td>
</tr>
</tbody>
</table>

Diffusion current doesn't have relation to bias voltage, but the other currents increase with reverse bias. The G-R current smoothly increase by bias increasing. It is found that a Generation-recombination process dominates the dark current in
the 77 K temperature, when the device is under small bias voltage (<300 mV). For larger bias conditions, the band-to-band tunneling current gradually overcomes the Generation-recombination. To calculate the dynamic resistance of a diode we can derive total current with respect to voltage.

According to this simulation we can say that p^+-n^+ diode, due to high impurity concentration has tunneling current at very low biasing voltages (even at zero bias). But in both p-n and p^-n diodes due to lower impurity concentration tunneling will appear in approximately high reverse voltage, in the p-n photodiodes because of lower concentration the tunneling becomes dominant at more reverse voltage compared to p^+-n. So the resistance peak shift to a higher reverse bias but diffusion current increasing cause the magnitude of peak to a lower value than p^+-n structure.

Figure 4 depicted the practical measuring I-V and R-V curves for a fabricated p^-n InSb photodiode, and analyzed using KEITHLEY R-V characterization at 77K (LN2) temperature.

4. Conclusion

Increasing impurity concentration is desired to fabricate a good photovoltaic diode with a big internal field and a small diffusion current. But (BTB) tunneling current originates due to the direct tunneling of carriers under the influence of high concentration in narrow band gap semiconductors and potentially important factor in device design and performance.

We have successfully made some InSb photodetectors by implanting p layer on n-type substrate using Be^+ implantation and RTA annealing. By investigating in R_0A, We show that the optimum concentration for fabricating a photodiodes is \( \approx 2 \times 10^{15} \) for n-type and \( \approx 1 \times 10^{16} \) for p-type, which exhibit a zero bias peak resistance of \( 1.5 \times 10^{5} \, \Omega \text{cm}^2 \). Reduction of resistance is at considerable level and
exceeding bias voltage for reverse bias voltages larger than 300mV is not allowed.

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References


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