OPTIMUM CONCENTRATION OF InSb PHOTODIODE FOR MINIMUM LOW REVERSE BIAS LEAKAGE CURRENT

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We have investigated a relation between the impurity concentration and the leakage current for three types of InSb diodes. They were fabricated with different impurity concentrations on both sides of the junction such as $p-n$, p^+-n, and p^+-n^+ in order to achieve the minimal level of noise. It is shown that the leakage current at a low reverse bias has a minimum for the p^+-n diode structure (impurity concentration of order of 2×10^{15} cm^{-3} for the n-type and 1×10^{18} cm^{-3} for the p-type). Increasing the impurity beyond these values may cause the tunneling at a low reverse bias voltage close to zero, and decreasing the impurity causes increasing the diffusion current.

1. Introduction

InSb photodiode is one of the most useful and applicable detectors at 3–5 μm wavelength [1]. These detectors have different applications in military, medical, and aerospace industries [2, 3]. In a qualified detector, the lower leakage current is essential in decreasing the noise and increasing the detectivity [4]. In photodiodes, the shot noise is a dominant noise at the near-zero reverse bias [5]. With regard for the shot noise relation (1) which is directly related to the current passing through a diode, minimizing the leakage current will minimize the shot and consequently detector noises [6]:

$$\overline{i^2_{\mathrm{shot}}} = 2eI_{\mathrm{dc}}\Delta f. \tag{1}$$

Here, I_{dc} is the dc current flowing through the diode, and Δf is the electric bandwidth. The aim of this article is to minimize the leakage current at low reverse biases in order to achieve the minimal level of noises. The leakage current (J_0) is the sum of the diffusion current (J_d), generation-recombination (J_{g-r}), parallel shunt (J_s), and tunneling (J_t) ones [7]:

$$J = J_d + J_{g-r} + J_T + J_s. \tag{2}$$

The diffusion current is due to the carrier generation-recombination outside the depletion region. The amount of this current is dependent on the carrier concentration on both sides of the junction; the increasing carrier concentration at both sides of the junction will cause decreasing this current. The generation-recombination current ($g-r$) is determined by traps in the depletion region. For example, the g-r current in an InSb photodiode is given by the relation [8]

$$J_{\mathrm{gen}} \propto T^{3/2}\exp\left(-\frac{E_g}{2KT}\right)(V_{\mathrm{bi}}-V)^{1/2}, \tag{3}$$

where V_{bi} is the built-in potential, and V is the applied bias. The shunt current is characterized by a linear $I-V$ characteristics. This current is caused by the current leakage at the junction-edge surface and is proportional to the temperature, energy gap, and bias voltage [8]:

$$J_{\mathrm{sh}} \propto VT^{3/2}\exp\left(-\frac{E_g}{2KT}\right). \tag{4}$$

Proper anodic oxides at the surface of the formed junction which contains few accumulated charges are very crucial to a decrease in this current. The tunneling current is a result of the thin potential barrier. A very high carrier concentration at both sides of the junction will cause the electrons to directly tunnel across the junction from the valence band to the conduction band (the band-to-band tunneling (BTB)) or to indirectly tunnel across the junction by intermediate trap states in the junction region (trap-assisted tunneling (TAT)). The band-to-band tunneling originates under the influence of a relatively high reverse bias but the TAT process occurs at a lower field than BTB. In comparison with BTB, TAT is critically dependent not only on the doping concentration but also on the density of recombination in the band gap [13]. The direct tunneling current in InSb is given by the relation [8]

$$J_T = K_1(V_{\mathrm{bi}}-V)\left(\frac{V^2}{T}\right)\exp\left(\frac{-K_2}{(V_{\mathrm{bi}}-V)^{1/2}}\right), \tag{5}$$

where K_1 and K_2 are constants with respect to V and T.

2. Fabrication Process

The $p-n$, p^+-n, and p^+-n^+ photodiodes considered in this study are fabricated on two different single-crystal n-type ⟨111⟩ Te-doped InSb substrates with concentration of n^+ (1×10^{18} cm^{-3}) and n (2×10^{15} cm^{-3}). To fabricate $p-n$ and p^+-n junction diodes, the closed-tube thermal diffusion is used for the Cd diffusion into the n substrate to levels of 5×10^{16} cm^{-3} and 3×10^{18} cm^{-3}. For a p^+-n^+ junction, the LPE method was applied to attain $p^+ = (2 \times 10^{19}$ cm$^{-3})$ on the n^+ substrate. The thickness of wafers is 500 μm, and that of the p-type layer is 5 μm. For this purpose, the wafers were initially cleaned by organic solvents and CP4A (HNO_3 : CH_3-COOH : HF : H_2O at 2:1:1:10) etchant [9]. The further cleaning was done by buffer HF followed by a long rinse in DI water and dried using a nitrogen gun [10]. Diffused impurity concentrations have been measured using the Hall effect. The mesostructure of a diode was constructed by using photolithography and etching in (HF : H_2O_2 : H_2O at 1:1:4) solution [12]. The etched region was anodized in a 0.1-N KOH solution by a constant current source, and then a 4000-Å SiO layer was coated to improve the anode oxide stability. Finally, Pt/Cr/Au and Cr/Au layers used as an ohmic contact were deposited, respectively, on the p- and n-type substrates. The total sensitive area of the diodes is 1 mm^2. A cross-sectional view of the detector test structure is illustrated in Fig. 1.

3. Results and Discussion

In order to identify the dark current at the corresponding bias, the diodes fabricated were analyzed, by using the KEITHLEY 236 $I-V$ characteristic at 77 K (LN2) which is the working temperature of InSb photodiodes. The devices were cover by a cold metal shield after the installation on a Dewar. The current-voltage characteristics for the forward and reverse biases of three different fabricated photodiodes $p-n$, p^+-n, and p^+-n^+ are shown in Fig. 2,*a* and 2,*b*, respectively.

In these graphs, three main regions of the $I-V$ curve (near the zero, forward, and reverse biases are shown. The results are tabulated in Table. Comparing these diodes at the forward bias, we see that the built-in voltage and the zero bias dark current for p^+-n^+ are higher than those for the other two because of a higher impurity concentration.

Comparison of parameters of three different InSb IR detectors

	N_d	N_a	V_{bi}	$I_{-0.1}$	I_{-3}
p^+-n^+	3×10^{18}	2×10^{19}	$178 \cdot 4$ mv	-22 mA	$\gg -100$ mA
p^+-n	2×10^{15}	1×10^{18}	128 mv	$-1 \cdot 99$ nA	$-96 \cdot 24$ μA
$p-n$	2×10^{15}	5×10^{16}	116 mv	$-7 \cdot 12$ nA	$-4 \cdot 23$ μA

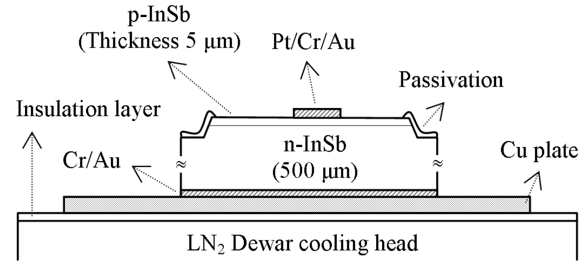

Fig. 1. Schematic of a fabricated InSb diode and a cooled test structure

The nature of the excess current of InSb photodiodes at the forward biases $V < 0.05$ is not known exactly, but it is seen that, at low reverse and forward biases, TAT and shunt components are the dominant components of the dark current, and the excess current is due to the TAT current [14]. The consideration of the tangent of the current at a reverse bias shows that, at p^+-n^+ due to a high impurity concentration (high field) and the exceeding degeneracy level, we have a BTB tunneling current at very low reverse bias voltages (also at zero). According to relation (5), at the increasing reverse bias, the current rate will increase exponentially, and a rapid breakdown will occur. But, in both $p-n$ and p^+-n due to a lower impurity concentration, the interband tunneling will appear at higher reverse biases (that appears for p^+-n at $V < -0.3$). The rate of current increase at a reverse bias is very low, and we have a soft breakdown. Since PV-InSb infrared detectors are usually used at a reverse bias very close to zero (0–300 mV) [11], the investigation of the leakage current of a detector at reverse biases close to zero is more important with respect to other two regions. The comparison of leakage currents near zero bias shows that the least leakage current is related to a p^+-n diode. The diffusion current, generation-recombination, and TAT are dominant at low reverse biases, and they are optimum for the p^+-n structure. At $p-n$ diode due to a low impurity concentration, the diffusion and g-r currents increase at low reverse biases, since the BTB tunneling current appears at more reverse biases. The dark current of the $p-n$ structure at high reverse biases is lower than those of p^+-n and p^+-n^+ due to a high impurity concentration, and the BTB and TAT tunneling currents are considerable even at zero bias.

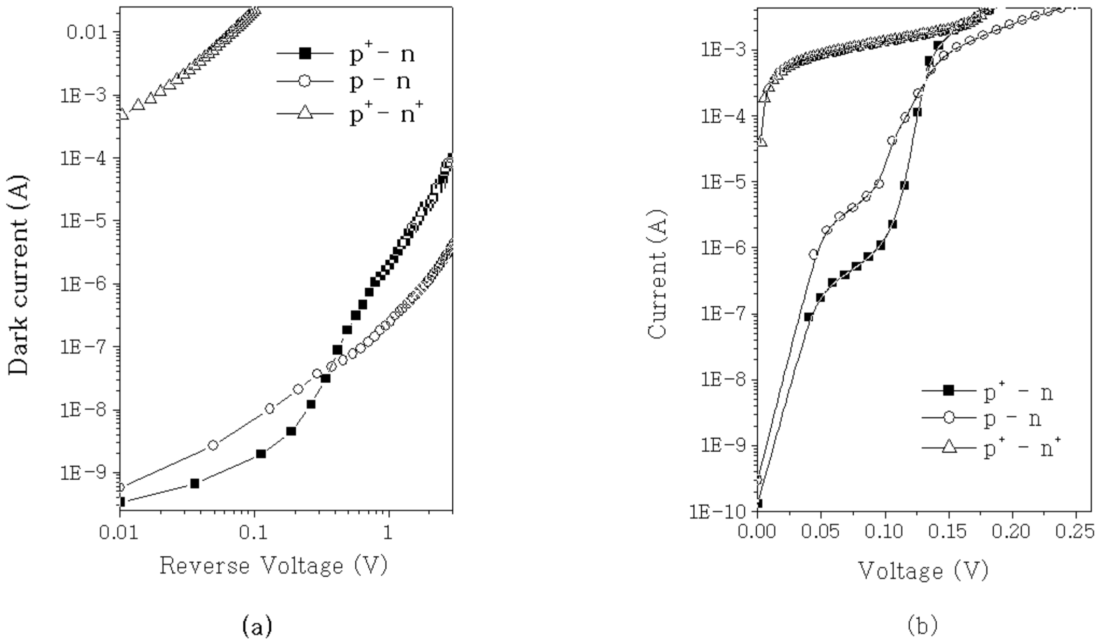

Fig. 2. Current-voltage curves of $p^+ - n^+$, $p^+ - n$, and $p - n$ InSb photodiodes at 77 K: (*a*) – semilog current-voltage curves for forward bias voltages, and (*b*) – log-log current-voltage curves for reverse bias voltages

4. Conclusion

Because a low noise is of great importance in infrared detectors and due to its direct relation to the leakage current, it is essential to decrease the leakage current as much as possible. In this respect, the selection of a proper substrate with minimum crystal defects is of crucial meaning. In performing the fabrication with a proper anodic oxide at the edges of a junction, the selection of a precise doping on both sides is of main priority. The experimental results show that a very high impurity concentration will cause the BTB tunneling current at a reverse bias close to zero (working bias of InSb photodiodes). In a $p - n$ diode due to a low impurity concentration, the diffusion and g-r currents increase. On the other hand, introducing the impurity at the degeneracy boundary of the $p^+ - n$ structure (impurity concentrations are of the order of 2×10^{15} cm^{-3} for the n-type and 1×10^{18} cm^{-3} for the p-type) is the optimum case. By selecting the impurity and approaching the bias to zero with the minimum leakage current, we can obtain the minimum noise and the highest detectivity.

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ОПТИМАЛЬНА КОНЦЕНТРАЦІЯ ДОМІШКИ В InSb ФОТОДІОДАХ З МІНІМАЛЬНИМ СТРУМОМ ВИТОКУ ПРИ НИЗЬКІЙ ЗВОРОТНІЙ НАПРУЗІ ЗМІЩЕННЯ

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Резюме

Досліджено зв'язок між концентрацією домішки та струму витоку для трьох типів InSb діодів. Діоди було виготовлено з різними концентраціями домішки на обох боках перехода, а саме $p-n$, p^+-n та p^+-n^+, щоб отримати найнижчий рівень шумів. Показано, що струм витоку має мінімальне значення при низьких зворотних напругах зміщення для p^+-n структури (концентрація домішки порядку $2\cdot10^{15}$ см$^{-3}$ для n-типу та $1\cdot10^{18}$ см$^{-3}$ для p-типу). Зростання концентрації домішки понад цих значень може викликати тунелювання при малих зворотних напругах зміщення, тоді як при зменшенні концентрації зростає дифузійний струм.