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Electrical and Optical Characteristics of n-GaSb/n-GaIn$_{0.24}$AsSb/p-GaAl$_{0.34}$AsSb Heterostructure Photodiode

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In the present paper, electrical and optical properties of n-GaSb/n-GaIn$_{0.24}$AsSb/p-GaAl$_{0.34}$AsSb double heterostructure (DH) with a diameter of 0.3 mm are reported. The current-voltage (I-V) characteristics of the structure were investigated at several temperatures in both, dark and under the illumination conditions. The effect of illumination was studied at different intensity values. Short circuit current and open circuit voltage as a function of intensity of incident light in photovoltaic mode are investigated.

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1. Introduction

In recent years, thermophotovoltaic (TPV) devices have attracted interest due to the capability of converting thermal radiation to electricity. Low band gap semiconductors, such as GaSb (0.72 eV) are suitable for fabrication of infrared devices, including light emitting diodes, infrared lasers, photodiodes, solar cells and TPV cells [1–8]. Band gap and lattice constant values can be adjusted with variation of the composition of quaternary semiconductors. GaInAsSb quaternary structure, lattice-matched to GaSb, have turned out to be a promising material for TPV applications [9–11]. In addition, thermophotovoltaic (TPV) devices based on III-V semiconductor alloys with bandgap energies corresponding to the mid-infrared wavelength range 2.2 to 2.5 μm (0.5 to 0.56 eV) are being developed. To date, the highest performing TPV devices in this wavelength range have been achieved for devices based on GaInAsSb and AlGaAsSb alloys, lattice-matched to GaSb substrates. The GaInAsSb TPV devices for the temperature range of 1200–1700 °C can operate as cheap, portable and ecological converters of energy from the heaters, using gas fuels, carbon, wood and biomass burning.

In this work, we present the characterization of GaSb/GaIn$_{0.24}$AsSb/GaAl$_{0.34}$AsSb heterostructure. The electrical properties under varying temperature conditions and the optical properties of the device were investigated.

2. Experimental

The GaSb/GaIn$_{0.24}$AsSb/GaAl$_{0.34}$AsSb structure was fabricated by liquid-phase epitaxy (LPE). High-quality GaIn$_{0.24}$AsSb solid solutions with composition near the miscibility gap boundary were grown at $T = 600$ °C on Te-doped GaSb(1 0 0) substrates ($n = (1-3)\times10^{17}$ cm^3, $\mu = 5720$ cm^2/(V s) at $T = 80$ K). According to X-ray diffractometry data, the lattice mismatch between the GaInAsSb epitaxial layer and GaSb(1 0 0) substrate was positive ($\Delta a/a = (2-5)\times10^{-4}$ at $T = 300$ K) [12]. The width of the GaIn$_{0.24}$AsSb band gap determined from PL data and transmission spectra was 0.58 eV at $T = 80$ K (0.53 eV at $T = 300$ K). The epitaxial layers have shown a good surface morphology and straight interface lines for investigated structures.

Mesa samples with a working area 0.3 mm in diameter were fabricated from these structures by photolithography. Thermal evaporated AuGe/Ni/Au and Cr/Au/Ni/Au Ohmic contacts with annealing at 300 °C for 30 s in H_2 atmosphere were applied to the p-GaAlAsSb top of each mesa and to the back of n-GaSb substrate, respectively. The wide-bandgap layer with 1.5–2 μm thickness was Ge-doped to $p = 8\times10^{18}$ cm^3.

Fabricated devices were mounted into a glass Dewar with a cold shield for detailed electrical measurements at various temperatures. I-V characteristics were performed using a KEITHLEY 6517A Electrometer and C-V measurements were carried out at room temperature with KEITHLEY 590 C-V Analyzer. All measurements were controlled by a computer via an IEEE–488 standard interface so that the data collecting, processing and plotting could be accomplished automatically. Photovoltaic measurements were employed using a 150 W halogen lamp and THORLABS FES1000 Infrared Filter. The intensity of halogen lamp radiation was varied by changing the current through it. The intensity of the incident light was measured by THORLABS Photo Diode Amplifier PDA200C with BPW41N Silicon PIN Photodiode.

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3. Results and Discussion

Figure 1 shows dark current-voltage characteristics of GaSb/$GaIn_{0.24}AsSb$/$GaAl_{0.34}AsSb$ structure in the temperature range of 77–300 K.

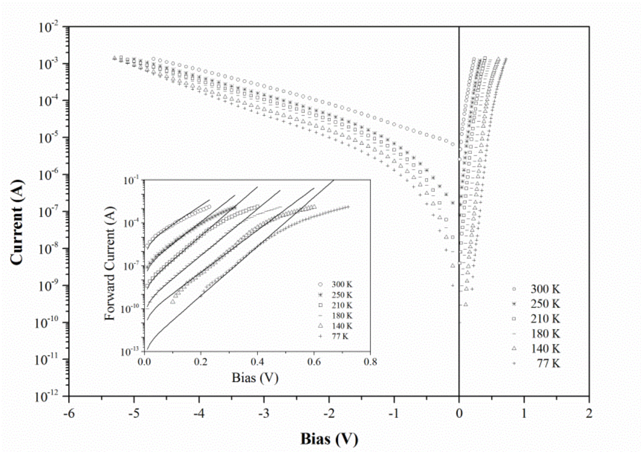

Fig. 1. *I-V* characteristics of the structure at several temperatures. In the inset, comparison of theoretically calculated (continuous line) and experimental (points) *I-V* characteristics in the forward bias region at several temperatures.

According to the results of analysis, *I-V* characteristics and the dependence of forward current on voltage can be described by this empirical expression [13]:

$$I = I_0 \left[\exp\left(\frac{qV}{\beta kT} \right) - 1 \right] \quad (1)$$

where β is the ideality factor which increases with decreasing temperature, from $\beta = 1.28$ at $T = 300$ K to $\beta = 3.68$ at $T = 77$ K. It is seen from Fig. 1 that at temperatures over the range from 300 K to 250 K and from 210 K to 180 K the forward current was determined by diffusion and recombination mechanisms, respectively. At low temperatures ($T \leq 180$ K) the contribution of tunneling component becomes essential for the mechanism of the flow of the current. This is proved by the weak dependence of the forward current on temperature in this temperature region. In addition, it can be seen from the inset of Fig. 1 that theoretical values of forward branch of *I-V* characteristics are in quite good agreement with the experimental values.

Figure 2 shows the capacitance-voltage characteristics taken at temperature of $T = 300$ K, at frequency of $f = 1$ MHz. Plot of $1/C^2$ vs. V produces a straight line for an abrupt junction. The slope of the plot leads to a carrier concentration of $N_B = 5.8 \times 10^{15}$ cm^{-3} in the active region.

Figure 3 shows the current-voltage characteristics of the investigated structure under different illumination intensities. As can be seen from the figure, the photocurrent under various illumination intensities moves upward along the current axis, giving a short-circuit current (I_{sc}) at $V = 0$.

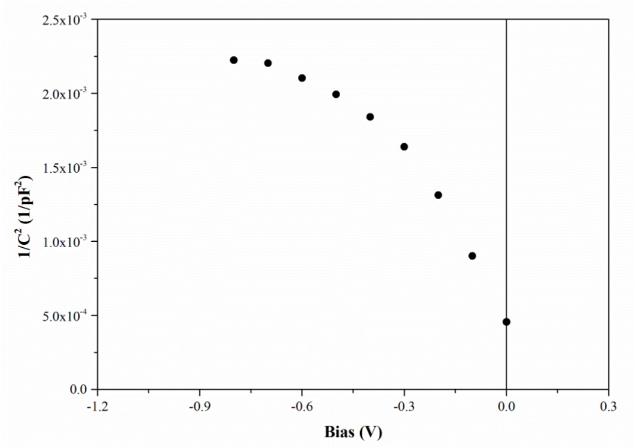

Fig. 2. Capacitance-voltage characteristics of the investigated GaSb/$GaIn_{0.24}AsSb$/$GaAl_{0.34}AsSb$ structure at room temperature.

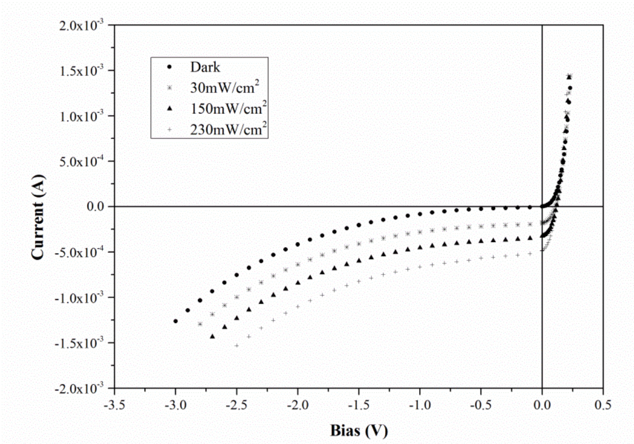

Fig. 3. *I-V* characteristics in dark conditions and under various illumination intensities.

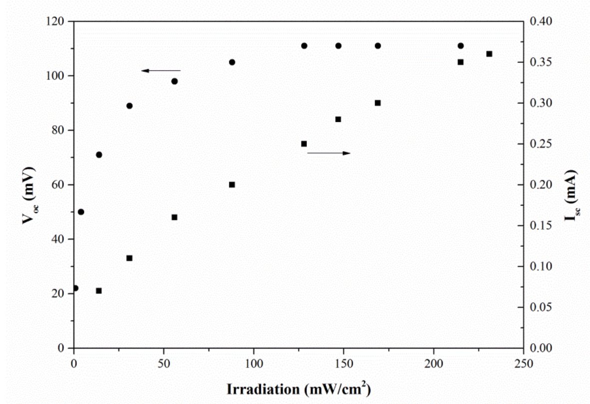

Fig. 4. Variation of the open circuit voltage and the short-circuit current with light intensity, under illumination with a 150 W halogen lamp with applied infrared filter, at room temperature.

It can be seen from Fig. 4 that both the short-circuit current (I_{sc}) and the open-circuit voltage (V_{oc}) depend on the light intensity. At high intensity of the incident light these dependences deviate from linearity.

The nonlinearity in the short-circuit current can be described by the increase of voltage drop across the serial resistance of the base. The reduced growth of V_{oc} with light intensity is explained by the decrease of the height of the potential barrier at the GaInAsSb/GaAlAsSb heterointerface, with the accumulation of excess electron charge in the n-GaInAsSb region and holes in the p-GaAlAsSb region. As the consequence of this process the electric field of p-n heterojunction less effectively separates the light carriers and the increase in the V_{oc} slows down with the increase of the light intensity.

4. Conclusions

In summary, we have presented the results of electrical characterization of GaSb/GaIn$_{0.24}$AsSb/GaAl$_{0.34}$AsSb heterostructure with a diameter of 0.3 mm in the temperature range of 77–300 K. It is demonstrated that diffusion current dominates at the high temperatures in small forward bias region, while generation-recombination current dominates in the intermediate temperature region. At low temperatures, the tunneling mechanism dominates in both forward and reverse biases. In addition, optical properties, including open circuit voltage and short circuit current, were investigated at room temperature. It is concluded that, for short circuit current, the increase of voltage drop across the serial resistance of the base causes deviation from linearity and the decrease of the potential barrier height slows down the increase of the V_{oc} with increasing light intensity.

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