Electrical Properties of Photodiodes Based on p-GaSb/p-GaInAsSb/N-GaAlAsSb Heterojunctions

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Received April 23, 2008

Abstract—We have studied the electrical characteristics of photodiodes based on p-GaSb/p-GaInAsSb/N-GaAlAsSb heterojunctions and investigated the mechanisms of current transfer in these heterostructures at various temperatures. A comparison of the theoretical results and experimental data showed that the tunneling charge transfer mechanism dominates at low temperatures \( T < 150 \text{ K} \) under both forward and reverse bias conditions. The tunneling current becomes a determining factor at an electric field strength in the \( p-n \) junction of no less than \( 10^5 \text{ V/cm} \), which is related to a small bandgap width of the materials studied and low effective masses of electrons and holes.

PACS numbers: 73.40.Kp, 85.60.Dw

DOI: 10.1134/S1063785008110114

In recent years, heterostructures based on GaInAsSb solid solutions have been widely used for the creation of optoelectronic devices (including both emitters and detectors) operating on a spectral range of 2–5 µm. Such devices are important components for the optical communication systems based on fluoride and chalcogenide glasses and for the systems of ecological monitoring [1], since the absorption bands of a series of industrial gases and atmospheric pollutants fall in this spectral range [2].

The main application fields for photodiodes are related to the laser diode spectroscopy (and its use for the analysis of gas media, food products, and biological objects), laser ranging, and remote sensing. All these applications have sharp differences in the principles of design of the receiving equipment for system employing different kinds of radiation sources (laser, light emitting diodes, natural radiating objects). This implies that photodetectors must also possess different parameters and characteristics. For example, in the laser ranging and remote sensing systems, the main parameter is the response speed and one of the main characteristics is the detector noise; in the systems for gas analysis, an important parameter is the detector area and an important characteristic is the detection ability. In turn, high detection ability in a broad frequency range is determined by the dark current.

This Letter presents the results of investigation of the electrical properties of p-GaSb/p-GaInAsSb/N-GaAlAsSb photodiode heterostructures at various temperatures. Our aim was to elucidate the mechanisms of current transfer with a view to creating photodiodes for the spectral range of 1.5–3.0 µm with a low level of reverse dark currents, which could be used in equipment for various applications [3, 4].

Heterostructures of the GaSb/GaInAsSb/GaAlAsSb type [5, 6] were grown by liquid phase epitaxy (LPE) on GaSb(100) substrates doped with tellurium to a hole concentration of \( (2–5) \times 10^{17} \text{ cm}^{-3} \). The narrow-bandgap \( p-\text{Ga}_{0.78}\text{In}_{0.22}\text{As}_{0.18}\text{Sb}_{0.82} \) active layer \( (E_g = 0.53 \text{ eV}, T = 300 \text{ K}) \) and the wide-bandgap \( \text{Ga}_{0.66}\text{Al}_{0.34}\text{As}_{0.025}\text{Sb}_{0.975} \) \( (E_g = 1.1 \text{ eV}, T = 300 \text{ K}) \) were doped with tellurium to \( p = (1–8) \times 10^{15} \text{ cm}^{-3} \) and \( N = (1–3) \times 10^{18} \text{ cm}^{-3} \). The epilayers were isoperiodic with the GaSb substrate, the lattice mismatch not exceeding \( \Delta a/a < 10^{-3} \).

Based on the wafers with LPE-grown heterostructures, mesa diodes with a sensitive pad diameter of 300–500 µm were fabricated using standard photolithographic techniques. The current–voltage \((I-U)\) and capacitance–voltage \((C-U)\) characteristics were measured using Keithley 2400 and Keithley 590/1M analyzers, respectively. The measurements were performed in a Janis CCS-150 cryostat, which allowed the sample temperature to be varied in a 10–360 K range. The results of measurements were fed via an IEEE-488 interface into a computer for storage and processing.

The \( I-U \) and \( C-U \) characteristics of \( p-\text{GaSb}/p-\text{GaInAsSb}/N-\text{GaAlAsSb} \) heterostructures were measured at various temperatures. The \( C-U \) curves are satisfactorily described by the relation \( C^2 = U \), which is typical of a sharp junction. The space-charge layer (depletion...
where $e$ is the electron charge, $U$ is the applied voltage, $k$ is the Boltzmann constant, $T$ is the absolute temperature, and $\beta$ is the nonideality factor. The latter factor increases with decreasing temperature from $\beta = 1.1$ at $T = 360–300$ K to $\beta = 4.9$ at $T = 80$ K (see Fig. 1b).

In the temperature intervals 360–230 K and 230–160 K, the current transfer is determined by different mechanisms—diffusion and recombination, respectively. At lower temperatures ($T \leq 150$ K), a significant role is played by the tunneling current, which confirmed by weak temperature dependence of the forward current in this range.

Figure 2a shows the reverse branches of the $I–U$ curves measured at various temperatures. In the interval of $T = 230–360$ K at $U = −(1–4)$ V, the reverse current in the dark is determined by carrier generation in the region of depletion and can be described by the following formula:

$$I = \frac{en_iWA}{\tau_{\text{eff}}},$$  \hspace{1cm} (2)

where $n_i$ is the intrinsic carrier concentration in a GaIn$_{0.22}$AsSb solid solution, $W$ is the space charge region width at a given applied voltage, $A$ is the heterostructure area, and $\tau_{\text{eff}}$ is the effective carrier lifetime. The effective carrier lifetime evaluated from the dark current magnitude amounted to $\tau_{\text{eff}} = (6–9) \times 10^{-8}$ s.

Figure 2b presents plots of the reverse current in the dark versus $10^3/T$ as measured at various bias voltages. The current transfer activation energy determined from these data at $U = −1$ V in the temperature interval of $T = 230–360$ K amounted to $E_A = 0.26 \pm 0.02$ eV, which is close to a half of the bandgap width for the narrow-bandgap GaInAsSb solid solution used in the active region of the heterostructure under consideration. This value of the activation energy is evidence of the determining role of the generation mechanism of the dark current transfer. The theoretical temperature [7] dependence of dark current according to the generation-recombination (GR) mechanism is also presented in Fig. 2b (dashed curve 4). As can be seen, the experimental data at low temperatures agree with the behavior predicted by the GR mechanism, according to which the current is described by the following formula:

$$I \sim T^{3/2} \exp(-E_g/2kT),$$  \hspace{1cm} (3)

where $E_g$ is the bandgap width and $T$ is the absolute temperature.

Deviation of the experimental data from theoretical predictions is related to an increasing influence of the tunneling component. This component weakly depends on the temperature and plays a determining role in narrow-bandgap direct-gap materials at low temperatures and/or large reverse bias voltages [8]. Our estimations showed that, in the region of room temperature, the tunneling mechanism predominates for reverse bias voltages $U > 5$ V, while at low temperatures it is dominating.