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Tunneling current via dislocations in InAs and InSb infrared photodiodes

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Abstract. Carrier transport mechanisms are investigated in InAs and InSb infrared photodiodes. The photodiodes were prepared by thermal diffusion of Cd and ion implantation of Be into InAs and InSb single-crystal substrates of *n*-type conductivity, respectively. The direct current was measured as a function of bias voltage and temperature. The excess tunneling current is observed in the investigated photodiodes at small forward bias voltages. Experimental proofs are obtained that dislocations are responsible for this current. A model for the tunneling current via dislocations is briefly discussed.

Keywords: infrared, photodiode, InSb, InAs, tunneling current, dislocation.

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1. Introduction

Despite the fact that InSb and InAs photodiodes are widely used in infrared (IR) technique, improvement of their performance still remains as an important problem [1-8]. An excess dark current frequently observed in these photodiodes at small reverse and forward biases results in decrease of their threshold parameters such as responsivity and specific detectivity. An excess current was also observed by many authors in IR photodiodes made of narrow-gap A_2B_6 and A_4B_6 semiconductors [1]. However, the nature of this current seems to be well understood in rare cases. For instance, the trap-assisted tunneling via single level in the gap introduced by point defects was proved to be the main reason for the excess current in HgCdTe IR photodiodes at rather small reverse biases followed by the direct band-to-band tunneling current at higher biases [1, 9-11]. Moreover, in HgCdTe photodiodes the trap-assisted tunneling current is shown to be a source of the low-frequency 1/*f* noise [9, 10]. Similar results were also obtained in HgCdTe MIS structures [11]. Dislocations are also known for a long time as a source of an excess current in semiconductor devices, especially when they intersect the depletion region of the $p-n$ junction [12-15]. As to InAs as well as InSb photodiodes, their role is not established clearly. Therefore, identification of the type of defects participating in the carrier transport in InAS and InSb IR photodiodes is a key problem for improvement of their performance.

To our knowledge, the tunneling current in IR photodiodes at forward biases seems to be not analyzed in details till now. Obviously, the trap-assisted and band-to-band tunneling mechanisms are less effective at forward biases in these photodiodes. Therefore, it is a most likely that the excess current at forward biases may have another nature. The aim of this study is to clarify the carrier transport mechanisms in InAs and InSb IR photodiodes at forward biases. For this purpose, the forward current as a function of temperature and bias voltage is investigated in InAs and InSb photodiodes of different quality.

2. Preparation of photodiodes

The monocrystalline substrates of *n*-type conductivity were used to prepare InAs photodiodes. In order to investigate the effect of dislocations on the dark current, these substrates were cut from different parts of ingots grown by Bridgman technique (Pure Metals Co., Svetlovodsk, Ukraine). The density of dislocations measured by the etch-pit method was of the order of 10^4 cm^{-2}. The damaged surface layers were removed using dynamic chemical-mechanical polishing in solution of methanol with 2% of Br_2. The electron concentration and mobility in the initial substrates were $(2-3)\times10^{16}\,\text{cm}^{-3}$ and $(2-2.5)\times10^{4}\,\text{cm}^2/\text{V}\cdot\text{s}$, respectively. The dislocation density was ranged from $(1-2)\times10\,\text{cm}^{-2}$ in the central part of ingots up to $4\times10^{5}\,\text{cm}^{-2}$ at the periphery ones. The $p-n$ junctions were prepared by thermal diffusion of preliminary synthesized $CdAs_2$ into substrates in sealed evacuated silica ampules. Mesa structures with the active area $A = 7\times10^{-3}\,\text{cm}^2$ were delineated using the standard photolithographic technique. Then Zn and In contact pads were thermally deposited onto *p*- and *n*-type sides of the junction, respectively, followed by a heat treatment in purified hydrogen atmosphere. InSb photodiodes were manufactured by implantation of beryllium into appropriately prepared substrates followed by thermal annelaing. In *n*-InSb substrates the electron concentration and mobility were of the order of $(1-2)\times10^{15}\,\text{cm}^{-3}$ and $(6-7)\times10^{5}\,\text{cm}^2/\text{V}\cdot\text{s}$ at 77 K, respectively. The dislocation density in InSb substrates did not exceed $5\times10^{2}\,\text{cm}^{-2}$. Photodiodes have a planar structure with the junction area $A = 1.33\times10^{-2}\,\text{cm}^2$.

3. Experimental results and discussion

The current-voltage characteristics measured in representative InAs and InSb photodiodes are shown in Fig. 1. Note that InAs photodiodes were prepared on substrates with different densities of dislocations. As seen, the measured characteristics consist of two exponential parts. At lower bias voltages, the forward current in InAs photodiodes increases with increasing the density of dislocations, whereas at higher voltages it has approximately the same magnitude for both photodiodes. Fig. 2 shows the temperature dependence of the forward current in InAs and InSb photodiodes measured at the bias voltage 10 mV. At low temperatures $T < 130$ K the measured current is weakly dependent on temperature. At the same time, at higher temperatures it exhibits an activation character. To clarify the observed peculiarities, the current-voltage characteristics were investigated in InAs photodiode subjected to ultrasonic treatment with the frequency 5 – 7 MHz and intensity close to 0.4 W/cm^2 for four hours at room temperature (Fig. 3). The dark current was measured as a function of bias voltage immediately after ultrasonic treatment as well as after approximately one-year storage of photodiodes under laboratory conditions. It must be pointed out that the ultrasonic treatment results in a pronounced increase of the dark current at lower bias voltages, whereas those parts of the current-voltage characteristics measured at higher voltages remained almost unchanged. Also, it is important to note that after storage of samples within one year the excess current caused by ultrasonic treatment is decreased to approximately the initial values.

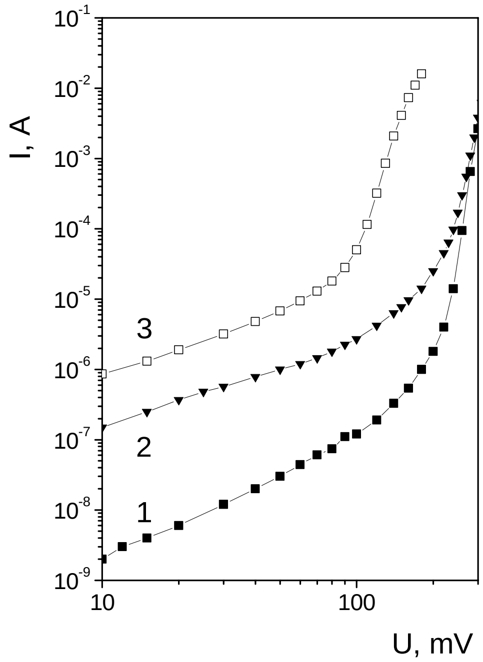

Fig. 1. Current-voltage characteristics in InAs (*1*, *2*) and InSb (*3*) photodiodes at 77 K. Curves (*1*) and (*2*) refer to the dislocation density in substrates 4×10^4 and $2\times10^5\,\text{cm}^{-2}$, respectively.

Our explanation of experimental results is based on the assumption that dislocations intersecting the depletion region are responsible for the excess current at small forward biases. A model for tunneling current via dislocations intersecting the depletion region of the junction has been proposed Evstropov et al. [16, 17]. Experimentally, it has also been investigated in [18]. According to this model, mobile carriers (holes and electrons) move along acceptor-like and donor-like dislocation lines, which has been modeled by a chain of parabolic potential barriers with a variable height. In a symmetric junction, the forward current flows due to direct recombination of electrons and holes at the middle of the depletion region. The current-voltage characteristics can be described by the formula

$$I = I_{01}\exp\left(\frac{e(U - IR_S)}{E_0}\right) + I_{02}\exp\left(\frac{e(U - IR_S)}{\beta kT}\right), \quad (1)$$

where I_{01} and I_{02} are the pre-exponential factors, E_0 is the characteristic energy; β is the ideality factor, and R_S is the series resistance.

The temperature dependence of the pre-exponential factor in the equation (1) is then given by:

$$I_{01} = e\rho\nu_D A\exp\left(-\frac{eU_D}{E_0}\right), \quad (2)$$

where ρ is the density of dislocations, ν_D is the Debye frequency, U_D is the diffusion potential. The current I_{02} can be calculated from the formula

$$I_{02} = \frac{e n_i W_0 A}{\tau_0}, \qquad (3)$$

where n_i is the intrinsic concentration of carriers, W_0 is the depletion region width. The carrier lifetime τ_0 serves as an adjusting parameter. Typical parameters of a representative InAs photodiode extracted from the measured $I-U$ characteristics are shown in Table.

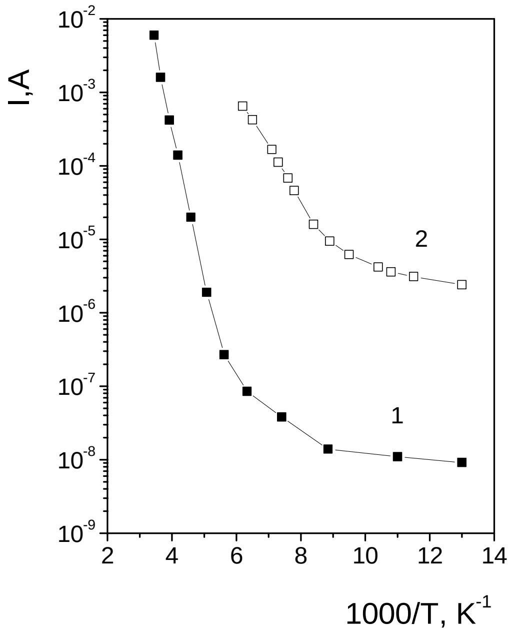

Fig. 2. Temperature dependences of the forward current measured at 10 mV in InAs (*1*) and InSb (*2*) photodiodes.

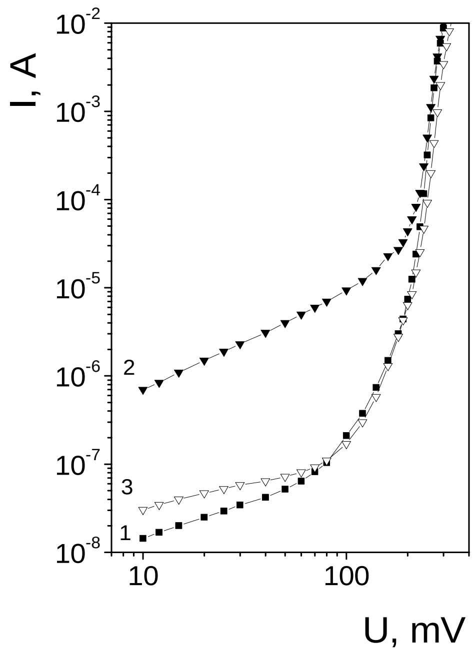

Fig. 3. Current-voltage characteristics in InAs photodiodes before (*1*) and after (*2*) ultrasonic treatment, and after one-year storage (*3*).

Table. Parameters of the tunneling current in InAs photodiodes.

T, K	eU_D, meV	E_0, meV	I_{01}, A calculated	I_{01}, A measured
77	365	40.5	4.3×10^{-8}	1.1×10^{-8}
113	305	41.4	2.2×10^{-7}	2.1×10^{-8}
135	208	39.6	3.5×10^{-7}	4.2×10^{-8}

Because of the fact that in the investigated photodiodes the diffusion potential linearly depends on temperature [8], the exponential dependence of I_{01} on temperature should be observed. Also, in accordance with [16, 17], the characteristic energy E_0 is independent of the concentartion of free carriers. These consequences of the analyzed model may be used for discrimination of the tunneling current via dislocations. For instance, by using the typical experimental data for InSb photodiodes at 77 K ($I_0 / A = 8.85\times10^{-5}$ A/cm^2, U_D = 160 mV, E_0 = 29 meV and $\nu_D = 3.3\times10^{12}\,\mathrm{s}^{-1}$, which was determined from the known value of Debye temperature T_D = 160 K [19]), the dislocation density $\rho = 4.2\times10^4\,\mathrm{cm}^{-2}$ was estimated. This value is almost two orders of magnitude higher than in the starting substrates. The relatively high density of dislocations can be explained by the fact that during the heat treatment the edge of junction was not removed from the zone of radiation defects formed by ion implantation of beryllium in InSb. However, the same descrepancy between experimental and theoretical data was also observed in InAs photodiodes prepared by the diffusion technique. Moreover, in the investigated InAs photodiodes the characteristic energy E_0 was found to be varied from ~30 up to ~60 meV in contrast to theoretical predictions. It must be stressed that values of E_0 experimentally obtained in this study are close to those observed in diodes made of wide-gap GaP and SiC [16-18]. It means that the tunneling current via dislocations is characterized by the same features independent of semiconductor materials used to manufacture the diode structures.

The observed desrepancy between theoretical and experimental data may be caused by several reasons. First of all, in the model developed in [16, 17] dislocation lines are assumed to be fully occupied by carriers and have a length of the order of the depletion region width. This situation seems to be non-typical for dislocations in semiconductors [12-14]. The presence of jogs, inclusions of impurity atoms, kinks, etc., results in a loss of translation symmetry along the dislocation line and spatial localization of mobile carriers. Thus, only short dislocation segments can contribute to the direct current transfer [13, 20, 21]. It is supposed that this is the main reason why the direct current transfer along dislocation cores is not clearly demonstrated so far [13]. Further, acacording to Shockley [13] and Labusch and

Schröter [22] dislocations in semiconductors introduce one-dimensional energy bands into the gap, located near the conduction and valence band edges. Direct recombination transitions between these bands seem to be not effective. The much more effective is recombination through deep defect states in the gap [23, 24].

Our further analysis of the experimental data is based on assumption that dislocations in the investigated photodiodes are non-uniformly distributed through the *p-n* junction. So, there are two conduction paths for mobile carriers: the tunneling current flows via those parts of the junction which are characterized by increased concentration of dislocations intersecting the depletion region, whereas the recombination current flows via homogeneous regions free of dislocations. At low bias voltages, the tunneling current is dominant, therefore the forward $I-U$ characteristic is described by the first term in the equation (1). Thus, the weak dependence of the forward current on temperature in Fig. 3 can be qualitatively understood. With increasing the bias voltage, this current is masked by the recombination one, which can be explained in terms of Shockley-Read-Hall model [25]. This change in the current mechanism is described by the second term in Eq. (1).

Due to the fact that recombination of carriers captured at dislocation bands can be substantially enhanced by the presence of small amount of impurity atoms at the dislocation core, we assumed that the low-temperature carrier transport mechanism consists of several steps, namely: a) injection of electrons into the depletion region under the forward bias, b) capture of electrons on the dislocation core by tunneling transitions, c) electron transport along the undisturbed segments of the dislocation core, and d) recombination of electrons with holes through the states in the gap related with "native" core defects (such as jogs and kinks) or impurity atoms segregated around the dislocation core. In the case when the dislocation core can exchange electrons directly with the conduction band, the energy E_0 is the dislocation barrier height. Using experimental values for the density of dislocations ($\sim 10^4\,\mathrm{cm}^{-2}$) and the forward current $\left(10^{-8}-10^{-7}\,\mathrm{A}\right)$, it is easy to show that dislocations form equipotential lines. If we take into account that the dislocation resistivity is of the order of 10^{10} Ohm/cm [26], the voltage drop along a segment of dislocation of $10^{-5}\,\mathrm{cm}$ is less than $10^{-4}\,\mathrm{V}$. So, it is likely that at low temperatures tunneling transitions of electrons to the dislocation core is the bottle-neck for the forward current in the investigated photodiodes. Also, based on results of ultrasonic treatment, tunneling transitions via local states in the gap, associated with point defects or their precipitates surrounding dislocations, should not be excluded. Because of the fact that in this study the pre-threshold intensity of ultrasonic treatment was used, the experimental data in Fig. 3 may be explained by rearrangement of existing defects rather than generation of new point defects. In accordance with the vibrating string model of Granato-Luecke [27], the intensive sonic-dislocation interaction results in an effective transformation of the absorbed ultrasonic energy into the internal vibration states of a semiconductor stimulating different defect reactions. The driving force of long-term relaxation of the forward current may be deformation fields around dislocations. Obviously, physical meaning of E_0 in this two-step process should be corrected taking into account the energy of local states.

4. Conclusions

The excess current experimentally observed in InAs and InSb photodiodes at forward biases is related to dislocations intersecting the depletion region. The pronounced effect of ultrasonic treatment on the forward current is explained by transformation of defects segregated around dislocations. The model for carrier transport via dislocations includes capture of electrons on the dislocation core by means of tunneling transitions and recombination with holes through the states in the gap.

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