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1/*f* noise and carrier transport mechanisms in InSb p^+-*n* junctions

V.V. Tetyorkin[1*], A.V. Sukach[1], A.I. Tkachuk[2], S.P. Trotsenko[1]

[1] *V. Lashkaryov Institute of Semiconductor Physics, NAS of Ukraine, 03680 Kyiv, Ukraine*
[*] *E-mail: teterkin@isp.kiev.ua*

[2] *V. Vynnychenko Central Ukrainian State Pedagogical University, 25006 Kropyvnytskyi, Ukraine*

Abstract. The dark current and 1/*f* noise spectra have been investigated in p^+-*n* InSb junctions. The photodiodes were prepared by Cd diffusion into single crystal substrates. The current-voltage characteristics have been explained within a model of inhomogeneous *p-n* junction. The junction inhomogeneities are caused by dislocations crossing the depletion region. The correlation between the trap-assisted tunneling current through the local inhomogeneous regions of the junction and 1/*f* noise has been shown to exist. The fluctuations of the junction resistance have been argued to be responsible for the origin of 1/*f* noise.

Keywords: InSb, infrared spectrum, *p-n* junction, trap-assisted tunneling, 1/*f* noise.

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1. Introduction

Now InSb is one of the most important materials for manufacturing photodiodes as well as photodiode focal plane arrays for middle wavelength infrared region λ = 3-5 μm [1]. The commonly used techniques to produce InSb photodiodes are Be implantation and Cd diffusion into bulk crystals of *n*-type conductivity. The performance of these photodiodes is essentially limited by excess current through the traps in the gap. The traps can act as effective recombination centers as well as can enhance interband tunneling, giving rise to excess dark current. The careful analysis of carrier transport mechanisms at medium and moderately large reverse bias voltages has been made in p^+-*n* junctions prepared using Cd diffusion into bulk crystals [2-5]. It was shown that the total dark current suffer from trap-assisted tunneling (TAT) and surface leakage phenomena. Also, the dark current is dependent critically on the conditions of the diffusion process.

The nature of low-frequency 1/*f* noise in InSb still remains the problem under investigation. It was treated both as bulk and surface phenomena [6-18]. Experimental data on low-frequency noise in InSb photodiodes are contradictory. For instance, published in literature the Hooge parameter values vary within the large range from 10^{-1} down to 10^{-6} [13-15, 18].

The aim of this work was to investigate the dark current and 1/*f* noise in InSb diffusion p^+-*n* junctions in order to clarify both carrier transport and noise mechanisms as well as to find possible correlation between them.

2. Device processing and measurement techniques

The starting materials were undoped and Te doped single crystals of *n*-InSb with the electron concentration within the range $10^{14}…10^{15}$ cm^{-3}. The dislocation density in the substrates was of the order of 10^2 cm^2. Earlier, we developed three methods of cadmium diffusion into *n*-InSb substrates labeled as TR1, TR2 and TR3 [5]. It was shown that the best parameters of diffusion *p-n* junctions were implemented in two-stage diffusion technique, when after isothermal diffusion of Cd at 380 °C the thermal annealing at 420 °C was carried out for 60 min in a separate ampoule. The worse data were obtained for the isothermal diffusion at 420 °C for 30 min. Like to the previous investigations, the mesa structures with an active area $1.2\cdot10^{-2}$ cm^2 were delineated by chemical etching. Ohmic contacts to *p*- and *n*-type regions of the junctions were prepared using In-Zn alloy and pure In, respectively. Formation of ohmic contacts and purification of mesas was carried out in a hydrogen atmosphere at ~350 °C for 5 to 10 min. Thin polycrystalline films of CdTe were used as passivative and protective layers due to good agreement between lattice parameters and thermal expansion coefficients of CdTe and InSb.

The current-voltage and high-frequency (1 MHz) capacitance-voltage characteristics were measured as a function of bias voltage and temperature. The noise spectra were investigated within the frequency range of $5…2\cdot10^4$ Hz at 77 K. The measuring set up consisted of a transimpedance amplifier and a spectrum analyzer CK4-74. The transimpedance amplifier is essentially

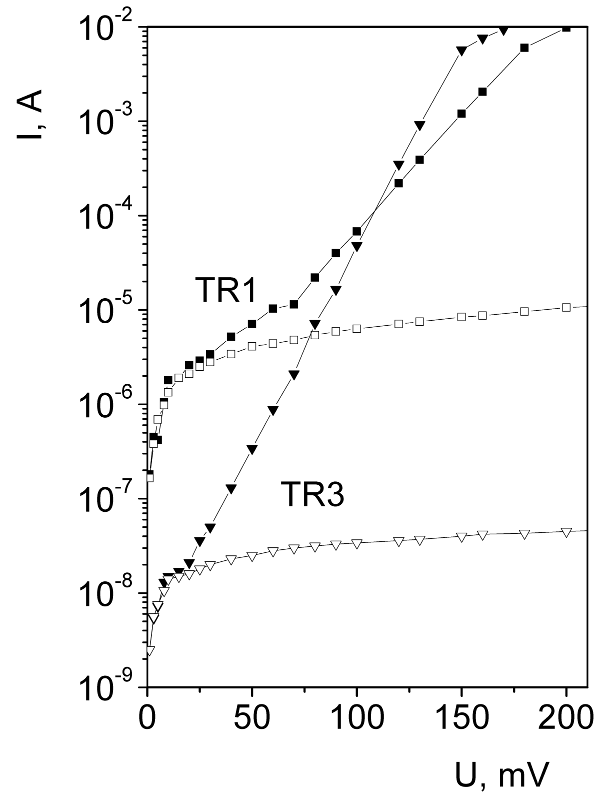

Fig. 1. Current-voltage characteristics in forward biased (close dots) and reverse biased (open dots) TR1 and TR3 junctions at 77 K.

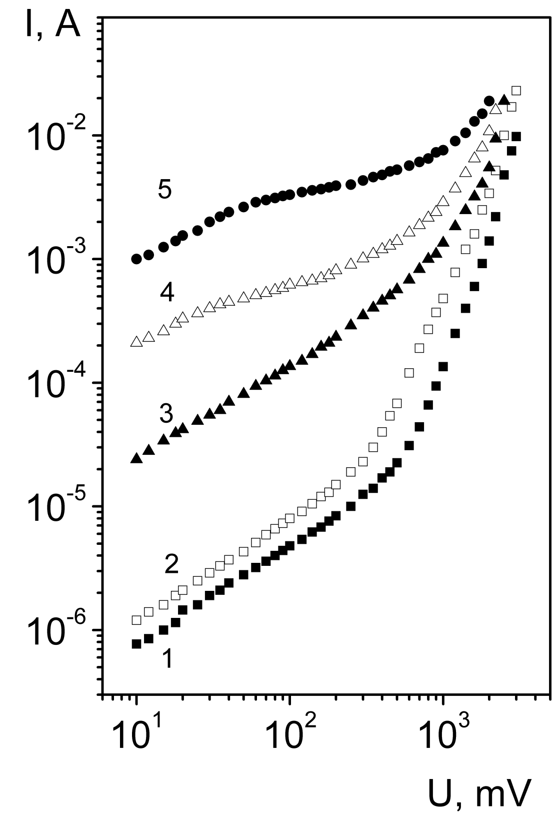

Fig. 2. Reverse *I-V* characteristics in TR1 junction at temperatures, K: 77 (*1*), 89 (*2*), 120 (*3*), 138 (*4*), 156 (*5*).

a low-noise field-effect transistor operational amplifier operating in a negative feedback current mode. The requirements to operational amplifiers for photodiodes A^3B^5 with rather low dynamical resistance are discussed in [19]. The developed amplifier allows correct measurements of noise in the junctions with the dynamic resistance >3 kOhm.

3. Results and discussion

In the investigated *p-n* junctions, the capacitance-voltage characteristics are linearized in C^{-3}-*V* coordinates indicating formation of linearly graded structures. The junction parameters such as the concentration gradient, built-in voltage and the depletion region width were determined from the *C-V* measurements.

The current-voltage characteristics measured in representative *p-n* junctions prepared by different diffusion techniques are shown in Fig. 1. It is necessary to emphasize the following features of the obtained *I-V* dependences. The junction prepared using TR3 method exhibits the lowest dark current at low and moderate bias voltages. At the same time, in the junction prepared using TR1 method (hereafter TR1 and TR3 junctions) the excess current at the forward bias voltages is clearly observed, Fig. 1. Within the temperature range 77…160 K, the forward current-voltage characteristic of the photodiode is expressed as

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

where $E_0 = 29$ meV is the characteristic energy. Other parameters in the equation (1) are shown in Table [5]. The *I-V* characteristic of the junction TR3 is described by the second term in (1). The junction parameters shown in Table indicate that the forward current in TR3 junction is composed of diffusion and recombination currents, whereas in TR2 junction it is mainly limited by tunneling current at small biases and recombination current at higher biases.

Table. Parameters of diffusion InSb *p-n* junctions at $T = 77$ K [5].

Diffusion method	I_{01}, A	R_0A, Ohm·cm^2	I_{02}, A	β	a, cm^{-4}	W_0, µm	τ_0, s
TR1	1.3×10^{-6}	6.8×10^2	2.2×10^{-7}	2.7	2.3×10^{19}	1.0	1.6×10^{-9}
				2.1	1.3×10^{19}	1.1	
TR2	8.4×10^{-8}	1.4×10^3	5.0×10^{-8}	1.6	8.5×10^{18}	1.3	7.9×10^{-9}
TR3	–	3.5×10^4	4.0×10^{-9}				1.2×10^{-7}

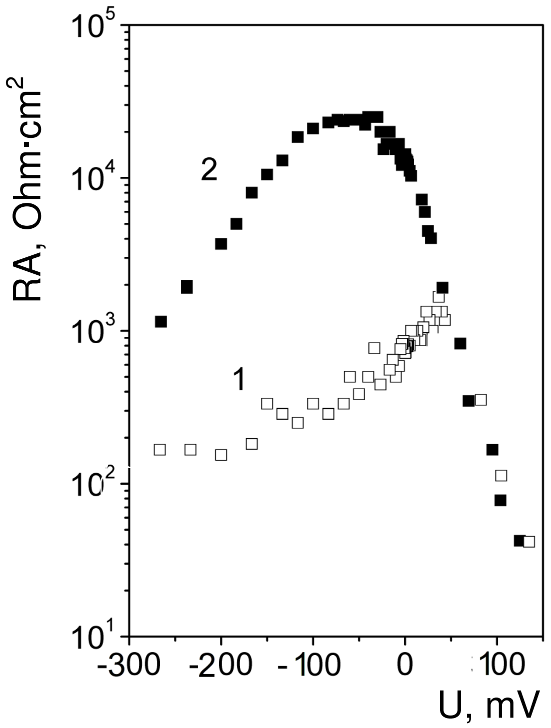

Fig. 3. Resistance-area product in TR1 (open dots) and TR3 (close dots) junctions at 77 K.

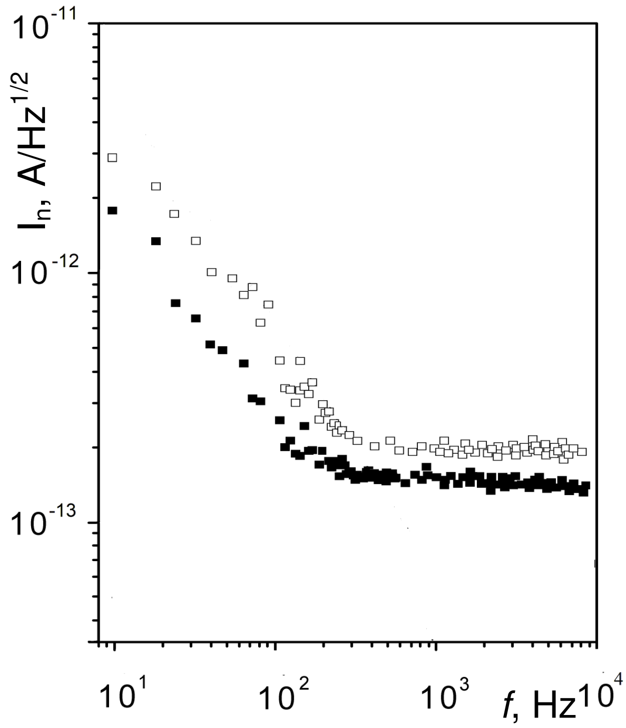

Fig. 4. Noise spectra measured in TR3 junction measured at the reverse bias -10 mV, T = 77 K.

The reverse *I-U* characteristics measured in TR1 junction within the temperature range 77…156 K are shown in Fig. 2. They are approximated by the power dependence $I \sim U^m$. At temperatures $T < 120$ K and bias voltages $U \le 0.2$ V, the sublinear *I-U* dependences with the exponent $m \cong 0.8$ are observed. At higher temperatures (curves *4*, *5*) $m \cong 0.7…0.8$ for bias voltages $U \le 0.03$ V and m equals approximately 0.3 for higher voltages $0.04 < U \le 0.2$. The reverse current tends to saturation, which is typical for the thermal generation mechanism of carrier transport in homogeneous *p-n* junctions. With the reverse bias increase, the current increases and m varies from 2-3 at U = 1…2 V up to 4.5…5.0 at higher biases. It must be pointed out that the reverse current varies within approximately three orders of magnitude over the temperature range 77…156 K.

Shown in Fig. 3 are voltage dependences of the differential resistance-area product (RA) at the temperature 77 K. Note that the $RA(U)$ dependence in TR1 junction is peaked at the forward bias, whereas in TR3 junction it has maximal value at the reverse bias of approximately 50 mV.

Noise spectra in the investigated junctions are shown in Figs. 4 and 5. All spectra were measured at 77 K for the reverse bias voltage –10 mV. As seen, the spectra are of the form 1/*f* at the frequencies $f \le 2 \cdot 10^2$ Hz in TR3 junction. In TR1 junction, the 1/*f* noise dominates in the whole range of the measuring frequencies. Note also the weak temperature dependence of the noise current in TR1 junction.

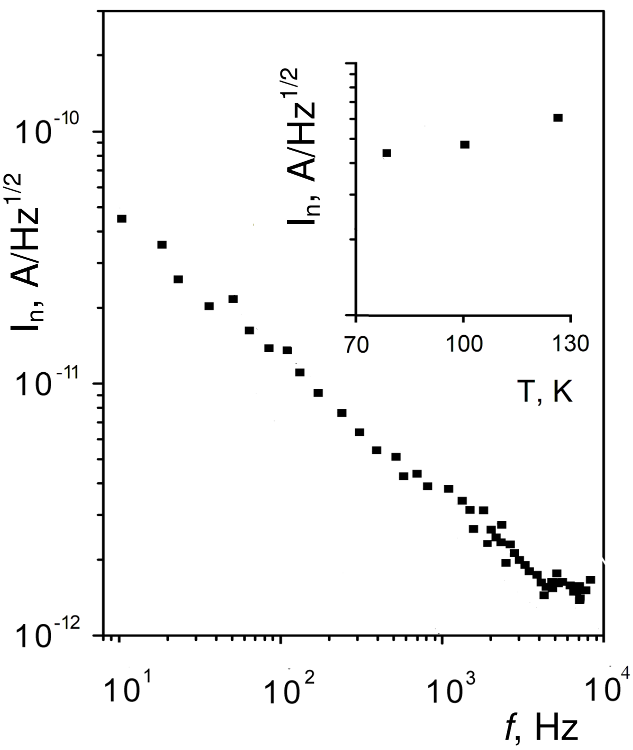

Fig. 5. Noise spectra in TR1 junction measured at the reverse bias –10 mV, T = 77 K. The inset shows the dependence of the noise current on temperature.

It is known that tunneling at forward bias in a junction composed of non-degenerate semiconductors is possible only if dissipation of energy is involved, due to the bottom of the conduction band of the *n*-type side of the junction is higher than the top of the valence band in the *p*-type side. Localized defect states in the forbidden gap may provide a path for carrier transport across the junction. However, this process is not efficient for a single level of the localized states in the gap. A multisteps tunneling-recombination model has been proposed by Riben and Feucht to describe tunneling currents in forward bias in Ge-GaAs heterojunctions [20]. It is important to note that for the multistep tunneling-recombination process the traps in the gap should be uniformly distributed in energy and space. Moreover, this process is possible only if the trapping levels density is sufficiently high.

In order to explain the excess current in the reverse-biased infrared photodiodes, a model of the TAT current in homogeneous *p-n* junctions was developed [21, 22]. Based on this model, the carrier transport mechanisms were explained in $Cd_xHg_{1-x}Te$ photodiodes (x = 0.2…0.3). However, attempts to explain experimental *I-V* characteristics in InAs and InSb junctions by this model were failed due to low electric field strength in the depletion region. For this reason, the model of inhomogeneous junction was proposed in order to explain experimental *I-V* dependences in InAs [2, 3]. The local inhomogeneities were proved to be related to dislocations or other extended defects. The stress field around dislocations is known to be responsible for segregation of foreign impurities and native point defects thus forming the so-called Cottrell atmospheres. It was shown that the electric field in the inhomogeneous regions of the junction may be two orders of magnitude higher than that in the homogeneous part of the junction. Thus, these regions can provide effective paths for the tunneling transition of carriers. The generation current flows through the homogeneous region of the junction free of dislocations. Further analysis of experimental data in InSb and InAs *p-n* junctions revealed that inhomogeneities are responsible for the tunneling current at both reverse and forward biases [2, 3]. The possible reason for the higher concentration of extended defects in TR1 junctions may be retrograde solubility of cadmium in InSb [5].

Because of the TAT current in the investigated junctions is related to inhomogeneities in the depletion region, one can suggest that 1/*f* noise arises due to fluctuations in the junction resistance. It should be pointed out that tunneling current in a semiconductor *p-n* junction has a strong (exponential) dependence on the electric field. So, small fluctuation in the concentration of defects results in exponentially large fluctuation in the tunneling current and, therefore, in the junction resistance. This fact is especially important for IR photodiodes due to several reasons. First, because the photodiodes are made of narrow-gap semiconductors potential barriers have rather low height. Second, electrons and holes have small effective masses. Third, technology of the starting materials is less mature in comparison with widely used Si and GaAs. Obviously, the resistance fluctuations are more pronounced in TR1 junctions due to the diffusion method used for their preparation. The weak dependence of the noise current on the temperature in Fig. 4 is in favour of the proposed model of 1/*f* noise.

The resistivity fluctuations responsible for the origin of 1/*f* noise in semiconductors can arise due to fluctuations of mobility and number of carriers. So, two models of 1/*f* noise were mainly discussed: the Hooge model assuming mobility fluctuations and the McWhorter model assuming number fluctuations [23-25].

In the Hooge model, the noise spectra of 1/*f* type are represented by the equation [23]

$$S_I = \frac{\alpha I^2}{f^{\gamma} N}, \tag{2}$$

where γ is close to unity, N is the number of carriers in the system, $\alpha = 2.3\cdot10^{-3}$ is the so-called Hooge parameter. The 1/*f* noise in infrared photodiodes has been theoretically analyzed in [11, 23-25, 26]. Relations for the magnitude of the 1/*f* noise based on the Hooge model were obtained by Kleinpenning for several types of diodes, including diffusion and GR current dominated diodes, long and short diodes, and illuminated photodiodes [23, 24]. If the dark current is dominated by generation and recombination of carriers in the depletion region, the spectral density of noise is expressed as

$$\begin{aligned} S_I &= \frac{2\alpha q I_0}{3 f \tau_0}\left[\exp\left(\frac{qV}{2kT}\right)-1\right]^2 \exp\left(-\frac{qV}{2kT}\right) = \\ &= \frac{2\alpha q I}{3 f \tau_0}\left[1-\exp\left(\frac{qV}{2kT}\right)\right] \end{aligned} \tag{3}$$

where

$$I_0 = \frac{q n_i^2 W A}{\tau_0} \tag{4}$$

is the generation current in the reverse biased diode. The noise current spectra were calculated for the parameters of Table 1. In order to adjust the noise current calculated using the formula (3) to the experimentally measured one shown in Figs. 4 and 5, the Hooge parameter α should be dependent on the dark current. By using the junction parameters listed in Table, it was found that α is of the order of 10^{-4} and 10^{-5} in TR1 and TR3 junctions, respectively.

The fluctuations of the junction resistance may be also caused by capture of carriers into traps and emission from them. In the case when trapping levels are distributed in the gap and have a wide range of time constants, these traps may be responsible for 1/*f* noise

[15]. Hence, a multisteps tunneling-recombination model proposed by Riben and Feucht [20] may be used for explanation of 1/*f* noise in the forward-biased junctions. However, as shown by Lukyanchikova [26] this model was not proved experimentally.

4. Conclusions

The current-voltage characteristics, differential resistance and noise spectra have been measured in InSb p^+-n-type junctions. It has been found that generation in the depletion region and trap-assisted tunneling are dominant carrier transport mechanisms at reverse bias voltages. The 1/*f* noise measured at low reverse bias can be attributed to fluctuations of the junction resistance. Obviously, the performance of InSb photodiodes is critically dependent of structural and electrical uniformity of the junction *n*-region.

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Authors and CV

Volodymyr V. Tetyorkin: Doctor of Sciences in Physics and Mathematics, Head of the Laboratory of Infrared Semiconductor Photoelectronics at the V. Lashkaryov Institute of Semiconductor Physics, NAS of Ukraine. The area of scientific interests includes physics, technology and application of narrow-gap semiconductors and infrared devices.
V. Lashkaryov Institute of Semiconductor Physics, NAS of Ukraine

Andriy V. Sukach: Senior Scientist at the Department of Semiconductor Chemistry, V. Lashkaryov Institute of Semiconductor Physics, NAS of Ukraine. The area of scientific interests includes physics and technology of infrared sensors
V. Lashkaryov Institute of Semiconductor Physics, NAS of Ukraine.

Andriy I. Tkachuk: assistant professor at the V. Vynnychenko Central Ukrainian State Pedagogical University, Kropyvnytskyi, Ukraine. The area of scientific interests includes physics and technology of infrared devices.
V. Vynnychenko Central Ukrainian State Pedagogical University, Kropyvnytskyi, Ukraine.

Stepan P. Trotsenko: graduated from the Taras Shevchenko National University of Ukraine in 2014 and postgraduate study at the V. Lashkaryov Institute of Semiconductor Physics, NAS of Ukraine.
Currently, he joined to the Laboratory of Infrared Semiconductor Photoelectronics at the *V. Lashkaryov Institute of Semiconductor Physics, NAS of Ukraine.*