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Dark current and 1/*f* noise in forward biased InAs photodiodes

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Abstract. Dark current and low-frequency noise have been studied in forward biased InAs photodiodes within the temperature range 77…290 K. Photodiodes were fabricated by diffusion of Cd into *n*-InAs single crystal substrates. It has been shown that, at the temperatures >130 K, the forward current is defined by recombination of charge carriers with participation of deep states in the middle of band gap. At these temperatures, a correlation is found between forward current and 1/*f* noise. At lower temperatures, the forward current and noise have been analyzed within the model of inhomogeneous *p-n* junction caused by dislocations in the depletion region. The experimental evidence has been obtained that multiple carrier tunneling is the main transport mechanism at low temperatures, which leads to an increase in low-frequency noise.

Keywords: InAs photodiodes, 1/*f* noise, tunneling, dislocations.

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1. Introduction

InAs and ternary compounds based on it are important materials for the manufacture of photodiodes (PDs) and light-emitting diodes for the short-wave and mid-wave infrared ranges [1]. Traditionally, InAs photodiodes with a homojunction can be produced using ion implantation, impurity diffusion or epitaxy. InAs detector technology has clear advantages, namely: chemical and thermal stability of the starting material, good additives, and high quality substrates. Commercially available photodiodes are manufactured by a number of companies, but their threshold parameters and characteristics are significantly lower than their theoretically predicted values. One of the possible reasons for this is the excess current, which is observed experimentally, and the nature of which is not precisely known. Currently, photodiodes of a new type based on InAs, including avalanche and superlattice type II photodiodes, have been developed for third-generation IR systems. As in the case of homojunction PDs, they suffer from an excess noise usually observed at the operation temperatures [1–6]. Thus, the mechanisms of noise in InAs photodiodes remain the subject of experimental and theoretical investigations.

In this work, results of 1/*f* noise and dark current measurements in diffused InAs PDs are presented. The relation between the forward current and noise has been examined as a function of temperature. The correlation between the 1/*f* noise and recombination current in the depletion region was ascertained at the temperatures $T > 130$ K. To interpret the experimental data obtained at lower temperatures, this model can’t be used. To interpret carrier transport and noise, a model of multiple tunneling of carriers in inhomogeneous junction should be used, in which the noise is associated with fluctuations in the carrier density.

2. Preparation of photodiodes

The photodiodes were manufactured using short-term diffusion of Cd into monocrystalline substrates of the *n*-type conductivity. The details of their technology have been described earlier [7]. The electron concentration and mobility in the substrates were, respectively, $n = (2…3)\cdot10^{16}$ cm^{-3} and $\mu_n = (2…2.5\cdot10^4$ cm^2/V·s at 77 K. The density of dislocations was within the range of $(2…4)\cdot10^4$ cm^{-2}. The mesa structures with the area $A = 1.45\cdot10^{-2}$ cm^2 were prepared using chemical etching and passivated in aqueous $(NH_4)_2S$ solution. Below, the results obtained for the passivated PDs are analyzed. Ohmic contacts were deposited using vacuum evaporation of Au-Zn alloy and In onto *p*- and *n*-type sides of the junction, respectively. PDs were characterized by measuring current-voltage and high frequency (1 MHz) capacitance-voltage characteristics as well as by the noise spectra within the temperature range 77…295 K. The latter were measured in the frequency range $5…2\cdot10^4$ Hz.

3. Experimental results and discussion

The capacitance-voltage characteristics in the diffused PDs are linearized in coordinates C^{-2}–U, indicating formation of an abrupt *p-n* junction. From the slope of C^{-2}–U dependences, the effective concentration of free carriers at the edge of the depletion region was estimated to be $n = (3.5…6)\cdot10^{15}$ at 77 K. Due to this reason, formation of p^+-n-n^+ diode structure with a compensated region is assumed [7]. Typical experimental and calculated current-voltage characteristics are shown in Figs 1 and 2. The experimental results can be interpreted as follows. At the temperatures $T > 130$ K, the forward current is defined by diffusion and recombination components, and the diffusion current becomes dominant at $T \geq 290$ K (Figs 1 and 2). With decreasing temperature, the charge transfer mechanism changes significantly. Depending on the bias voltage, two successive parts are clearly observed in the measured *I–U* characteristics (Fig. 2). Plotted in the double logarithmic scale, they show different dependences on temperature (Fig. 3). The current measured at low bias voltages has a weak temperature dependence at $T < 130$ K, followed by an activation dependence at higher temperatures (Fig. 3). On the contrary, for the current measured at high voltages an activation dependence on temperature was observed within the whole temperature range (not shown in Fig. 3). To calculate the recombination current, the model of discrete level in the middle of the band gap was used. The corresponding formulas for calculating the dark current and noise are given in the Appendix. In the calculation, the adjustable parameter was the lifetime of carriers in the depletion region τ_0. Note that the best fit to the measured data was obtained for practically independent of temperature value $\tau_0 = 2\cdot10^{-9}$ s. To fit the diffusion current, the minority carrier lifetime of the order of approximately 10^{-7} s was used. This value of the carrier lifetime is caused by the Shockley–Read recombination mechanism, since the theoretical values for radiative and Auger recombination mechanisms should be much higher [4].

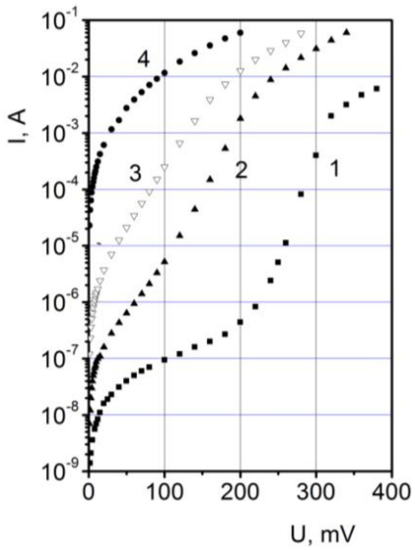

Fig. 1. Typical current-voltage characteristics of an InAs photodiode measured at the temperatures, K: 77 (*1*), 158 (*2*), 197 (*3*), 255 (*4*).

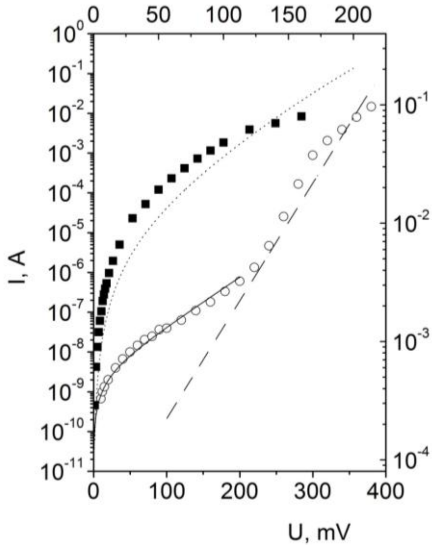

Fig. 2. Forward current as a function of bias voltage measured at 77 K (open points) and 255 K (closed points). The dotted and dashed lines represent the recombination current calculated using the equations (A1) and (A3) for the effective carrier lifetime $\tau_0 = 2\cdot10^{-9}$ s. The solid line represents the excess current calculated according to the equation (3) for $E_0 = 35$ meV.

The low-temperature behavior of the *I–U* characteristics in Figs 2 and 3 can be interpreted as the presence of excess tunneling current in the investigated PDs [8]. In this case, the forward current can be approximated as

$$I = I_{01}\exp\left(\frac{eU - IR_S}{E_0}\right) + I_{02}\exp\left(\frac{eU - IR_S}{2kT}\right), \qquad (1)$$

where I_{01} is the pre-exponential factor and E_0 – characteristic energy representing the tunneling transparency of related energy barriers. The experimental values of E_0 were found to be within the range 30…60 meV at 77 K. In this regard, it should be noted that in the studied PDs a significant spread of the excess current at low temperatures was observed, while for the recombination current it was much lower (Fig. 2). The reason for this may be the effect of dislocations crossing the depletion region. Experimental evidence of this effect has been proven for diffused p^+-n junctions subjected to ultrasonic treatment [9]. A significant increase in the forward current during ultrasonic treatment with subsequent restoration to the initial values after holding the junctions under laboratory conditions was explained by participation of point defects associated with dislocations in charge transfer. The spread of the excess current can be formally described by a change in the characteristic energy E_0, the physical meaning of which must be ascertained.

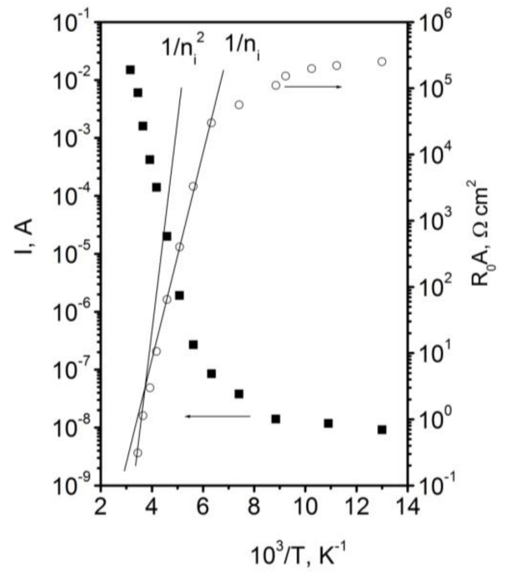

Fig. 3. Temperature dependences of the forward current at U = 10 mV and differential resistance-area product at zero bias R_0A in a representative photodiode. Also, shown are approximations R_0A for diffusion ($\sim 1/n_i^2$) and recombination ($\sim 1/n_i$) currents.

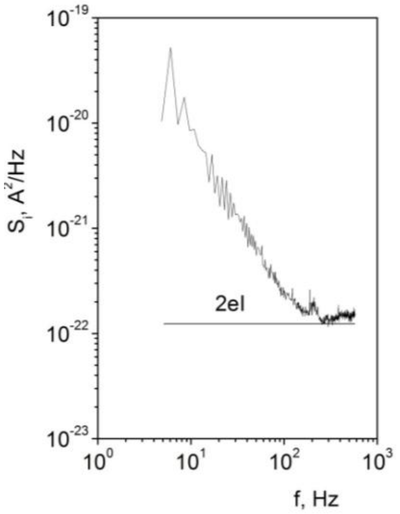

Fig. 4. Typical noise spectrum at 255 K. The solid line represents the shot noise level $2eI$.

A typical frequency dependence of noise is shown in Fig. 4. As in the case of *I–U* measurements, in as-prepared and passivated PDs the magnitude and shape of noise spectra were essentially the same. At low frequencies, the measured noise has the form $1/f^{\gamma}$ with $\gamma = 1.0\ldots1.2$. At high frequencies, the experimental data are close to the case of shot noise $S_i = 2qI$. This means that the recombination of charge carriers in the depletion region occurs through a discrete level in the middle of the band gap. To calculate the $1/f$ noise, we used the model developed by Kleinpenning for p^+-n junctions in narrow-gap semiconductors [10]. In this model, the noise arises from fluctuations in the carrier mobility. The main result obtained in this work is that at $T > 130$ K the measured noise follows the recombination current in the depletion region (Fig. 5). The Hooge parameter was estimated from fitting calculations by using the equation (A7). The best fit was obtained for an α_H of the order of 10^{-5}. As far as the authors know, this parameter for homojunction InAs PDs has not been described yet in the literature. In this regard, it is important to note that the Hooge parameter within the range $10^{-4}\ldots10^{-5}$ was also observed in InAs-based field-effect transistors and superlattices [3, 7]. Since excess noise in semiconductor devices is usually associated with lattice defects, it can be assumed that in these devices manufactured using different methods, the effect of intrinsic structural defects of indium arsenide is manifested.

At low temperatures, the noise in the investigated PD follows the dark current, but its magnitude varies from diode to diode, which correlates with the results of measurements of the current-voltage characteristics. To clarify its origin, the spectral density of noise current, S_i, was measured as a function of the excess current. According to Hooge, S_i must be proportional to the square of the dark current, when noise is caused by the mobility fluctuations [10, 11]. The measured dependences are shown in Fig. 6. As seen, they can be approximated as $S_i \sim I^{\beta}$ with $\beta = 2.1\ldots3.0$. This result seems to be not typical for IR PDs, because the dependence $S_i \sim I^{2.8}$ has been only reported for InSb PDs [12]. However, these dependences are well known for LEDs based on A^3B^5 compounds, which were characterized with a non-uniform distribution of the injection current in the junction caused by generation of dislocations in active region of LEDs [13].

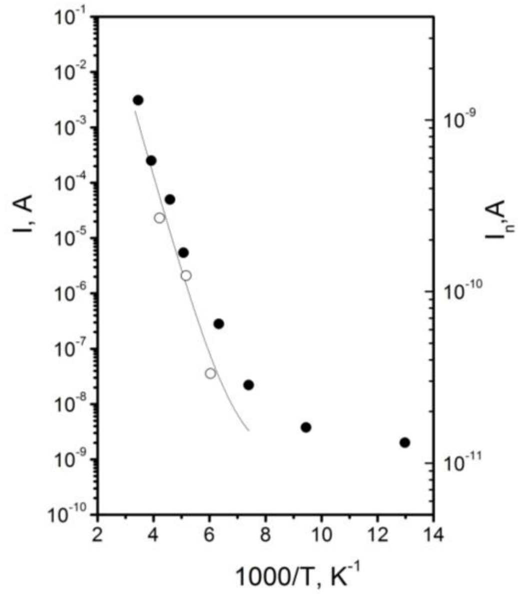

Fig. 5. Forward and noise currents (closed and open dots, respectively) measured at the forward bias 10 mV as a function of temperature. The noise current (solid line) is calculated using the equation (A7).

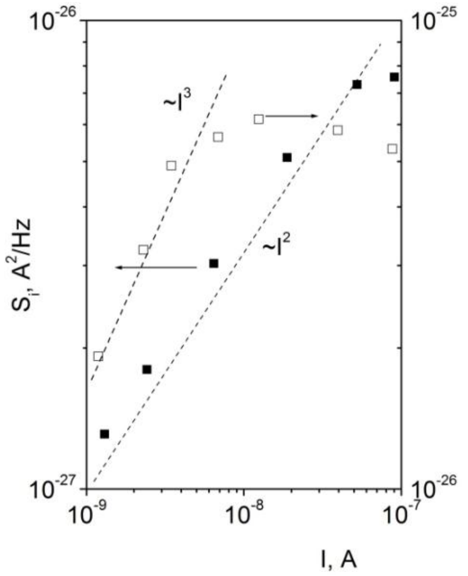

Fig. 6. Dependence of the noise current on the excess current for non-annealed (open dots) and annealed (closed dots) photodiodes at 77 K. The dashed lines show the approximations $S_i \sim I^2$ and $S_i \sim I^3$.

Further analysis stems from the fact that there are two conduction channels for the current flow in the investigated PDs. The tunneling current is associated with dislocations crossing the depletion region, and the recombination current flows through a homogeneous region free of dislocations. At low bias voltages, the tunneling current predominates; therefore, the forward current is described by the first term in (1), whereas at higher voltages it is described by the second term. Note in this relation that interband tunneling is unlikely, since the width of the depletion region in the studied diodes is approximately 0.4…1.0 μm. These values are much higher than the de Broglie wavelength for electrons in InAs, which is close to 14 nm [14]. Thus, the process of multiple tunneling proposed by Riben–Feucht may be responsible for the excess current at low temperatures [15]. To clarify the probabilities of tunneling, the characteristic energy was calculated using the following equation [16]

$$E_0 \approx 8e\hbar \left(\frac{N_I}{m_T \, \varepsilon_r \, \varepsilon_0} \right)^{1/2}, \qquad (2)$$

where N_I is the ionized impurity concentration, ε_r – static dielectric constant, ε_0 – vacuum permittivity, and m_T – tunneling effective mass. The latter is the reduced effective mass of light holes and electrons for an interband diagonal tunneling or the effective mass of a specific type of carriers for deep-level tunneling. It is difficult to conclude which holes (light or heavy) are involved in the tunneling process. For instance, if the low-voltage current is caused by tunneling of heavy holes to deep levels on the *n*-side of the junction, for $m_T = 0.41m_0$ and $E_0 = 30$ meV, one can obtain the impurity concentration $N_I \sim 10^{17}$ cm^{-3}. In the case of light hole tunneling, N_I has the order of 10^{16} cm^{-3}. According to Lukyanchikova [17], multiple tunneling in a homogeneous junction should lead to a decrease in noise, which has not been experimentally confirmed. To overcome this disagreement with the experimental results, the model of inhomogeneous junction has been proposed. In agreement with the results of ultrasonic treatment of diffused *p-n* junctions as well as measurements of current-voltage characteristics and noise in the studied PDs, the multiple tunneling can occur with participation of point defects surrounding the dislocations. It is a most likely that in this case the low-frequency noise is caused by fluctuations in the density of local states in the band gap, and not to fluctuations in the carrier mobility.

The presence of dislocations in the investigated *p-n* junctions can be caused by several reasons. For example, due to the retrograde solubility of cadmium in indium arsenide, which leads to formation of precipitates enriched with impurity atoms. As a rule, the relaxation of deformation stresses around precipitates is accompanied by formation of dislocations. The second reason is the rate of cooling the samples after the diffusion process. A cubic dependence of S_i on the current was observed only in PDs that were rapidly cooled (Fig. 6). But when the PDs were subjected to 10-day annealing with a gradual decrease in temperature, a quadratic dependence was usually obtained.

4. Conclusion

Forward current and 1/*f* noise measurements were carried out in diffused InAs PDs within the temperature range 77…300 K. The contribution of various current components to 1/*f* noise has been analyzed. It has been found that diffusion and recombination within the depletion region are the dominant transport mechanisms within the temperature range 130…300 K. At these temperatures, the noise current calculated in accordance with the theoretical model developed by Kleinpenning can be fitted to the experimental data for the Hooge parameter $\sim 10^{-5}$. However, this model cannot be used at temperatures < 130 K, where excess tunneling current prevails. In this case, it is necessary to use the model developed by Lukyanchikova for an inhomogeneous *p-n* junction in which channels of excess conductivity exist. Experimental evidence has been obtained that these channels can be associated with dislocations crossing the depletion region. Therefore, it can be concluded that in the studied PDs the generation-recombination and tunneling currents are realized through different defect states in the band gap.

Appendix

The current-voltage characteristic in the case of p^+-*n* junction is given by

$$I = I_0 \left[\exp\left(\frac{eU}{\beta kT} \right) - 1 \right], \qquad (A1)$$

where I_0 is expressed as

$$I_0 = \frac{q n_i^2 A}{n} \cdot \left(\frac{kT}{q} \cdot \frac{\mu_p}{\tau_p} \right)^{1/2} \tag{A2}$$

and

$$I_0 = \frac{q n_i WA}{\tau_0} \tag{A3}$$

for diffusion and generation-recombination currents, respectively. In the above formulas, U is the bias voltage applied to p-n junction, A – junction area, n_i – intrinsic concentration of carriers, n the concentration of electrons determined from the barrier capacitance measurements, τ_0 – effective lifetime of carriers in the depletion region, τ_p and μ_p are, respectively, lifetime and mobility of minority carriers in the quasi-neutral n-type region of the junction. The built-in potential φ_{bi} was estimated from measurements of I–U characteristics at large forward biases, where the current linearly depends on the applied bias. In accordance with C–U measurements, the depletion region width was calculated using the equation

$$W = \left(\frac{2\varepsilon_s \varepsilon_0 \left(U_{bi} - U \right)}{qn} \right)^{1/2}. \tag{A4}$$

The noise spectra of 1/f type can be represented by empirical Hooge's equation based on assumption of thermal fluctuations in carrier mobility [10]

$$\frac{S_I}{I} = \frac{\alpha_H}{f^{\gamma} N}, \tag{A5}$$

where γ is close to unity, N is the total number of carriers in the system, α_H – so-called Hooge parameter. Theoretical expressions for 1/f noise were taken from [10] for diffusion

$$S_I(f) = \frac{\alpha_H q I_0}{4 f \tau_p} \left[\exp\left(\frac{qU}{kT} \right) - 1 - \frac{qU}{kT} \right] \tag{A6}$$

and generation-recombination current

$$S_I(f) = \frac{\alpha_H q I_0}{3 f \tau_i} \left[\exp\left(\frac{qU}{2kT} \right) - 1 \right]^2 \exp\left(-\frac{qU}{2kT} \right). \tag{A7}$$

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Темновий струм та 1/*f* шум на прямо зміщених фотодіодах InAs

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Анотація. У діапазоні температур 77… 290 K досліджено темновий струм та 1/*f* шум на прямо зміщених фотодіодах InAs. Фотодіоди були виготовлені шляхом дифузії Cd у монокристалічні підкладки *n*-InAs. Показано, що при температурах > 130 K прямий струм визначається рекомбінацією носіїв заряду за участю глибоких станів у середині забороненої зони. При цих температурах виявляється кореляція між прямим струмом і 1/*f* шумом. При більш низьких температурах прямий струм і шум були проаналізовані в рамках моделі неоднорідного *p*-*n* переходу, зумовленого дислокаціями в області виснаження. Отримано експериментальні докази того, що багатократне тунелювання носіїв є основним механізмом перенесення носіїв при низьких температурах, що призводить до збільшення низькочастотного шуму.

Ключові слова: фотодіоди InAs, 1/*f* шум, тунелювання, дислокації.