Dark Current and Noise in Diffused and Epitaxial InAs Photodiodes

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***Abstract* — A comparative analysis of the mechanisms of dark current and noise in InAs homo- and heterojunction photodiodes is carried out. It is shown that an excess current of a tunneling nature is the cause of the low-frequency 1/f noise at low temperatures. At high temperatures, the main source of noise is the generation-recombination current in the depleted area. Theoretical models of noise in infrared photodiodes are analyzed as applied to the experimental results obtained in this work.**

Keywords — InAs, photodiodes, noise, dislocations, dark current.

1. Introduction

A key problem affecting the performance of IR photodiodes (PDs) based on narrow gap semiconductors, including HgCdTe, InAs, InSb, is the excess dark current at low bias, commonly referred to as the shunt leakage current. The fact is that the shunt current is varied unpredictably from one photodiode to another, even if the photodiodes are manufactured nominally under the same conditions. This leads to a low yield of IR focal plane arrays with predictable parameters. The purpose of this work was to study the nature of the excess current and noise mechanisms in InAs PDs prepared by different methods.

2. Samples and experimental methods

PDs of two types were studied, namely, heterojunction p^+-InAsSbP/n-InAs PDs grown by LPE technique and homojunction PDs prepared by Cd diffusion in n-InAs substrates. In the first case, the lattice matched InAsSbP epitaxial layers of approximately 3 µm thickness were grown on (111)B surfaces of InAs substrates. The energy gap of epilayers was 0.43 eV at T= =297 K. They were doped to about 10^{18} cm^{-3} by addition of Zn to the melt. The substrates were n-type single crystals with an electron concentration n=(2-3)·10^{16} cm^{-3}. Homojunction PDs were prepared by short-term (20-30 min) diffusion of Cd into n-InAs substrates at 875 K. In the substrates, the carrier concentration and mobility were found to be (2-3)·10^{16} cm^{-3} and (2-2.5)·10^4 cm^2/Vs, respectively. The density of dislocations was in the range of (2-4)·10^4 cm^2. Mesa structures with an area 1.45·10^{-3} cm^2 were made on (111)A side of substrates. The surface of mesas was passivated using aqueous $(NH_4)_2S$ solution and covered by thin layer of CdTe thermally deposited in a vacuum chamber at temperature 150 °C. Ohmic contacts to the p^+-type side of the junction were prepared by thermal vacuum evaporation of Au-Zn alloy followed by thermal annealing in an atmosphere of purified H_2. Ohmic contacts to n-InAs were deposited by thermal vacuum evaporation of In. Photodiodes were characterized by measuring DC current, barrier capacitance and noise spectra versus bias voltage and temperature.

3. Experimental results and discussion

The formation of abrupt p-n junctions has been proven for both types of PDs by measuring the barrier capacitance. Note that in diffused PDs the effective concentration of free carriers at the edge of the depletion region was estimated to be n=(3.5-6)·10^{15} at 77 K. For this reason, the formation of a p^+-n-n^+ diode structure with a compensated region was assumed. In epitaxial PDs the concentration of electrons determined from

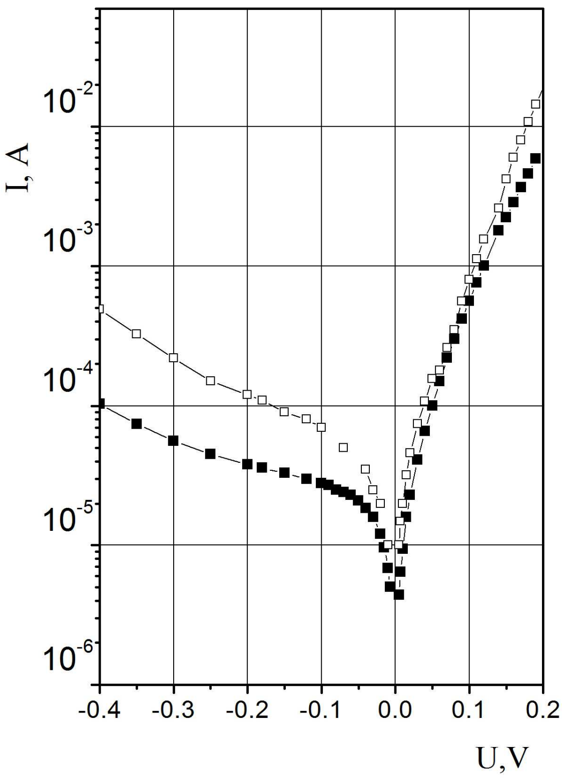

Fig. 1. Current-voltage characteristics in diffused (open dots) and epitaxial (close dots) PDs at 290 K.

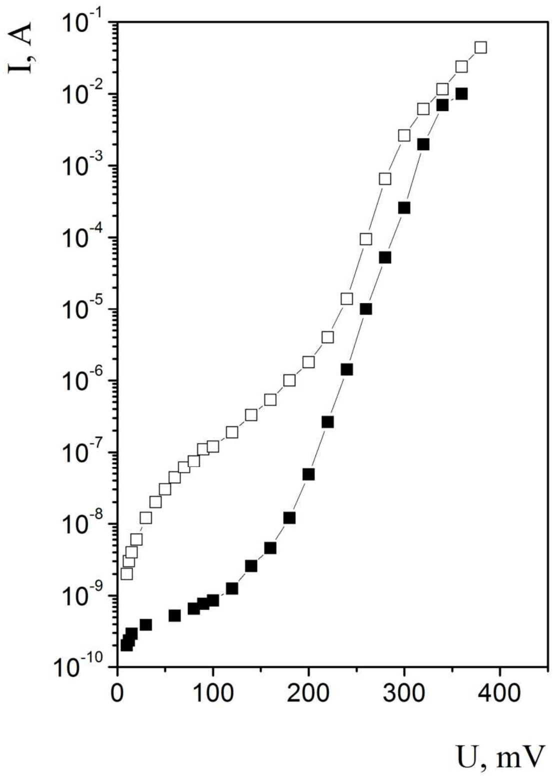

Fig. 2. Forward current-voltage characteristics in diffused (open dots) and epitaxial (close dots) PDs at 77 K.

C-U measurements was found to be n=(4-8)·10^{16} cm^{-3}, that corresponds to its value in the starting material.

From the experimental results, it can be concluded that in both types of PDs, the forward current consists of diffusion and recombination components. Moreover, their magnitude had close values. The more pronounced difference was observed for the reverse currents, Fig. 1. Note also that in forward biased epitaxial PDs the recombination current in the depletion region prevailed in the whole temperature region. At the same time, a significant excess current was observed in diffused PDs at low temperatures, Fig. 2. In this case, two successive parts of *I-U* characteristics are presented, depending on bias voltage. The low-voltage part weakly depends on temperature, which can be explained by the tunneling mechanism of charge transfer. The high-voltage part is caused by the recombination current in the depletion region. To calculate its magnitude, a model of the local level in the middle of the band gap was used. The carrier lifetime in the depletion region τ_0 served as a fitting parameter. For diffused PDs the best fit was obtained for the value $\tau_0=2\cdot10^{-9}$ s, which was practically independent on temperature. In epitaxial PDs the fitted values of τ_0 were (6-8)·10^{-8} s. The diffusion current at 290 K in PDs of both types was adjusted for the minority carrier lifetime of the order of ~10^{-7} s. This value is due to the Shockley-Read recombination mechanism.

The excess tunneling current in diffused PDs can be expressed as

$$I = I_{01} \exp\left(\frac{eU - IR_S}{E_0}\right), \quad (1)$$

where I_{01} is the pre-exponential factor, E_0 is the characteristic energy. The dependence of I_{01} on temperature, which has been obtained by extrapolating the experimental *I-U* curves to zero bias voltage, is shown in Fig. 3. The characteristic energy E_0=30-60 meV was

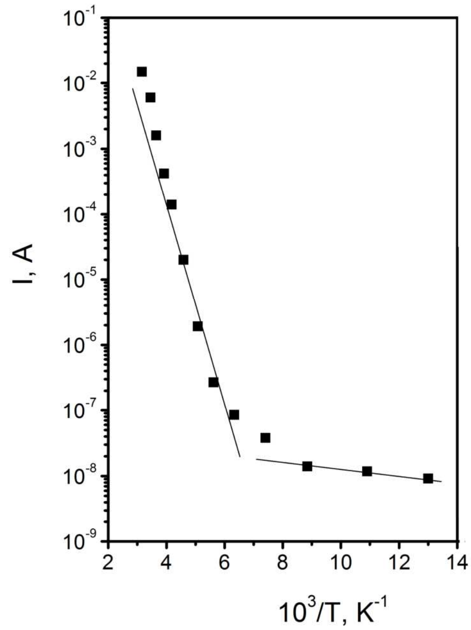

Fig. 3. Temperature dependence of I_{01} in a diffused PD. The straight lines is shown as a guide for the eye.

determined from its slope at low temperatures. It should be pointed out that in diffused PDs the excess current had a significant spread at low temperatures, which can be explained by the presence of dislocations crossing the space charge region [1]. For the recombination current, the spread in the current magnitude was insignificant.

Experimental data shown in Fig. 2 and 3, it can be explained assuming existence of two conduction paths in diffused PDs. The tunneling current flows via the states related to dislocations. Since the energy E_0 is less than $E_g/2$, the forward current can be caused by multistage tunneling of Riben and Feucht through the states in the band gap associated with dislocations [2]. The $1/f$ noise caused by recombination-tunneling current in non-homogeneous *p-n*-junctions was analyzed in [3].

The recombination current flows through a homogeneous region of a junction free of dislocations. In epitaxial PDs, the depletion region appears to be more uniform, and dislocations do not affect the current-voltage characteristics.

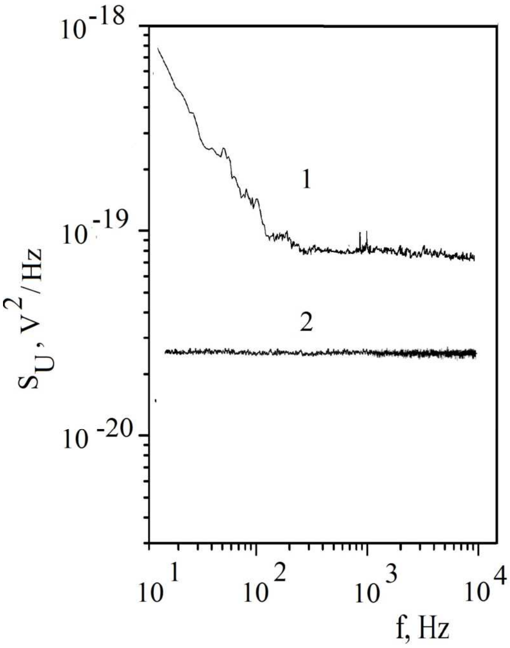

Fig. 4. Noise spectra measured at room temperature in diffused (1) and epitaxial (2) PDs at zero bias voltage.

Typical dependences of noise spectra are shown in Fig. 4. As can be seen, they differ significantly for diffused and epitaxial PDs, which correlates with the results of measurements of current-voltage characteristics. First, in diffused PDs at low frequencies, the noise spectra are of the $1/f$ type. Such spectra can be represented by the empirical Hooge equation based on the assumption of thermal fluctuations in the carrier mobility [4]:

$$\frac{S_I}{I^2} = \frac{\alpha_H}{f^{\gamma} N}, \qquad (2)$$

where γ is close to unity, N is the total number of carriers in the system, α_H is the Hooge parameter. For *p+-n* homojunctions theoretical models of $1/f$ noise were developed by Kleinpenning [4]. At forward bias the spectral densities for diffusion and recombination currents is given by

$$S_I(f) = 2qI\left[1 + \frac{\alpha_H}{8f\tau}\right], \qquad (3)$$

where τ_0 is the lifetime of carriers in the depletion region.

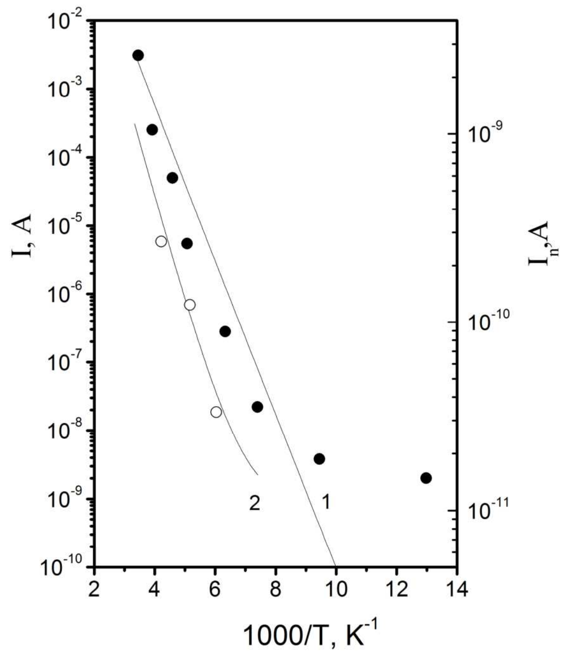

Fig. 5. Measured forward and noise current (close and open dots, respectively) in the diffused PD as a function of temperature. The noise current was calculated using Eq. 3 for the band width Δf=1Hz. The solid lines are shown as a guide for the eye.

The main result obtained in this study is that at $T > 135$ K the measured noise follows the recombination current in the depletion region, Fig. 5. The Hooge parameter estimated from the fitting calculations was of the order of 10^{-5}. As far as the authors know, this parameter has not yet been determined in InAs PDs. For comparison, in polycrystalline InAs films prepared by the method of flash evaporation, its value was reported to be $1.8 \cdot 10^{-3}$ [5]. Also, in HgCdTe and InSb PDs this parameter varies over a wide range from 10^{-7} to 10^{-3} [6].

At temperatures close to 77 K the noise generally follows the dark current, but its magnitude is changed from one photodiode to another as well as in the case of dark current measurements. In order to clarify its origin the spectral density of the noise current was measured as a function of the dark current, Fig. 5. According to Hooge, the spectral density of the noise current, S_i, must be proportional to the square of the dark current when noise is caused by the mobility fluctuations. Instead of this, non-monotonic dependences were observed in diffused PDs at 77 K for low forward currents, the initial pats of which can be approximated as $S_i \sim I^{\beta}$ with β = 2.1-3.0. Such dependences are well known for LEDs with the inhomogeneous distribution of injection current in the junction. It is commonly believed that this phenomenon is associated with dislocations generated in LEDs by injection currents.

4. Conclusions

Measurements of the dark current and 1/*f* noise were carried out in InAs diffused and epitaxial p^+-n PDs in the temperature range 77-300 K. The contribution of various current components to 1/*f* noise in forward-biased photodetectors is analyzed. It was found that diffusion, recombination in the depletion region and tunneling associated with dislocations are the dominant carrier transport mechanisms. It was shown that the partial contribution of each current component is critically dependent on temperature. Some parameters of PDs were estimated from fitting calculations. The 1/*f* noise in the tested PDs is explained within the framework of existing theoretical models.

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