Semiconductor Physics, Quantum Electronics & Optoelectronics. 1999. V. 2, N 3. P. 21-25.

PACS: 85.60.D, 07.57.K, 85.60.G, 73.40

Noise spectra and dark current investigations in n^+-p-type $Hg_{1-x}Cd_xTe$ ($x \cong 0.22$) photodiodes

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Abstract. The dark current and noise spectra were investigated in $Hg_{1-x}Cd_xTe$ ($x \cong 0.22$) photodiodes at zero and low reverse bias voltages. The photodiodes were prepared by boron implantation into LPE films. The $1/f$ noise is proved to be correlated with tunneling current via the deep defect states in the gap at low reverse biases $U \leq 0.1$ V. In the photodiodes, where the tunneling current is found to be dominating, the $1/f$ noise is observed up to frequencies 10^4 Hz. The decrease of tunneling current results in the decrease of $1/f$ noise.

Keywords: long wavelength intra-red photodiode, trap assisted tunneling, $1/f$ noise.

Paper received 07.09.99; revised manuscript received 30.09.99; accepted for publication 11.10.99.

1. Introduction

$Hg_{1-x}Cd_xTe$ ternary compounds are recognized to be the most important materials for fabrication of long wavelength infrared (LWIR) photodiodes for 3-5 and 8-12 μm wavelength regions [1]. Ion implantation seems to be the most important method for manufacturing single n^+-p-type photodiodes as well as multi-element focal plane arrays [1]. Carrier transport mechanisms in implanted LWIR photodiodes has been investigated both theoretically and experimentally by many authors [1-9]. It has been found that in general case at temperatures close to 77 K total dark current are composed of several components: bulk diffusion, generation-recombination (GR) current in the depletion region, trap assisted tunneling (TAT) current, band-to-band (BTB) tunneling current and surface leakage current. GR and TAT currents dominate the total dark current at zero and low reverse bias voltage as well as BTB current is dominant at large reverse bias voltage. In the photodiodes with improved characteristics dark current is dominated by the diffusion current. Due to the fact that carrier transport mechanisms listed above are influenced by deep defect states in the gap, fitting procedure can be used for estimation of several important parameters of these states such as concentration N_t, energy E_t and capture rates [4-9]. Because of some discrepancies exist in the models used for the fitting calculation the values of above mentioned parameters are changed in a rather wide range (e.g., N_t is changed from $\sim 10^{12}$ cm^{-3} up to $\sim 10^{17}$ cm^{-3} [6,7,8,14]).

As to investigations of noise mechanisms in HgCdTe photodiodes the origin of the $1/f$ noise still seems to be the most important and unsolved problem. Several sources of the $1/f$ noise have been proposed in application to these photodiodes [10-15]. One of the possible source is lattice defects of different types unintentionally or intentionally introduced during growth of starting material. Fluctuation of deep point defects, shallow etch pits, dislocation multiplication and clustering are recognized to be possible for $1/f$ noise source. As shown in [12], $1/f$ noise in LWIR photodiodes is a bulk phenomenon associated with defects in the depletion region. However, the states at the interface of HgCdTe and passivating layer can also contribute to $1/f$ noise [11,13,14]. Finally, the dark current is suspected to be a possible source of $1/f$ noise, too. In several papers [4, 9] the correlation between 1/f noise and bulk BTB tunneling current was observed. Quite the contrary, the correlation between $1/f$ noise and surface BTB tunneling current has been found in the papers published earlier [15]. The role of trap assisted tunneling current at zero and low reverse bias voltages seems to be not investigated yet.

The aim of this work is to investigate dark current and $1/f$ noise in LWIR HgCdTe photodiodes in order to find possible correlation between these phenomena. More than thirty diodes were investigated to obtain statistical results.

2. Experimental results and discussion.

The starting materials were undoped $Hg_{1-x}Cd_xTe$ ($x \cong 0.22$) films of p - type conductivity. The films were used for p-n-junction fabrication by boron ion implantation. The hole concentration in the films was close to $1 \cdot 10^{16}$ cm^{-3} at temperature 77 K.

The dark current in the photodiodes has been measured at 77 K. By differentiation of *I-U* curves the dynamic resistance *R* characteristics versus voltage bias *U* were obtained. To estimate the cut-off wavelength λ_c values the photoresponse spectra were measured at 82 K. The noise spectra were investigated in the frequency range 0.07÷10^4 Hz at 77 K using CK4-73 spectrum analyzer.

Typical normalized photoresponse spectra of the photodiodes are shown in Fig.1. The cutoff wavelength λ_c for the photodiodes investigated are shown in Table 1 together with intrinsic carrier concentration, n_i, and energy band gap, E_g, values. The last two parameters were calculated using appropriate empirical expressions from [2].

Table 1.Fitting parameters used for modeling calculations

1. Band gap, eV, T=77 K	0.130
2. Cutoff wavelength, λ_c, μm, T=82K	10.3±0.2
3. Intrinsic carrier concentration, n_i, cm^{-3}, T=77 K	$4.87\cdot10^{12}$
4. Trap density, N_t, cm^{-3}	10^{13}-10^{16}
5. Capture rate, C_p, cm^3/s	10^{-7}-10^{-6}
6. Trap energy, E_t, eV	0.72 E_g

Measured and calculated current-voltage characteristics are shown in Fig.2 (a,b). In calculations several components were taken into account: bulk diffusion current, generation current in the depletion region and TAT current. The formulae used for calculations of each current component are briefly discussed in Appendix. In calculation of TAT current thermal and tunnel transitions from the valence band to deep defect states in the gap followed by tunnel transitions to the conduction band were taken into account. The dark current caused by band-to-band tunneling was not taken into account because of investigations were mainly performed at zero and low reverse bias voltage ($U \leq 0.1$ V). Surface leakage current seems to be negligibly small in these photodiodes (see Appendix).

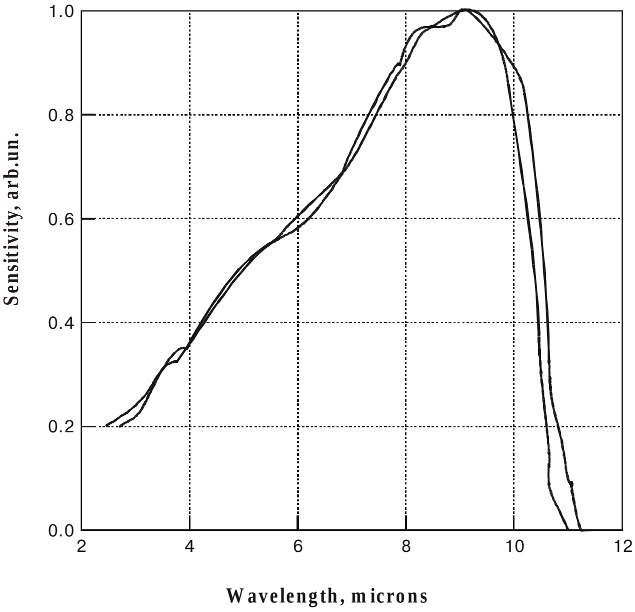

Fig.1. Normalized photoresponse spectra of implanted n^+-p photodiodes $Hg_{1-x}Cd_xTe$ ($x \cong 0.22$) at 82 K.

It is seen from Fig.2 that the photodiodes with different type of current-voltage *I-U* characteristics were investigated. In the photodiode with the lowest values of the reverse current (curve 1in Fig.2(a)) the tendency to its saturation at reverse bias is clearly seen. With increasing the reverse current this tendency diminishes (curve 2). Further increasing of the current is accompanied by appearance of the soft breakdown characteristic (curve 3). Sharp soft breakdown characteristics were observed in several photodiodes, Fig.2(b).

Typical dependencies of the R_0A vs. voltage bias U (R_0 is the differential resistance at zero bias, A is the junction area) for the photodiodes investigated are shown in

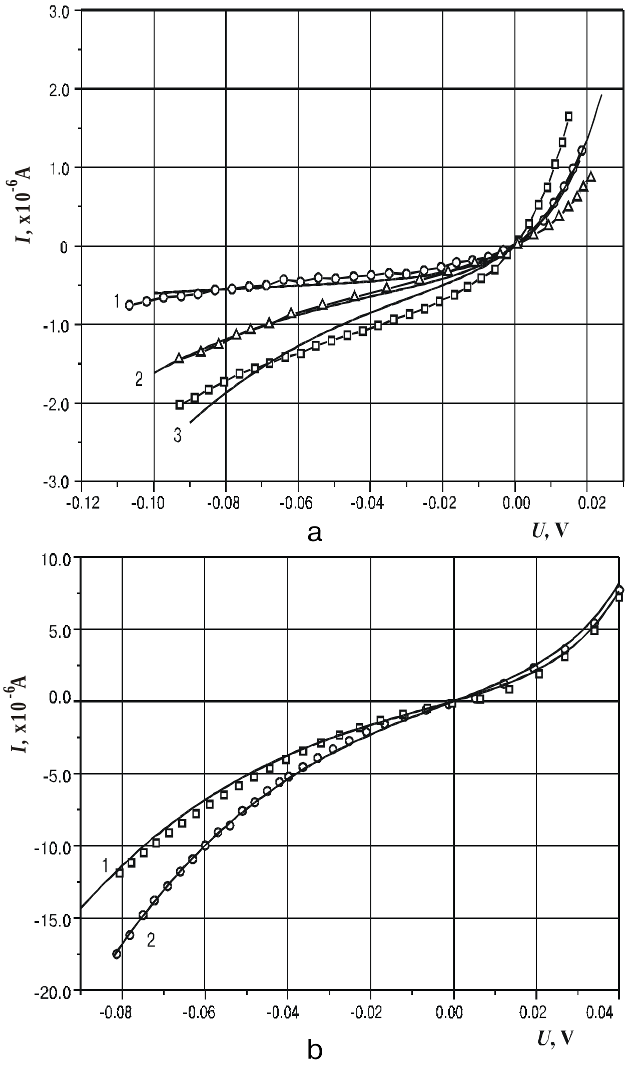

Fig.2. Measured and calculated current-voltage characteristics of n^+-p photodiodes at 77 K. The dots represent measured data and the solid lines represent theory. The fit was obtained for N_t = $1.2\cdot10^{13}$; $2\cdot10^{14}$; $4\cdot10^{14}$ for curves 1-3 (a), respectively. The values E_t = $0.72E_g$, C_p = $8\cdot10^{-7}$ and C_n = $0.01C_p$ were the same for all three curves. To fit experimental and calculated curves in (b) trap density was taken to be N_t =$3.2\cdot10^{15}$; $4.8\cdot10^{15}$ cm^{-3}, for curve 1 and 2, respectively. Also, the values E_t = $0.72E_g$, C_p = $1\cdot10^{-7}$ and C_n = $0.01C_p$ were the same for these curves.

Fig. 3 (a,b). At zero bias the R_0A value less than 1.0 Ω×cm^2 has been found to be typical for the photodiodes in which soft breakdown was observed. Note that maximum in R_0A vs. U curves is shifted towards zero bias in these photodiodes. The parameters used in calculations I-U and R_0A-U characteristics are listed in Table 1.

Noise power spectral density measurements were performed in the frequency range of $0.7 \div 10^4$ Hz for the same photodiodes in which the dark current was measured. Typical noise spectra measured at 77 K are shown in Fig. 4 together with the calculated curves. As one can see, each noise curve consist of frequency-dependent as well as frequency-independent parts which can be attributed to $1/f$ noise and to generation-recombination noise, respectively. The transition region between them is rather narrow and it shifts towards the higher frequency as the dark current increases.

From the measured and calculated data shown in Fig.2(a,b) one can conclude the following. The best fit was obtained for energy of deep defect states $E_t \cong 0.72E_g$ (E_t is measured from the top of the valence band). This value correlate well with previously observed one $E_t \cong 0.75E_g$ [7] in photodiodes prepared by boron implantation to bulk material. Also this value is in agreement with the results of DLTS measurements in undoped HgCdTe crystals [16]. It seems that these centers are introduced into the bulk of HgCdTe materials during their preparation and can be attributed to different states of the Hg vacancies [7].

Some contradiction exists in the concentration of deep defect centers with previously published values $N_t =$ $= 0.1\text{-}10\ N_A$ [7], where N_A is the shallow acceptor concentration (N_A is approximately equal to the hole concentration). The values of N_t obtained in present work range from $\sim 10^{13}$ cm^{-3} to $\sim 10^{16}$ cm^{-3} in photodiodes with $N_A \cong 10^{16}$ cm^{-3}. This contradiction may be explained as follows. The concentration of shallow acceptors as well as deep defects in HgCdTe implanted photodiodes is not uniform in the region adjacent to n^+-p-junction. Nemirovsky et al. [4] have found that n^+-p-junctions can be formed with low concentration of shallow acceptors near the junction. Since the measurements were performed at zero and low reverse bias voltage the concentration N_t derived from the fitting procedure can be smaller than in the bulk (e.g., in implanted $Hg_{1-x}Cd_xTe$ ($x \cong 0.22$) photodiodes investigated previously [7] N_t reached the bulk value at reverse bias $U \cong 0.6$V).

The capture rates found at this study $C_p \approx 10^{-7} \div 10^{-6}$ cm^3/s and $C_n = (0.1 \div 0.01)C_p$ differ much from the result previously obtained for $C_p = (10^{-10} \div 10^{-9})$ and $C_n = (10 \div 100)\ C_p$ [8,14]. It should be pointed out that in these studies deep defect centers in p-HgCdTe material were assumed to be donor-like type. However, in present investigation the best fit was obtained for acceptor-like centers in the gap. This result are in accordance with the results of comprehensive study performed by Rosenfeld and Bahir [7].

The correlation between $1/f$ noise and tunneling dark current was previously observed by Nemirovsky et. al. [4] at rather high reverse bias voltages $U \geq 200$ mV. In present investigation the correlation is revealed at low reverse bias $U \leq 100$ mV. The result obtained seems to be important because of HgCdTe photodiodes are mainly used at zero and low reverse bias voltage operating conditions [1]. The calculation of the $1/f$ noise was performed by the formula (A6) [4]. To fit experimental and calculated data the constant α was assumed to lie in the range from 10^{-8} to 10^{-7} . These values agree with the value $\alpha = 10^{-7}$ found in [4]. Because of the increase of the dark current in the investigated photodiodes is related with the tunneling through deep defect states in the gap, one can assume the origin of both phenomena to be the same. Also it should be pointed out that no correlation has been observed between GR current in the depletion region and $1/f$ noise.

The mechanism of $1/f$ noise in diodes with dominant trap-assisted tunneling current is unknown yet. One possibility of its origin has been pointed out in [14]. The fundamental fluctuations in the process rates can exist due to the infrared divergent coupling of free carriers to low-frequency photons and other infraquanta.

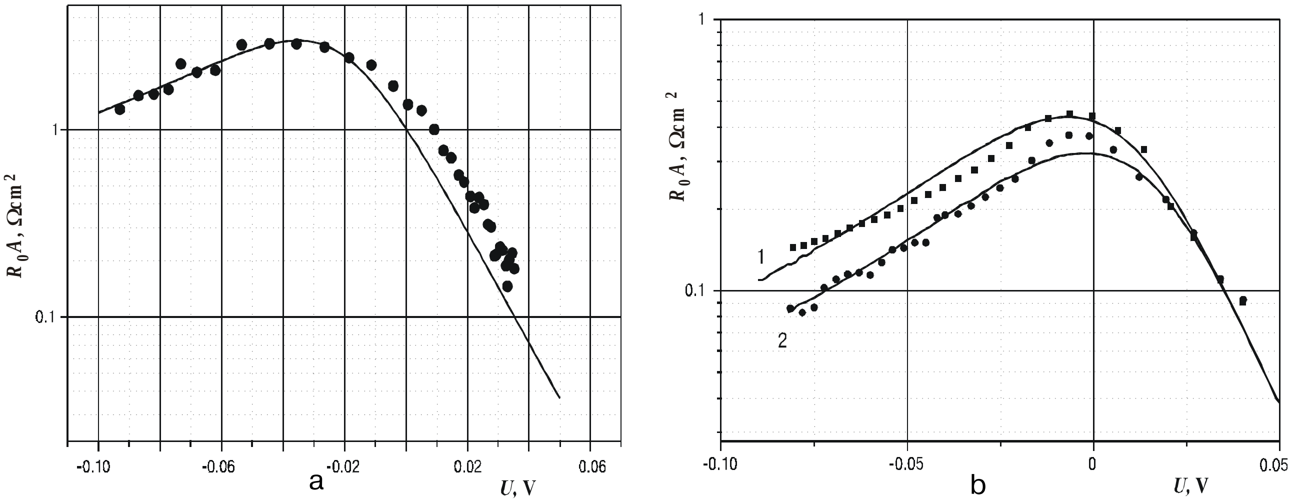

Fig.3. Typical resistance-area versus bias voltage characteristics for several photodiodes at 77 K. The designations are the same as in Fig.2a (curve 1) and Fig.2b (curves 1 and 2).

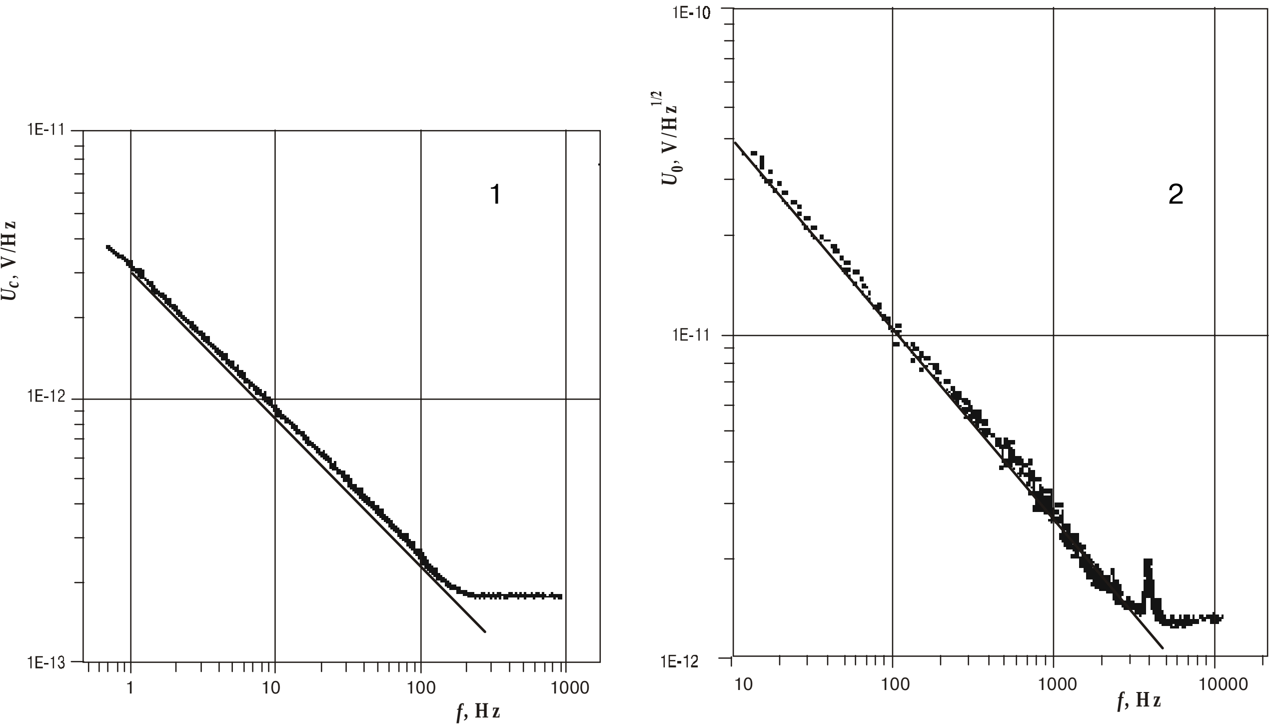

Fig. 4. Measured (dots) and calculated (solid lines) noise spectra for the photodiodes with R_0A = 1.0 Ω·cm^2 (1) and R_0A = 0.3 Ω·cm^2 (2) at 77 K. The reference shot noise level $(2qJ)^{1/2}$ at reverse bias 10 mV is $1.7 \cdot 10^{-13}$ and $7.92 \cdot 10^{-13}$ A/Hz$^{-1/2}$, respectively.

Conclusion

Dark current have been measured and calculated in n^+-p-type $Hg_{1-x}Cd_xTe$ ($x \cong 0.22$) photodiodes at 77 K. It has been found that generation in the depletion region and tunneling through deep defect states in the gap are dominant carrier transport mechanisms at low reverse bias voltage. From the fitting procedure the density of the tunneling centers $N_t = 10^{13}$ –10^{15} cm^{-3} and their energy $E_t \cong 0.72 E_g$ has been estimated. The 1/f noise measured at low reverse bias can be attributed to the tunneling dark current through deep defect states.

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Appendix

The dark current in the photodiodes investigated can be given by the sum of several components, namely

$$J = J_D + J_{GR} + J_{TAT} + J_{BTB} + J_{surf}, \tag{A1}$$

were J_D is diffusion current, J_{GR} is the depletion generation-recombination current, J_{TAT} is the trap-assisted current, J_{BTB} is the band-to-band tunneling current and J_{surf} is the surface leakage current.

For asymmetric junctions the first two components are given by expressions:

$$J_D = \frac{qn_i^2}{p_0} \cdot \left[\frac{kT}{q} \cdot \frac{\mu_n}{\tau_n} \right]^{1/2}, \qquad \text{(A2)}$$

$$J_{GR} = \frac{qn_i^2 W}{\tau_{n0} p_1 + \tau_{p0} n_1}, \qquad \text{(A3)}$$

where p_0 is the hole concentration, μ_n and τ_n are the electron mobility and the minority carrier lifetime in the bulk, where $\tau_{n_0} = (c_n N_t)^{-1}$, $\tau_{p_0} = (c_p N_t)^{-1}$, c_n and c_p are the capture coefficients for electrons and holes, respectively, N_t is the trap density, $p_1 = N_v \cdot \exp(-E_t/kT)$, $n_1 = N_c \cdot \exp(-E_g + +E_t/kT)$, N_v and N_c are the effective density of states in the valence and conduction bands, W is the depletion region width, E_t is the trap energy measured from the valence band edge. The second and third terms in (A1) were intensively discussed earlier [1]. In this work, the appropriate equations for J_{TAT} current were taken from [7]. The trap-assisted tunneling current is given by

$$J_{TAT} = qN_t W \left(\frac{1}{c_p p_1 + \omega_v n_v} + \frac{1}{\omega_c n_c} \right), \qquad \text{(A4)}$$

were $\omega_c N_c$ and $\omega_v N_v$ are the tunneling rates .

The surface leakage current caused by the fast surface states is given by [14]

$$J_{surf} = \frac{qn_i S}{2}, \qquad \text{(A5)}$$

where S is the surface recombination velocity. In properly prepared photodiodes the value of S does not exceed 100 cm/s [14]. As one can see from the formula (5), the contribution of the surface leakage current to the dark current can be neglected in our case. In order this current to be dominant, the value S should be higher than 10^3 cm/s. However, so high values of S were not observed in the diodes investigated.

The calculation of the $1/f$ noise current was carried out with

$$J_n = \alpha \left(\frac{J_{TAT}}{f} \right), \qquad \text{(A6)}$$

where J_{TAT} current was calculated using (A4).