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Researches of temperature dependencies in volt-ampere characteristics of CdHgTe photodiode grown on GaAs, Si, and CdZnTe substrates

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The temperature dependences of CdHgTe photodiode current-voltage characteristics have been investigated. The influence of the substrate for epitaxy on the charge transfer mechanisms in semiconductor structures has been identified and studied. It has been revealed that CdHgTe photodiodes on Si substrates have an increased generation-recombination current compared to photodiodes grown on CdZnTe and GaAs substrates.

Keywords: photodiode structure, CdHgTe, volt-ampere characteristic (VAX), dark current.

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1. Introduction

The fabrication of infrared focal plane arrays with high quantum efficiency makes it necessary for developers to design new architectures of photosensitive elements (PSEs) based on cadmium mercury telluride solid solutions [1–4].

Analysis of the current-voltage characteristics (I–V curves) is a powerful tool for understanding the dark current mechanisms, optimizing device designs, and predicting performance characteristics [5, 6]. An important scientific and technical task is to study of the temperature dependence of the I–V curves of CdHgTe photodiodes, since the operating cryogenic temperature determines the ratio of various charge carrier transport mechanisms and, ultimately, the limiting characteristics of the FPAs.

2. Description of the samples and the mathematical model

A study investigated three samples of CdHgTe photodiode structures with a composition of $x = 0.39$ with a size of the p – n junction area of $6 \times 6 \mu\text{m}$ and a pitch of $30 \mu\text{m}$.

The photodiode arrays were fabricated using CdHgTe heterostructures obtained by molecular beam epitaxy (MBE) and liquid phase epitaxy (LPE) on cadmium zinc telluride (CdZnTe), silicon (Si), and gallium arsenide (GaAs) substrates (Table 1).

Table 1

Samples under study

Sample number	Substrate	Epitaxy method
Sample 1	CdZnTe	LPE
Sample 2	Si	MBE
Sample 3	GaAs	MBE

The temperature dependences of the dark current-voltage characteristics of four test photodiodes from each sample were measured; the measurement results are presented below.

The experimental data were approximated by the photodiode current model:

$$I = I_{\text{off}} + I_{01} \left[\exp \left(\frac{V - (I - I_{\text{off}}) R_s}{V_T} \right) - 1 \right] + I_{02} \left[\exp \left(\frac{V - (I - I_{\text{off}}) R_s}{2V_T} \right) - 1 \right] + \frac{V - (I - I_{\text{off}}) R_s}{R_{sh}},$$

where R_s is the series resistance, R_{sh} is the shunt resistance, I_{off} is the current offset, I_{01} is the diffusion-drift dark saturation current in the reverse branch of the photodiode I–V curve, I_{02} is the generation-recombination dark saturation current in the reverse branch of the photodiode I–V curve, V_T is the thermal voltage across the p – n junction, $V_T = \frac{kT}{q}$.

Variable parameters of the model: I_{01} , I_{02} , R_s , R_{sh} , I_{off} .

This model enables the separation of the diffusion-drift and generation-recombination components of the dark current, isolating them from the contribution of the substrate series

resistance and the shunt leakage current. The absence of a tunneling current component in the model is due to its small contribution to the dark current of CdHgTe photodiodes with a composition of $x = 0.39$ in the studied voltage range from -400 mV to 200 mV [7].

3. Results

Processing of the experimental data according to the photodiode current model made it possible to obtain the temperature dependences of the following parameters: the diffusion-drift saturation current in the reverse branch of the photodiode I–V curve (Fig. 1), the generation-recombination saturation current (Fig. 2).

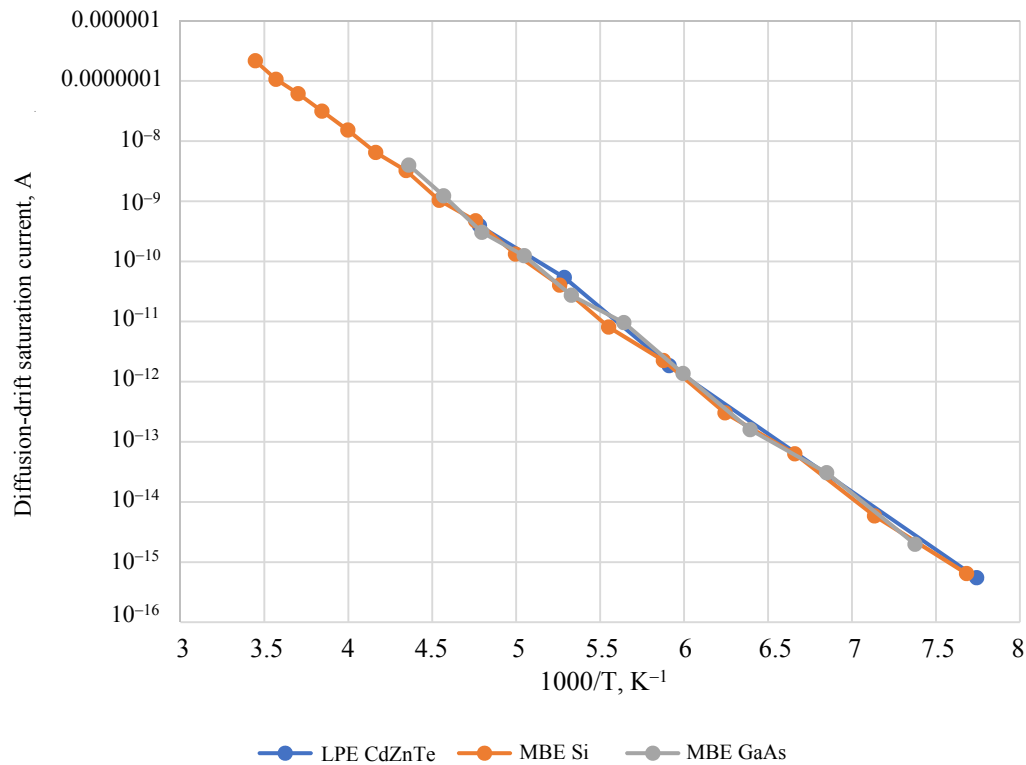


Fig. 1. Temperature dependence of the approximation parameter – the diffusion-drift dark saturation current in the reverse branch of the photodiode I–V curve (I_{01})

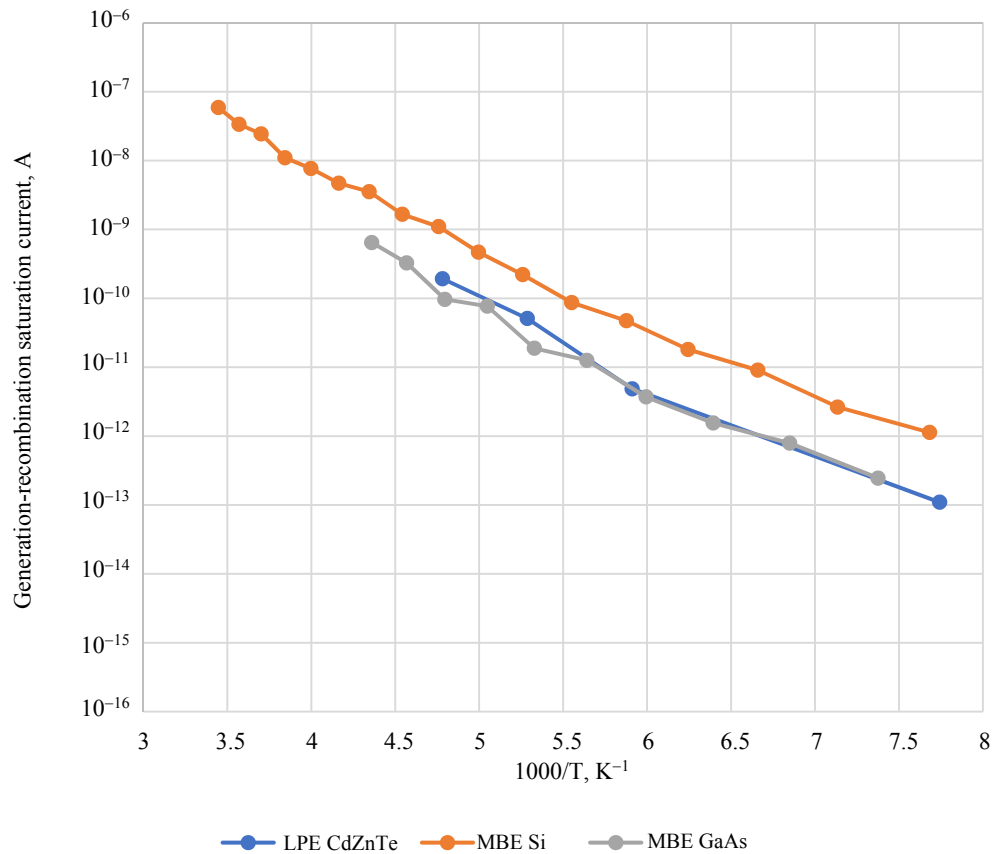


Fig. 2. Temperature dependence of the approximation parameter – the generation-recombination dark saturation current in the reverse branch of the photodiode I – V curve (I_{02})

According to the classical monograph by Sze [8], the following estimates of the temperature dependences of the dark current are valid:

$$I_{01} \sim q \sqrt{\frac{D_p}{\tau_p}} * \frac{n_i^2}{N_d} \sim T^{\frac{3+\gamma}{2}} \exp\left(-\frac{E_g}{kT}\right), \quad (1)$$

where D_p is the hole diffusion coefficient, τ_p is the hole lifetime, n_i is the intrinsic charge carrier concentration, N_d is the donor concentration in the n -region, E_g is the band gap, γ is a constant determined by the temperature dependence of

$$\frac{D_p}{\tau_p} \sim T^\gamma;$$

$$I_{02} \sim \frac{qn_i W}{\tau_e} \sim n_i \sim T^{\frac{3}{2}} \exp\left(-\frac{E_g}{2kT}\right), \quad (2)$$

where W is the width of the depletion layer, τ_e is the effective charge carrier lifetime.

As shown in Fig. 1, the diffusion-drift component of the dark current exhibits the same exponential temperature dependence for all three samples. Such a result expectedly follows from Equation (1), since the exponential term exerts a dominant influence compared to the power-law part, and the bandgap of the samples is the same.

The generation-recombination component of the dark current also exhibits a near-exponential temperature dependence for all samples; however, for sample 2 the parameter I_{02} is an order of magnitude larger than for the other samples.

According to the Shockley–Read–Hall (SRH) theory, the increased generation-recombination current in photodiodes on the silicon substrate may be due to a larger density of deep SRH centers in the middle of the bandgap, resulting from the lower structural perfection of the CdHgTe heterostructures grown on a silicon. . The large lattice mismatch and the difference in the space groups of the substrate and CdHgTe

epilayer induce a higher threading dislocation density, with dislocations serving as SRH recombination centers. The characteristic parameters of the crystal lattices of the materials used in the study are presented in Table 2.

The total dark saturation current in the reverse branch of the I–V curve, excluding the contribution of the series and shunt resistances, is calculated as the sum of the above current components

$$I_0 = I_{01} + I_{02}.$$

When considering the dependence of I_0 on temperature (Fig. 3), it can be noted that for the operating temperature $T = 170$ K (5.88 1/mK) the dark current of sample 2 (CdHgTe heterostructure on Si) is an order of magnitude greater than the dark current of samples 1 (CdHgTe heterostructure on CdZnTe) and 3 (CdHgTe heterostructure on GaAs). To achieve the same dark current level as that of photodiodes on GaAs and CdZnTe substrates, the photodiode on a silicon substrate must be cooled by 23 K lower compared to samples of photodiodes 1 and 3.

Table 2

Parameters of the materials used in the study

	Lattice constant	Lattice type	Space group	Dislocation density in CdHgTe
Si	5.431	diamond-like cubic	Fd-3 m	10^6 – 10^7
GaAs	5.653	zinc blende	F-43 m	10^5 – 10^6
CdZnTe	6.46–6.48	zinc blende	F-43 m	10^4 – 10^5
CdHgTe	6.461–6.482	zinc blende	F-43 m	—

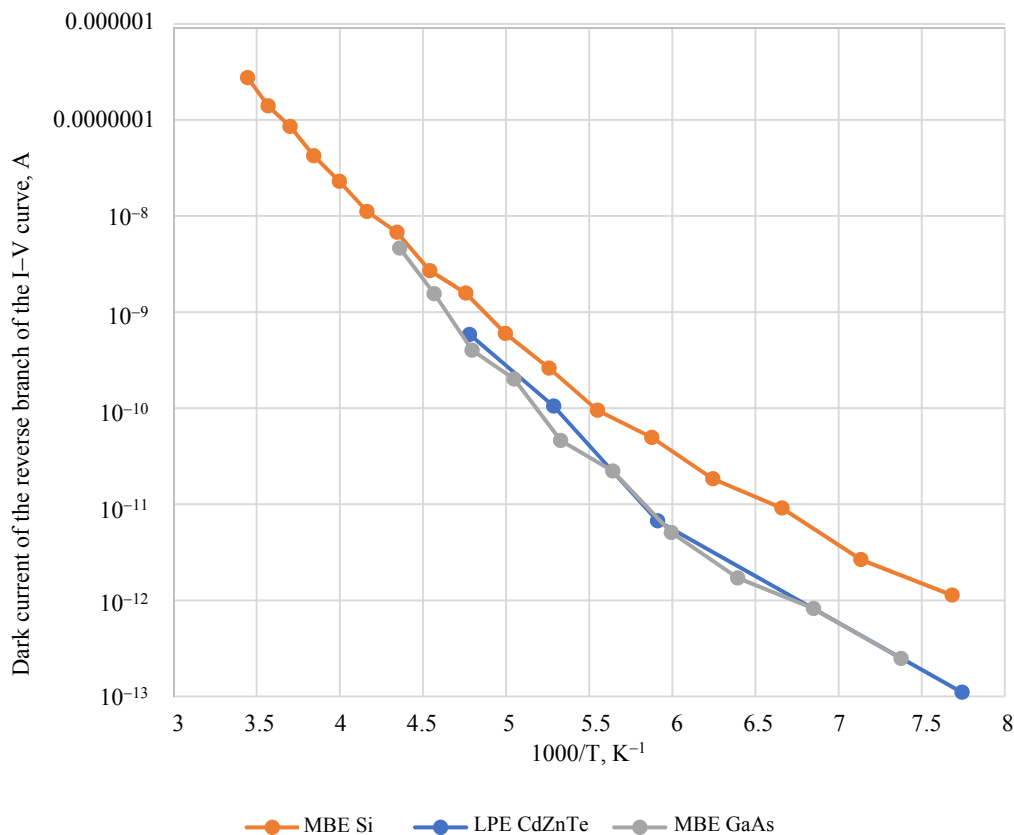


Fig. 3. Dependence of the total dark current I_0 on temperature for photodiode structures fabricated in CdHgTe heterostructures grown on Si, CdZnTe, and GaAs substrates

4. Conclusions

In the temperature range from 130 K to 290 K, the generation-recombination saturation current and the dark current of CdHgTe photodiodes on a Si substrate are an order of magnitude higher compared to those on GaAs and CdZnTe substrates. Thus, to achieve the same dark current value under the operating reverse bias voltage, sample 2 must be cooled by 23 K lower than the other samples.

Comparing this findings with the lattice parameters of the studied materials, it can be assumed that the discrepancies originate from the varying dislocation densities in the MCT material grown on a CdZnTe substrate matched in crystal structure and on alternative Si and GaAs substrates.

This conclusion is further validated by a qualitative analysis of the shunt resistance, which reveals higher leakage currents for the CdHgTe photodiodes on Si substrates compared to photodiodes on CdZnTe and GaAs substrates.

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