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In–HgCdTe–In structures with symmetric nonlinear *I–V* characteristics for sub-THz direct detection

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Abstract. This paper reports on the development and investigations of In–$Hg_{1-x}Cd_xTe$–In structures with symmetric nonlinear *I–V* curves that are sensitive to sub-terahertz radiation. It is shown that at low currents photoresponse of the detectors based on these structures is due to the presence of potential barriers at the contacts. The dependences of the photoresponse as the function of the bias current are measured at the radiation frequency ν = 140 GHz in 77–300 K temperature range. The studied structures may be used as the detectors of sub-terahertz radiation at room temperature or under weak cooling. The calculated NEP of investigated In–*n*-$Hg_{0.61}Cd_{0.39}Te$–In detectors was $3.5\cdot10^{-9}$ W/Hz$^{1/2}$, if taking into account thermal and shot noise.

Keywords: indium–mercury cadmium telluride–indium structures, sub-THz detectors, current-voltage characteristics..

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1. Introduction

The radiation frequency range ν ~ 0.1…0.3 THz sometimes called the sub-THz range has a number of advantages including high bandwidth of communication lines, high-resolution of radar systems, nonionizing nature of the radiation, capability of radiation to propagate through many non-conducting materials, *etc.* [1]. As applications field of THz technology continue to expand, demands for the compact, low cost, suitable for manufacturing and meeting the specific requirements THz and sub-THz detectors increase as well.

Since in this work, In–HgCdTe–In structures with symmetric nonlinear current-voltage (*I–V*) characteristics have been studied for detection of sub-THz radiation, the comparison should be made with other known detector structures with non-linear *I–V* characteristics. Up to date, Schottky diodes occupy a special place among the THz and sub-THz detectors, in particular, due to their high operation speed. Schottky detectors are one of the basic devices among the THz ones due to their fast response. The response time is of the order of <~10^{-11} s resulting a detection broad bandwidth of heterodyne detectors in the range of several gigahertz. Schottky barrier diode as a radiation detector can operate in the mixer or direct detection modes. In the direct detection mode, the Schottky diode operates as a rectifying detector. Due to the nonlinearity of the *I–V* characteristic, the high-frequency voltage generated by the incident radiation results in appearance of a DC component that is proportional to the power of a signal. A feature of the Schottky diode as the electronic device is that the semiconducting layer has two contacts with metal, one of which is ohmic, and the second forms a potential barrier. To obtain it, two different metals are used or additional processing steps are applied, such as changing the semiconductor surficial region composition.

In [2], a new type sensing element based on a low-barrier metal-semiconductor-metal structure with a symmetrical *I–V* characteristic for the electromagnetic radiation detectors was proposed. In [3], the characteristics of the GaAs THz-detector based on planar metal-semiconductor-metal structure were presented. A feature of this detector is the absence of ohmic contacts.

In this paper, we describe the results of photo-response measurements of symmetrical In–HgCdTe–In structures at 140 GHz incident radiation. This structure forms two Schottky barriers and has sensitivity in the sub-terahertz range. Current dependences of photoresponse were measured. The voltage sensitivity and noise-equivalent power were calculated at low bias currents.

2. Sensitive structures based on $Hg_{1-x}Cd_xTe$ and their electrical characteristics

The contact between metal and semiconductor can result in the ohmic junction or the rectifying one. The necessary condition for the achievement of a rectifying junction is the presence of a depletion layer in the semiconductor at the interface. The layer depleted of free charge carriers occurs as a result of the electrons transfer from semiconductor to metal during equilibrium state establishing. The presence of a depletion layer causes the energy bands bending, which results in formation of an energy barrier for the electron flow from metal to semiconductor. This barrier is called as the Schottky barrier and sets properties of junction. The Schottky barrier height (Φ_B) for the contact between the metal and *n*-type semiconductor is the difference between the metal workfunction (W_m) and the semiconductor electron affinity (χ) [4]:

$$\Phi_B = W_m - \chi \,. \tag{1}$$

In the case of contact between the metal and *p*-type semiconductor, the Schottky barrier height can be calculated as follows:

$$\Phi_B = E_g - (W_m - \chi), \tag{2}$$

where E_g is the bandgap of semiconductor.

The Schottky barrier is independent of the semiconductor doping and is controllable by the choice of materials. The Schottky barrier height determines the rectifying characteristic of contact: the more a barrier height is, the better rectification. If the surface state density in semiconductor is low (Fermi level is not pinned at the surface) $\chi < W_m$ and $\chi + E_g > W_m$ are the conditions of the rectifying junction for *n*-type and *p*-type semiconductor, respectively.

The surface state density for $Hg_{1-x}Cd_xTe$ (MCT) grown using molecular beam epitaxy was determined in [5], and its value was ~10^{11} $eV^{-1}cm^{-2}$. Assuming that the surface state density varies slightly during processing, the influence of surface states on the Schottky barrier height can be neglected. In this case, the MCT-metal contact type can be estimated by the metal workfunction. The In workfunction value is 3.97 eV, while the dependence of $Hg_{1-x}Cd_xTe$ electron affinity on the composition *x* can by described by the following empirical expression [6]

$$\chi(x,T) = 4.23 - 0.813\left[E_g(x,T) - 0.083\right] \,. \tag{3}$$

The temperature and composition dependence of the $Hg_{1-x}Cd_xTe$ energy gap is given by the expression [7]:

$$E_g = -0.302 + 1.93x - 0.81x^2 + 0.832x^3 + \\ + 5.35 \cdot 10^{-4}(1-2x)T, \tag{4}$$

where E_g is in eV, T in K.

The results of χ and $\chi + E_g$ calculations for $Hg_{1-x}Cd_xTe$ in the range of *x* values between 0 and 1 are shown in Fig. 1. As seen from the plots, the sum of the MCT electron affinity and the value of band gap is higher than the In-workfunction in the whole range of *x*, while χ can be higher or lower than the In-workfunction, depending on *x*. Thus, it can be expected to obtain the Schottky barrier junction in the case of contact between indium and *p*-type $Hg_{1-x}Cd_xTe$ in all range of *x* and *n*-type $Hg_{1-x}Cd_xTe$ at $x <$ ~0.4.

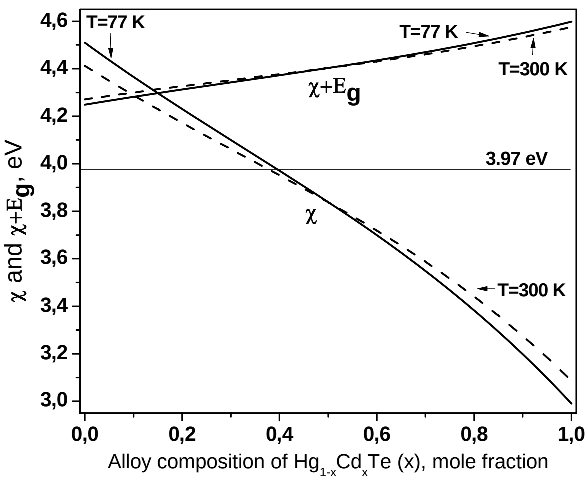

Fig. 1. Electron affinity χ and $\chi + E_g$ of $Hg_{1-x}Cd_xTe$ vs composition *x* as calculated using the equations (3) and (4).

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In general, the barrier heights of metal-semiconductor systems are determined by both the metal workfunction and interface states. When the surface state density is sufficiently high, then the Fermi level at the interface is pinned by the surface states. In this case, the barrier height is independent of the metal workfunction and is determined entirely by the surface properties of semiconductor [4]. Thus, the properties of contacts are greatly influenced by the quality of surface preparation, sputtering technology, *etc*. It is known that metal-MCT contact can be ohmic, or it can form a potential barrier of different heights depending on the MCT surface composition, metal deposition technique, availability of annealing, *etc*. [8].

Mercury cadmium telluride samples with indium contacts were used for the studies. The composition of the *n*-type MCT was selected in such a way that, in accordance with approximation in Fig. 1, there was a potential possibility of barrier forming at the contacts.

The structures based on *n*-type and *p*-type MCT ($x = 0.39$ and 0.31, respectively) with indium contacts were made from the epitaxial films $Hg_{1-x}Cd_xTe$ grown using molecular beam epitaxy. Indium was deposited by electrolytic deposition on the MCT film, from which the passivation layer was preliminarily etched. Fig. 2 shows the schematic drawing of the fabricated devices. The indium contacts serve simultaneously as bow-tie antennas. The structures of this type were investigated earlier in the framework of hot-electron bolometer theory [9], and it demonstrated sensitivity to radiation in $\nu = 0.037\ldots1.54$ THz frequency range at temperatures $T\sim70\ldots300$ K. However, during studying the electrical characteristics and sensitivity of these structures to radiation, we found that current-voltage characteristics of some samples deviate from linear behavior even at room temperature. In this case, their photoresponse as a function of the bias current does not match the behavior, predicted by the theory for hot-electron bolometer [9] and observed experimentally in $Hg_{1-x}Cd_xTe$ structures with ohmic contacts previously [10]. Some samples had linear current-voltage characteristics at room temperature, but at liquid nitrogen temperature these characteristics were significantly nonlinear. To our mind, nonlinearity of *I–V* curves indicates formation of potential barriers near the contacts between semiconductor and metal.

Fig. 3 shows current-voltage characteristics for some In–*n*-$Hg_{0.61}Cd_{0.39}Te$–In samples at $T = 293$ K and $T = 77$ K. The form of *I–V* curves at $T = 77$ K indicates that both contacts have potential barrier and the resulting current-voltage characteristic consists of the reverse currents from both of junctions. Investigated In–*p*-$Hg_{0.69}Cd_{0.31}Te$–In structures demonstrates nonlinear current-voltage characteristics for both $T = 293$ K and 77 K temperatures.

3. Results and discussion

The photoresponse of samples was measured using an IMPATT diode as 140 GHz radiation source. The source output power was measured using the Gentec-EO power monitor M-Link with thermopile sensor THZ12D-3S-VP, and it was 25 mW. The radiation source was equipped with a horn antenna, and output signal was modulated at $f = 220$ Hz frequency. System of teflon lenses were used to focus radiation at the detector that were fed from the constant current source Keithley 2400. To measure the photo-response of the samples at low temperatures, they were placed to a cryostat with the teflon window. The photoresponse was measured with SR830 Lock-In Amplifier.

At room temperature, the experimental dependence of the photoresponse against current in HgCdTe detector structures ($x = 0.39$) exhibits the almost linear character (Fig. 4a) (in this case *I–V* curve is close to the linear one, too). At $T = 77$ K, when the current-voltage characteristics of samples deviate from linear behavior, dependences of the photoresponse on current demonstrate complicated forms: there are local maxima of signal in the low bias currents for both current directions, as well as the multiple change in the signal sign (Fig. 4b). For *p*-type samples, which current-voltage characteristics are nonlinear at room temperature, the experimental dependences of the photoresponse against current are nonlinear as well.

It was supposed that the photoresponse observed in samples with nonlinear *I–V* curve has components not only from carrier heating mechanism as in hot-electron bolometers but also from processes occurring at Schottky contacts.

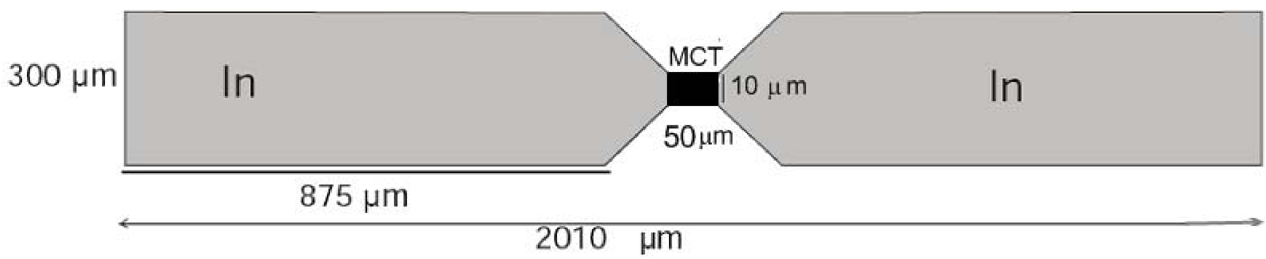

Fig. 2. Schematic drawing of In–$Hg_{1-x}Cd_xTe$–In structure.

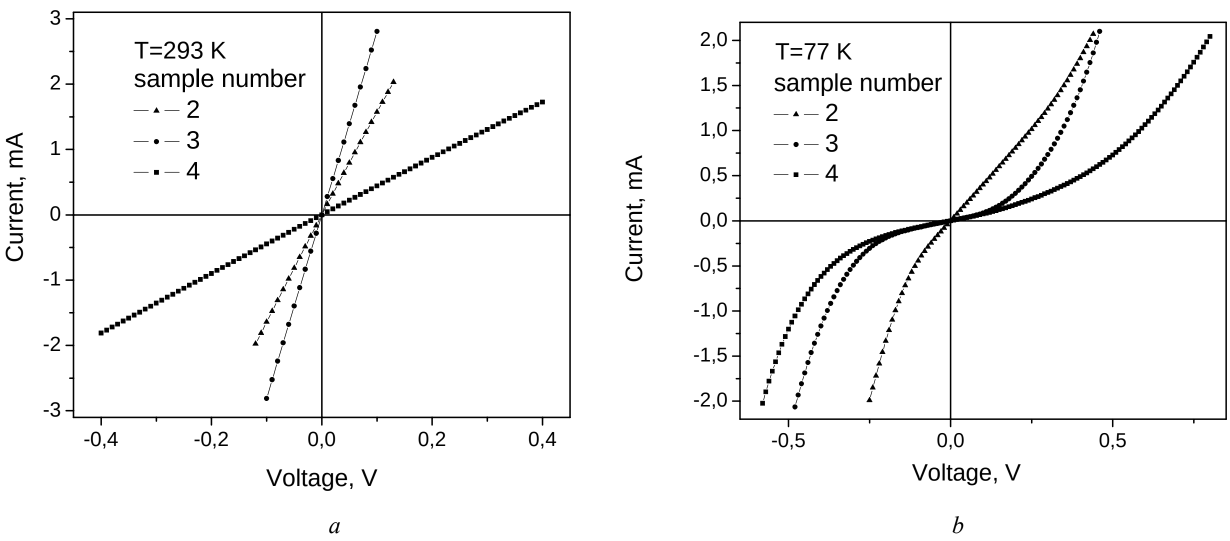

Fig. 3. Current-voltage characteristics of In–*n*-$Hg_{0.61}Cd_{0.39}Te$–In structures for T = 293 K (a) and T = 77 K (b) (hole concentration is $7.69 \cdot 10^{14}$ cm^{-3} at T = 77 K).

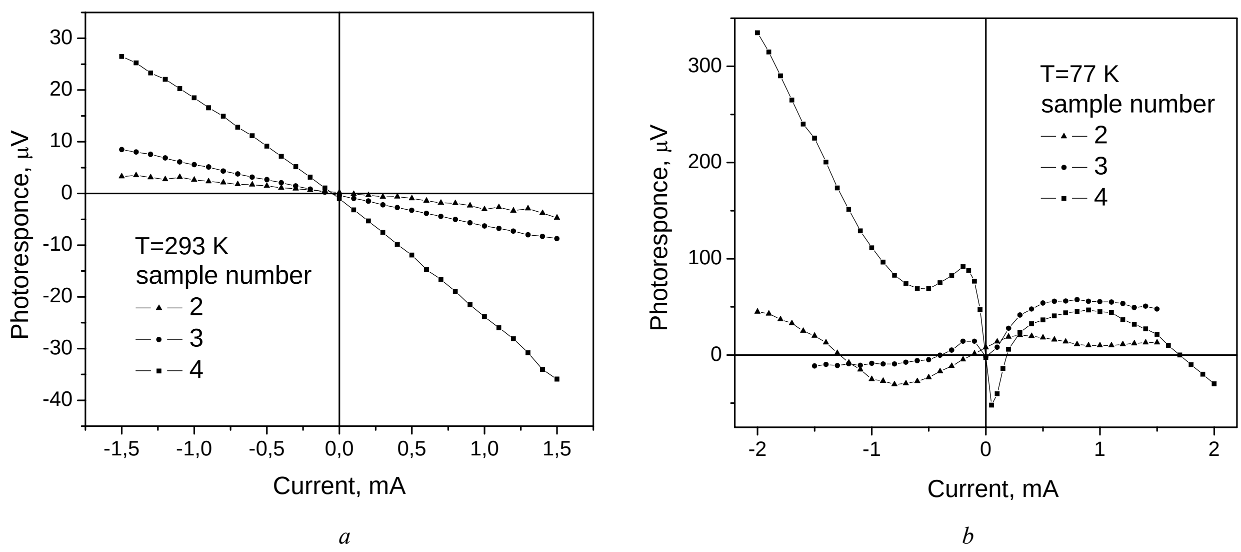

Fig. 4. Photoresponse of In–*n*-$Hg_{0.61}Cd_{0.39}Te$–In structures versus the bias current for T = 293 K (a) and T = 77 K (b) ($N_n = 7.69 \cdot 10^{14}$ cm^{-3} at T = 77 K).

The current responsivity of the non-linear detector can be written as [11]

$$\beta = \beta_0 \left(\frac{1+\Delta_1}{1+\Delta_2} \right), \quad (3)$$

where $\beta_0 = \frac{1}{2}\frac{f^{(2)}}{f^{(1)}}$, $\Delta_1 = \frac{A^2}{16}\frac{f^{(4)}}{f^{(2)}}$, $\Delta_2 = \frac{A^2}{8}\frac{f^{(3)}}{f^{(1)}}$, $f^{(1)} - f^{(4)}$ are derivatives of the function $I = f(V)$. Voltage V is superposition of the constant voltage V_0 and small alternating signal voltage: $V = V_0 + A\cos\omega t$.

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At a low value of the input signal, the current responsivity of the detector is determined by the factor

$$\beta_0 = \frac{1}{2}\frac{f^{(2)}}{f^{(1)}}.$$

The voltage responsivity of detector is equal to the product of the current responsivity and its differential resistance R_d:

$$\gamma = \beta \cdot R_d . \quad (4)$$

At a small magnitude of the signal

$$\gamma_0 = \beta_0 \cdot R_d . \quad (5)$$

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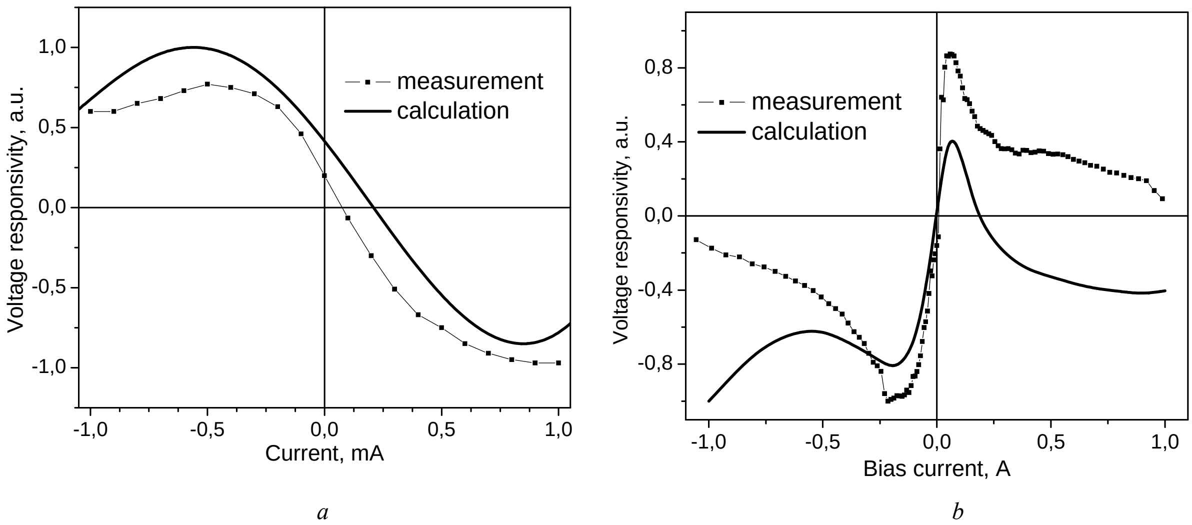

Fig. 5. Calculated using Eq. (5) and measured voltage responsivity versus the sample bias current. (a) T = 293 K, p-type MCT-sample with x = 0.31. (b) T = 77 K, n-type MCT-sample with x = 0.39. The photoresponse is presented in arb. units to compare the position of peaks.

Fig. 5 shows the measured and calculated voltage responsivity of the investigated samples as a function of the bias current. Calculations were performed using Eq. (5) with the measured $I–V$ curves of these samples. At low currents, the obtained experimental dependences of signal on the magnitude and direction of current correlate with the calculated γ_0 versus I curves, and it indicates the dominant contribution of Schottky contacts to the photoresponse of the structures under studying.

At low currents, main noises arising from the Schottky barrier presence are the thermal and shot ones related with the random motion of thermally agitated electrons in the epilayer and from the fluctuations of the number of electrons crossing the Schottky barrier, respectively [12].

The thermal noise voltage from the device is

$$V_T = \sqrt{4kTR} \tag{6}$$

for one hertz bandwidth, where k is Boltzmann's constant, T – physical temperature, R – diode resistance at a given voltage $V = V_0$:

$$R = dV / dI\big|_{V=V_0} . \tag{7}$$

The mean squared value of the shot noise current is

$$I_{sh}^2 = 2eI \tag{8}$$

for one hertz bandwidth, where e is the charge of electron, I – average DC current. The shot noise voltage from the device, without taken into account the space charge depression factor, is

$$V_{sh} = \sqrt{I_{sh}^2 R} . \tag{9}$$

For the sample 4 (Fig. 4b) at I = 0.2 mA and T = 77 K, the thermal noise voltage is $1.6 \cdot 10^{-9}$ V, the shot noise voltage is $4.8 \cdot 10^{-9}$ V.

The NEP is the signal level that produces a signal-to-noise ratio of 1. It can be written in terms of responsivity

$$\mathrm{NEP} = \frac{V_{noise}}{S_V} , \tag{10}$$

where S_V is the volt–watt responsivity.

Assuming that the antenna area is equal to the maximum effective area $A_\lambda = \frac{\lambda^2}{4\pi} G$ [13] (where λ is the radiation wavelength and G is the antenna gain), NEP at current point I = 0.2 mA for the sample 4 in Fig. 4b is $3.5 \cdot 10^{-9}$ W/Hz$^{1/2}$ (the calculated value of G is equal to 0.4 for this MCT epitaxial structure and antenna design at 140 GHz radiation frequency, the volt–watt responsivity is equal to 1.42 V/W).

4. Conclusions

In this work, In–$Hg_{1-x}Cd_xTe$–In structures with ohmic at room temperature and non-ohmic at liquid nitrogen temperature contacts that are caused by presence of potential barriers at the contacts have been investigated. At low currents, the photoresponse of detectors based on these structures is due to the presence of potential barriers at the contacts. At the low biases, the calculated NEP of investigated In–n-$Hg_{0.61}Cd_{0.39}Te$–In detectors was $3.5 \cdot 10^{-9}$ W/Hz$^{1/2}$, when there available are the thermal and shot noises. The presence of Schottky barriers does not affect strongly on the NEP value, as compared to the same structures that were investigated in the framework of hot-electron bolometer theory [9, 10].

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