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On performance limits for long-wavelength non-cooled photoconductive (CdHg)Te detectors

Basic material properties and fabrication methods, which affect (CdHg)Te photoconductive detector performances, are discussed. The voltage responsivity R_λ and detectivity D^+_{max} are calculated. For detectivity limit a dimensionless expression of the form:

$$D^+_{max} = 0.64 \left(\frac{a\tau}{n_i}\right)^{1/2} \cdot \frac{\lambda}{hc}$$

has been obtained.

Domination of Auger recombination stated in a near intrinsic (CdHg)Te has allowed to predict the detector detectivity limits versus the wavelengths.

(CdHg)Te epitaxial layers which have been elaborated, allowed to fabricate detectors with performances near to theoretical ones. A new method for preparation of noisless electrical ohmic contacts and a good power dissipation was also elaborated. Special attention was given to the development of uncooled and high output voltage 10.6 μm detectors.

1. Introduction

To obtain (CdHg)Te high performance infrared detectors able to work in the wavelength range longer than 1 μm, criogenic cooling of a semiconductor element is necessary.

In many cases the cooling procedure may introduce serious problems. In many applications, however, sufficiently good parameters can be obtained for uncooled detectors. The analysis [1–3] has shown that responsivity and detectivity limits of noncooled photoconductive long-wave detectors are higher than those of photovoltaic ones. For long-wave noncooled photoconductive detectors the response speed is also sufficiently high, being equal to about $(10^{-4}$ $-10^{-10})$s, depending on the spectral range. The possibility of construction of fast photoconductive detectors for wavelengths ranging within 10.6 μm has been shown in [2–3]. This paper deals with the optimization of the detector parameters and gives some results in this field.

2. Detector performance evaluation

Suppose that the detector has the form of a square plate with area $d \times d$ mm² and thickness l. Suppose also that the reflection coefficients from frontal and rear surfaces are equal to 0 and 1, respectively, and that the recombination time of holes and electrons is τ, and that a is the absorption coefficient of the material. Because of high ratio of electron to hole mobilities the influence of holes on the conductivity may be neglected.

If the detector is biased with current source, then in case of weak illumination the following relations can be obtained [1, 3] for basic detector parameters:

2.1. Voltage responsivity R_λ

$$R_\lambda = V\frac{\lambda}{hc}\frac{1}{d^2}\frac{1-e^{-2al}}{l}\frac{\tau}{n_i}, \tag{1}$$

where V denotes bias voltage of the detector, n_i is the intrinsic carrier concentration, τ — recombination time.

The voltage responsivity increases monotonically with the decrease of the detector thickness, and reaches its maximum value for $2al \ll 1$.

In the latter case:

$$R_\lambda = \frac{2V\lambda}{hcd^2}\frac{\tau a}{n_i}. \tag{2}$$

2.2. Noise

In the discussed case three types of noises play an important role.

a) Johnson-Nyquist noise

$$\overline{U_J^2} = 4kTR\Delta f, \tag{3}$$

R — detector resistance.

b) Generation-recombination noise

For $n = p = n_i$ and $f \ll \frac{1}{2\pi\tau}$ [4]

$$V^2_{G-R} = \frac{2\tau}{n_i l}\frac{V^2}{d^2}. \tag{4}$$

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c) $1/f$ noise. This noise must be taken into account mainly in the case of low frequencies of radiation modulation.

For frequencies high enough the influence of $1/f$ noise can be neglected.

2.3. Detectivity D^+

If $1/f$ noise is neglected, then using (1), (3) and (4) the following relation for detectivity can be obtained:

$$D^+ = \frac{\lambda}{\sqrt{2}hc}\left(\frac{\tau a}{n_i}\right)^{1/2} \cdot F(X, C) \tag{5}$$

where

$$F(X, C) = \frac{1-e^{-2X}}{X^{1/2}(CX+1)^{1/2}}$$

and $X = l$, a — denotes a normalized thickness of the detector, CX is a ratio of Johnson noise to generation-recombination noise:

$$C = \frac{kTd^2}{P}\frac{n_i}{a\tau},$$

and P — denotes electrical power dissipated in the detector.

The graph of $F(X, C)$ function is given in fig. 1. From this graph it is seen that for each C value,

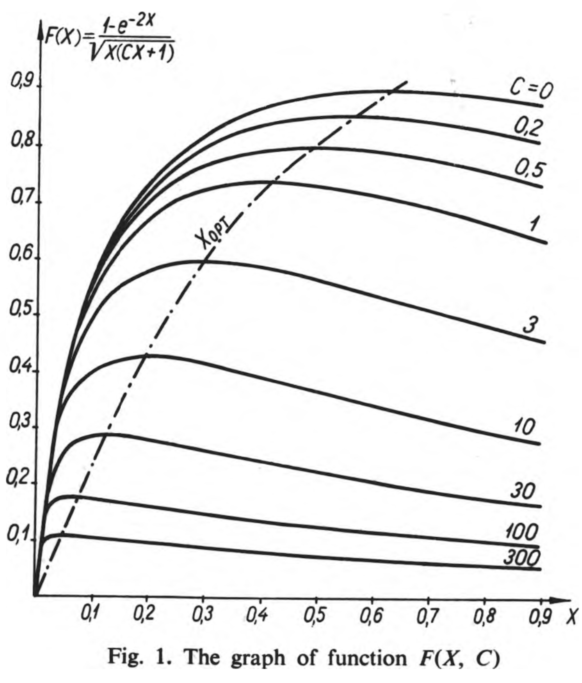

Fig. 1. The graph of function $F(X, C)$

the optimum detector thickness X_{opt} can be found. For $C = 0$ $X_{opt} = 0.625$, and in this case $F(X, C)$ reaches its maximum value, equal to 0.903. It is the case of detectivity limitation by generation-recombination noise. In this way the detectivity limit can be expressed by:

$$D^+_{max} = 0.64\frac{\lambda}{hc}\left(\frac{a\tau}{n_i}\right)^{1/2}, \tag{6}$$

From the last relation it follows that for radiation with a given wavelength, the maximum D^+ values is defined by $\left(\frac{a\tau}{n_i}\right)$ quantity. This quantity depends on composition of (CdHg)Te alloy and reaches its maximum for the optimum composition.

At present, the dependence of n_i on composition is well known [5]. In an intrinsic material at $T = 300$ K, the lifetime of the carriers is limited by Auger recombination. However, in $Cd_xHg_{1-x}Te$, for $x > 0.28$ Shockley-Read mechanism of recombination plays a certain role. The lifetimes for Auger recombination have been defined theoretically [6] and proved experimentally [7]. Unfortunately, there is a lack of reliable data for $a = f(x, \lambda)$ and the optimalization of the detector parameters cannot be realized analytically. However, the estimation of detectivity limits becomes possible by assuming that for photons with energies slightly higher than E_g, a reaches the value 500 cm^{-1}. The dependence of detectivity limit on the wavelength value is shown in fig. 2. In the calculations the dependences n_i and E_g on x were taken from [5] and the values of τ_{Ai} from [6, 7].

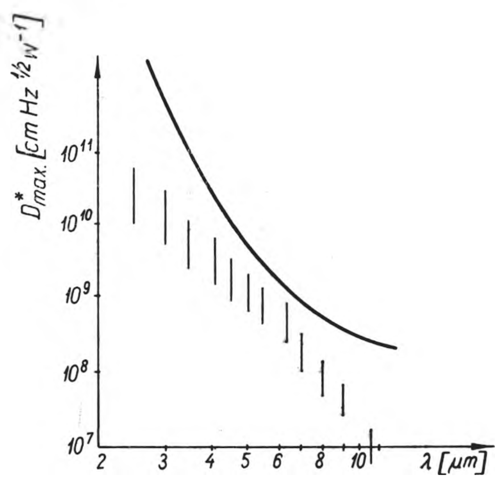

Fig. 2. Detectivity limit as a function of wavelength for PC (Cd,Hg)Te detectors

3. Experimental results

In the construction of detectors epitaxial layers with alloy composition gradient were applied. The layers were prepared by isothermal deposition of HgTe onto CdTe [8, 9]. The structure of the photoelement is shown in fig. 3.

Because of high resistivity of the CdTe substrate (10^7 Ωcm) the photoelement could be soldered directly to a copper plate. If the photoelement was

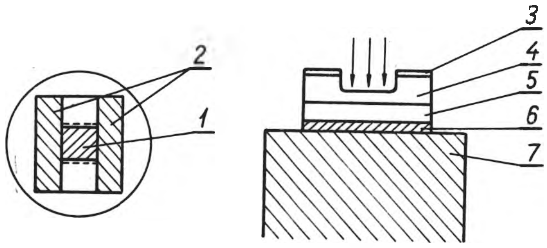

Fig. 3. Configuration of PC (Cd,Hg)Te detector
1 — sensitive area; *2* and *3* — contacts; *4* — (Cd, Hg)Te; *5* — CdTe; *6* — indium alloy; *7* — substrate

fastened carefully then the permissible density of the power dissipated in the detector was equal to about 100 W/cm^2 (for the detector areas smaller than $0.3 \times \times 0.3$ mm^2).

The transparency of CdTe made it possible to utilize also the radiation reflected from the metal covered rear surface.

The photosensitive element was made by selective etching of the structure with gradient alloy composition. The electrical contacts were obtained by the deposition of indium in photosensitive region with lower band gap. The latter allows to obtain low resistive and noiseless contacts.

The experimental values of the detectivities of the obtained detectors are shown in fig. 2. In the spectral range 4–7 μm the detectivities approach their limit values. Much lower experimental values were obtained for $\lambda < 4$ μm and $\lambda > 7$ μm. There are different reasons responsible for the discrepancies in these two spectral regions. For long wavelengths the relation $CX \ll 1$ is not fulfilled even when the heat is well transferred from the photosensitive element. Low values of the detectors own noises in these regions, as well as of their resistance produce so high demands on preamplifiers that the reduction of the latter is almost impossible. It is more convenient to apply detectors whose active thicknesses are smaller than the optimum thicknesses obtained from the calculations performed for an ideal amplifier. The detailed investigations were carried out for 10.6 μm detectors. The 10.6 μm detectors used in the experiment were characterized by thicknesses lower than the optimal for the maximum D^+ value, and by dark resistivities 50–200 Ω/□. For detector dimensions 0.3×0.3 mm^2 the responsivities were obtained of the order of several V/W. The investigation of noise has shown the existence of $1/f$ type noise, which practically disappeared at frequencies higher than 100–1000 Hz. For higher frequencies the values of the detectivities were equal to about 10^7 cmHz$^{1/2}$ W^{-1}.

In some applications the value of maximum output voltage of the detector plays an important role. It was found that in detectors with 50–100 Ω/□ resistivity about 0.5 V/mm output signal can be obtained.

In detectors with 10 mm length it was possible to obtain 10V output signals with linearity ranging within 20%.

A further considerable increase of the maximum signal is possible in the case of a pulsed bias of the detector. For example, the maximum signals, equal to about 100V, were observed by applying a bias with 5 μs duration. For pulsed bias the generation-recombination limit of the detectivity can be obtained. The carried out investigations and measurements have shown (fig. 4) that the detector time response can be very short and equal to single nanoseconds. The time response can be decreased to the order of picoseconds due to the increase of HgTe content. It can be however done at the expence of the decrease of responsivity and detectivity values.

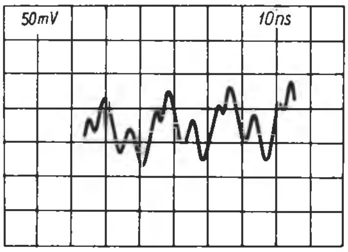

Fig. 4. Detector response to self-mode-locked CO_2 TEA laser pulse

In noncooled detectors, for $\lambda < 4$ μm, considerably different features, as compared to 10.6 μm detectors, could be found. The detectivity limit for low bias current is reached due to longer life-time and lower concentrations of the carriers. The difficulties in obtaining the detectivity limits are different from those in the case of 10.6 μm detectors. It is difficult to obtain intrinsic carrier concentration in the material and connected with it upper limits of carrier life time, limited by Auger recombination. The detector parameters are also influenced by surface recombination. The increasing role of the difficulties listed above increases with the decrease of long wave limit of the photosensitivity.

4. Conclusions

1. Ultimate value of D^+_{max} for PC detectors depends only on basic material properties and can be expressed by (1, 3)

$$D^+_{max} = 0.64\left(\frac{\alpha\tau}{n_i}\right)^{1/2} \frac{\lambda}{hc}.$$

2. Recombination time is Auger limited for uncooled $\lambda > 4$ μm (Cd, Hg)Te PC detectors. This allows to estimate ultimate detectivity as a function of wavelength, (1, 3).

3. (Cd, Hg)Te epitaxial layers technology makes it possible to obtain near theoretical performance of 4–7 μm uncooled PC detectors. For $\lambda < 4$ μm and $\lambda > 7$ μm experimental values are much lower than theoretical ones.

4. It is possible to obtain uncooled 10.6 μm PC detectors with nano- and subnanosecond response time. The sensitivity and detectivity values for 10.6 μm detectors are much higher than the ones for other types of high speed (subnanosecond range) uncooled detectors. Pulse biasing highly increases D^+, R_λ, and the maximum output voltage values.

О пределах эффективности неохлаждаемых фотопроводниковых детекторах (CdHg)Te для длинноволнового излучения

В работе обсуждены основные свойства материала и методы его изготовления, которые влияют на эффективность фотопроводниковых детекторов из (CdHg)Te. Рассчитана характеристика напряжения R_λ и детектирующая способность $D^+_{\max}$. Для предела детектирующей способности было получено безразмерное выражение в виде

$$D^+_{\max} = 0{,}64\left(\frac{\alpha\tau}{n_i}\right)^{1/2}\cdot\frac{\lambda}{hc}.$$

Преобладание рекомбинации Аугера, выявленное в (CdHg)Te, близких к насыщению, позволяет предусматривать пределы детектирующей способности детектора в зависимости от длины волны излучения. Разработанные авторами эпитаксиальные слои (CdHg)Te позволяют создавать детекторы с эффективностью, близкой к теоретической. Разработан также новый метод изготовления бесшумных электрических контактов с удовлетворительным рассеянием мощности. Особое внимание уделено развитию неохлаждаемых детекторов с высоким напряжением выхода для излучения 10,6 мкм.

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