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Ultimate parameters for $Cd_xHg_{1-x}Te$ photodiodes

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Assuming that the basic current component for *p–n* junction in a photodiode is a diffusion current determined by the Auger lifetime of carriers the limiting parameters of photodiodes: voltage responsivity, differential resistance and normalized defectivity have been evaluated. The calculations have been carried out for 28–300 K temperature range and 2–40 μm spectral region. The obtained theoretical results have been compared with the experimental data.

Introduction

Rapid development of measuring techniques and devices based on employing the infrared radiation became the reason for undertaking complex examination of infrared detectors. Cd_x–Hg_{1-x} Te seems to be promissing semiconductor material for photovoltaic and photoconductive detectors working in the spectral range 2–14 μm. A number of theoretical and experimental works [1–11] have been devoted to investigation of properties of this material and to detectors produced of this material. As it is well known the responsivity and detectivity of (CdHg)Te detectors depend to a considerable degree upon their working temperature.

Few attemps to evaluate the ultimate parameters of photodiodes at temperatures 77 and 300 K have been published [8,11]. Due to wider and wider application of thermoelectric refrigerators allowing to produce arbitrary temperatures between 190 and 300 K the evaluation of ultimate parameters for photodiodes within the whole practically useful temperature range is of a great interest. This problem is discussed in the present paper.

Analysis of photodiode parameters

The basis parameters determining the application of detectors are: voltage sensitivity, normalized detectivity and differential resistance.

The voltage sensitivity of photodiode $R_v = dV/dP$, where dV denotes the change in voltage at the photodiode under the influence of change in power dP of the incident radiation, may be written in the form:

$$R_v = \frac{q\lambda}{hc}\eta R_d, \tag{1}$$

where:

$R_d = dV/dt$ — differential resistance of photodiode,
λ — wavelength of the incident radiation,
η — quantum efficiency,
q — elementary change.

The quantity η in an appropriately designed photodiode may reach the values close to unity for $\lambda < \lambda_{co} = hc/E_g$.

If the photodiode surface is A, then it is convenient to represent the values of R_v and R_d in the normalized forms R_dA and R_vA independent of that area. The value of R_dA may be determined from the I–V characteristics of photodiode.

The total current density passing through the photodiode may be written in the form:

$$J = J_D + J_{G-R} + J_T + J_Z. \tag{2}$$

The particular components denote successively the following current densities: diffusion c.d., generation recombination c.d., tunneling c.d., and leakage current of the diode.

The relations between the values of currents depend upon the material composition, working temperature, doping, carrier lifetime and photodiode design. The value of leakage current may be small, if an appropriate technology is applied. The generation-recombination current depends upon the carrier lifetime within the space charge region and may be also neglected, provided that the material quality is high enough [8]. The value of the tunneling current depends strongly upon the degree of doping; if the width of the space charge region is not too small J_T may be neglected.

Under these circumstances the fundamental role is played by diffusion current of the junction. The diffusion current J_D of the junction is connected with the minority carrier diffusion from the neutral junctions and may be described by the formulae:

$$J_D = (J_n + J_p)\,(\exp(qV/kT) - 1), \tag{3}$$

$$J_n = n_i^2/N_a\left(\frac{qkTu_n}{\tau}\right)^{1/2}, \tag{4}$$

$$J_P = n_i^2/N_d\left(\frac{qkTu_p}{\tau}\right)^{1/2}, \tag{5}$$

(J_n and J_p — respective electron and hole components of the saturation diffusion current),

where:

n_i — concentration of intrinsic carriers,

N_a, N_d — concentration of acceptors and donors, respectively,

u_n, u_p — carrier mobilities,

τ — carrier lifetime,

q — elementary charge.

From the carried out investigations [12] it follows that a large value of electron component J_n of diffusion current results from poor quality of p-type material. In the material of good quality the lifetime is defined by interband Auger recombination and for p-type material it is many time greater than that for n-type material of the same doping degree. For this case J_n is neglegible and

$$J_D = n_i\left(\frac{qkTu_p}{2\tau_{A_i}}\right)^{1/2}\cdot(\exp(qV/kT)-1), \tag{6}$$

where τ_{A_i} — Auger carrier lifetime in the intrinsic material.

This current does not depend on doping degree of the material, but only on parameters characterizing the intrinsic material, therefore its value can be estimated as a function of temperature.

The formula (6) defines the minimum possible value of the diode current. If the formula (6) is fulfilled then the quantities R_dA and R_vA at zero bias are determined by [8]:

$$R_{d_0}A = 1/n_i\left(\frac{2\tau_{Ai}kT}{q^3up}\right)^{1/2}, \tag{7}$$

$$R_{v_0}A = \frac{\eta\lambda}{hcn_i}\left(\frac{2\tau_{A_i}kT}{qu_p}\right)^{1/2}. \tag{8}$$

These are maximal values of the parameters $R_{d_0}A$ and $R_{v_0}A$ possible to achieve if technological and constructional difficulties are overcame for the photodiode.

Since the value of τ_{A_i} may be determined by the expression [13], then:

$$\tau_{A_i}(s) = 7.55\cdot 10^{-9}T^{-3/2}\lambda_{co}^{-1/2}\varepsilon_0^2\times\exp\left(\frac{1.42\cdot 10^4}{T\lambda_{co}}\right)\left(\frac{\lambda_{co}+0.247}{\lambda_{co}+0.1234}\right), \tag{9}$$

where:

T — temperature of diode, in K,

λ_{co} — cut-off wavelength, in μm,

ε_0 — low-frequency dielectric constant of material on the base of [14]:

$$n_i(\mathrm{m}^{-3}) = 5.045\cdot 10^8\lambda_{co}^{-3/4}T^{3/2}\exp-\frac{0.72\cdot 10^4}{T\lambda_{co}}. \tag{10}$$

By substitution of values to formulae (7) and (8) we obtain

$$R_{d_0}(\Omega\mathrm{m}^2) = \frac{\lambda_{co}^{1/2}k^{1/2}\varepsilon_0}{4.12\cdot 10^{22}T^{7/4}q^{3/2}u_p^{1/2}}\times\exp\left(\frac{0.72\cdot 10^4}{T\lambda_{co}}\right)\left(\frac{\lambda_{co}+0.247}{\lambda_{co}+0.1234}+1\right), \tag{11}$$

$$\begin{aligned} R_{v_0}A\left(\frac{V}{W}m^2\right) &= \frac{\lambda_{co}^{3/2}k^{1/2}\varepsilon_0}{4.12\cdot 10^{26}T^{7/4}q^{1/2}u_p^{1/2}hc}\times \\ &\times\exp\left(\frac{0.72\cdot 10^4}{T\lambda_{co}}\right)\left(\frac{\lambda_{co}+0.247}{\lambda_{co}+0.1234}+1\right), \end{aligned} \tag{12}$$

or if one substitutes the physical constants

$$R_{d_0}A = 2.25\cdot 10^{-6}\frac{\lambda_{co}^{1/2}}{T^{7/4}}\exp\left(\frac{0.72\cdot 10^4}{T\lambda_{co}}\right)\left(\frac{\lambda_{co}+0.247}{\lambda_{co}+0.1234}+1\right), \tag{13}$$

$$R_{v_0}A = 1.81\cdot 10^{-6}\frac{\lambda_{co}^{3/2}}{T^{7/4}}\exp\left(\frac{0.72\cdot 10^4}{T\lambda_{co}}\right)\left(\frac{\lambda_{co}+0.247}{\lambda_{co}+0.1234}+1\right)\cdot \tag{14}$$

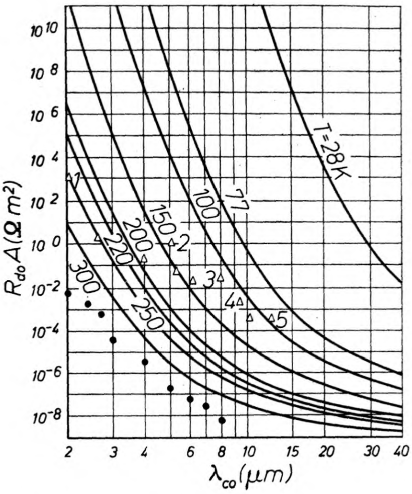

Fig. 1. Normalized differential resistance vs. the cut-off wavelength and the temperature. The experimental values for 300 and 77 K temperatures are marked with points. The ciphered point 2 and 4 are taken from work [15] the point 1 from paper [16], and the point 3 and 5 from [17]

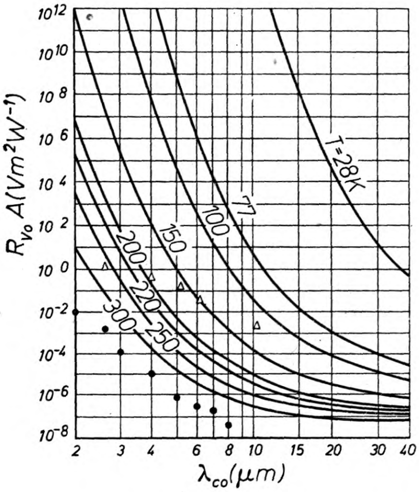

Fig. 2. Normalized voltage responsivity of photodiodes vs. the cut-off wavelength and the temperature. The experimental values obtained in our laboratory for 300 K are marked by points, for 77 K being marked by triangles

For calculations it has been assumed that $\eta = 1$ and $\mu_p = 10^{-2}$ m^2/Vs. The graphs of these dependences are presented in figs. 1 and 2.

The normalized detectivity is conditioned by the value of voltage responsivity and detector noise. The fundamental role in photodiode is performed by the thermal Johnson–Nyquist noise, the current noise and the noise of "$1/f$" type. The low-frequency "$1/f$" noise depends essentially upon the way of diode production. For proper technology the "1/*f*" noise contribution may be negligible, especially in the high frequency region.

At zero bias of diode the total current flowing in the external circuit is equal to photoelectric current

$$I_{\Phi} = \eta q A \Phi_s,$$

where:

I_{Φ} — photoelectric current,
Φ_s — flux of incident photons,

In this case the mean square value of the total noise voltage may be expressed [8] by the relation

$$V_n^2 = (4kT + 2qI_{\Phi}R_{d_0})\Delta f R_{d_0}, \tag{15}$$

and the normalized detectivity amounts to

$$D^* = \frac{q\eta\lambda(R_{d_0}A)^{1/2}}{hc(4kT + 2qI_{\Phi}R_{d_0})^{1/2}}. \tag{16}$$

For the last formula we may distinguish two cases:

— limitation due to photon radiation, if $4kT \ll 2qI_{\Phi}R_{d_0}$, and then

$$D^* = \lambda/hc(\eta/2\Phi_s)^{1/2}, \tag{17}$$

— limitation by thermal noise, if $4kT \gg 2qI_{\Phi}R_{d_0}$, and then

$$D^* = \frac{q\eta\lambda(R_{d_0}A)^{1/2}}{2hc(kT)^{1/2}}, \tag{18}$$

or on the basis of (18) and (7)

$$D^*_{\max} = \eta\lambda/2hc\left[\frac{1}{n_i}\left(\frac{2q\tau_{A_i}}{kTu_p}\right)^{1/2}\right]^{1/2}. \tag{19}$$

By substitution of relations (9), and (10) to (19) we obtained the expressions

$$D^*_{\max}(ms^{-1/2}W^{-1}) = \frac{\lambda_{co}^{5/4}q^{1/4}\varepsilon_0^{1/2}}{4.08\cdot 10^{15}hcT^{11/8}u_p^{1/4}k^{1/4}}\times$$
$$\times\exp\left(\frac{0.36\cdot 10^4}{T\lambda_{co}}\right)\left(\frac{\lambda_{co}+0.247}{\lambda_{co}+0.1234}+1\right), \tag{20}$$

or after substitution of physical constants:

$$D^* = 1.62\cdot 10^8\frac{\lambda_{co}^{5/4}}{T^{11/8}}\exp\left(\frac{0.36\cdot 10^4}{T\lambda_{co}}\right)\left(\frac{\lambda_{co}+0.247}{\lambda_{co}+0.1234}+1\right). \tag{21}$$

The dependence (21) for different temperatures within the 28–300 K range are presented in fig. 3.

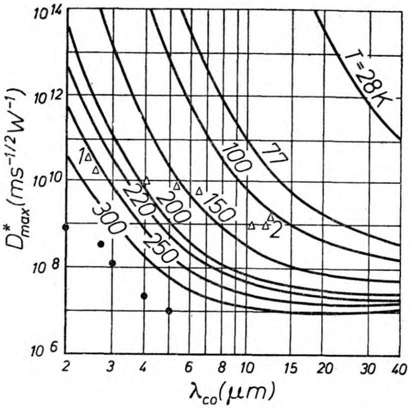

Fig. 3. Normalized detectivity photodiodes vs. the cut-off wavelength and the temperature. The experimental data for 300 K are marked with points and for 77 K by triangles. The points denoted by cyphers 1 and 2 are taken from the works [16] and [17], respectively

Comparison with the experimental data

In figs. 1–3 the highest experimental values of R_{p_0}, R_{v_0} and D^* obtained recently by us and other authors [15–17] are marked by points. The photodiodes examined by us have been produced with the help of a method described in [9].

In the case of uncooled detectors we observe sufficiently good agreement of experimental data with the respective calculated ultimate values for the case of detectors of 3–6 μm wavelength range. The consistency in the intermediate wave range is particularly good, considering that in this case that the real quantum efficiency was 0.2–0.4 and not 1, as it has been assumed in formulas for R_{d_0} and D^*. In the shorter wavelength range significant differences are observed between the experimental and theoretical data. It seems that in this case the recombination by Shockley–Read centres is of an essential significance.

In the long-wavelength range $\lambda_{co} > 6$ μm the recombination model due to Auger mechanism is well satisfied. Experimental limitations connected with the values of the voltage responsivity and detectivity are mainly due to the decrease of the quantum efficiency. A large quantum efficiency is difficult to achieve, because of low value of the diffusion length which is comparable with (or even smaller than) the width of the absorption region ($L_D \leqslant 1/\alpha$). It should be emphasized that for $\lambda_{co} > 6$μm values of $R_{d_0}A$ and $R_{v_0}A$ are very small.

In the latter case ultimate value of D^* in the uncooled diodes is relatively high for long-wavelength range, the latter cannot be practically employed due to very small values of $R_{d_0}A$ and $R_{v_0}A$. This situation may be improved in photodiodes of very small areas to which the radiation is led with the aid of lightguide [18].

In the cooled photodiodes the region of good consistency of experimental and theoretical data is shifted toward the greater values of λ_{co}. In particular, in the photodiodes cooled down to 77 K the experimental data are essentially lower than the ultimate values. Only for photodiodes working in a more longwave region (8–14 μm) the poorer consistency as to the order of magnitude is achieved.

These relationships are understandable as there exist a strong dependence of the diffusion current on the temperature and the energy gap. In strongly cooled materials of greater energy gap the value of the diffusion current is small and the other current components in a diode may have a strong influence on the operation of the latter.

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Предельные параметры фотодиодов Cd_xHg_{1-x} Te

При предположении, что в фотодиоде (CdHg)Te основной составляющей тока электронно-дырочного перехода является диффузионный ток, определенный временем жизни Оже носителей, вычислены предельные параметры фотодиодов: чувствительность по напряжению, дифференциальное сопротивление и стандартная обнаружимость. Расчет произведен для температур 28–300 K и области спектра 2–40 мкм. Результаты теоретического расчета сопоставлены со значениями, полученными опытным путем.