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Numerical optimization of an extracted HgCdTe IR-photodiodes for 10.6-μm spectral region operating at room temperature

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Abstract

The electrical and photoelectrical properties of long wavelength $\underline{n}^+p\underline{p}^+$ $Hg_{1-x}Cd_xTe$ structures have been optimized by using an exact numerical analysis. In this analysis we have been taking into account the degeneracy, non-parabolicty, deviation from thermodynamical equilibrium and graded interfaces. The band diagram, electrical field, carrier mobility, photoelectrical gain, responsivity, noise and detectivity have been calculated and optimized as a function of different variable such as alloy composition, doping concentration, thickness, and applied voltage to obtain optimized performance at room temperature. This numerical simulation can be used to optimize the mentioned parameters for other structures such as $\underline{n}^+n\underline{p}^+$, $\underline{n}^+p$ operating in photodiode, or photovoltaic mode.

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Keywords: HgCdTe multi-junction photodiodes; Long-wavelength infrared photodetector (LWIR); Device simulation

1. Introduction

During the past four decades mercury cadmium telluride (HgCdTe) has became the most important semiconductor for the middle and long wavelength IR photodetectors [1–7]. There have been numerous attempts to replace HgCdTe with alternative materials [8–12]. Nevertheless, HgCdTe remains the leading semiconductor for IR detectors, especially for operation at room temperature.

The $Hg_{1-x}Cd_xTe$ alloys form a direct band-gap system whose energy gap depends on alloy composition. For alloy composition $x<0.3$, band gap energies are less than 0.5 eV occur, thus making these alloys, at low temperature, suitable as infrared detectors for wave length between 3 and 40 μm. But at temperatures higher than 200 K, the intrinsic carrier concentration in these alloys is larger than the doping concentration and hence the intrinsic recombination process dominates. At temperatures close to room temperature the Auger-1 and Auger-7 thermal generation-recombination mechanism have largest rate and special constructions must be used to suppress the Auger generation and recombination [13–15]. Some authors proposed non-equilibrium photodiode structures which employ both minority carrier exclusion and extraction to suppress the Auger generation [16–28]. The non-equilibrium photodiode structures consist of three layers. Layer one may be wide gap and heavily doped, $\underline{n}^+$, layer two is narrow gap with lightly doped, p, and layer three may be wide gap and heavily doped, $\underline{p}^+$, as shown in Fig. 1. The width of layer two should be small compared to minority carrier diffusion length. Calculations of the electron mobility show that it is higher than the hole mobility in $Hg_{1-x}Cd_xTe$ [29]. These data together with the carrier lifetimes indicate that p-type alloys are expected to have photodetector performance superior than of n-type alloys [30–32].

This structure when used for detection of long wavelength IR radiation at room temperature, suffer from two major deficiency, namely, poor quantum efficiency and low dynamic resistance [33,34]. These two problem can be solved though adoption of more sophisticated device architectures, such as multiple heterostructure devices [34]

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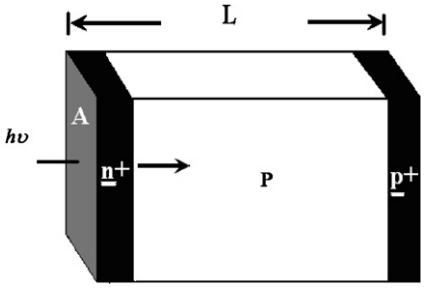

Fig. 1. Cross section of the $\underline{n}^+p\underline{p}^+$ HgCdTe photodiode.

or stacked multi-junction photodiodes [32]. In either case, a single $\underline{n}^+p\underline{p}^+$ photodiode is used as primary cell for construction of such devices. Using of optimized parameters of a single $\underline{n}^+p\underline{p}^+$ photodiode such as thickness, composition and doping (for both contact and active region) could have a considerable impact on performance of the devices. In this paper we propose an exact numerical analysis to optimize all the basic parameters of a long wavelength $\underline{n}^+p\underline{p}^+$ $Hg_{1-x}Cd_xTe$ photodiode at room temperature. This analysis can be also applied to optimize the parameters of similar structure operating in different modes. We believe that our method can give more reliable result than obtained by previous optimization [35,36].

2. Theoretical model

The steady-state analysis of photoelectric effects in any heterostructure can be performed by simultaneously solution of five nonlinear differential equations of the transport, continuity and the Poisson equations. The nonlinear set equations to be solved are:

(I) Two transport equations for electrons and holes:

$$J_n(x) = \mu_n(x)\, n(x) \frac{dF_n(x)}{dx}, \tag{1}$$

$$J_p(x) = \mu_p(x) p(x) \frac{dF_p(x)}{dx}, \quad J = J_n + J_p. \tag{2}$$

(II) Two continuity equations:

$$\frac{dJ_n(x)}{dx} = qU(x) = q[R(x) - G(x) - G_{ph}(x)], \tag{3}$$

$$\frac{dJ_p(x)}{dx} = -qU(x) = -q[R(x) - G(x) - G_{ph}(x)] \tag{4}$$

(III) the Poisson's equation:

$$\frac{d^2\psi(x)}{dx^2} + \frac{1}{\varepsilon_r(x)} \frac{d\varepsilon_r(x)}{dx} \frac{d\psi(x)}{dx} = \frac{q}{\varepsilon_0 \varepsilon_r(x)} [N_d^+(x) - N_a^-(x) + p(x) - n(x)], \tag{5}$$

where n, J_n, μ_n and F_n are electron concentration, current density, mobility, and qausi-fermi level, respectively, and p, J_p, μ_p and F_p are the same values for holes. Also q is the electron charge, G and R are the generation and recombination rates, ψ is electric potential, N_d^+ and N_a^- are the ionized donors and acceptors concentration. The ε_0 is permittivity of free space and ε_r is the dielectric constant. In narrow-band gap semiconductors with including non-parabolicty of bands and degeneracy, $n(x)$ and $p(x)$ are expressed by well-known relations [37]:

$$n(x) = \frac{4}{\pi^{1/2}} \left(\frac{2\pi m_e^*}{h^2}\right)^{3/2} \times \int_{E_C}^{\infty} \frac{(E - E_C)^{1/2}(1 + \alpha(E - E_C))^{1/2}[(1 + 2\alpha(E - E_C))]dE}{1 + \exp[(E - F_n)/KT]}, \tag{6}$$

$$p(x) = \frac{4}{\pi^{1/2}} \left(\frac{2\pi m_p^*}{h^2}\right)^{3/2} \int_{E_V}^{-\infty} \frac{-(E_V - E)^{1/2}\, dE}{1 + \exp[(F_p - E)/KT]}, \tag{7}$$

where α and m_e^* are, respectively, non-parabolicty factor and electron effective mass at the conduction band edge, and according to the Kane's band model they are

$$\alpha = \left(1 - \frac{2m_e^*}{m_0}\right) \frac{1}{E_g} \left(1 - \frac{E_g \Delta}{3(E_g + \Delta)(E_g + 2\Delta/3)}\right),$$

$$\frac{m_0}{m_e^*} = 1 + \frac{2m_0 P^2}{3\hbar^2} \left(\frac{2}{E_g} + \frac{1}{E_g + \Delta}\right),$$

$E_C = -q\psi - \chi$ and $E_V = -q\psi - \chi - E_g$ are the bottom edge of conduction band and upper edge of valence band, E_g—width of band gap, χ—electron affinity, h—Plank constant, $m_p^* = .443m_0$—hole effective mass [38], $P^2 = (18 + 3x)q\hbar^2/2m_0$—the momentum matrix element [39], $\Delta = .893 + .165x$—the spin orbit splitting [40] , m_0—the free electron mass and x is alloy composition of Cd in $Hg_{1-x}Cd_xTe$.

The low field electron mobility is computed by taking into account the ionized impurity and polar optical–phonon scattering [41]. The high field corrections in electron mobility are then computed for each scattering mechanism [31,42]. It should be mentioned that the heavy hole mobility is taken as proportional to the electron mobility ($\mu_p = .01\mu_n$) [35].

At near room temperature, the thermal generation and recombination rates are determined by the Auger 1 and Auger 7 processes and the corresponding net recombination-generation rate is [43]:

$$U(x) = R_A(x) - G_A(x) - G_{ph}(x) = (G_{an}n + G_{ap}p)\left(\frac{np - n_0p_0}{n_0p_0}\right) - G_{ph}(x), \tag{8}$$

where G_{an} and G_{ap} are the Auger coefficients for electrons and holes, respectively [31]. n_0, and p_0 are electron and hole concentration in equilibrium condition. The position dependent optical generation rate, $G_{ph}(x)$, has been