Numerical estimation of photon reabsorption process and optical crosstalk in arrays of HgCdTe photodiodes

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Abstract-**The effect of photon reabsorption on photoelectric parameters of non-equilibrium $P^+\nu(\pi)N^+$ photodiodes, which are pixels of the detector array, was analyzed. This phenomenon results in a drastic reduction in the rate of radiative recombination and generation. Additionally, the phenomenon of optical crosstalk between the nearest pixels in the matrix was examined. The increase in the dark current caused by this phenomenon was estimated. It depends on the size of the pixel and distance between pixels and the value of bias voltage. Increase in the current is around 0.5% for pixel with surface 10x10µm^2 and around 1% with 5x5µm^2, reverse biased with 0.2V.**

I. INTRODUCTION

In the method developed by us, we treat photons as the Einstein gas of particles described by Bose-Einstein statistic. Next, using the method proposed by Humpreys [1], we divide photons into groups in specific energy ranges to determine the average values of the absorption coefficient and the radiative generation factor for them. The more groups, the more accurate is the approximation. We take into account additional effects accompanying the radiative generation (RG) and recombination (RR) phenomenon, i.e. secondary absorption (reabsorption) of photons generated by RR [2]. This effectively reduces the rates of RR and RG. However the emission of photons by the detector caused by the acts of RR may cause an unfavorable effect of the so-called optical crosstalk, which generates a false signal in neighboring pixels of the detector array. This phenomenon is a bane for constructors of detector matrices, and it becomes increasingly important as pixels produced in matrices are getting smaller and smaller (the surface area reaches the size of just 5µm x 5µm), and the distances between pixels are in the order of one micrometer. The motivation to do this work was the need to analyze the impact of non-equilibrium photons on single-pixel photoelectric parameters and optical crosstalk in a detector array.

II. NUMERICAL METHOD AND RESULTS

To solve the problem of optical crosstalk and photons reabsorption phenomenon we consider equations additional to the standard set of carrier transport equations. These equations, named the transport equations for photons were presented in some previous works [2,3], and are related to the carrier transport equations of through the inter-band radiative GR mechanism and by equation of energy balance. The equation of energy balance (eq.5) has been now modified by us and expanded so as to take into account the participation of photons. This modification of the energy balance equation is extremely important, because only now we have the full energy coupling between the field of photons and current carriers in the semiconductor structure. The calculations we have performed give results that differ from those in [2] and [3]. The transport equation for photons of density q^i, for which the energy $E^i < h\nu \leq E^i + \Delta E^i$ is expressed by [2,3]:

$$\frac{\partial q^i}{\partial t} = G^i_{RAD}\frac{np}{n_0 p_0} - q^i \alpha^i \frac{c}{\eta_i} - \nabla j_{q^i} \tag{1}$$

where $.G^i_{RAD} = \int_{E^i}^{E^i+\Delta E^i} \frac{c q(\nu)\alpha(\nu)}{\eta(\nu)} d\nu$, $\alpha(\nu)$ is the absorption coefficient, and the current density of i-kind photons reads $j_{q^i} = q_i c / 4\eta_i^3$ Following Humpreys [1], the quantities in Eq. (1) can be expressed by appropriate averages

$$q^i_0 = \int_{E^i}^{E^i+\Delta E^i} q(\nu)\, d\nu \tag{2}$$

$$\frac{\alpha^i}{\eta^i} = \frac{1}{q^i_0}\int_{E^i}^{E^i+\Delta E^i} \frac{q(\nu)\alpha(\nu)}{\eta(\nu)} d\nu \tag{3}$$

$$\bar{E}_{q_i} = \frac{1}{q^i_0}\int_{E^i}^{E^i+\Delta E^i} q(\nu) h\,\nu d\nu \tag{4}$$

Here h is the Planck constant, $q(\nu)$ is the Planck distribution function, ν is the photon frequency. Other symbols in equations (1)-(5) denote: p-index refers to holes and index n to electrons respectively, index 0 applies to thermal equilibrium c is the speed of light, η refractive index, ∇ gradient, e is the elementary charge, C_V specific heat, and ζ is the coefficient of thermal conductivity, ρ_s denotes the density of entropy, μ is the mobility and j is the current density. Solving the set of transport equations for electrons and holes together with the Poisson equation, transport equations for photons (equations (1)) and energy balance equation (5) by using the iterative methods we obtain a spatial distribution of quasi Fermi energies Φ_n and Φ_p ,electric potential Ψ, temperature T and density of photons q_i.

$$C_V \frac{\partial T}{\partial t} = -\nabla(\zeta \nabla \mathrm{T}) - \nabla\left(\rho_{s_p}\mu_p \nabla\Phi_\mathrm{p} + \rho_{s_n}\mu_n\nabla\Phi_\mathrm{n}\right) - \nabla\left(\Phi_\mathrm{n}\mathrm{j_e} + \Phi_\mathrm{p}\mathrm{j_p}\right) + \sum_i \left(q^i_0 \frac{\alpha^i}{\eta^i} c \frac{np}{n_0 p_0} - q^i\alpha^i\frac{c}{\eta_i}\right)\bar{E}_{q_i} \tag{5}$$

Having them we can determine all physical quantities occuring in transport process in a heterostructure. Below, we will present a sketch of the method, developed by us, of calculating

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the optical signal generated in a pixel as a result of the optical crosstalk phenomenon. The phenomenon concerns an adjacent pair ofpixels.

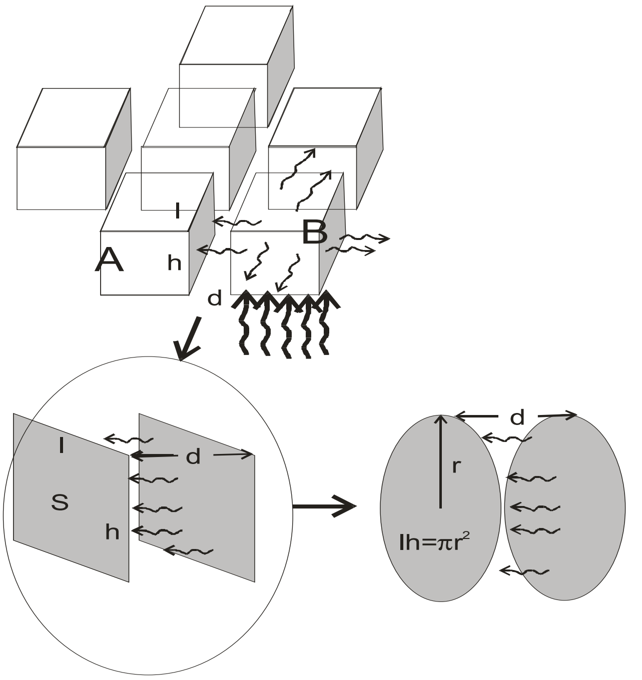

Fig. 1 The diagram of a matrix of the detectors. The selected area of pixel A is illuminated by the neighboring surface of pixel B. The parasitic non-equilibrium radiation arises as a result of the radiative recombination of non-equilibrium carriers generated in pixel B by the radiation absorbed in it, which is to be detected. To roughly determine how many of these photons reach pixel A from pixel B, we convert rectangular side faces of surface S into equivalent circular surfaces with the same area. The problem of circular symmetry is much simpler to analyze. We will count optical cross-talk based on an equivalent circular area

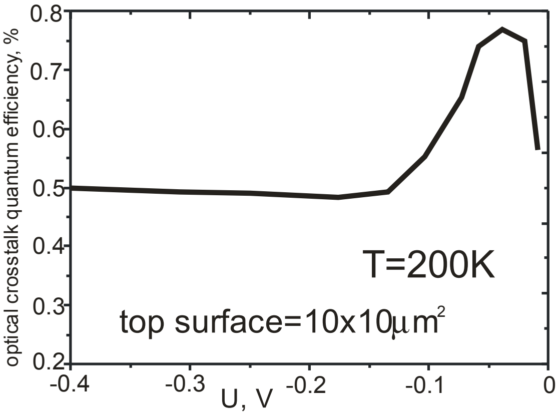

Fig.2. Quantum efficiency of the optical crosstalk effect between 10x10μm^2 pixels in distances of 1μm as a function of the bias voltage. Illumination of a selected pixel with a light wavelength of 10.6 mm causes the creation of a photocurrents in the adjacent 4 pixels. The ratio of the amount of electrons generated as a crosstalk photocurrent to the number of photons illuminating the selected pixel is defined as the quantum efficiency of the optical crosstalk effect. For a pixel of area 5x5μm^2 the quantum efficiency is about two times higher.

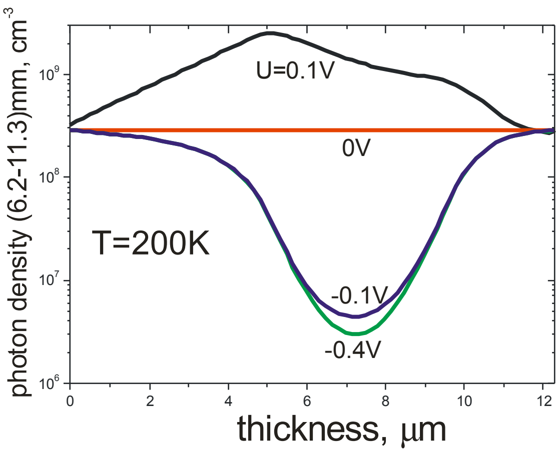

Fig.3. Spatial distribution of photons density in the range $6.2<\lambda<11.3$ μm in structure b for different polarization voltages (indicated next to the curves)

Figure 3 shows the calculation of the photon density distribution along the axis of symmetry of a pixel for a chosen, analyzed wavelength range at 200K. The effect of exclusion and extraction of carriers, that reduces the concentration of electrons and holes, acts similarly to lowering the temperature. This results in the reduction of photon concentration visible in Fig.3. Accumulation of charge carriers after polarization in the direct contributes to an increase in photon concentration. When analyzing photoelectric phenomena in semiconductors, we should take into account real density of photons that strongly influence radiative G-R processes. Fig. 4 shows the influence of the bias voltage on carriers concentration in a pixel,

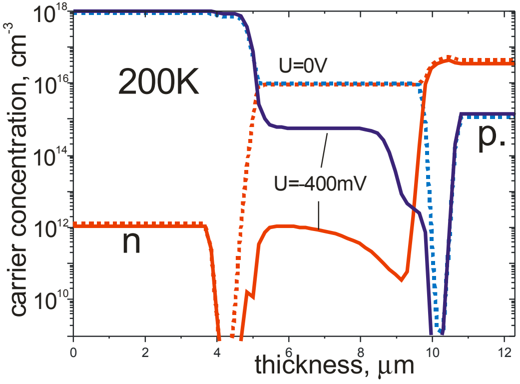

Fig. 4. Spatial distribution of electron and hole concentration in equilibrium (dotted lines) and after reverse biasing with 400mV

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