Photoconductive gain and generation-recombination noise in quantum well infrared photodetectors

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Photocurrent and excess current noise in a quantum well infrared photodetector are considered using a drift-diffusion model of charge carrier transport. The effect of quantum well recharge under the influence of the nonuniform generated charge carriers is addressed. The recharging effect drastically changes the dependency of both photoconductive gain and excess current noise gain upon detector parameters. We have found that for uniform generation, both gains coincide. For nonuniform generation, noise gain is essentially different from photoconductive gain. This distinction is of the order of 100% for the real device parameters. The existing discrepancy in formulae for photoconductive gain and excess current noise derived in different models, which implicitly assumed drift transport of electrons, is cleared up.

I. INTRODUCTION

Quantum well infrared photodetectors (QWIPs) based on optical transitions between bound and extended states are analogous to some extent to the extrinsic bulk photoconductive detectors. The photoconductive gain G_p is determined by an equation for photocurrent I_p

$$I_p = e\Phi_s \eta G_p,$$

where e is the electron charge, Φ_s is the signal optical flux, and η is the quantum efficiency of photoabsorption.

The experimental method usually employed to obtain the value of photoconductive gain relies on current noise measurements. The generation-recombination (g-r) noise dominates over other sources of noise in QWIPs. Generation-recombination noise in the photoconductive detector is described by an equation for excess noise current

$$I_n = \sqrt{4eG_n I \Delta f},$$

where I_n is the mean square root noise current, G_n is the noise gain, I is the total current, and Δf is the measurement frequency bandwidth. It is usually assumed that both gains are equal $G_p = G_n$.[1,2]

The origin of the photoconductive gain for QWIPs was considered in a number of works.[3–9] The consideration in Refs. 3 and 4 is based on analogy with conventional photoconductive detectors by using the drift model of current transport. The gain calculations performed in Refs. 5–7 are based on the electron flow balance equations considered for each of the quantum wells. Some differences exist in equations for G_p obtained by this method.[5–7] The origin of these distinctions has been clarified in Ref. 8. Excess current noise gain in QWIPs has been considered in Refs. 7 and 9. A drift model of carrier transport was implicitly assumed in calculations of both gains in Refs. 5–7 and Ref. 9.

What all of these approaches have in common is that they are based on consideration of uniform generation of excess charge carriers. It is known that QWIPs are operating in or near the background limited infrared performance (BLIP). In BLIP, both dark and signal charge carriers are produced by absorbing either infrared background or signal radiation. For an optimally designed photodetector with good absorption efficiency ($\alpha L \simeq 1$) and a steep profile of generated charge carriers, the condition of uniform generation is no longer valid (here, α is the coefficient of photoabsorption and L is the detector active area length). From continuity of current, it follows that the electric field should be increased if electron concentration decreases in the barrier region. In this manner, the nonuniformity of generated charged carriers will induce a built-in electric field. The Debye length of free charge carriers in QWIPs exceeds the photodetector active layer length. What this means is that built-in electric field will be produced by the charges accumulated in the wells. Charging of quantum wells will change the electric fields in adjacent barriers by a constant value depending upon a magnitude of charge in the wells. The built-in electric field influences transport of photoelectrons and causes difference in both photoconductive and noise gains as compared to the case of uniformly generated charge carriers. The nonuniformity in generation can be caused by different reasons. In this article, we will consider the nonuniform generation due to attenuation of radiation flux in the direction of the radiation propagation. The concept of the built-in electric field due to nonuniformity of generated carriers can be applied to the both n- and p-type QWIPs based on both intersubband and bound-to-extended state transitions. In this article, we will also refer mainly to the n-type of QWIP with photoelectrons generated from the single subband into the extended states over the barriers.

As far as we know, the influence of the nonuniform light absorption on photoconductive and noise gain was considered only in Ref. 10 for conventional bulk semiconductors. Despite some similarity, QWIPs are different from extrinsic

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bulk photodetectors in that the regions of generation-recombination (quantum wells) are separated from the regions where transport of excess charge carriers occurs (i.e., barriers). Thus, results obtained in Ref. 10 cannot be directly applied to QWIPs.

In this article, we will consider multiple quantum well structures with sufficiently thick barriers, so thick that current transport occurs via extended states over the barriers. For that reason we will neglect tunneling processes including sequential tunneling, which is another cause of charge and electric field redistribution in QWIPs.[10] We will consider the photoconductive detector with ideal ohmic contacts and will concentrate on the recharging processes which occur in the bulk of the detector, i.e., in quantum wells.

II. PHOTOCONDUCTIVE GAIN FOR NONUNIFORM PHOTOGENERATION

Our consideration will be essentially based on a drift-diffusion model of charge carrier transport in QWIPs.

Photocurrent will be examined first. We consider N quantum wells separated by barriers with spatial period l. The equations for photocurrent are

$$\frac{1}{e}\operatorname{div}\mathbf{j}=\sum_{i=1}^{N}\{g_i-[n(x)-n_0]S\}\delta(x-x_i), \tag{1}$$

$$j_x=-en\mu E_x-eD\frac{dn}{dx}, \tag{2}$$

where j_x is the xth component of the electron current density vector $\mathbf{j}=(j_x,0,0)$, n is the volume density of electrons in extended states, n_0 is the equilibrium density, S is the rate of capture of electrons into confined states, $\delta(x)$ is the delta-function, E_x is the x-component of the external electric field, and μ and D are the electron mobility and diffusion coefficient, respectively. Value of S can be expressed via lifetime τ of nonequilibrium electrons in extended states:[3,4] $S=l/\tau$.

It is worthwhile to note that characteristic velocity S acts as recombination velocity for charge carriers in the problem under consideration. The recombination velocity S is related to the probability of capture p_c into the quantum well for electrons moving with a drift velocity along quantum well structure axis. The value of p_c is traditionally used in phenomenological consideration of the carrier transport in QWIPs.[2] The subsequent relation between S and p_c reads as

$$p_c=\frac{S}{S+v_d},$$

where v_d is the drift velocity. We have to emphasize that in the drift-diffusion model, as well as in the pure drift model, the distribution function of electrons is rather symmetrical over the directions of electron's velocities. Under this condition, a drift velocity is small in comparison with thermal velocity of electrons and a real probability of capture electrons passing over the quantum well does not coincide with the value of p_c defined as capture probability for electron moving with drift velocity in normal to quantum well layer direction. Ignoring this difference may result in errors especially in consideration of problems related to noise. It should be also noted that value of p_c does not participate directly in the transport or continuity equations deduced from the kinetic equation. Thus, the value of p_c, although it may be useful in treating the final result for photocurrent, seems to cause misuse in considerations based on the assumption of p_c as a net rate of captures of charge carriers in the quantum wells.

It follows from Eq. (2) that current density in each barrier does not depend on coordinate x. In a steady state, conservation of the current densities in different barriers should be taken into consideration. After integration of Eq. (4) over a slab which includes the ith quantum well we obtain

$$j_{i+1}-j_i=eg_i-e(n_i-n_0)S=0, \tag{3}$$

where j_i is the xth component of current density in the ith barrier which separates the $(i+1)$th and ith quantum well.

In this article, we will consider high photogeneration rates which apply to BLIP, i.e., $g_i \gg n_0 S$ and $n_i=g_i/S$. Considering Eq. (2) as a differential equation for concentration of electrons with boundary conditions on $n(x)$ imposed by Eq. (3), we obtain the formula for current density in ith barrier after the integration of Eq. (2):

$$\frac{1}{e}j_i=\frac{g_i v_i}{S}+\frac{(g_i-g_{i+1})v_i}{S\{\exp[l/l_i(E)]-1\}}, \tag{4}$$

where $v_i=\mu E_i$, E_i is the electric field in ith barrier, and $l_i(E)=D/\mu E_i=kT/eE_i$. The first addendum in Eq. (4) is the drift component of the current density, while the second is the diffusion component. The rate of photogeneration g_i equals

$$g_i=\Phi_i\eta_0,$$

where Φ_i is the photon flux at $x=x_i$, and η_0 is the quantum efficiency of photoabsorption of the single quantum well: $\eta_0=\alpha l$.[10]

The diffusion component in Eq. (4) is comparable to its drift counterpart under condition

$$E<E_{\mathrm{dif}}=\frac{kT\eta_0}{el}\simeq 10(\mathrm{V/cm}).$$

In what follows, we will consider $E>E_{\mathrm{dif}}$, when transport can be viewed as a drift motion of electrons. The photoconductive gain, according to definition, equals

$$G=\frac{j_i}{e\Phi_0\eta}=\frac{j_i}{e\Sigma_{i=1}^{N}g_i}. \tag{5}$$

Equaling current densities in two barrier regions adjacent to the ith quantum well, we obtain a recursion equation for electric fields in the ith and $(i+1)$th barrier layers

$$v_i g_i=v_{i+1}g_{i+1},$$

or

$$E_{i+1}=\frac{g_i}{g_{i+1}}E_i.$$

In the presence of the nonuniform absorption $(g_i\neq g_{i+1})$, the electric fields in different barriers are different. The Debye length of electrons in QWIPs is large in comparison with the active layer thickness, so quantum wells are charging until the continuity of the photocurrent is satisfied. If the quantum well structure is illuminated from the cathode side then $g_{i+1}<g_i$, and consequently, $E_{i+1}>E_i$. Under this condition, quantum wells are charged by negative charge. The negative charge of the ith well equals

$$N_i^- = (\epsilon/4\pi e)E_i(g_i - g_{i+1})/g_{i+1},$$

where ϵ is the dielectric permittivity of the barrier. By choosing illumination from anode side, we obtain that the electric field in barriers is increased in the direction from anode to cathode. In this case, quantum wells are charged positively with amount of charge N_i^+, which can be determined in full analogy with the above equation for N_i^-. Except electric field distribution all other values we consider here are not dependable upon direction of the radiation propagation. Average electric field $\langle E\rangle$ in the detector active region equals

$$\langle E\rangle = \frac{1}{N}\sum_{i=1}^{N} E_i = \frac{g_1 E_1}{N}\sum_{i=1}^{N} g_i^{-1}.$$

After some simple algebra we obtain

$$G_p = G_0 K, \tag{6}$$

where G_0 is the gain for a detector under uniform electric field $E=\langle E\rangle$

$$G_0 = \frac{\langle v\rangle}{SN},$$

and

$$K = \frac{1}{(1/N)\Sigma_{i=1}^{N} g_i (1/N)\Sigma_{i=1}^{N} g_i^{-1}}.$$

Here $\langle v\rangle$ is the low-field drift velocity of electron in uniform electric field, which is equal to average electric field in the detector active area $\langle v\rangle = \mu\langle E\rangle$.

The equation for G_0 can be rewritten in terms of capture probability p_c. By using the earlier deduced relation between S and p_c, we obtain equation

$$G_0 = \frac{1-p_c}{p_c N}.$$

In general, $K\leqslant 1$. For uniform generation, we obtain $K=1$ and $G_p=G_0$. Analytical formulas for the photoconductive gain under nonuniform photoabsorption can be obtained in simple cases. For a detector without a back reflecting mirror (one-pass of the radiation flux), we obtain $g_i=\Phi_0(1-\eta_0)^{i-1}\eta_0$, where photon flux Φ_0 entering the first ($i=1$) quantum well can be expressed through external flux Φ_s. For the radiation introduction method which employs a prism with angle θ, we have a correspondence $\Phi_0=(1/2)\Phi_s \sin^2\theta$.[10] Quantum efficiency for one-pass equals

$$\eta = \frac{\Sigma_{i=1}^{N} g_i}{\Phi_s} = \frac{1}{2}[1-(1-\eta_0)^N]\sin^2\theta. \tag{7}$$

The photoconductive gain for a detector in one-pass geometry equals

$$G_p = 2G_0 \frac{N^2\eta_0^2}{(1-\eta_0)\{\cosh[N\ln(1-\eta_0)]-1\}}. \tag{8}$$

For $\eta_0 N \ll 1$, we get $G_p=G_0$, and for $\eta_0 N \gg 1$ we obtain $G_p \simeq G_0(N\eta_0)^2\exp(-\eta_0 N)$.

Numerical calculations for a structure containing $N=50$ quantum wells produce $K=0.92$ for $\eta_0 N=1$ ($\eta\simeq 0.16$) and $K=0.72$ for $\eta_0 N=2$ ($\eta\simeq 0.22$) in one-pass geometry. Corresponding numbers for QWIP with a back reflecting mirror (double-pass) are $K=0.98$ and $K=0.84$. As for quantum efficiency of photoabsorption in double-pass, it is equal to

$$\eta = \frac{1}{2}[1-(1-\eta_0)^{2N}]\sin^2\theta.$$

We estimate that for $\theta=45°$, quantum efficiency of photoabsorption is equal to $\eta\simeq 0.22$ for $\eta_0 N=1$ and $\eta\simeq 0.24$ for $\eta_0 N=2$.

III. GENERATION-RECOMBINATION NOISE

We consider the Langeven-type equation for fluctuations in drift approximation. The equation for low-frequency fluctuations averaged over the coordinates of the points in the plane perpendicular to the superlattice axis is formulated as

$$\left(\frac{1}{e}\right)\frac{d\delta j_x}{dx} = \sum_{i=1}^{N}[-\delta n(x)S + \delta g_i - \delta r_i]\delta(x-x_i), \tag{9}$$

where the x-component of the averaged in-plane current density fluctuation equals

$$\delta j_x(x) = \delta j_i = e\mu E_i \delta n_i + e\mu n_i \delta E(x); \quad x_i \leqslant x \leqslant x_{i+1}. \tag{10}$$

Here, δg_i and δr_i are the Langeven sources for fluctuation of the generation and recombination rates, $\delta E(x)$ is the fluctuation parallel to the structure axis component of electric field in the barrier region, and $\delta n_i = \delta n(x_i)$. Estimation shows that the electric field induced by free electrons over the barriers can be neglected due to large Debye length l_D, which is of the order $l_D \simeq 10$ μm for typical doping concentrations $N_D \simeq 10^{18}$ cm^{-3} and $N=50$. In this case, $\delta E(x)=\delta E_i$ for $x_i \leqslant x \leqslant x_{i+1}$.

For stationary fluctuations, we have an equality

$$\delta n_i = (\delta g_i - \delta r_i)S^{-1}.$$

After integration of Eq. (10) over the $x_{i-1}<x<x_{i+1}$, we obtain

$$\delta j_i - \delta j_{i-1} = -S\delta n_i + \delta g_i - \delta r_i = 0; \quad i=1,2,\ldots,N. \tag{11}$$

The electric field fluctuation in the ith barrier, which we determine from Eqs. (10) and (11), equals

$$\delta E_i = \frac{\delta j - e\mu E_i \delta n_i}{e\mu n_i}, \tag{12}$$

where we used designation $\delta j = \delta j_i$. Imposing a condition of stabilized bias voltage across a sample

$$\sum_{i=1}^{N} \delta E_i = 0,$$

we obtain δj after integration of Eq. (12) along a QW active length

$$\delta j = e\mu \frac{\sum_{i=1}^{N} E_i n_i^{-1} \delta n_i}{\sum_{i=1}^{N} n_i^{-1}}. \tag{13}$$

General approach to evaluation of correlation functions of noise sources δg_i and δr_i is developed in Ref. 11 for a spatially homogeneous system with single recombination time τ. For processes concentrated in very narrow well regions, we follow Ref. 12 and express the correlation functions via recombination velocity S and concentration of free electrons n_i over wells

$$\langle \delta g_i \delta g_k \rangle_\omega = \langle \delta r_i \delta r_k \rangle_\omega = 2 n_i S A^{-1} \delta_{ik},$$

$$\langle \delta g_i \delta r_k \rangle_\omega = 0,$$

where A is the detector cross-section square, and $n_i = g_i S^{-1} + n_0$. Mean square current noise in the frequency bandwidth Δf equals

$$\langle \delta I^2 \rangle = \langle \delta j^2 \rangle_\omega A^2 \Delta f. \tag{14}$$

Finally, we obtain equation

$$\langle \delta I^2 \rangle = 4 \frac{(e\mu)^2 A}{S} \frac{\sum_{i=1}^{N} E_i^2 n_i^{-1}}{(\sum_{i=1}^{N} n_i^{-1})^2} \Delta f. \tag{15}$$

For the uniform thermal generation $n_i = n_0$, we obtain from Eq. (15)

$$\langle \delta I^2 \rangle = 4 e G_0 I_T \Delta f,$$

where $I_T = e \langle v \rangle n_0 A$ is the dark thermal current. Thus, in this case photoconductive and noise gains coincide: $G_n = G_p = G_0$. Equation (15) presents typical for g-r noise dependence $\langle \delta I^2 \rangle \propto I^2 \propto E^2$.

It is worthwhile to make some remarks about discussed in Ref. 7 relation of g-r current noise to the short noise current. It has been shown by Van Vliet in Ref. 13 that the short noise is actually a transport related noise and is associated with extraction of charge carriers from the active volume of a device. The characteristic frequency for this process is determined by the drift transport across the active region, i.e., $\langle v \rangle / lN \simeq (10-100)$ GHz. Thus, low-frequency g-r noise considered here is not related to the short noise.

For high level photogeneration by using the relation between E_i and $\langle E \rangle$

$$E_i = \frac{\langle E \rangle}{g_i (1/N) \sum_{i=1}^{N} g_i^{-1}},$$

we obtain the equation for excess current noise $\langle \delta I^2 \rangle = 4 e I G_n \Delta f$, where

$$G_n = G_p F; \quad F = \frac{\sum_{i=1}^{N} g_i \sum_{i=1}^{N} g_i^{-3}}{(\sum_{i=1}^{N} g_i^{-1})^2}. \tag{16}$$

Excess factor F is equal to the ratio of G_n and G_p. Generally $F \geqslant 1$. For one-pass geometry ($\eta_0 \ll 1$), we obtain

$$F = \frac{(1-\eta_0)^{2N}[(1-\eta_0)^{-3N} - 1]}{3[1-(1-\eta_0)^N]}. \tag{17}$$

In this case, we estimate $F \simeq 1$ for $\eta_0 N \ll 1$, and

$$F \simeq \frac{\exp(\eta_0 N)}{3}$$

for $\eta_0 N \gg 1$.

The nonuniformity in photogeneration influences noise gain more than photoconductive gain. This is evident after comparison of the subsequent equations for both gains. Numerical calculations performed for the structure with $N = 50$ wells show that $F = 1.72$ for $\eta_0 N = 1$ and $F = 3.23$ for $\eta_0 N = 2$ in one-pass geometry. The corresponding numbers for double-pass geometry are $F = 1.45$ and $F = 2.90$.

IV. CONCLUSIONS

We calculated the photoconductive gain G_p and excess current noise gain G_n of QW detector. A model of drift transport, which was implicitly included in all previously treated models of QWIPs, has been used in our calculations. We proved that both quantities are dependent upon attenuation of the optical or background radiation flux. Coincidence between both gains exists only for uniform generation. Under nonuniform generation, there is a significant difference between both gains. Generally, the noise gain is greater than the photoconductive gain. For reasonable parameters of QWIPs' photoabsorption efficiency, the distinction between photoconductive and noise gain amounts to as much as 100%. The nonuniformity of steady concentration of the photogenerated electrons from well to well accompanied with electric field changes in order to maintain the continuity of the steady current is the reason why both gains are different from their values characteristic of uniform generation. We have considered the nonuniform generation due to infrared flux attenuation only not going into other reasons for nonuniform generation. We have restricted ourselves to the pure BLIP case. The intermediate solutions should be realized in mixed situations when the thermogeneration and photogeneration rates are comparable.

We proved that weak electric field domains occur in QWIPs in the ohmic region of current-voltage characteristics. We considered structures with wide barriers when tunneling current can be neglected. Unlike strong electric field domains caused by quantum well levels adjustments due to sequential resonant tunneling, the phenomenon we investigated is not accompanied by instabilities in current. The electric field redistribution considered in the present article influences mainly a signal-to-noise ratio.

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