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Langevin approach to the generation–recombination noise of a multi quantum well infrared photodetector

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Abstract

The current noise power spectrum of a multi quantum well infrared photodetector is calculated using a Langevin-transport equation where a discrete distribution of the electric field in the quantum well region, rather than the homogeneous one valid for bulk semiconductors, has been considered. The discreteness of the electric field arises as a consequence of the discrete structure of the quantum well layers. The inhomogeneous charge distribution in the quantum well structure affects the intensity and the frequency dependence of the noise power spectrum, giving rise to deviations from the behavior expected on the basis of a simple model based on fully uncorrelated fluctuation processes. The model reproduces the different N-dependence of the current noise power spectral density in the dark and in the presence of radiation. In particular, its relation to the discrete structure of the device arises as a consequence of the imbalance between the current injected at the emitter and the stream of photoelectrons drifting through the structure, whose effect seems particularly relevant for small values of the number of quantum wells N.

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Keywords: Dark noise; Photocurrent noise; Quantum well infrared photodetectors

1. Introduction

Quantum Well Infrared Photodetectors (QWIPs) based on the intersubband transitions in GaAs/AlGaAs have been developed over the past decade mainly to overcome the limits of the bulk IR semiconductor technologies [1,2]. To date, the QWIP can be considered the ideal candidate for the manufacturing of large-area focal plane array thanks to the higher detectivity, uniformity, stability, narrow band responsivity and flexible wavelength-tailorability compared to the standard

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MCT technology. Very recently, the simple QWIP concept has been further extended to propose more sophisticated heterostructures, such as the multi-band tunable QWIPs, the Quantum Cascade and Superlattice Photodetectors, the Quantum Dot Photodetectors [3–6].

The level of noise in background and under irradiation conditions, represents the ultimate limit to the practical usability of any IR detector. Relevant figures of merit are the background detectivity D^*, the specific detectivity D^*_λ and the Background Limited Infrared Performance Temperature T_{blip}. The fluctuations related to the thermally activated processes and to the background radiation limits the device performance at temperatures above T_{blip}. The *photoinduced noise* limits the detectivity of a photodetector operating below T_{blip}. At the same time, the noise is a very sensitive tool to investigate the charge transport processes in materials for optoelectronic applications. This ability mainly relies on the fact that the photogenerated carrier dynamics is analyzed by exploiting the spontaneous fluctuations of the photocurrent, thus avoiding the nonlinearity arising when time-dependent excitation sources, as modulated/pulsed laser light, ac electric fields and others, are used. The characterization of the photocurrent noise allows investigating the presence of photosensitive point-like deep-energy centers at the AlGaAs/GaAs interface, that could have an effect on the dielectric relaxation processes in the interwell barriers. These processes should contribute low-frequency components to the photocurrent, that can be evidenced only when the devices are operated well below the background limited infrared photodetection conditions.

Despite the relatively simple structure of the QWIPs, the physical processes responsible for their operation is fairly complex [7–13]. It has been shown that the non-uniformity of the space charge regions over the quantum well periods may affect the QWIPs operation. The dynamic build-up of domains of charge with the periodicity of the QW structure may give rise to a spatio-temporal variation of the electric field in the interelectrode region resulting in a complex correlation in the current flow [14,15]. The experimental and theoretical investigation of the fluctuation processes in QWIPs is thus relevant when the ultimate sensitivity and the dynamics of the charge transport should be assessed.

Many physical properties of the Quantum Well Infrared Photodetectors have been, at a given extent, deduced from those of the standard bulk semiconductors. One specific feature of the QWIPs is the discrete structure of the generation–recombination centers (QWs) that play a critical role especially if the number N of periods is small. As far as the basic physics of bulk semiconductors is used to describe the photoconduction process, the standard model of generation–recombination noise is used to describe the current fluctuations of QWIPs. Several papers dealing with the noise in Quantum Well Infrared Photodetectors have appeared in the literature [16–27]. Apart from differences in the relationship between the photoconductive gain g and the capture probability p_c, and in the way to perform the sum over the periods, all these works rely on a noise model based on a photoconductivity relaxation dynamics occurring via a simple exponential process.

2. Noise model for a continuous distribution of generation–recombination centers

Let us first recall the main steps to calculate the $g-r$ noise in bulk semiconductors [28–31]. The transport and the recombination of carriers in bulk semiconductors is described by a first-order continuity equation:

$$\frac{\partial \delta n}{\partial t} + v_d \frac{\partial \delta n}{\partial x} = -\frac{\delta n}{\tau_c} \tag{1}$$

In this equation, δn is the fluctuation of the excited charge in the semiconductor at the time t, at a distance x from the emitter. The dominant transport mechanism is *drift* with velocity v_d. The drift time between the electrodes is $\tau_d = L/v_d$, being L the interelectrode distance. The solution of Eq. (1) is $\delta n(x,t) = \delta n_0 \delta(x - x') \exp(-t/\tau_c) U(\tau_d - t)$. Therefore, the charge carrier relaxation occurs via a simple exponential, with τ_c the recombination lifetime. Integrating $\delta n(x,t)$ from 0 to L, the total fluctuations $\delta n(t)$ of the number of charge carriers is found. The fluctuations is calculated by adding a white noise excitation term $\xi(x,t)$ to the right hand side of the Eq. (1). The function $\xi(x,t)$ can be a thermal or a photon excitation source. The power spectrum of the fluctuations is calculated by multiplying the Fourier transform $\delta n(f)$ by its complex conjugate $\delta n^*(f)$.

Under the assumption that $\tau_d \gg \tau_c$, the power spectral density $S_n(f)$ of the fluctuations in the photogenerated charge carrier density n:

$$S_n(f) = 2\eta S_\phi(f)\frac{\tau_c^2}{1+4\pi^2 f^2\tau_c^2} \tag{2}$$

where $S_\phi(f)$ is the power spectrum of the photon excitation noise source $\xi_\phi(x,t)$. $S_\phi(f)$ is *white* for all the frequencies of practical interest, η is the quantum efficiency, f is the frequency and τ_c is the recombination time. The quantity $\eta S_\phi(f)$ is the optical generation rate.

If the carriers are thermally generated, the noise power spectrum is still given by the relationship (2) provided that $2\eta S_\phi(f)$ is replaced by $4g_0$, being g_0 the thermal generation–recombination rate:

$$S_n(f) = 4g_0\frac{\tau_c^2}{1+4\pi^2 f^2\tau_c^2} \tag{3}$$

The frequency-dependent response $R_n(f)$, defined as the number of excited carriers $\delta n(f)$ per incident optical power $\phi(h\nu)$, can be also deduced from the Eq. (1), it is:

$$R_n(f) = \eta\frac{\tau_c}{1+i2\pi f\tau_c} \tag{4}$$

Since each generated carrier induces a current pulse of height eg/τ_c, with g the optical gain, in the external circuit before recombination, the current noise power spectral density $S_I(f)$ can be calculated by:

$$S_I(f) = \frac{I^2}{n^2}S_n(f) \tag{5}$$

where I is the total current, n is the total average density of free carriers. n is given by $g_0\tau_c$ when the carriers are thermally generated. n is given by $\eta S_\phi(f)\tau_c$ when the carriers are optically generated. Using (5) and (2) (or (3) for thermally activated processes), one obtains:

$$S_I(f) = 4eIg\frac{1}{1+4\pi^2 f^2\tau_c^2} \tag{6}$$

Analogously, the current responsivity $R_I(f)$, defined as the current per the incident radiation power $\phi(h\nu)$, i.e. $\delta I(f)/\phi(h\nu)$, can be obtained multiplying Eq. (4) by the elementary current carried by each electron, i.e. eg/τ_c. Moreover, keeping in mind that the current responsivity is usually normalized to the photon energy $h\nu$, one obtains:

$$R_I(f) = \frac{e\eta}{h\nu}g\frac{1}{1+i2\pi f\tau_c} \tag{7}$$

The previous relationships have been used to describe the noise and the responsivity of QWIPs. The current noise power spectrum $S_I(f)$ and the responsivity $R_I(f)$ (Eqs. (6) and (7)) are written in terms of the number N of quantum wells and of the capture probability p_c

$$p_c = \frac{\tau_d}{\tau_d+\tau_c} \tag{8}$$

in the following form:

$$S_I(0) = \frac{4eI}{N}\left[\frac{1}{p_c}-\frac{1}{2}\right] \tag{9}$$

$$R_I(0) = \frac{e\eta_p}{h\nu}\frac{1}{p_c} \tag{10}$$

where the relationships $g = 1/Np_c$ and $\eta = \eta_p N$, with η_p the quantum efficiency of each period, have been also used. Moreover, it is worthy of note that in Eq. (9) the term $2eI/N$ has been subtracted. The term $2eI/N$ corresponds to the shot noise of a chain of N uncorrelated diodes in series [32]. This subtraction is necessary since the shot noise component, of the chain of the N uncorrelated QW periods above considered, is already taken into account in the $g-r$ noise component (the first term in square brackets of Eq. (9)). In fact an electron emitted from a QW has to recombine not in the same but in an adjacent QW layer to contribute to the $g-r$ noise of the chain of N uncorrelated QW periods. The need to subtract the term $2eI/N$ can be demonstrated by rigorous calculations for single and multi QWIPs [17,21,23–25].

According to the relationships (9), (10), for a given value of the current I, the current noise power spectrum should therefore vary as $1/N$ and the responsivity should be independent of N. However, deviations of the behavior of the dynamic and static photoresponse [7–11] and of the noise power spectra [26,27] have been reported.

The validity of the previous relationships for real QWIPs requires a number of limiting assumptions:

(1) the modulation noise arising as a consequence of the stochastic dynamics of the dielectric relaxation processes occurring in the interwell *AlGaAs* regions, is neglected,
(2) the device is treated as a medium with a continuous distribution of generation–recombination centers, i.e. as a bulk semiconductor whose noisy behavior is described by the standard *g–r noise* theory,
(3) the carrier drift velocity, lifetime and generation rate are taken constant across the structure,
(4) the statistical correlation among the noise sources in each QW is disregarded,
(5) the diffusion noise is neglected.

This work is devoted to the development of a noise model based on a continuity equation of the free charge carrier including the discreteness of the quantum well layer, i.e. valid for a multi-quantum well infrared photodetector (MQWIP). The noise model is based on a transport continuity equation including the discrete geometry of the quantum well layers, whereas the Eq. (1) is valid for homogeneous semiconductors with a uniformly distributed set of generation–recombination centers [13–15].

This work has been motivated by an extensive experimental study that has evidenced characteristic features related to the discreteness of the structure in the noise power spectra of QWIPs [24,26].

3. Noise model for a discrete distribution of Quantum Wells

Let us consider the simplest quantum well structure constituted by N identical doped QW's, separated by identical relatively thick undoped barriers. In the absence of external photoexcitation, the processes of emission and capture of electrons are thermally activated, therefore the *linearized* electron balance in each QW can be written:

$$\frac{\partial \delta \Sigma_k}{\partial t} = \frac{p_c}{e} \cdot \delta j|_{x=kL} \qquad (11)$$

where Σ_k is the electron sheet concentration in the bound state with Σ_{0k} the steady state value, k is the QW index, L is the width of each period of the QW structure. $\delta\Sigma_k$ represents the fluctuation of the electron sheet concentration Σ_k around Σ_{0k}. Furthermore

$$\delta j = e v_s \delta n \qquad (12)$$

is the current change due to a change $\delta n = n(t) - n_0$ in the concentration of the charge carriers, $n(t)$ being the electron concentration in the continuum states with n_0 the steady state value. In the previous equation, the bias voltage is assumed constant and high enough to provide the electron drift across the barriers with the saturation velocity v_s. Thus the electron diffusion can be disregarded.

Under the same assumptions, the continuity equation for the electrons in the continuum states can be written [13–15]:

$$\frac{\partial \delta n}{\partial t} + v_s \frac{\partial \delta n}{\partial x} = -\sum_{k=1}^{N} \frac{\partial \delta \Sigma_k}{\partial t} \delta(x - kL) \qquad (13)$$

The carrier concentration n in the continuum states fluctuates due to the fluctuations of the electron sheet concentration Σ_k in the kth Quantum Well. The power spectrum of the fluctuating carrier concentration $\delta n(t) = n(t) - n_0$ can be calculated by means of Eq. (13) after introducing a white noise $\xi_k(x,t)$ excitation source in the Eq. (11):

$$\frac{\partial \delta n}{\partial t} + v_s \frac{\partial \delta n}{\partial x} = -\sum_{k=1}^{N} \left[\frac{p_c}{e} \cdot \delta j|_{x=kL} + \xi_k(x,t) \right] \delta(x - kL) \qquad (14)$$

The previous equation is the Langevin-transport equation for a semiconductor having a discrete set of generation–recombination centers. Eq. (14) has been solved numerically. The response $\delta n(t)$ and its Fourier transform $\delta n(\omega)$ are related to the current density by Eq. (12). The current noise power spectral density can be obtained by multiplying $\delta j(\omega)$ by its complex conjugate $\delta j^*(\omega)$ and summing over the ensemble of the quantum wells. The sum has been performed here by assuming the independence of the noise source in each period. Typical results of the numerical calculation are shown in Fig. 1 for $p_c \to 0$ and in Fig. 2 for $p_c \to 1$. In these figures, we plot the current noise power spectra for $N = 4, 8, 16, 32$, since these values of N have been considered in the experimental work reported in the papers [24,26]. It is worthy of note that the curves shown in Fig. 1 for $p_c \to 1$ are more regularly distributed over the well number N with a tendency towards the $1/N$-dependence. Conversely, in Fig. 2, the power spectral density tends to saturate for small N: the values of $S_I(f)$ for $N = 4$ and $N = 8$ practically coincide in the low frequency range and do not exhibit a $1/N$-dependence.

The condition $\tau_c \gg \tau_d$, i.e. $p_c \to 0$ means that the rate of capture from the QW is low. The quantum wells are weakly depleted (dark or low radiation power). Conversely, when $p_c \to 1$, i.e. $\tau_c \ll \tau_d$, the rate of capture from the QW is high, thus the quantum wells are strongly depleted (high radiation power). The effect of noise saturation at low values of the capture probability $p_c \to 0$ at small number of wells N might have an origin similar to the reduction of noise in the two port devices: the so-called *partition noise*. The partition noise is due to the random distribution of the electrons

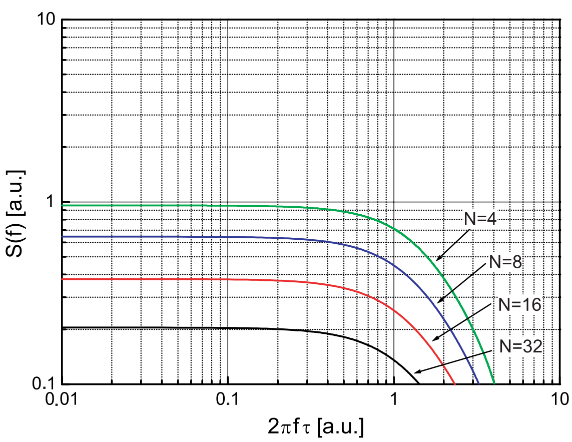

Fig. 1. Power spectral densities of current noise obtained by numerical solution of Eq. (14). The curves refer to $N = 4{,}8{,}16{,}32$ and to $p_c \to 0$.

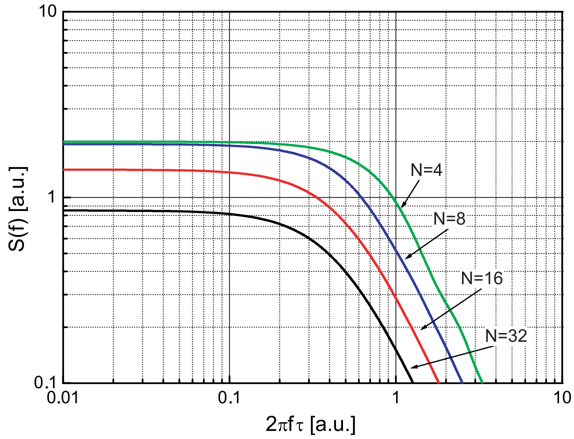

Fig. 2. Power spectral densities of current noise obtained by numerical solution of Eq. (14). The curves refer to $N = 4{,}8{,}16{,}32$ and to $p_c \to 1$.

between the base and the collector, in a transistor, or between the screen grid and the anode, in a vacuum pentode. In the QWIP, the strongly depleted quantum wells close to the emitter might act as the base or equivalently as the screen grid [28].

4. Conclusion

The current noise in Quantum Well Infrared Photodetectors has been modeled by means of the Eq. (14) including the discrete structure of the recombination centers in the device (QWs) instead of Eq. (1) valid for homogeneous semiconductors.

The numerical results qualitatively reproduce the experimental ones [26,27], particularly for what concerns the anomalies observed in the N-dependence of the noise intensity. The anomalous behavior of the photocurrent noise in excess to the dark noise is intrinsically related to the imbalance between the photoelectron emission and the electron capture processes in the quantum wells.

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