Noise gain in single quantum well infrared photodetectors

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A new approach to the calculation of current noise in single quantum well infrared photodetectors is proposed. The modulation noise due to the fluctuation of the emitter barrier potential is taken into account by considering the correlation between the elementary pulses constituting the excess current injected from the emitter when the quantum well is depleted by electrons. A simple relationship between the noise gain and the photoconductive gain of the device is obtained. A comparison with experiments is also reported. © *1997 American Institute of Physics.* [S0003-6951(97)04101-6]

In the last decade, an impressive effort has been devoted to the understanding of optical and electrical behavior of quantum well infrared photodetectors (QWIPs) in order to achieve as high as possible detectivity, sensitivity and optical gain.[1] A great deal of attention has also been paid to the analysis of the current noise, both because the amount of noise sets the lower limit for photon detection of the device and because the noise measurements provide a means for optical gain determination.[2–8]

A photoconductive gain g_{opt} higher than unity with a detectivity $D^*=1\times10^{10}$ cm Hz$^{1/2}$/W at 68 K for a detector cutoff wavelength of $\lambda_c=10.7\mu$m, was for the first time found in a GaAs/Al$_x$Ga$_{1-x}$As QWIP, based on *bound-to-continuum* intersubband transitions, by Hasnain *et al.*[9] QWIP infrared detectors similar to that described in Ref. 9 were later studied by other authors.[10–12] In these papers a modulation mechanism was invoked to explain the current transport processes in such devices. The electron depletion of the first QW causes the building up of a high-field region in the emitter barrier, which enhances the current injection from the emitter contact into the QW structure.

Excess noise with respect to the simple shot noise was experimentally observed in the device studied in Ref. 11. These results were explained on the basis of the following expressions:[13]

$$\Phi_n(f)=2g_{noise}\Phi_{shot}(f), \tag{1}$$

where $\Phi_{shot}(f)=2eI$ indicates the equivalent vacuum tube shot noise power spectrum at low frequencies and the noise gain g_{noise} was assumed to be equal to $g_{opt}=\tau_L/\tau_t$. Equation (1) is however obtained under the assumption that the electron stream, corresponding to the current I, may be represented as a superposition of independent pulse trains constituted by Poisson distributed pulses of average duration τ_L, and whose individual duration $\tau_L^{(i)}$ is also Poisson distributed. In other words, these pulses must be produced by the passage of τ_L/τ_t electrons correlated in such a way that ''exactly'' when one electron reaches the anode another one is injected.

In this letter we shall show that the transport mechanism introduced in Refs. 10 and 11 allows one to also account for the current noise behaviour without the above assumption. Both the optical and the noise gains have the same origin: a transition of one electron from a bound state in the QW to the continuum state affects the potential across the emitter barrier and gives rise to an extra current injection until the capture of the electron takes place. This process corresponds to a clustering of the elementary current pulses relative to the passage of each electron. The independent trains of correlated pulses are generated by the processes of depletion and filling of the QW by each bound state electron. Let τ_D and τ_F be the average time intervals during which the QW is respectively depleted or filled by an electron. This approach has been already used in Ref. 14 to evaluate the photoconductance noise in conventional high gain photoconductors. The power spectrum of the noise in excess with respect to the simple shot noise, due to the pulse clustering in each train, is given by

$$\Phi(\omega)=2\nu_0\langle a\rangle^2|\langle S(\omega)\rangle|^2\frac{\rho(1-\nu_0\tau_0)^2}{\omega^2\tau_0^2(\rho+1-\rho\nu_0\tau_0)^2+1}, \tag{2}$$

where a, τ_0, ρ and ν_0 indicate respectively the height of a single pulse, the average time interval between subsequent pulses within the cluster, the average number of pulses within the cluster and the average number of pulses per unit time. $S(\omega)$ is the Fourier transform of the elementary pulse of unitary height, $||$ indicates the modulus and $\langle\rangle$ indicates an averaging operation over the pulse ensemble.

In Ref. 14, it was taken into account that for bulk photoconductors the electron transit between the electrodes is interrupted by thermally activated processes in shallow defect centers. In this letter we shall consider a single quantum well device as in Ref. 11, whose energy band structure is that represented in Fig. 1. We will assume that only a negligible fraction of the electrons crossing the device is dynamically captured and released by the QW. Thus in the present case the height of the elementary rectangular pulse, corresponding to the current of a single electron crossing the interelectrodic region, is $i=e/\tau_t$. By neglecting the fluctuations of the electron mobility, one obtains $\langle a\rangle^2=i^2$ and $|\langle S(\omega)\rangle|^2=2\ \sin^2(\omega\tau_t/2)\pi\omega^2$.

It can be observed that ρ, the number of current pulses crossing the device during the QW ionization time τ_D, corresponds to the optical gain g_{opt}. On account of this, the excess current due to the emission of a single electron from a QW during τ_D can be written as $\Delta i=g_{opt}e/\tau_D$. Furthermore, the quantities τ_D, τ_0, ρ are related by the following relationship: $\tau_D=\tau_0\rho=\tau_0 g_{opt}$, while the average number of pulses per unit time ν_0 is equal to: $\nu_0=\rho/(\tau_D+\tau_F)$. Therefore the following relationship holds: $\nu_0\tau_0=\tau_D/(\tau_D+\tau_F)=n_D^*/N_D^*$, where N_D^* is the total number of the QW bound

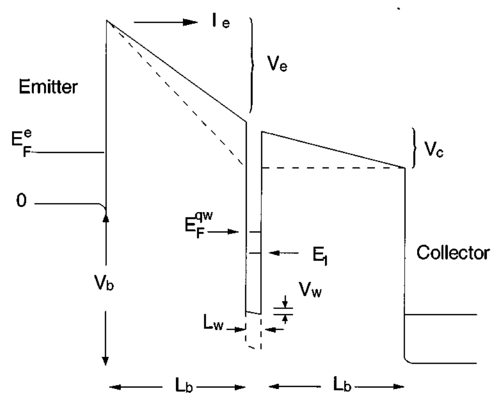

FIG. 1. Conduction band diagram of a single quantum well infrared photodetector. The solid line corresponds to the conduction band profile for a given external potential under quasiequilibrium conditions. The dashed line corresponds to the conduction band profile if a negative fluctuation of the number of bound electrons, with respect to its average value, occurs in the QW.

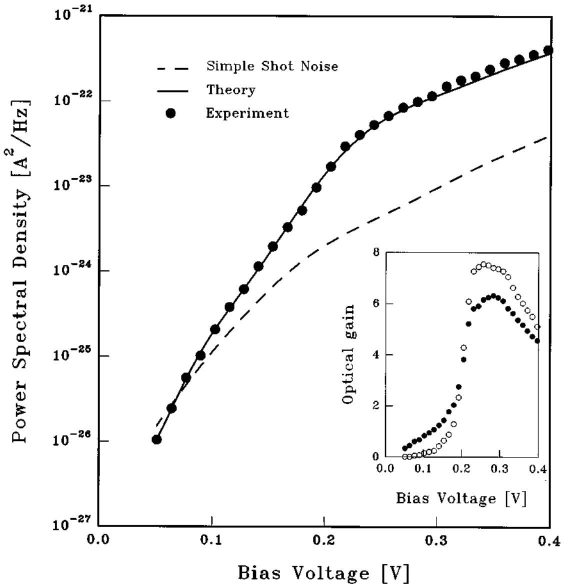

FIG. 2. Current noise power spectral density as a function of the applied bias. Results refer to 77 K. Points are experimental values. The continuous line is the theoretical curve obtained according to the present model. The simple shot noise $2eI$ is also plotted (dashed line). The best fit of the experimental data is obtained by means of the optical gain shown in the inset (open circles), while the filled circles correspond to the optical gain obtained on the basis of the Rose model (Ref. 13).

states corresponding to the number of doping atoms, and n_D^* is the average number of depleted bound states. If the depletion-filling processes of the QW bound states are independent and the fluctuation of the current is small with respect to its average value, the total current noise power spectrum, exceeding the simple shot noise, can be obtained by summing over N_D^*:

$$\Phi_{excess}(\omega)=2en_D^*\Delta i\cdot\frac{2}{\pi\omega^2}\sin^2\left(\frac{\omega\tau_t}{2}\right)\cdot\frac{g_{opt}\left(1-\frac{n_D^*}{N_D^*}\right)^2}{\omega^2\tau_D^2\left(1+\frac{1}{g_{opt}}-\frac{n_D^*}{N_D^*}\right)^2+1}. \tag{3}$$

The noise power spectral density, in terms of the frequency f and in the low frequency range ($\omega\tau_D<<1$), is thus given by

$$\Phi_n(f)=2eI+4en_D^*\Delta i g_{opt}\left(1-\frac{n_D^*}{N_D^*}\right)^2, \tag{4}$$

where the simple shot noise $2eI$, present also in the absence of emitter barrier modulation, has been added.[15] By using the definition of g_{noise} given by Eq. (1), we get

$$g_{noise}=\frac{1}{2}+\frac{n_D^*\Delta i}{I}g_{opt}\left(1-\frac{n_D^*}{N_D^*}\right)^2. \tag{5}$$

Only in the particular case where $g_{opt}>>1$, $n_D^*/N_D^*<<1$ and $n_D^*\Delta i=I$, may it be assumed that $g_{noise}=g_{opt}$. Since, by definition $\Delta i=dI/dn_D^*$, the last relationship requires that I varies linearly with n_D^*. Therefore Eq. (5) can be considered more general than Eq. (1).

In order to show that Eq. (5) gives the correct order of magnitude of the current noise, a comparison with the experimental data reported in Ref. 11 is now carried out. A symmetrical rectangular barrier *bound-to-continuum* QWIP consisting of an $L_w=40$ Å GaAs quantum well surrounded by two $L_b=500$ Å undoped $Al_{0.27}Ga_{0.73}As$ barriers was studied.[11] The area of the structure was $A=3.1\times10^{-4}$ cm^2. The quantum well was Si doped and had a density ($N_D=1\times10^{18}$ cm^{-3}).

The quantity Δi has been determined as

$$\Delta i=\frac{dI}{dn_D^*}=\frac{dI}{dV_e}\frac{dV_e}{dn_D^*}, \tag{6}$$

where the quantity dI/dV_e can be deduced from the data of Figs. 2 and 3 of Ref. 11. The quantity dV_e/dn_D^* is equal to $e/2C$ where C is the capacitance of the emitter, given by $\epsilon_0\epsilon_r A/L_b$, and the value $\epsilon_r=12.4$ was taken as the relative dielectric permittivity of the AlGaAs. The quantity N_D^* is equal to $N_D A L_w$. The quantity n_D^* is equal to $(N_D-n)AL_w$, where n is the three-dimensional free electron density in the quantum well and is reported in Fig. 8 of Ref. 11 as a function of the applied bias. In Fig. 2, we have plotted the current noise power spectral density against the bias voltage V_b. The data refer to 77 K in the dark. Circles are the experimental data from Ref. 11, the broken line corresponds to the simple shot noise, while the continuous line was obtained by using Eq. (4). The optical gains shown in the inset of Fig. 2 were obtained as best fit parameters respectively of Eq. (4) (hollow circles) and of Eq. (1) (filled circles) to the noise data. The fitting was also performed for the experimental data at 12 K (reported by the same authors), again obtaining very good agreement. In conclusion, we can say that the transport model proposed in Refs. 10 and 11 is also supported by considerations of the modulation effect of the emitter barrier potential on current noise. Further work is needed to develop an analog noise theory accounting for the behavior of the current fluctuations in multiquantum well infrared detectors. A reduction of the noise gain in multiple QWIPs should however be expected because of the reduction of the quantity dI/dn_D^* due to the diminished effect of the QW's ionization when the electrons escape from QWs far from the emitter barrier.[12] Finally, it is worth remarking that the deviations from full shot noise observed in resonant tunneling diodes were also accounted for by a mechanism of modulation of the double-barrier transmission probability by charge stored in the first quasibound level in the quantum well.[16]

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