Current noise in quantum well infrared photodetectors: effect of electron Coulomb interaction

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ABSTRACT

The power spectrum of current noise in quantum well infrared photodetectors (QWIPs) is calculated, considering the smoothing effect of long-range Coulomb interaction on the noise in order to account for the shot-noise suppression observed in QWIPs at low external biases. When the external voltage is low, the random emission of each electron from the cathode, due to the potential distribution through the device, reduces the transmission probability of the triangular emitter barrier during its transit time, giving a feedback effect on the current fluctuations. From a statistical point of view, in each interaction volume the time interval between two consecutive electron injections cannot be therefore described by Poisson statistics, which are valid for fully independent electrons. The work will be thus addressed to deducing a statistics accounting for the correlation between electrons during their transit through the device. Finally, it will be shown that at low frequencies the power spectral density of noise, calculated using such statistics, is reduced by a factor of up to 0.5, depending on the operating conditions of the device.

§1. INTRODUCTION

Quantum well infrared photodetectors (QWIPs) are semiconductor devices which can be tuned during the fabrication process to obtain suitable characteristics for the detection of infrared radiation of different wavelengths (Levine 1992, Bandara *et al.* 1993). Depending on their structure and materials these devices may present optical gains larger than unity and a corresponding noise which may be much larger than simple shot noise. In a previous paper a theoretical model of the noise generation in a QWIP, showing the origin of the large noise gain observed in a single-well QWIP (Carbone and Mazzetti 1997), has been developed and compared with experiments (Bandara *et al.* 1993). Similar results have been obtained also by other workers using the Langevin approach to noise power spectrum calculation (Ershov and Korotkov 1997). The above-cited model will be reconsidered here, introducing the effect of electron Coulomb repulsion during the carrier injection from the emitter electrode. In fact, under particular physical conditions, these devices show a current noise lower than simple shot noise, an effect which can be explained by taking into account the feedback effect of the negative charge density of the injected electrons on the emitter barrier. This effect becomes particularly evident when the bias voltage of the device is lower than a threshold value, a situation where
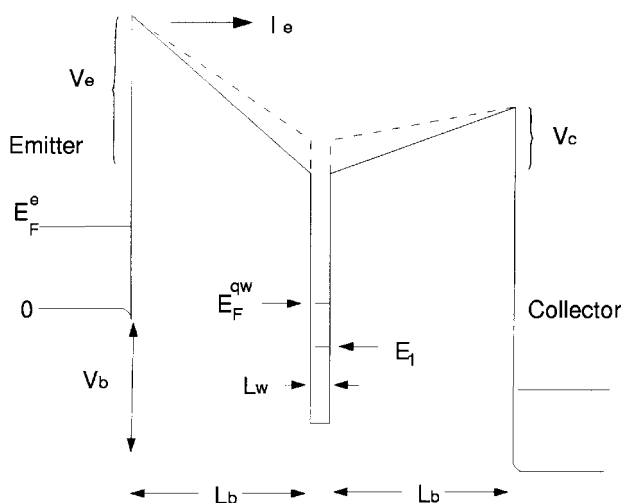
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Figure 1. Conduction-band diagram of a single QWIP: (———), conduction-band profile for a given external potential under quasiequilibrium conditions (it is important to observe that at low external biases, the collector is negatively biased); (- - - - -) redistribution of the potential energy as a consequence of a stochastic entry of an electron in the device.

there is an inversion of the collector voltage with respect to the well (figure 1). As a consequence, at these voltage values, the fluctuation of the positive charge within the well, produced by thermal excitation or photoexcitation, responsible for both the photoconduction process and the noise enhancement, can be completely disregarded. This is possible because the electrons remain trapped, giving rise to a strong reduction in the optical gain (Bandara *et al.* 1993).

§2. ELECTRONIC BAND STRUCTURE OF A QUANTUM WELL INFRARED PHOTODETECTOR AND THE NOISE GENERATION MODEL

As stated in the introduction, the main aspects of the noise generation model during photoconduction in a QWIP have been described by Carbone and Mazzetti (1997). The assumed photoconduction mechanism was based on the fact that the infrared radiation produces electron transitions from bound states in the quantum well to the continuum state. The consequent electron depletion of the quantum well gives rise to a potential drop that reduces the emitter barrier width and increases the device conductance. A similar mechanism was also invoked to explain the noise in excess of simple shot noise. The stochastic reduction in the triangular emitter barrier related to the fluctuation in the positive charge in the well was indeed regarded as responsible for the fluctuation in the emission probability at the cathode. By introducing a suitable probability density function for these time intervals, the power spectrum of noise related to the charge transport process described above was also calculated. The current noise was characterized by two additive components: the former corresponding to simple shot noise and the latter related to the fluctuation in the emitter barrier produced by the fluctuation in charge density within the well. As shown by Carbone and Mazzetti (1997), this second component may be in some instances much larger than the first component but has, in general, a lower cut-off

frequency of its spectrum. Since at low bias voltages this noise component vanishes, according to the above-cited paper only pure shot noise should be expected. However, as experimentally observed in this situation, a further reduction in the noise occurs, which might be partially ascribed to a feedback effect of the injected charge on the emitter barrier.

Before calculating the noise power spectrum, the following remark is necessary. The energy band diagram reported in figure 1 should be considered as the electron energy plot along a direction perpendicular to the surface of the device at a given point on the film surface, while the energy barrier should be considered as fluctuating in time and space over the film surface during electron transport. In fact, when an electron is injected from the cathode within the semiconductor in the framework of a semiclassical model, it may be assumed that during its transit time τ_t, it increases locally the emitter barrier, reducing the probability of further electron injection within an interaction zone whose characteristic dimension is the thickness d of the film. This effect may be considered as a sort of Coulomb electron repulsion and in this sense this definition is intended in the following. We shall thus consider the transport process taking place inside one of these interaction zones, adding up the power spectra of the noise produced to obtain the noise spectrum for the whole device. While, in the absence of electron interactions, simple shot noise is expected on the basis of a Poisson distribution of the time intervals separating subsequent electron emissions from the cathode, Coulomb repulsion changes this distribution to a new distribution, which accounts for the reduction in the electron emission probability described above. A suitable distribution function for the time interval t between subsequent electron injections within an interaction zone can be written:

$$Q(t) = k \exp\left(-\mu_1 t\right)\left[1 - \exp\left(-\mu_2 t\right)\right]. \tag{1}$$

Its behaviour is represented in figure 2 for different parameter values. In equation (1), k is a normalizing constant, and

$$\mu_2 = \frac{1}{\tau_t}, \tag{2}$$

τ_t being the electron transit time. The relations

$$\int tQ(t)\,\mathrm{d}t = \langle t \rangle = \tau_0, \tag{3}$$

where τ_0 is the average time interval between subsequent electron emissions, and

$$\int Q(t)\,\mathrm{d}t = 1 \tag{4}$$

determine the quantities k and μ_1. As shown in figure 2, this distribution gives a reduction in the probability of electron injection during a time interval of maximum duration τ_t, when $\tau_0 > \tau_t$, while the repulsion time interval becomes smaller than τ_t when $\tau_0 < \tau_t$.

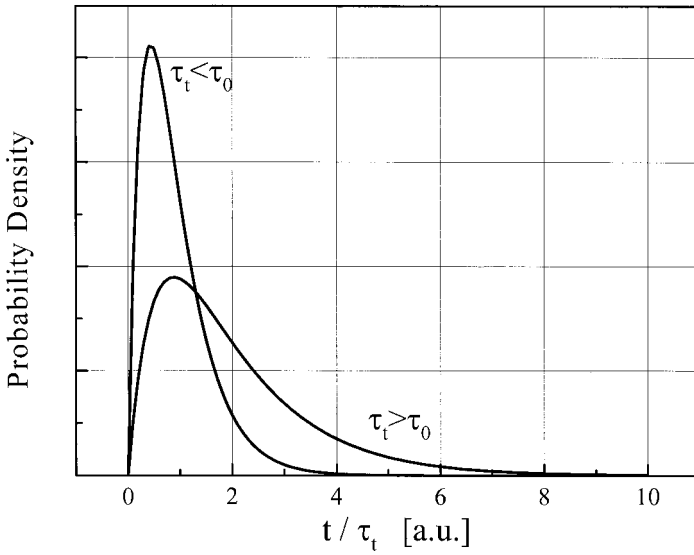The current noise power spectrum can be calculated through the expression (Mazzetti 1964)

Figure 2. Behaviour of the distribution function $Q(t)$ describing the time interval between two subsequent pulses (a.u., arbitrary units). τ_t and τ_0 indicate the average transit time of the electrons and the average distance between two subsequent electron pulses respectively. The two curves correspond respectively to the following values: upper curve, $\tau_t = 10^{-6}$ s and $\tau_0 = 2 \times 10^{-6}$ s; lower curve, $\tau_t = 10^{-6}$ s and $\tau_0 = 0.9 \times 10^{-6}$ s.

$$\Phi(\omega) = \nu_0 \left[|\langle S(\omega)\rangle|^2 + 2|\langle S(\omega)\rangle^2| \, \mathrm{Re} \left(\frac{\int Q(t)\,\exp(i\omega t)\,dt}{1 - \int Q(t)\,\exp(i\omega t)\,dt} \right) \right] \qquad (5)$$

where $|\langle S(\omega)\rangle|^2$ and $|\langle S(\omega)\rangle^2|$ are respectively the mean square value of the modulus and the square modulus of the mean value of the Fourier transform of the current pulses related to the passage of each electron. Re indicates the real part of the quantity within large parentheses. Actual calculation of these quantities depends on the physical condition under which the device operates. If electron trapping in the quantum well during the transit from the emitter to the collector is disregarded and a constant value of the transit time τ_t of each electron is assumed, the equation (5) simplifies and becomes

$$\Phi(\omega) = \nu_0 \frac{2e^2}{\pi\omega^2\tau_t^2} \sin^2\left(\frac{\omega\tau_t}{2}\right) \left[1 + 2\,\mathrm{Re}\left(\frac{\int Q(t)\,\exp(i\omega t)\,dt}{1 - \int Q(t)\,\exp(i\omega t)\,dt} \right) \right]. \qquad (6)$$

By using equations (1)–(4) the final expression for the power spectrum becomes

$$\Phi(\omega) = \nu_0 \frac{2e^2}{\pi\omega^2\tau_t^2} \sin^2\left(\frac{\omega\tau_t}{2}\right) \left(1 - \frac{2\tau_t(\tau_0^2 + 4\tau_t^2)^{1/2} + 4\tau_t^2}{\tau_t^2\tau_0^2\omega^2 + 4\tau_t(\tau_0^2 + 4\tau_t^2)^{1/2} + \tau_0^2 + 8\tau_t^2} \right) \qquad (7)$$

The power spectrum of the noise for the whole device is obtained by adding the spectra of each interaction zone. One obtains
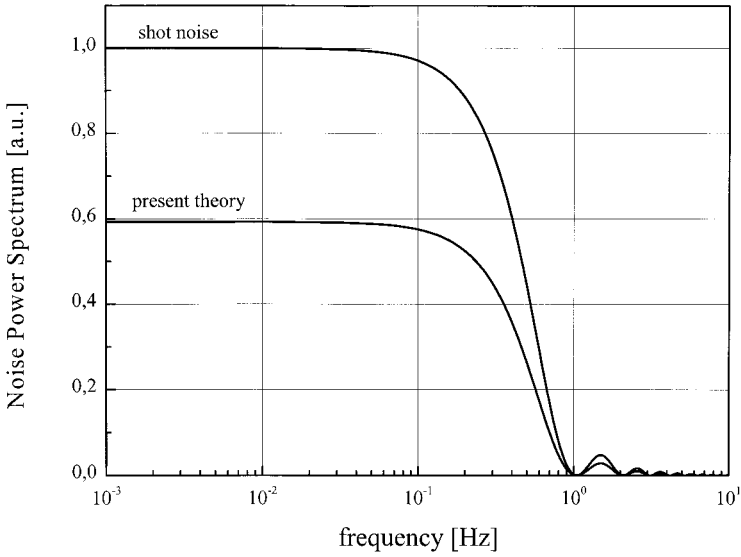
Figure 3. Noise power spectrum densities corresponding respectively to simple shot noise $2eI$ and to suppressed shot noise obtained by using equation (7) with $\tau_t = 10^{-6}$ s and $\tau_0 = 5 \times 10^{-6}$ s (a.u., arbitrary units).

$$\Phi_T(\omega) = \frac{I}{\nu_0 e}\Phi(\omega), \tag{8}$$

where I is the current crossing the device and e the electronic charge. In equation (7) the second term within the second set of large parentheses represents the negative factor giving the correction to the simple shot noise power spectrum due to the feedback effect of the injected charge on the emitter barrier. If trapping of injected electrons in the quantum well occurs, the quantities $|\langle S(\omega)\rangle|^2$ and $|\langle S(\omega)\rangle^2|$ appearing in equation (5) should be calculated on the basis of the distribution function of the trapping times. This calculation will not be reported here but it can be anticipated that at very low frequencies the power spectrum of the noise will be still approximately given by the equation (7) by including in τ_t the average trapping time of the injected electron. In figure 3, the effect of the correction factor appearing in equation (7) is evidenced for the values of τ_0 and τ_t reported in the figure caption.

§3. DISCUSSION AND CONCLUSIONS

The results reported in figure 3 show the reduction in the shot noise power spectrum when τ_0 becomes of the order of or smaller than the transit time τ_t. As expected, this reduction vanishes when $\tau_0 \gg \tau_t$, since Coulomb repulsion also vanishes. It is important to note that these results are not strongly dependent on the choice of the analytical form of the distribution function $Q(t)$ used to evaluate the noise power spectrum. Any distribution function giving a reduction in the probability that the time interval between subsequent electron injections within the interaction volume becomes shorter than the transit time τ_t and representing a Poisson distribution for the time intervals much larger than τ_t would have given approximately the same results. In particular a maximum reduction of 50% in the power spectrum can be achieved in the ambit of the proposed model. As stated in §2,

when the bias voltage exceeds the thresholds voltage V_{th}, current noise much larger than simple shot noise would mask completely the effect of Coulomb repulsion. This effect can thus be detected when the bias voltage becomes very low. In the last case the energy diagram reported in figure 1 shows the presence of a potential minimum which hampers the electrons excited from the quantum well into the continuum states from moving towards the anode. This strongly reduces the current and its associated noise, allowing shot-noise reduction to be demonstrated.

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