Noise gain vs. capture probability in single quantum well infrared photodetectors at low bias voltages

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Abstract

A model of low frequency current noise $S_i(0)$ is developed for single quantum well (QW) infrared photodetectors. A retarding mechanism, between subsequent electron injections in the QW structure, might dominate under a given threshold voltage value corresponding to the inversion of the electric field at the collector barrier. By considering this effect in terms of correlation between subsequent stochastic elementary events, the expressions of $S_i(0)$ and of noise gain $g_n$, defined as $S_i(0)/4eI$, are deduced. In particular, it is found that, when the applied voltage $V \rightarrow 0$ and the capture probability $p_c \rightarrow 1$, the noise gain $g_n$ reaches the minimum value $g_n = 1/4$. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

Quantum well infrared photodetectors (QWIPs) are, in practice, photoconductive devices whose structure can be tailored to detect infrared radiation of a given wavelength [1]. Under ideal operating conditions, QWIP photoconductivity should behave linearly vs. incident infrared power. Strong nonlinearities have been however observed at high excitation power or in QWIPs with a small number of wells [2,3]. These nonlinearities have been related to the nonuniform distribution of the electric field through the quantum well (QW) structure and, in particular, to the voltage drop on the injection emitter barrier. Since the mechanisms ruling carrier injection from the contacts (thermionic emission or thermionic field assisted tunneling) and carrier drift through the QW structure have a different dependence on the electric field, the first wells must deplete in order to supply the charge required to maintain equilibrium between the current injected from the emitter and the total current flowing through the QWIP [4–6]. Current noise in QWIPs has been widely analyzed both experimentally and theoretically [7–14]. In particular in Ref. [12], a modulation noise mechanism related to the effect on the emitter barrier potential of QW electron depletion has been introduced. The excitation of each electron from a bound state to a continuum one and its exit from the collector increases the number of QW positive charges by one. The main result is an increase of the potential drop across the emitter barrier, which enhances the injection probability of a subsequent electron. A correlation mechanism between consecutive

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electrons crossing the device has been therefore suggested. If the pulses were uncorrelated, they would be emitted at constant rate and the time interval between them would be Poisson distributed; in the case of the above described modulation mechanism, the time interval probability distribution has been demonstrated not to be a simple exponential. On the basis of the relationships deduced in Refs. [11–14], when the capture probability $p_c \rightarrow 1$ (i.e. $V \rightarrow 0$), the minimum noise gain is $g_n = 1/2$ (1/2N for multi QWIPs), corresponding to full shot noise. However, according to the experimental results reported in Refs. [7–9], the current noise at low bias voltages takes values much lower than the simple shot noise. In the present paper, we will suggest a possible mechanism of shot noise suppression which could dominate over the positive feedback effect described above at low bias voltages and which could be responsible for the low noise gain values experimentally observed.

2. Theory

It has been shown that, under a given threshold voltage, the electric field at the collector contact may disappear, or even change its sign [4–7]. The main consequence is that the escape of injected electrons from the QW structure is hampered. The electrons injected from the contacts not having enough energy to reach the other electrode, remain longer in the interelectrode region, where the potential takes its minimum value. Each injected electron, while staying in the QW structure, exerts a sort of long range Coulomb repulsion on the subsequent electron which should enter and therefore the probability of an electron injection decreases.

The calculations will be performed using the random point process approach, as done in Ref. [12]. Consider thus the elementary current pulse $i = e/\tau_d$, corresponding to the electron charge $e$ crossing the emitter (or the collector) barrier during the time $\tau_d$. The stochastic electron transport through a QWIP structure, like that in Fig. 1, can be modeled as follows: consider first the stochastic emission of one electron from the contact to the QW structure. If the repulsion effect was absent, the probability distribution of the time interval $t_1$ between two emission events would be Poissonian, with average frequency $v_1$, and the noise would be full “shot noise”. In the presence of Coulomb repulsion, a subsequent emission from the contact into the QW structure should occur with a certain delay with respect to the case of independent pulses. Actually a second electron, which could promptly enter in the absence of electron repulsion, must wait after the first emission event until an electron escape from the QW structure. Let $t_2$ be this delay. The probability distribution function of the time intervals $t_2$ can be taken Poissonian, with try-to-escape frequency $v_2$. The time interval $t$ between two injected electrons in the presence of negative feedback effect is therefore given by $t_1 + t_2$. The probability distribution function $Q(t)$ of time intervals $t$ can be calculated by the convolution of those of $t_1$ and $t_2$ [15]:

$$Q(t) = \frac{v_1 v_2}{v_1 - v_2} \left[ \exp(-v_1 t) - \exp(-v_2 t) \right],$$

which leads to the following expression of low frequency current noise:

$$S_i(0)_{nf} = 2ef \left[ 1 - 2 \frac{v_1 v_2}{(v_1 + v_2)^2} \right].$$

It is worth remarking that an expression as the previous one has been already used for describing shot noise suppression in double-barrier resonant tunneling diodes [16,17].

In order to compare Eq. (2) with noise behavior in real QWIP, it should be expressed in terms of phenomenological parameters, depending on the actual conditions under which the device operates, in particular, the capture probability $p_c$.

As discussed above, $v_1$ is the emission frequency of an electron over the emitter barrier in the absence of repulsion effect. As done in Ref. [12,14], it can be assumed that:

$$v_1 = v_{QW}$$

$^{1}$ It can be shown by simple algebra that the expressions of noise gain deduced in Refs. [12–14] coincide with that of Ref. [11] under the same assumptions, when $N = 1$. 

$^{2}$
where \( v_{QW} \) is the frequency of excitation of an electron from the QW to the continuum. Eq. (3) means that a carrier, escaping to the collector, behaves as a carrier captured in the collector. In Refs. [12, 14], it was assumed that an electron escaped from the collector causes the injection of another electron from the emitter. In the present model, this effect is neglected to calculate the Coulomb repulsion effect on noise.

The frequency \( v_{QW} \) is defined as \( 1/\tau_{QW} \), \( \tau_{QW} \) being a phenomenological lifetime related to QW recombination velocity \( v_{QW} \) and to \( L_p \) via \( \tau_{QW} = L_p/v_{QW} \) [14].

Concerning \( v_2 \), it coincides with the try-to-escape frequency of an electron from the QW structure. The escape will occur as a consequence of (a) an electron, not captured in the QW, drifting towards the collector, or (b) an electron excited from a bound to a continuum state of the QW. The event (a) occurs with a frequency \( v_d = 1/\tau_d \), where \( \tau_d \) is the drift time through the first period. It is related to the period length \( L_p \) and to the drift velocity \( v_d \) via \( \tau_d = L_p/v_d \). The event (b) occurs with frequency \( v_{QW} \). \( v_2 \) can be thus taken equal to:

\[
v_2 = v_d + v_{QW}.
\]

Let us finally recall the definition of the QW capture probability \( p_c \) in terms of the capture velocity \( v_{QW} \) and of the drift velocity \( v_d \):

\[
p_c = \frac{v_{QW}}{v_{QW} + v_d}.
\]

On the basis of Eqs. (3)–(5), the low-frequency current noise of single QWIP results:

\[
S_I(0)_{nf} = 2eI \left[ 1 - \frac{2p_c}{(p_c + 1)^2} \right]
\]

and the noise gain \( g_n \), calculated as \( S_I(0)_{nf} / 4eI \), results:

\[
g_n = \frac{1}{2} \frac{p_c^2 + 1}{(p_c + 1)^2}.
\]

At low bias voltages, i.e. when \( v_d \gg v_{QW} \) and \( p_c \to 1 \), Eq. (6) gives a reduction of 1/2 with respect to the simple shot noise. At higher applied voltages, i.e. when \( p_c \to 0 \), simple shot noise is
obtained. Accordingly, \( g_n \) varies between 1/4 and 1/2.

Eq. (6) has been obtained by neglecting the positive feedback effect due to QW electron depletion leading to shot noise enhancement [11–14]. To attain a complete description of noise behavior in real single QWIPs, with the two feedback effects simultaneously occurring, the calculations should be performed taking both the correlation mechanisms into account. Consider thus the following uncorrelated pulse sequences. The first sequence is constituted by current pulses distributed according to Eq. (1), whose noise power spectrum is \( S_f(0)_{nf} \). The second sequence is constituted by current pulses whose noise power spectrum has been calculated in Ref. [12]. Let \( S_f(0)_{pf} \) indicate this noise component. A fraction \( p_c \) of pulse sequences will contribute a component \( S_f(0)_{nf} \) to the noise. Analogously, a fraction \( (1-p_c) \) of pulse sequences will contribute a noise component \( S_f(0)_{pf} \). The total low frequency current noise can be written:

\[
S_f(0) = (1 - p_c)S_f(0)_{pf} + p_cS_f(0)_{nf}
\]  

that is:

\[
S_f(0) = 2eI \left[ 1 - p_c \frac{2p_c}{(p_c + 1)^2} + (1 - p_c) \frac{2(1 - p_c)}{p_c} \right].
\]

The second term in square brackets corresponds to the noise component responsible for shot-noise suppression, while the third term corresponds to the noise component responsible for shot-noise enhancement, according to Refs. [11–14].

3. Conclusion

A phenomenological model has been proposed accounting for shot noise reduction observed in QWIPs at low bias voltages. The model is based on the hypothesis that a Coulomb repulsion effect acts between charge carriers. The analytical expressions have been obtained under a number of simplifying assumptions. The effect of Coulomb interaction has been taken into account by a repulsion mechanisms acting between couple of elementary current pulses. To describe the effect in realistic QWIP devices, the collective action of the negative space charge lying in the QW structure and the nonuniform electric field should be considered. Furthermore, Eq. (9) has been obtained summing the noise components \( S_f(0)_{pf} \) and \( S_f(0)_{nf} \), corresponding respectively to the enhancement and suppression of shot noise. This can be done if the correlation mechanisms causing respectively the positive and negative feedback effects are uncorrelated. In spite of the crudeness of such assumptions, the model here presented allows to account for shot noise suppression experimentally observed at low bias voltages by means of a simple function of QW capture probability.

References