Photocurrent noise in QWIPs: Signatures of Nonuniform Potential Distribution over Periods

A. Carbone[a] and H.C. Liu [b]

[a] Physics Department and National Institute of Matter Physics, Politecnico di Torino, Corso Duca degli Abruzzi 24, I-10129 Torino, Italy

[b] Institute for Microstructural Sciences, National Research Council, Ottawa, Ontario, K1A 0R6, Canada

ABSTRACT

The photocurrent noise has been investigated in Quantum Well Infrared Photodetectors (QWIPs) having identical growth sequence, layer width and composition, but different number of wells. It has been found that the power spectral density exhibits characteristic features related to the discrete structure of the device. This behavior might be caused by the strong potential nonuniformity arising as a consequence of the imbalance between the current injected at the emitter and the stream of photoelectrons drifting through the structure, which is also responsible for the anomalies in the steady-state and transient photoconductivity. In the present work, we will add further evidence to our preliminary study by presenting results of the power spectral density obtained by numerical solution of the continuity equation of the electrons in the continuum state, with a discrete distribution of the electric field in the active region, instead of the homogeneous one valid for conventional photodetectors.

Keywords: Photocurrent Noise, Quantum Well Infrared Photodetectors QWIPs

1. INTRODUCTION

High performance Quantum Well Infrared Photodetectors (QWIPs) are required for a variety of applications ranging from space astronomy, night vision, recognition, environmental spectroscopy and medical imaging. An active research is thus ongoing to yield a deep insight into the physical properties of QWIPs in order to achieve the best optoelectronic performances. A primary role has been played by the current noise analysis technique.[1–9] In this context, the photoinduced current noise, i.e. the noise measured in the presence of an IR radiation impinging on the device, has recently revealed high potential for the assessment of quality and for the understanding of the basic physics of the device. The *photoinduced noise* limits indeed the detectivity of a photodetector operating below the BLIP temperature and, at the same time, is a very sensitive tool to investigate the charge transport processes in photosensitive materials. 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 effects related to external time-dependent excitation sources (as well as modulated/pulsed laser light, ac electric fields) used by the other characterization techniques.

The transport properties of QWIPs are, in certain aspects, analogous to those of standard photoconductors. The main difference of the QWIPs is the discrete structure of the generation-recombination centers (QWs) that play a critical role especially if the number of QWs is small. As far as the basic principles of conventional photoconductors are used to describe the photoconduction process in QWIPs, the standard model of generation-recombination noise is applied to the current fluctuations in QWIPs.

The transport and the appearance-disappearance of carriers in standard semiconductors can be described by the first-order continuity equation[11–13]:

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

In this equation, δn is a charge excited at $t = 0$ in the semiconductor, the dominant transport mechanism is drift with velocity v_d, the charge carrier relaxation occurs via a simple exponential mechanism, with τ_c the

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recombination lifetime. In order to calculate the spectral intensity of the fluctuations, a white noise excitation source $\xi(x,t)$ (Langevin source) must be applied to the system described by Eq.(1).

Under the assumption that the transit time τ_d is much longer than the recombination time τ_c, the power spectral density $S_n(f)$ of the fluctuations of the photogenerated charge carrier density n is given by[11,13]:

$$S_n(f) = 2\eta S_J(f)\frac{\tau_c^2}{1+\omega^2\tau_c^2} \tag{2}$$

In this relationship, $S_J(f)$ is the power spectrum of the photon noise (excitation source), white for all the frequencies of practical interest, η is the quantum efficiency, $\omega = 2\pi f$ is the radian frequency and τ_c is the recombination time. If the carriers are thermally generated, the previous relationship still holds provided that $2\eta S_J(f)$ is replaced by $4g_0$ where g_0 is the thermal generation-recombination rate.

The frequency-dependent response $R_n(f)$ is also derived by Eq.(1), it is:

$$R_n(f) = \eta\frac{\tau_c}{1+i\omega\tau_c}. \tag{3}$$

Since each photogenerated carrier induces a current pulse eg/τ_d in the external circuit, the current noise power spectral density $S_I(f)$ and the responsivity $R_I(f) = \delta I(f)/P(h\nu)$, with $P(h\nu)$ the incident radiation power, can be deduced respectively from Eqs.(2) and (3):

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

$$R_I(f) = \frac{e\eta}{h\nu}g\frac{1}{1+i\omega\tau_c}. \tag{5}$$

In the case of QWIPs, $S_I(f)$ and $R_I(f)$ are usually expressed in terms of the well number N and of the capture probability $p_c = \tau_d/(\tau_d+\tau_c)$ by introducing the photoconductive gain $g = 1/Np_c$ in Eqs. (4,5).

Several papers dealing with the noise in multi Quantum Well Infrared Photodetectors have appeared in the literature.[1–5,8,9] Apart from differences in the definition of the photoconductive gain g and in the way to perform the sum over the periods, all these theories are based on a photoconductivity model valid for homogeneous materials relaxing through a simple exponential process, like the above described one. The applicability to real QWIPs of the previous relationships is limited by several simplifying assumptions:

1. the device is treated as a medium with a continuous distribution of generation-recombination centers as in the standard g-r theory;
2. the carrier drift velocity, lifetime and generation rate are assumed to be constant across the structure;
3. the statistical correlation among the different noise sources is disregarded;
4. the diffusion noise term is disregarded;
5. the modulation noise term related to the dielectric relaxation dynamics of the interwell barriers, is neglected.

In the present work, the current noise will be modeled by means of a transport continuity equation accounting for the discrete structure of the QWIPs instead of Eq.(1) valid for homogeneous semiconductors with uniform distribution of recombination centers. 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.[10] Therefore, before discussing the main advances of this work, we will briefly recall such experimental results.

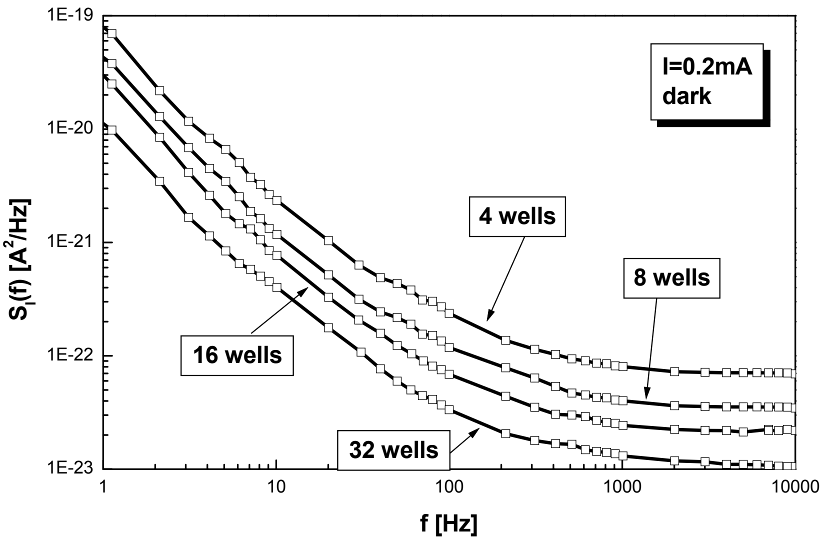

Figure 1. Power spectral densities of the current noise for AlGaAs/GaAs QWIPs respectively with $N = 4, 8, 16, 32$. All the curves refer to dark condition, temperature $T = 90K$ and current $I = 0.2mA$. The noise spectra are $1/f$-like at low frequencies, while at the high frequencies become flatter. The $1/N$-dependence is almost rigorously respected all over the investigated range of frequencies.

2. EXPERIMENT

Noise measurements have been carried out in AlGaAs/GaAs QWIPs with the same design and different number of wells (respectively $N = 4, 8, 16$ and 32). The QWIPs have $62\mathring{A}$ wide wells, separated by barriers of $241\mathring{A}$. The barriers are undoped and the QWs are center δ-doped with silicon to about $9 \cdot 10^{11} cm^{-2}$. The barrier x value is 0.25. The GaAs contacts, doped to $1.5 \cdot 10^{18} cm^{-3}$, are separated from the QW by rectangular barriers. The QWIPs have an area of $240 \times 240 \mu m^2$. The samples were mounted in a cold finger inserted in a high-vacuum double-shield cryostat. The internal shield was at $T = 140K$. The radiation, impinging on the sample, is produced by a blackbody source, kept in the same vacuum system. The IR power impinging on the samples is $15\mu W$. The background limited infrared performance temperature T_{BLIP}, in the described experimental conditions, vary between 100K and 110K for the range of biases used in this work. The analysis has been performed in the dark and under IR radiation, with current ranging from $50\mu A$ to $5mA$. The noise measurement circuit, made only by passive components, is used in balanced configuration allowing to use the Stanford Research low noise voltage amplifier (SR 560) in differential mode. The power spectra are detected by means of a two-channel dynamic signal analyzer (Hewlett Packard Model 3562A).

In Fig.[1], the power spectral densities of dark current noise are shown. Curves refer to the temperature $T = 90K$ and to the current $I = 0.2mA$. It is important to observe that the spectra scale as $1/N$ with good approximation all over the investigated frequency range. Similar behavior has been obtained for different temperatures and biases.[10]

In Fig.[2], the power spectral densities of photo-current noise are shown. Curves refer to the temperature $T = 90K$ and to the current $I = 0.2mA$. In this case, the power spectral densities do not scale as $1/N$. Similar behavior has been obtained for different temperatures and biases.[10]

The above described experimental results are part of an extensive experimental work recently reported.[10] There, the characteristic behavior of the photocurrent noise has been compared with the steady-state responsivity $R_I(0)$. The steady-state responsivity, defined as the ratio of the photocurrent to the incident radiation

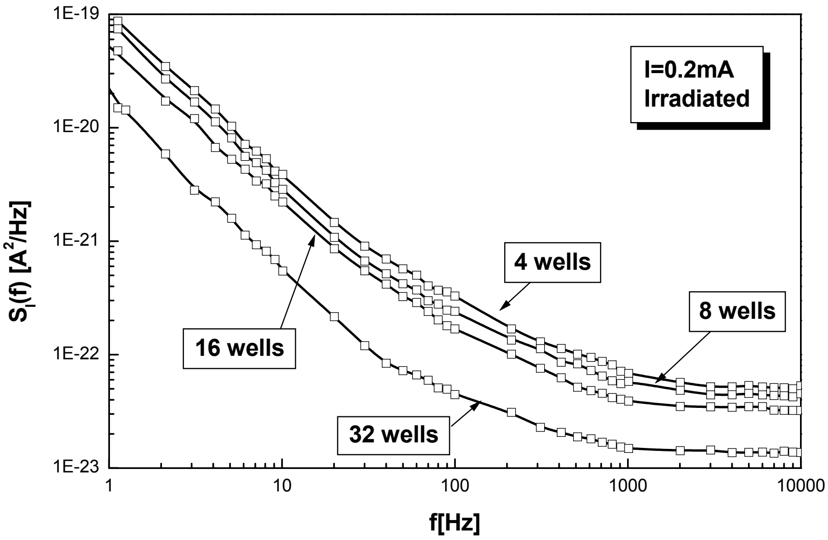

Figure 2. Power spectral densities of the current noise for AlGaAs/GaAs QWIPs respectively with $N = 4, 8, 16, 32$. Curves refer to a temperature $T = 90K$ and to a current $I = 0.2mA$ for all the devices. The noise measurements have been carried out in the presence of IR radiation. The noise spectra are $1/f$-like at low frequencies, while become flatter at the high frequencies. Under IR radiation, strong deviations from the $1/N$-dependence are observed all over the investigated range of frequencies.

power $P(h\nu)$, can be written as $R_I(0) = \frac{e\eta g}{h\nu}$. In QWIPs having the same growth sequence, layer widths and compositions, the photoconductive gain g can be written as $1/Np_c$ and the quantum efficiency η can be expressed in terms of N and of the one-period quantum efficiency η_p as $N\eta_p$. By taking into consideration these relationships, one yields $R_I(0) = \frac{\eta_p e}{h\nu p_c}$. Moreover, in ideal QWIPs having the same growth sequence, layer widths and compositions, τ_c, τ_d and therefore p_c should not depend on N. The current noise power spectral density $S_I(f)$, given by Eq.(4), is expected to vary as the inverse of the number of periods N, if the current I is kept constant and the responsivity $R_I(0)$ should be independent of N.

Deviations from this picture, valid in the framework of the photoconduction process summarized in the previous section, have been however theoretically predicted[16, 17] and experimentally observed[19–21] in real devices. The steady-state responsivity, the transient photoconductivity and the frequency response of the QWIPs strongly deviate from the behavior expected by a simple first-order kinetics equation leading to a simple exponential relaxation of the photoconductivity.

The anomalies exhibited by the photocurrent noise should thus complete the picture of a nonlinear photoconduction dynamics not ruled by a simple exponential relaxation process. In this paper, we will add further evidence to the above reasoning by performing a numerical evaluation of the current noise based on a photoconductivity model consistent with the structure of QWIPs[14–18] instead of Eq.(1) valid for homogeneous semiconductors.

3. NOISE MODEL

Let us first recall the photoconduction model on which our simulation is based.

The QWIPs are constituted by N identical doped QW's, separated by identical relatively thick undoped barriers. The bias voltage is assumed constant and high enough to provide the electron drift across the barriers with the saturation velocity v_s and the electron diffusion negligible. If the photoexcitation of the electrons

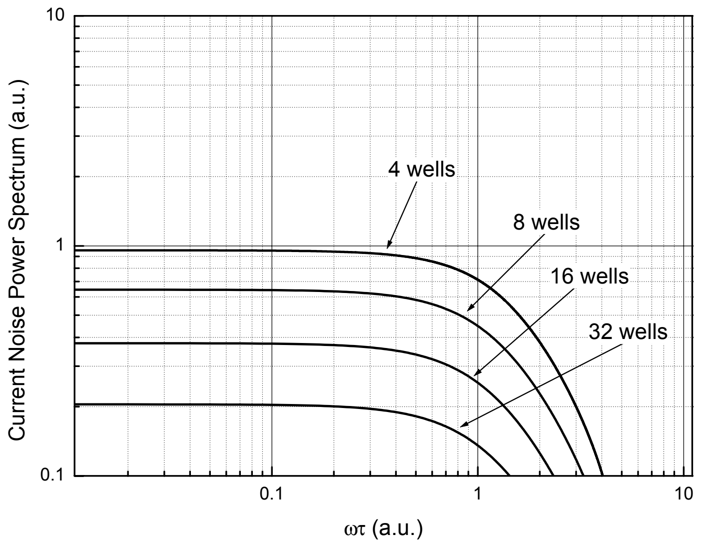

Figure 3. Power spectral densities of current noise obtained by numerical solution of Eqs.(7) and (8). The curves refer to $N = 4, 8, 16, 32$ and to $p_c = 0.75$.

dominates over the electron thermionic emission from the QW wells, the *linearized* electron balance in the QW is:

$$\frac{\partial \delta \Sigma_k}{\partial t} = \frac{p_c}{e} \cdot \delta j|_{x=kL} - \sigma \Sigma_{0k} \delta \phi(t) \tag{6}$$

and the continuity equation for the electrons in the continuum state can be written:

$$\frac{\partial \delta n}{\partial t} + v_s \frac{\partial \delta n}{\partial x} = -\sum_{k=1}^{N} \frac{\partial \delta \Sigma_k}{\partial t} \delta(x - kL). \tag{7}$$

In Eqs.(6) and (7),

$$\delta j = e v_s \delta n \tag{8}$$

is the current fluctuation due to a fluctuation δn in the concentration of the charge carriers, k is the QW index, L is the period of the QW structure, Σ_k is the electron sheet concentration in the bound state with Σ_{0k} the steady state value, n is the electron concentration in the continuum state with n_0 the steady state value, σ is the photoexcitation cross-section and $\delta\phi(t)$ is the photon source.[15–17]

The carrier concentration n in the continuum state fluctuates due to the fluctuations of the electron sheet concentration Σ_k. The fluctuating carrier concentration $\delta n(t) = n(t) - n_0$ can be calculated by Eqs.(6,7) replacing by a white noise $\xi_k(x,t)$ the photoexcitation source in Eq.(6). Since the response $\delta n(t)$ and its Fourier transform $\delta n(\omega)$ are related to the current density by Eq.(8), 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. This sum has been here performed by assuming the independence of the noise source in each period.

The results of the numerical calculation are shown in Fig.[3] for $p_c = 0.75$ and in Fig.[4] for $p_c = 0.35$.

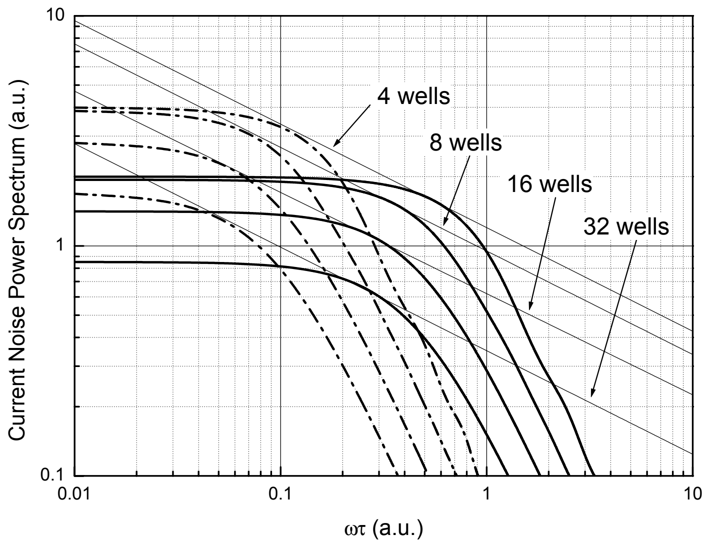

Figure 4. Power spectral densities of current noise obtained by numerical solution of Eqs.(7) and (8). The curves refer to $N = 4, 8, 16, 32$ and to $p_c = 0.35$. Continuous lines and dashed lines differ for the characteristic time τ used in the Fourier transform algorithm. It can be observed that a 1/f slope is obtained by adding several noise components like the single lorentzian curves plotted in this figure.

It is worthy of note that in Fig.[4], 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. Conversely, the curves shown in Fig.[3] for $p_c = 0.75$ are more regularly distributed over the well number N with a tendency towards the $1/N$-dependence.

In the framework of this model, $p_c \to 0$ means that, the capture term is negligible with respect to the random excitation source in the Eq.(6). On the other hand, when $p_c \to 1$, the photo-excited stochastic events are negligible with respect to the capture processes (Eq.(6)). This condition should occur in the dark curves of Fig.[1]. The previous considerations must not lead to conclude that the capture probability p_c dramatically changes from dark to irradiated condition: the difference between Fig.[3] and Fig.[4] is only due imbalance of the photoexcited fluctuation source with respect to the capture process and to the consequent charging of the wells.

It has been noted that the curves of Figs.[3,4] qualitatively reproduce those of Figs.[1,2]. However, while the frequency dependence of the experimental power spectra is $1/f$-like, the simulated curves show a lorentzian behavior. The numerical calculation has been performed in this work considering only one characteristic time τ. A wide distribution of characteristic times might be necessary in order to account for the modulation noise component arising from the dielectric relaxation processes at the AlGaAs barriers. As widely observed, due to the emptying (filling) of the QWs by electrons, the electric field in the barriers varies to supply extra electron injection.[15–18] These processes should contribute a low-frequency noise component with $1/f$ slope. For the sake of example, the simulated lorentzians with different value of τ have been plotted in Fig.[4] (dot-dash curves). The straight lines represent the $1/f$ noise that would be obtained by the superposition of lorentzians with the use of a suitable distribution of τ as done in the standard theories of $1/f$ noise.

4. CONCLUSION

The current noise in Quantum Well Infrared Photodetectors has been modeled by means of a continuity equation including the discrete structure of the recombination centers in the device (QWs) instead of Eq.(1).

The numerical results qualitatively reproduce the experimental curves. 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 well, proportional to the current flowing through the period, as deduced by the Eq.(6).

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