Photocurrent noise in multi-quantum-well infrared photodetectors

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We report on photocurrent noise in AlGaAs/GaAs quantum-well infrared photodetectors having nominally the same design, except the number of wells N. The power spectral density does not scale as the inverse of the number of wells N in the presence of infrared radiation. These features can be understood by taking into account the nonlinearity arising at high infrared power as a consequence of the nonuniform potential distribution through the quantum-well structure. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1581388]

The analysis of current noise, carried out in the most appropriate experimental conditions, is crucial to achieve a deeper insight into the charge transport dynamics of optoelectronic devices. Current noise has been therefore extensively investigated from the theoretical and the experimental points of view, as a function of bias, number of quantum wells, and temperature in n-type and p-type quantum-well infrared photodetectors (QWIPs).[1–10]

A study of noise in the presence of IR radiation has not appeared so far, in spite of the interest for applications. In this work, results of photocurrent noise in n-type AlGaAs/GaAs QWIPs with nominally the same structure, layer width, and composition, but different number of wells, will be reported.

Let us first recall a few relationships useful for the discussion of the photocurrent noise spectra, without, however, aiming to cover the whole issue of noise theory in QWIPs.

The excitation of an electron from the bound to the continuum state and its drift towards the collector increases by one the number of positive charges in the QW layer. The main result is the enhancement of the potential drop between the QW and the emitter barrier and also of the probability of injection of a subsequent electron. If the current pulses were uncorrelated, they would have been emitted at Poisson distributed rate; in the case of the just-described modulation mechanism, the probability distribution is not a simple exponential. The expression of the current noise power spectrum for a single QW period ($N=1$) has been deduced in Ref. 5:

$$S_I(f)=2eI+4e\left(\frac{1}{p_c}-1\right)n_D\frac{dI}{dn_D}\frac{1}{(2\pi f\tau_{\mathrm{QW}})^2+1}. \quad (1)$$

In the previous relationship, I is the average current, p_c is the capture probability of the well, n_D is the average number of charges emitted from the QW (i.e., the net positive charge due to the depleted states in the QW), dI/dn_D is the derivative of the emitter current with respect to the charge emitted (or captured) in the well. τ_{QW} is the QW recombination lifetime. The second term on the right side of Eq. (1) is the modulation noise source related, respectively, to the fluctuation processes in injection at the emitter barrier.

It can be demonstrated that the previous relationship, under several limiting assumptions (absence of contact effect, fully *drift* regime ($n_D dI/dn_D=I$) and, at low frequencies ($2\pi f\tau_{\mathrm{QW}}\ll 1$), yields the expression of noise gain worked out in Refs. 1 and 2. Furthermore, by assuming that the current noise generators, corresponding to each QW period, are completely uncorrelated, the noise of a multi-quantum-well infrared photodetectors can be obtained by simply adding N identical noise sources:

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

It has been already pointed out that the previous equation is unable to fully describe the behavior of noise in QWIPs,[3–8,10] due to the several simplifying assumptions. In the present work, we will add further evidence of the inadequacy of Eq. (2) through the analysis of photocurrent noise. At the same time, we will demonstrate the noise ability to yield an in-depth insight in the optoelectronic properties of QWIPs. We have indeed found that the relative photocurrent noise power spectral density exhibit a nonmonotonic behavior with the number of wells (Fig. 3). These features can be understood by taking into account the nonlinear electric field distribution through the QW structure.[11–15]

Dark and photocurrent noise measurements have been carried out on $Al_xGa_{1-x}As$/GaAs QWIPs with different number of wells. The QWIPs have, respectively, 4, 8, 16, and 32 wells. The wells are 62-Å wide and are separated by barriers of 241 Å. The barriers were undoped and the QWs were center δ-doped with silicon to about 9×10^{11} cm^{-2}. The barrier x value is 0.25. The GaAs contacts were doped to 1.5×10^{18} cm^{-3}. The QWIPs have an area of 240×240 μm^2. During the measurement, the device was placed in a double-shield high-vacuum cryostat, allowing temperature variation from 20 K to room temperature. The internal shield, which surrounds the device, is kept at 150 K. This is the temperature of the radiating background. In this condition, the background limited infrared performance temperature (T_{BLIP}), determined in the range of the applied biases

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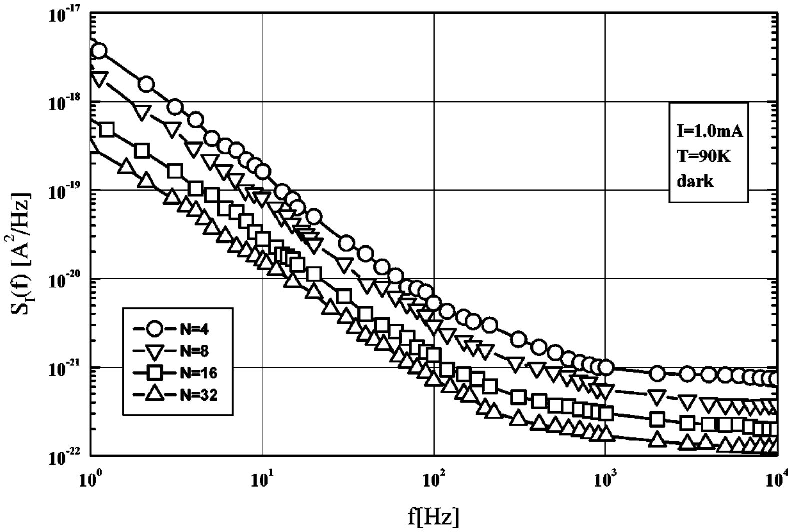

FIG. 1. Power spectral densities of the dark current noise for AlGaAs/GaAs QWIPs with $N=4,8,16,32$. The spectra are $1/f^{\alpha}$ with $\alpha>1$ at low frequencies and flat at higher frequencies. Curves refer to a temperature $T=90$ K and a current $I=1.0$ mA. The $1/N$ behavior, expected by the model, is accurately found over the whole range of measured frequencies and currents.

reported here, varies from 100 to 110 K. Since we are interested in studying the effect of the IR power on noise, all the measurements are performed at temperatures lower than 100 K so that the photocurrent noise exceeds the background one. The IR radiation impinging on the sample, is produced by a blackbody source kept in the same vacuum system.

In Fig. 1, the power spectral density of the dark-current noise measured at a temperature $T=90$ K and with a current $I=1.0$ mA is plotted. The power spectra are $1/f^{\alpha}$-sloped at low frequencies (up to about 1 kHz) and white above. They vary almost exactly as $1/N$, in agreement with the Eq. (2). It can therefore be deduced that charge transport is dominated by pure drift and the correlation effects are negligible in this condition. In Fig. 2, the photocurrent noise power spectral density is plotted for the same temperature and current as Fig. 1. Samples were irradiated by constant IR power: $P(h\nu)=15$ μW. Note that the current here is the *total* current including both dark and photocurrent components. In this case, the $1/N$ scaling rule does not hold. The curves plotted in Figs. 1 and in 2 are only two examples of an extensive set of measurements summarized in Fig. 3. Here, the values of the normalized power spectral density $S_I/4eI/N$ have been plotted as a function of the current I. Dashed curve represents the quantity $S_I/4eI/N$ in dark condition. It is independent of N, confirming that since the QWIPs have the same growth sequence, $1/p_c$ is constant, and the transport regime is dominated by drift. In the same figure, the symbols correspond to the noise data in the presence of constant IR radiation, respectively for the $N=4$ (○), the $N=8$ (▽), the $N=16$ (□), and the $N=32$ (△) devices. In this case, the quantity $S_I/4eI/N$ changes with N.

In Fig. 3, the quantity $1/p_c$ has been also plotted as a function of the current I. It has been evaluated, in the same experimental conditions as noise measurements, according to the following procedure. The responsivity R_i is defined as the ratio of the photocurrent $[I(E)-I_{\text{dark}}(E)]$ to the incident radiation power $P(h\nu)$. It can be written as $R_i=(e/h\nu)\,\eta g_{\text{photo}}$, where $g_{\text{photo}}=1/Np_c$ is the photoconductive gain and η is the quantum efficiency, that 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 $R_i=(\eta_p e/h\nu)(1/p_c)$ and the quantity $1/p_c$ can be extracted from the data of Fig. 4.

According to the Eq. (2), the quantity $S_I/4eI/N$ should be independent of N if the capture probability p_c is constant for each value of the current I (linear photoconductive regime). We found that, for a fixed value of the average current, $S_I/4eI/N$ is not constant under IR radiation. $S_I/4eI/N$ takes its minimum for $N=4$, increases for $N=8$, and finally decreases again with N. Moreover $S_I/4eI/N$ does not behave

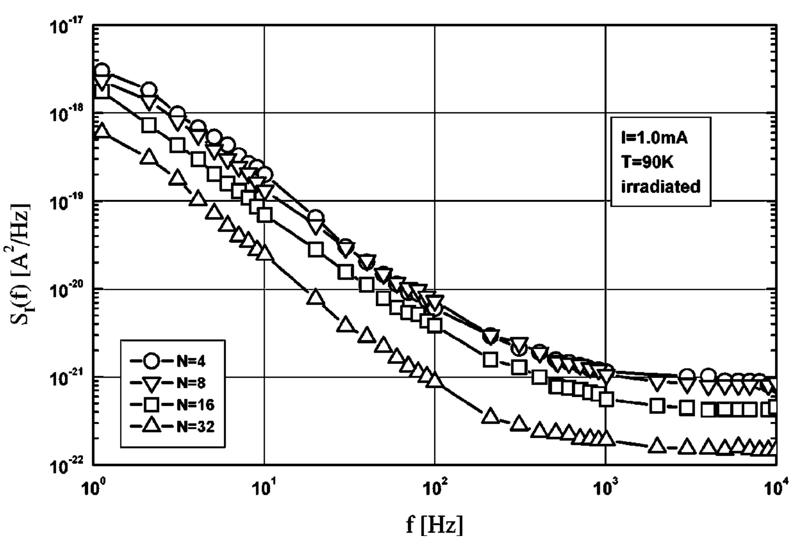

FIG. 2. Power spectral densities of the photocurrent noise for AlGaAs/GaAs QWIPs with $N=4,8,16,32$. Temperature and current are the same as in Fig. 1. The IR radiation power impinging on the samples is 15 μW. As for the dark power spectral densities, the noise spectra are $1/f^{\alpha}$ at low frequencies and flat at higher frequencies, but, in this case, the $1/N$ behavior is not observed.

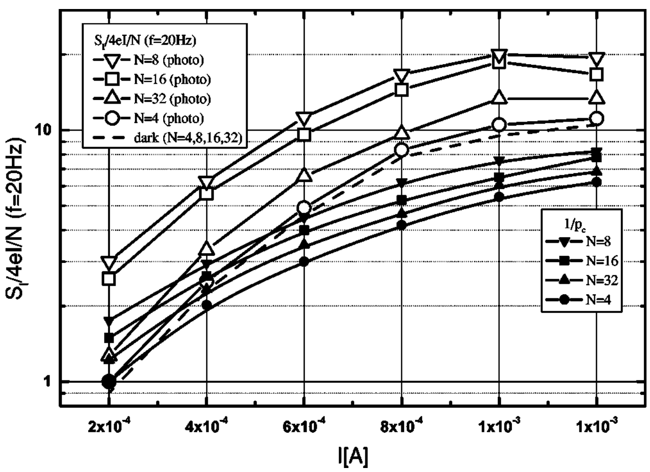

FIG. 3. Normalized current noise power spectral density at $f=20$ Hz in the dark (dashed line) and under IR light (line+ hollow symbol) for QWIPs, respectively, with $N=4,8,16,32$. All the values are referred to the four-well sample at $I=0.2$ mA under IR radiation (line+circle). The inverse capture probability vs current has also been plotted (line+filled symbol). Temperature is 90 K. It can be noticed that, while in the dark, $S_I/4eI/N$ is a constant, as it should be if p_c is constant for all the devices, under IR light, $S_I/4eI/N$ depends on N. As N varies, the set of the power spectral densities $S_I/4eI/N$, at a given value of the current I, roughly follows that of the inverse capture probability. These features can be accounted for by considering the effect of the nonlinear potential distribution on the current noise.

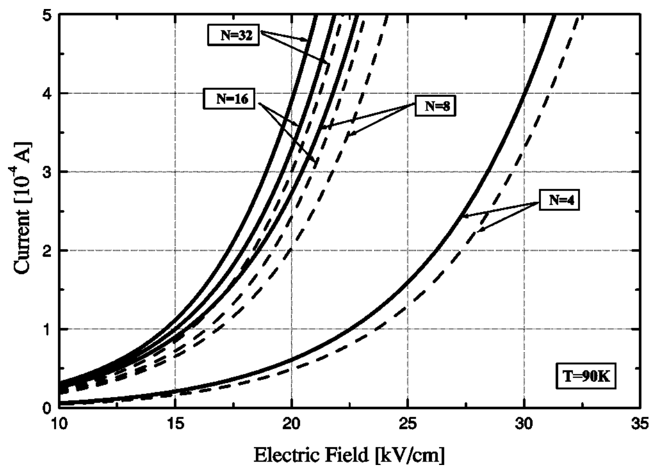

FIG. 4. Photocurrent (solid curve) and dark current (broken curve) vs electric field for QWIPs with $N=4,8,16,32$. The IR radiation power impinging on the samples is kept constant: $P(h\nu)=15$ μW. These curves have been used to calculate the inverse capture probabilities of FIG. 3.

as $1/p_c$: $S_I/4eI/N$ varies approximately as $1/p_c^{1.5}$ as the current I increases, for each value of N. It has been already observed that a redistribution of the potential takes place under IR radiation, causing the QWIP responsivity to depend on N, on frequency and on light intensity.[11–15] The electric field increases at the barriers close to the emitter, at the expense of the barriers close to the collector, in order to balance the charge flow due to the drift towards the collector. This results in (1) the enhancement of the charge emission process at the emitter (gain) and (2) the hampering of the electron drift towards the electrodes (suppression). Both effects are stronger in QWIPs with smaller N, but the former enhances and the latter reduces the current. The maximum photocurrent per incident power should thus be expected at an intermediate number of wells, causing the nonmonotonic dependence of $1/p_c$ on N shown in Fig. 3. The occurrence of nonlinearities in the potential distribution is responsible for the onset of correlations among the noise sources, that, if correctly taken into account, should give rise to higher powers of $1/p_c$.

In summary, we have found that, for QWIPs having the same design except N, the photocurrent noise power spectral density does not scale as the inverse of the number of wells N as it does in dark condition for the same value of the average current. Such anomalies might be ascribed to the potential nonlinearity causing the capture probability p_c to be dependent on N, instead of being constant as expected for ideal QWIPs. The correlation degree is higher as the potential nonuniformity is stronger, the photocurrent noise spectra at lower temperatures and biases exhibit indeed even more deviation. The main conclusion is that the assumption of pure drift regime and independence among the noise sources should be abandoned in favor of a photocurrent noise model able to reproduce the reported features.

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