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Electric field redistribution under IR radiation in quantum well infrared photodetectors as deduced from current noise measurements at low temperature and bias

A. Carbone [a,*], R. Introzzi [a], H.C. Liu [b]

[a] *Dipartimento di Fisica, Istituto Nazionale di Fisica della Materia, Politecnico di Torino, Corso Duca degli Abruzzi 24, I-10129 Torino, Italy*
[b] *Institute for Microstructural Sciences, National Research Council, Ottawa, Ont., Canada, K1A 0R6*

Abstract

Current noise has been investigated in AlGaAs/GaAs quantum well infrared photodetectors (QWIPs), having nominally the same design except the number of wells N. The experiments have been carried out in the dark and under infrared (IR) radiation in a wide range of currents and temperatures. We have found that the current noise scales as the inverse of the number of wells N in the dark condition. In the presence of IR radiation, the noise exhibits strong deviations from the simple $1/N$ behavior. These effects are still more evident when the photocurrent noise is measured at low biases and temperatures. Nonlinear effects in the QWIPs operation at high IR power, related to the potential redistribution in the interelectrodic region, are probably responsible for such anomalies. This conclusion is consistent with results of the steady-state responsivity obtained in the QWIPs in the same experimental conditions.

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1. Introduction

Spontaneous fluctuations set the lowest limit to the usability of any infrared (IR) photodetectors. The detectivity D^* (signal-to-noise ratio per unit incident power, area and bandwidth) and the blip temperature T_{blip} (background limited IR performance temperature) are critical figures of merits to assess the device performance. 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 any optoelectronic devices. Current noise has been extensively investigated from both the theoretical and the experimental point of view in QWIPs [1–7], however, to the best of our knowledge, an in-depth analysis of the photocurrent noise has not yet been published. The interest of such a study is twofold: the photo-induced noise, on one side, limits the sensitivity of photodetectors operating below the *blip* temperature and, on the other one, represents a powerful tool to understand the charge transport processes in IR detectors. The accuracy of the noise analysis technique mainly relies on the fact that the photogenerated carrier dynamics is studied by exploiting the

* Corresponding author. Fax: +39-11-5647399.
E-mail address: anna.carbone@polito.it (A. Carbone).

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spontaneous fluctuations of the photocurrent in steady-state conditions, thus avoiding the spurious effects due to the external time-dependent excitation sources (as well as modulated/pulsed laser light, ac electric fields) used by other characterization techniques.

At low frequencies, the current noise power spectrum of a multiple QWIPs is described by the relationship:

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

where N is the number of wells, p_c is the capture probability and I is the average current. The previous relationship is obtained if the fluctuation processes in QWIPs are treated as in the standard *generation–recombination*, *g–r*, noise in extrinsic semiconductors. Furthermore, as far as the simple *g–r* picture is used, the noise under photoexcitation obeys to the same equation except that the thermal *g–r* rate is substituted by the photogeneration rate $\eta\phi$ [9]. It has been widely observed that the applicability of Eq. (1) to the QWIPs is limited by several simplifying assumptions: (1) the fluctuation processes occurring in adjacent wells are considered independent, (2) the charge carrier transport occurs only by drift, (3) the slow dielectric relaxation processes at the interwell barriers are disregarded. Nevertheless, thanks to its simple structure, it is very helpful when the general aspects of noise are studied. In a previous paper [8], we have reported preliminary results showing anomalies in the behavior of noise under IR radiation with respect to the prediction of Eq. (1). According to the Eq. (1), the current noise power spectral density should decrease as the inverse of the well number N, with the capture probability being p_c independent of N, for QWIPs with the same growth sequence. We have found that the $1/N$ behavior is satisfied in the dark condition, while, in the presence of IR radiation, strong deviations are observed in the noise power spectra.

In this work, we report on an extensive experimental study of dark and photocurrent noise in AlGaAs/GaAs QWIPs having identical periods but different number of wells. We will show here that these deviations are more evident at low temperatures and biases. The above arguments support the hypothesis that the current noise behavior in the presence of IR radiation is strongly affected by the dynamics and by the distribution of the electric field across the emitter and interwell barrier during the photoexcitation process. This hypothesis is consistent with the results of responsivity and transient photoconductivity in QWIPs reported in papers [10–13].

2. Experiment and discussion

Current noise and I–V measurements have been carried out on four $Al_xGa_{1-x}As$/GaAs QWIPs with different number of wells. The QWIPs have respectively 4, 8, 16 and 32 wells, 62 Å wide and 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. The experiment has been performed in the dark and under IR radiation. The samples were mounted in a cold finger inserted into a double-shield high-vacuum system. The T_{blip} of the devices vary between 100 and 110 K for the range of bias used in this work. 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 μW. The measurement circuit, made only by passive components, has a balanced configuration allowing to use the low noise voltage amplifier (Stanford Research 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(a) and (b), the dark current noise power spectrum is plotted. The measurements are carried out at a temperature $T = 90$ K. The average currents flowing in the QWIPs are respectively equal to $I = 1.0$ mA (a) and to $I = 0.2$ mA (b). It can be observed that the power spectra are $1/f^{\alpha}$-sloped at low frequencies (up to about 1 kHz) and white above. The dark current noise spectral density varies almost exactly as $1/N$ for all the investigated frequencies, in agreement with the Eq. (1).

In Fig. 2(a) and (b), the photocurrent noise power spectrum is shown, for the same temperature

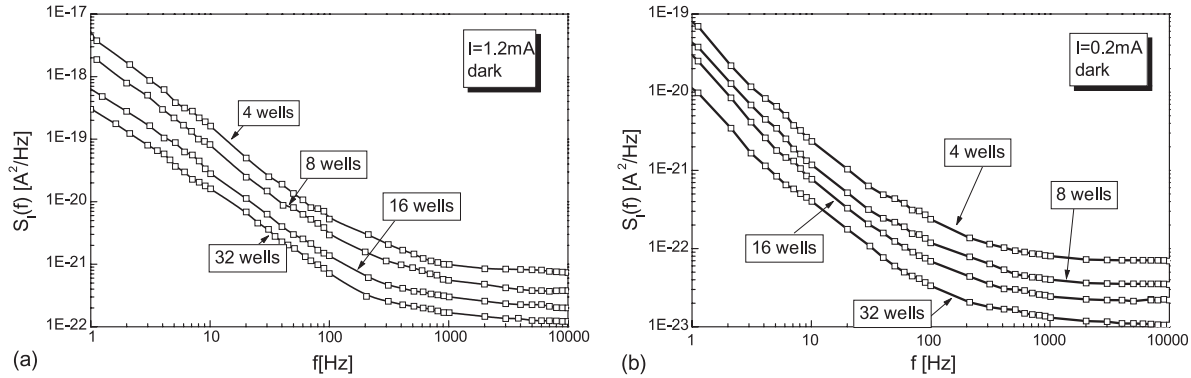

Fig. 1. Power spectral densities of the dark current noise for AlGaAs/GaAs QWIPs respectively with $N = 4$, 8, 16, 32 wells. Curves refer to a temperature $T = 90$ K. The average currents flowing in the devices are respectively $I = 1.2$ mA (a) and $I = 0.2$ mA (b). The $1/N$ behavior, expected by the model, is accurately respected in the whole range of measured frequencies and currents.

and current as in Fig. 1(a) and (b). By comparing these curves with the corresponding of Fig. 1(a) and (b), it can be observed that the noise does not obey the $1/N$ scaling rule. In Fig. 3, the photocurrent noise power spectral density is shown for the $N = 16$ sample, at temperature $T = 30$ K and different biases. Samples were irradiated by the same IR power as above specified. From these curves, it can be noticed that the photocurrent noise in excess with respect to the dark one increases at lower current and lower temperature.

In order to understand the basic physical processes responsible for the anomalous behavior of the photocurrent noise, it is convenient to consider the normalized photocurrent noise power spectral density $S_I/(4eI/N)$. The quantity $S_I/(4eI/N)$ has been plotted as a function of the current I in Fig. 4, using the power spectral density data at $I = 0.2$ mA, $I = 0.4$ mA, $I = 0.6$ mA, $I = 0.8$ mA, $I = 1.0$ mA and $I = 1.2$ mA at $f = 20$ Hz.

In Fig. 5, the inverse capture probability $1/p_c$ has been plotted. The quantity $1/p_c$ has been evaluated by means of the current–voltage characteristics measured in the same experimental conditions as noise measurements. The steady-state responsivity R_I is defined as the ratio between the photocurrent and the incident radiation power:

$$R_I = \frac{I(E) - I_{\mathrm{dark}}(E)}{P(h\nu)}. \tag{2}$$

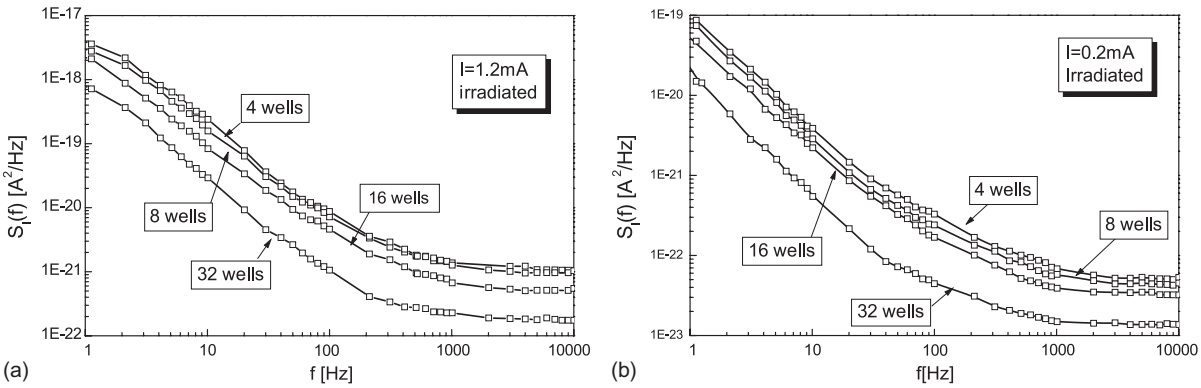

Fig. 2. Power spectral densities of the photocurrent noise for AlGaAs/GaAs QWIPs respectively with $N = 4$, 8, 16, 32 wells. Temperature is the same as in Fig. 1. The IR radiation power impinging on the samples is 15 μW. The average currents flowing in the devices are respectively $I = 1.2$ mA (a) and $I = 0.2$ mA (b). In this case, the dependence of the power spectral density on N does not follow the $1/N$ law.

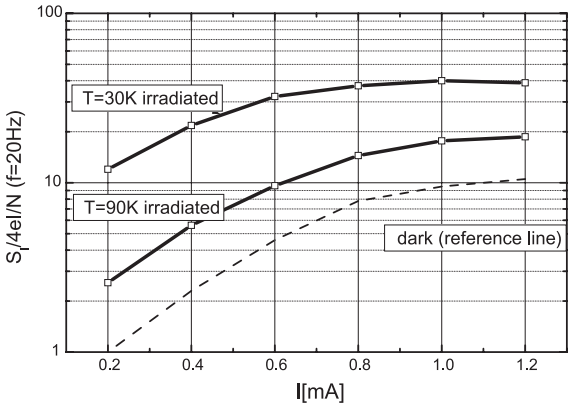

Fig. 3. Relative power spectral densities of the photocurrent noise for the $N = 16$ wells AlGaAs/GaAs QWIP respectively at $T = 30$ K and at $T = 90$ K. The IR radiation power impinging on the samples is 15 μW. Dashed line represents a reference baseline corresponding to the noise in the dark.

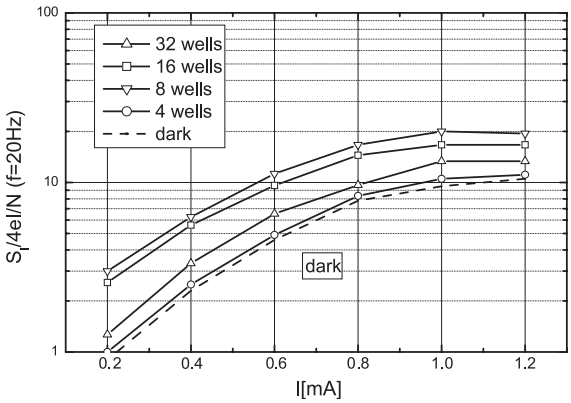

Fig. 4. Normalized current noise power spectral density at $f = 20$ Hz in the dark (dashed line) and under IR radiation (line + symbol) for QWIPs respectively with $N = 4$, 8, 16, 32. All the values are referred to those of the four-wells sample at $I = 0.2$ mA under IR radiation (line + circle). Temperature 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.

It can be written in terms of the photoconductive gain g_{photo} and of the quantum efficiency η as

$$R_I = \frac{e}{h\nu}\eta g_{\text{photo}}. \tag{3}$$

For QWIPs having the same growth sequence, g_{photo} can be expressed in terms of p_c and N as $1/Np_c$ and η can be expressed in terms of N and of the one-period quantum efficiency η_p as $N\eta_p$, the steady-state responsivity results:

$$R_I \simeq \frac{\eta_p e}{h\nu}\frac{1}{p_c}. \tag{4}$$

The inverse capture probability obtained as described above has been thus plotted in Fig. 5 against the current I. It can be observed that $1/p_c$ does not take the same value as N changes. The anomalous behavior of the steady-state responsivity has been extensively discussed in the literature concerning QWIPs and it has been ascribed to the fact that under IR radiation a redistribution of the potential takes place. This phenomena is enhanced at low applied biases and at low temperatures [10–13]. The sheet concentration of the electrons in the QW's and, consequently, the injected current vary under the influence of IR radiation due to the electron photoexcitation and their escape from the QW's. The positive charge build-up in the QW's is responsible for the formation of the high field domain and enhancement of electron injection from the emitter. 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.

As already mentioned, the quantity $S_I/(4eI/N)$ should be independent of N and should vary as the inverse capture probability $1/p_c$ for QWIPs with

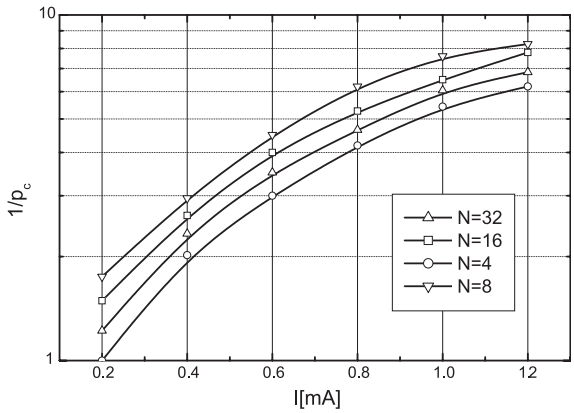

Fig. 5. Relative values of the inverse capture probability vs. current at $T = 90$ K.

periods having identical design if Eq. (1) would be fully applicable. These issues directly follow from the assumption that the current noise generators corresponding to each QW period are uncorrelated. Due to the discrete structure of the QWIPs, these assumption are far to be realistic, especially for small number of wells. Let us now reasoning from a stochastic standpoint. Consider (a) the random elementary event related to the electron release from the QW bound state to the continuum. As the QW is depleted by one electron, the field on the barriers close to the emitter is stocastically increased (b). The process (b) contributes to the noise power spectrum with a modulation low frequency noise component, related to the long dielectric relaxation times of the emitter and interwell barriers. The stochastic process (a) drives the process (b) and thus (a) and (b) are correlated. The correlation degree is higher if the potential nonuniformity is stronger and this happens under strong IR radiation, at low biases or at low temperatures. As already noted, for a fixed value of the average current, $S_I/(4eI/N)$ is not constant under IR radiation: it takes its minimum for $N = 4$, then increases and finally decreases again with N. At fixed current, the sequence of the $S_I/(4eI/N)$ values behaves analogously to the inverse capture probability. These deviations can be ascribed to the loss of validity of the simple g–r noise picture. The occurrence of nonlinearities in the potential distribution is responsible for the onset of correlations among the noise sources, that should be introduced in the noise model.

3. Conclusion

In summary we have found that for QWIPs having the same design except N:

- the dark current noise power spectral density scales as the inverse of the number of wells N as expected by Eq. (1);
- the photocurrent noise power spectral density strongly deviates from the $1/N$ behavior.

The anomaly of the photocurrent noise power spectral density has been qualitatively explained taking into account the potential nonlinearity. Such nonlinearity causes the capture probability p_c to depend on the well number N too. Furthermore, the deviations are even more evident at low biases and at low temperatures. These findings indicate that the assumptions underlying the simple g–r noise should be suitably reviewed in order to develop a model able to reproduce the noise behavior in the different operative conditions of multi QWIPs.

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