Low-frequency photocurrent noise in semiconductors: Effect of nonlinear current–voltage characteristics

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A current noise model for planar metal–semiconductor–metal photodetectors is proposed, which allows one to account for the low-frequency excess-noise behavior measured in several semiconductor devices. According to the proposed model—based on a multiplicative noise mechanism—the photocurrent noise power can be directly related to the carrier density and to the photogeneration level. Moreover, in the absence of potential-barrier fluctuations, the standard $1/n$ behavior of the simple g–r noise model is recovered. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1368188]

Photodetectors are basic components to instrumentation operating in optical communication and environmental-control fields. A severe concern associated to such systems is the level of electrical noise, mainly in those applications requiring very high sensitivity.[1] For a fully homogeneous semiconductor device in the absence of defects and donors, if noise is due to fluctuations of sample resistance and, ultimately, to uncorrelated carrier number fluctuations, the relative noise power $\langle \delta G^2 \rangle / G^2$ varies as $1/G$, G being the average conductance of the sample.[2,3] This property is, however, rarely satisfied: real samples are far from being fully homogeneous and fluctuations always show a certain correlation degree. A variety of inhomogeneous systems and devices indeed exhibits a relative current noise exceeding the corresponding homogeneous value.[4–6] In such cases, the earlier relationship plays the unique but important role of reference to evaluate at what extent noise deviates from the ideal behavior.

The aim of this letter is twofold: (i) we shall present a variety of results showing how different semiconductor materials exhibit an universal low-frequency photocurrent noise behavior and (ii) we shall propose a noise model able to account for such excess-noise phenomena in terms of a multiplicative noise mechanism. Our experimental results are reported in Fig. 1; here, the relative conductance noise power $\langle \delta G^2 \rangle / G^2$ is shown as a function of the conductance G for PbS, PbSe, and HgCdTe photoconductors at different temperatures. Instead of decreasing according to the $1/G$ rule when G increases—due to increasing light intensity with respect to the background level—the relative noise power grows, reaches a maximum, and then decreases monotonically. Moreover, the amount of noise power exceeding $1/G$ is larger for materials with narrower energy gaps [see Fig. 1(a)] and for lower temperatures [see Fig. 1(b)]. Similar behaviors have been previously reported on by other authors for GaAs, Si, and GaN.[7,8] In order to explain such a general behavior, we propose a physical model, which generalizes those recently proposed in Refs. 5 and 6, based on a multiplicative noise mechanism due to fluctuations of a photosensitive interface potential barrier. Indeed, semiconductor surfaces and interfaces are characterized by accumulation or depletion layers due to ionized states and compensating space-charge regions on either side.[9] Under illumination, the occupancy of the interface levels changes, causing a readjustment of the space-charge regions and thus changing the average current and its fluctuations. The electric field at a semiconductor interface fluctuates as a consequence of the following processes: (i) stochastic emptying/filling of carrier traps at the barrier and within the space charge region, and (ii) fluctuations of carrier density at space-charge boundary in the semiconductor bulk. The multiplicative noise term can be easily obtained introducing the effect of light on potential barrier in the current–voltage ($J-V$) characteristics as follows. Let us consider a symmetric n-type planar metal/semiconductor/metal photodetector characterized by potential barriers—at surface or at metal/semiconductor contact—operating in thermionic-emission mode. The electron current density flowing through the device is given by[9]

$$J = nev_{\mathrm{th}} e^{-\phi/KT}(e^{eV/KT}-1), \tag{1}$$

where n denotes the free-carrier density in the semiconductor, v_{th} is the thermal velocity, and ϕ is the potential-barrier height with respect to the conduction band. Under steady photoexcitation, the free-charge density n is given by the sum of the thermally excited carrier density n_0 and of the photogenerated carrier density n_{ph}. In the case of uncorrelated fluctuations of n_0 and n_{ph}, the current noise power spectral density is given by the sum

$$S_J(\omega) = \left(\frac{\partial J}{\partial n_0}\right)^2 S_{n_0}(\omega) + \left(\frac{\partial J}{\partial n_{\mathrm{ph}}}\right)^2 S_{n_{\mathrm{ph}}}(\omega), \tag{2}$$

where $S_{n_0}(\omega)$ and $S_{n_{\mathrm{ph}}}(\omega)$ are the spectral densities of the fluctuations δn_0 and δn_{ph} which, according to the standard g–r noise model in semiconductors,[2] take the form

$$S_n(\omega) = 4\langle \delta n^2 \rangle \frac{\tau}{1+(\omega\tau)^2}, \tag{3}$$

where a single characteristic recombination time, for optically and thermally activated processes, is considered. The

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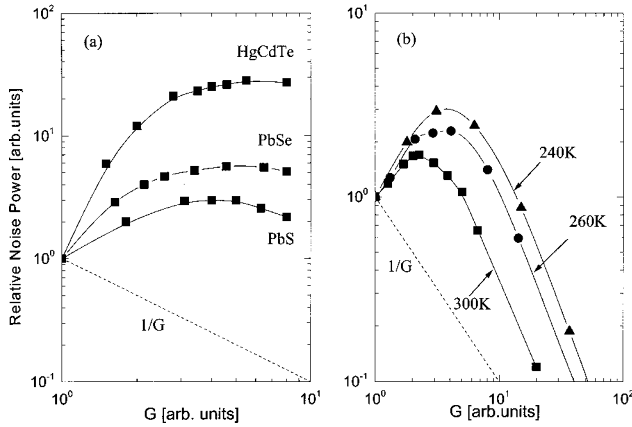

FIG. 1. Relative conductance noise power as a function of the conductance G (a) for PbS, PbSe, and HgCdTe measured at $T=240$ K, and (b) for PbS measured at different temperatures ($T=240$, 260, and 300 K). The first value of each curve corresponds to dark conditions. The conductance G increases as light intensity increases. Details concerning the experimental setup can be found in Ref. 6. Photodetectors are by Hamamatsu Photonics. Dashed line corresponds to the ideal $1/G$ behavior.

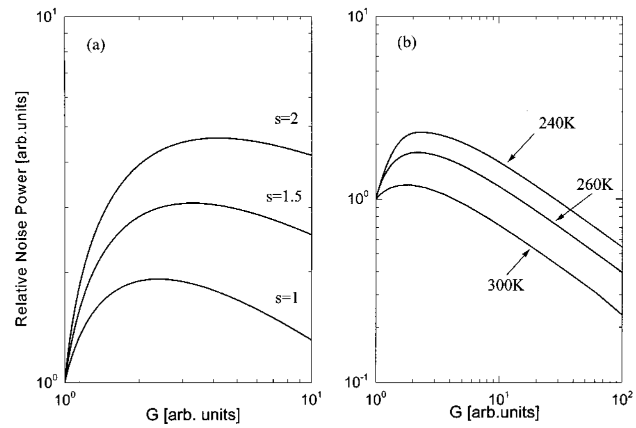

FIG. 2. Relative conductance noise power vs conductance G (a) for different values of the recombination parameter s, and (b) at different temperatures ($T=240$, 260, and 300 K) calculated by means of Eq. (8). The first value of each curve corresponds to dark conditions.

partial derivatives in Eq. (2) can be obtained by differentiating Eq. (1), keeping in mind the dependence of ϕ on n_{ph} due to processes like (i) and (ii):

$$\frac{\partial J}{\partial n_0}=Ce^{-\phi/KT}, \quad \frac{\partial J}{\partial n_{\mathrm{ph}}}=Ce^{-\phi/KT}\left(1-\frac{n}{KT}\frac{\partial \phi}{\partial n_{\mathrm{ph}}}\right) \tag{4}$$

with $C=ev_{\mathrm{th}}(e^{eV/KT}-1)$. By introducing Eq. (4) into Eq. (2) and dividing both members by J^2, we finally get the desired relative current-noise power spectrum

$$\frac{S_J(\omega)}{J^2}=\frac{S_{n_0}(\omega)+[1-(n/KT)(\partial\phi/\partial n_{\mathrm{ph}})]^2 S_{n_{\mathrm{ph}}}(\omega)}{n^2}. \tag{5}$$

Here, the term in square brackets corresponds to the amplification effect acting on $S_{n_{\mathrm{ph}}}$ due to the dynamic response of the interface potential barrier to the fluctuations δn_{ph}. In the absence of potential barrier fluctuations, the quantity $\partial\phi/\partial n_{\mathrm{ph}}$ vanishes and Eq. (5) reduces to the standard generation-recombination noise term. In order to compare Eq. (5) to the experimental data, a relationship between carrier density n and optical and thermal generation rates L and g is required. Under steady conditions, the total generation rate $L+g$ is balanced by the total recombination rate $nv_{\mathrm{th}}\Sigma_j S_j N_j$, S_j and N_j denoting, respectively, the capture cross section and the number of recombination centers of type j. By introducing an average capture cross section S we have $L+g=nv_{\mathrm{th}}SN$, where N denotes the total number of recombination centers and the quantity $\tau=1/v_{\mathrm{th}}SN$ corresponds to an average recombination time. Following the approach in Ref. 12, we shall assume $\tau^{-1}=bn^s$, where b and s are parameters depending on the recombination process considered. The exponent s ranges from 0 to 2, taking a value approximately equal to: 0 for Shockley–Read–Hall (SRH) recombinations, 1 for band-to-band recombinations, and 2 for Auger recombinations. The parameter b varies in a very wide range of values.[10] However, it plays no role in our model, since the final expression for the relative current noise in Eq. (8) will not depend on b. The total generation rate is then given by $L+g=bn^{s+1}$ and, therefore, we get $n(\partial\phi/\partial n_{\mathrm{ph}})=(s+1)(L+g)(\partial\phi/\partial L)$. Equation (5) can then be rewritten as

$$\frac{S_J(\omega)}{J^2} = \frac{S_{n_0}(\omega)+[1-(s+1)(L+g)1/KT(\partial\phi/\partial L)]^2 S_{n_{\mathrm{ph}}}(\omega)}{n^2}. \tag{6}$$

Finally, the total noise power can be obtained by integrating Eq. (6) over all positive frequencies ω:

$$\frac{\langle \delta J^2\rangle}{J^2} = \frac{\langle \delta n_0^2\rangle+[1-(s+1)(L+g)\,1/KT(\partial\phi/\partial L)]^2\langle \delta n_{\mathrm{ph}}^2\rangle}{n^2}. \tag{7}$$

Since carrier-density fluctuation processes have been assumed to be independent, we have $\langle \delta n_0^2\rangle = n_0$ and $\langle \delta n_{\mathrm{ph}}^2\rangle = n_{\mathrm{ph}}$; by combining these results, the relative noise power is given by

$$\frac{\langle \delta J^2\rangle}{J^2}=\frac{\alpha_L}{n} \tag{8}$$

with

$$\alpha_L=1-2(s+1)L\left(\frac{1}{KT}\frac{\partial\phi}{\partial L}\right)+(s+1)^2 L(L+g) \times\left(\frac{1}{KT}\frac{\partial\phi}{\partial L}\right)^2. \tag{9}$$

Equation (8) gives the relative power of current fluctuations as the product of $1/n$—which should be expected on the basis of a simple g–r noise process—times α_L. According to Eq. (9), the function α_L depends on the photogeneration level L, on the main recombination process (through the parameter s), on temperature, and on the derivative of the interface potential barrier ϕ with respect to L. It should be observed that $\alpha_L = 1$ (simple g–r noise) is obtained for $L = 0$ (dark conditions) or for $\partial\phi/\partial L = 0$ (absence of barrier fluctuations).

Let us now discuss the noise behavior given by Eq. (8). The relative noise power $\langle \delta J \rangle^2 / J^2$, evaluated using Eq. (8), is plotted in Fig. 2. The values of $\partial\phi/\partial L$ have been calculated on the basis of the theory developed in Refs. 11 and 12, where also experimental results concerning the dependence of ϕ on L for silicon are reported. The thermal-generation rate g has been taken equal to the minimum value of the photogeneration rate ($L_{\min} = 10^{20}$ cm^{-3} s^{-1}), while its temperature dependence has been obtained using $g = n_0 v_{\mathrm{th}} S N$. The theoretical curves in Fig. 2 reproduce with excellent qualitative agreement the nonmonotonic behavior of the experimental noise. As shown in Fig. 1(a), the amount of noise exceeding $1/G$ diminishes in semiconductors with wider energy gap at a given temperature. This can be explained observing that the contribution of SRH ($s = 0$) and band-to-band ($s = 1$) dominates over the Auger ($s = 2$) recombination processes in semiconductors with wider energy gap and that the amount of noise exceeding $1/G$ is smaller for lower values of s [see Fig. 2(a)]. Moreover, since the thermal generation rate g is smaller as wider is the energy gap, posing $g \ll L$ and, according to the results of the paper[11] concerning $\partial\phi/\partial L$, α_L becomes L independent. Thus, a stronger reduction of the nonmonotonic part of the noise power should be expected. We stress that the above quantitative analysis has been partially based on the experimental and theoretical results of papers;[11,12] further support to the present noise model could be obtained if experimental data of ϕ_L for other semiconductor materials would be available.

In conclusion, a general model of photoinduced noise in semiconductors has been proposed. In spite of many simplifying assumptions, the main features of the experimental noise have been qualitatively accounted for. In the development of the theory the current–voltage characteristics of a single Schottky barrier system has been used. The analysis has been performed within the thermionic emission model, considering only majority carrier transport under the assumption of a single recombination mechanism. We finally stress that Eqs. (6) and (8) are unchanged if (i) current–voltage characteristics of grain-boundary semiconductors or (ii) current–voltage characteristics based on *drift-diffusion* model are considered. This strongly supports the universality of the excess photocurrent noise behavior experimentally observed and theoretically predicted by our noise model.

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