Grain-boundary effects on photocurrent fluctuations in polycrystalline photoconductors

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(Received 12 June 1997)

The effect of light-dependent potential barriers at the grain boundary interface has been taken into account in the derivation of the photoconductance noise in polycrystalline photoconducting films. The noise power spectrum has been calculated considering the contribution of many elementary systems constituted by two homogeneous crystalline grains separated by an adjacent photosensitive potential barrier. The noise relative to each elementary system has been studied taking into account the modulation effect on the current crossing the grains of the spontaneous fluctuation of the intergrain barrier under illumination. The theoretical results are compared with a set of experimental data concerning the photoconductance noise in polycrystalline PbS under several experimental conditions. The proposed model allows us to explain several features of the current noise both in the dark and under illumination. In particular, the origin of the $1/f$ *noise* component, arising in the power spectrum in the presence of light, and the unusual behavior of the noise spectral density vs conductance when light intensity is changed are discussed and clarified on the basis of the present theory. [S0163-1829(98)01304-6]

I. INTRODUCTION

The charge carrier transport through grain boundaries in polycrystalline semiconductors has stimulated continuous investigation over a long period of time, owing to the wide applied and theoretical interest of the electronic properties of these materials. The recognition of the role played by the intercrystalline barriers in the electronic transport processes, both in the dark and under illumination, has been pointed out since the early studies concerning such materials.[1–6] Nevertheless, the charge transport properties of polycrystalline semiconductors still represent an open question in the semiconductor physics community.[7–17]

The intergrain potential barriers result from the charge trapped on gap states localized between two adjacent grains. Such interface states are created either by dislocations introduced by the crystallographic misfit between the adjacent grains or by impurity or dopant atoms trapped at the interface and acting as acceptor or donor levels. The trapped carriers create a potential barrier of height ϕ_0 within the adjacent grains, which reduces the mobility of free carriers, and increases the local resistivity. In several cases the intergrain potential barriers show a remarkable photosensitivity. In the dark, only thermally activated electronic transitions from and to the shallow energy levels in the grain are allowed. In the presence of light of suitable wavelength, electronic transitions from the photosensitive traps at the intercrystalline boundary can also occur. The optically activated transitions produce several effects: they increase the density of free carriers, decrease the intergrain barrier height, or reduce the depletion layer width at the end of the barrier. The predominance of one of the previous effects over the other two depends on the electronic properties of the material and on the operative conditions (temperature, voltage). When the barrier reduction is more effective than the carrier generation process in increasing the charge transport in the presence of light, the device is said to operate according to the *barrier mechanism of photoconductivity*.[18]

Several experimental techniques have been adopted to test as many physical quantities as possible depending upon the characteristics of these intergrain barriers. To this purpose also the properties of the current noise of polycrystalline semiconductors have been exploited by a few authors (see Ref. 19 for a recent review). The characteristic behavior of the resistance fluctuations has been first related to that of the grain boundary potential barriers in Refs. 5 and 6. A more recent study has been carried out by Madenach and Werner,[20] who analyzed the resistance fluctuations in the bicrystal and in the multicrystal of p silicon in the dark. The voltage fluctuations at the end of the samples have been related to the stochastic capture and emission processes of holes at the interface states of the intercrystalline barrier due to thermally activated transition. The fluctuations of the interface charge give rise to fluctuations $\delta\phi$ of the barrier height, which controls the current J_{th} across the boundary according to the Richardson-Dushmann law. By interpreting the capture and emission of holes at the interface as a fluctuating current J_T, the mechanism of fluctuation of the current across the boundary can be assimilated to the mechanism of current amplification in a bipolar transistor, giving rise to considerable fluctuations in the emitted current J_{th}.

In Ref. 21 it has been shown that a light-dependent potential barrier strongly affects the average current as well as its fluctuations, by adding a modulation component to the noise power spectrum. Such a mechanism has been adopted to explain photocurrent noise in insulating photoconductors[22] and in single-quantum-well infrared photodetectors.[23] In the present paper the theory developed in[21] will be extended to a polycrystalline photoconducting device characterized by (a) an appreciable dark conductance and (b) a distributed set of light-sensitive intergrain barriers localized at the grain interfaces. A comparison with the experimental results obtained on polycrystalline PbS is given and discussed in Sec. IV. The proposed theory explains some aspects of the behavior of the

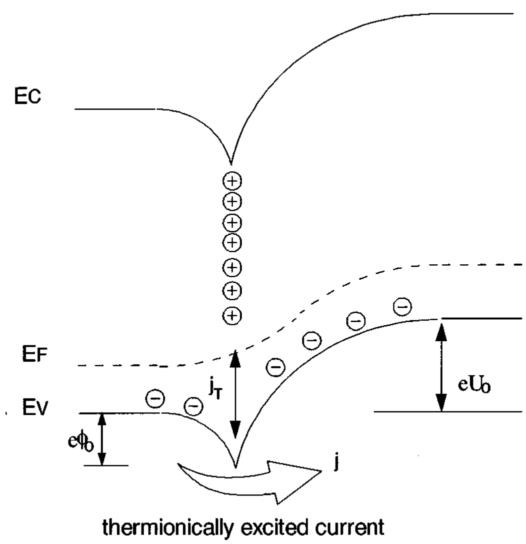

FIG. 1. Energy-band diagram at the interface between two grains of a p-type polycrystalline semiconductor. The positive interface charge is due to electrically charged defects, which act as hole traps. It is compensated by negative acceptor ions within the space-charge region. The current J_T represents the capture and emission of holes by the interface states and corresponds to a fluctuation of the barrier height $e\phi_o$, which modulates the current J induced by the applied voltage U_o (after Ref. 20). In the present case, the capture and emission of holes by the interface states is activated by light.

noise power spectrum in infrared (IR) photoconductors under different conditions: in particular, the onset of a $1/f$ noise component under illumination results from the modulation effect of the light-sensitive barriers.

An estimate of the contribution of the quantum $1/f$ noise is also reported.[24] Since there is no quantum $1/f$ noise in the photogeneration of electron-hole pairs,[25] the source of quantum noise should be envisaged in the conductance fluctuations in the grain and in the intercrystalline regions.[26] Quantum $1/f$ noise should also be expected from the fluctuation of the intergrain barrier crossing rate. As reported in Sec. IV, the power spectrum of this noise arising from the above-mentioned processes turns out to be some orders of magnitude lower than the experimental one in the analyzed range of illumination and frequency values.

II. PHOTOCURRENT NOISE MODEL

A polycrystalline semiconductor can be schematically represented as a collection of more or less homogeneous grains coupled to each other by higher resistive intergrain regions. In the case of a photoconductor such a system can be represented as a network of noisy resistors whose values depend on the degree of illumination of the device. The following discussion will be restricted to p-type semiconductors, in order to compare theoretical results with the experimental ones obtained on PbS infrared photoconducting devices. With minor modifications this approach can be extended also to n-type semiconductors. Each branch of the network is constituted by a pair of crystalline grains separated by an adjacent photosensitive barrier, whose energy band diagram is shown in Fig. 1. It behaves as a resistor characterized by an average value and a fluctuation of its resistance strongly dependent on the illumination. The theory developed in Ref. 21 will be applied to the calculation of the current noise power spectrum relative to such a system. Finally, the whole resistor network will be considered in order to obtain the total current noise power spectrum.

Let our attention be focused on the elementary system shown in Fig. 1. We shall first consider the stochastic processes occurring in the dark. In this condition only thermally activated electronic transitions from and to shallow acceptor centers are allowed. If the charge carriers have enough energy to overcome the intergrain potential barrier, an electric current will pass through the photoconductor. While the charge carriers pass across the region indicated in Fig. 1, a series of stochastic processes (trapping-detrapping or generation-recombination) occurs, giving rise to a noise, the power spectrum of which can be calculated on the basis of the standard theories of g-r noise in semiconductors. In the ambit of the random point processes approach, the contribution of each transition to the intergrain conductance can be described as a rectangular pulse of height g and duration $\tau_g^{(i)}$ representing the carrier lifetime. As a good approximation, $\tau_g^{(i)}$ may be considered the capture time of a given shallow acceptor center. The quantity g is related to the mobility μ by the following relationship:

$$g=\frac{e\mu}{d_g{}^2}, \tag{1}$$

where d_g is the average dimension of the crystalline grain. In the present context mobility fluctuations are disregarded. Assuming, as usual, that $\tau_g^{(i)}$ is distributed according to an exponential law,

$$P(\tau_g^{(i)})=\frac{1}{\tau_g}\exp\left(\frac{\tau_g^{(i)}}{\tau_g}\right), \tag{2}$$

the dark conductance noise power spectrum $\Phi_{\text{dark}}(\omega)$ can be easily calculated, and is given by

$$\Phi_{\text{dark}}(\omega)=\frac{1}{\pi}\nu_d\ \ g^2\frac{\tau_g^2}{1+\omega^2\tau_g^2}=\frac{1}{\pi}G_d\ \ g\frac{\tau_g}{1+\omega^2\tau_g^2}, \tag{3}$$

where τ_g is the average value of $\tau_g^{(i)}$, ν_d is the number of elementary pulses per unit time in the dark, and G_d is the dark conductance. As will be shown in the following section, the experimental results concerning the current noise in dark conditions in PbS polycrystalline photoconductors agree well with the results of Eq. (3).

Let us now consider the conductance fluctuations under illumination. As will be reported in the next section, there are several indications that a different mechanism of noise generation is switched on by light. Actually, the experimental results show that the noise power spectra in the presence of light cannot be simply interpreted in terms of an enhancement of the noise related to the increment of the conductance G (due both to a lowering of the intergrain barrier and to the interband electronic transitions produced by light) nor to a change of τ_g. The deviations of the noise behavior from the simple Lorentzian given by Eq. (3) will be accounted for by considering the effect of light on the intergrain potential barriers.

In the presence of light of suitable wavelength, electronic transitions from the deep traps at the intercrystalline boundary are allowed. As already mentioned, optically excited transitions increase the average conductance by increasing the density of free carriers and by decreasing the intergrain barrier height, thus allowing the charge carriers to overcome more easily the barrier. The latter mechanism accounts for an optical gain larger than unity, as found in these devices. Since the electronic transitions from and to the photosensitive traps lying at the grain boundary interface are stochastic, the height of the potential barrier will fluctuate accordingly. Such a mechanism strongly affects the probability distribution describing carrier injection: time intervals between elementary events cannot anymore be considered Poisson distributed, as in the dark [Eq. (3)], since their occurrence depends upon the statistics of the filling-emptying processes of the grain boundary interface traps. Therefore the calculation of the noise power spectrum has to be performed taking into account this correlation between the elementary events. As already pointed out, the modulation noise arising from this process can be described according to the mechanism cleared up in Ref. 21. In practice the noise power spectrum is obtained by a superposition of elementary pulse trains related to the emptying-filling processes of each single trap. In correspondence to the random emission (capture) of each hole from the interface traps, the barrier will be slighty reduced (enhanced). The stochastic reduction will allow an excess number of charges to pass over the barrier. The stream of *excess* injected carriers can be described by means of a train of clusterized elementary conductance pulses of height g and duration $\tau_g^{(i)}$ distributed according to the same exponential distribution function used for dark condition. Furthermore each train is characterized by the quantities τ_e and τ_f, representing, respectively, the average time intervals during which the trapping interface state is respectively empty or filled. These quantities also represent the average duration of the cluster and the average time interval between clusters in each train corresponding to a given interface trap. It is assumed that $\tau_e^{(i)}$ and $\tau_f^{(i)}$, corresponding to each elementary event of emptying-filling of the trap, are exponentially distributed, as expected for processes having a constant probability to be excited by light in any time interval. Furthermore, if the elementary events *within the cluster* are assumed to be Poisson distributed, the current noise power spectrum is given[21]

$$\phi(\omega)=\nu_0 g^2\langle|S(\omega)|^2\rangle + 2\nu_0 g^2|\langle S(\omega)\rangle|^2 \frac{\rho(1-\nu_0\tau_0)^2}{\omega^2\tau_0^2(\rho+1-\rho\nu_0\tau_0)^2+1}. \tag{4}$$

The quantities ν_0, τ_0, ρ, in this relationship represent, respectively, the average number of pulses per unit time, the average value and the average number of the time intervals between subsequent pulses within the cluster. Furthermore $S(\omega)$ indicates the Fourier transform of the elementary unitary pulse, the brackets $\langle\rangle$ indicates an averaging operation over the pulse ensemble and the bars $||$ represent the modulus. It must be observed that the first term in the Eq. (4) represents the power spectrum of the same pulse sequence in the absence of clustering. It corresponds to an intrinsic noise related to the transport process within the grain of the excess carriers crossing the barrier for each ionized photosensitive trap. The second term is the effect of clustering produced by the stochastic emptying-filling processes of the photosensitive trap. This term gives the power spectrum of the noise component generated by the barrier fluctuation when the effect of all the photosensitive traps localized at the grain boundary interface is considered.

We shall now express the various parameters appearing in Eq. (4) in terms of more physical quantities characterizing the trap emptying-filling process. Let Δg be the average increment of the conductance produced during the trap emptying time τ_e. Since the elementary conductance pulse has an average area $g\tau_g$, the average number of conductance pulses in a cluster is given by

$$\rho^*=\rho+1=\frac{\Delta g}{g}\frac{\tau_e}{\tau_g} \tag{5}$$

and

$$\tau_e=\rho\tau_o \tag{6}$$

also holds. From the definition of ν_0, taking into account Eq. (5),

$$\nu_0=\frac{\rho^*}{\tau_e+\tau_f}=\frac{\Delta g}{g\tau_g}\frac{n_{te}}{N_t}, \tag{7}$$

where n_{te} is the average number of empty traps and N_t is the total number of photosensitive traps. The quantity n_{te} is related to the photon flux n_{ph} and to the quantum efficiency η by the equation

$$n_{te}=\eta n_{\mathrm{ph}}\tau_e. \tag{8}$$

Finally, the quantities $\langle|S(\omega)|^2\rangle$ and $|\langle S(\omega)\rangle|^2$ can be calculated by suitably averaging the Fourier transform of a set of rectangular pulses of duration $\tau_g^{(i)}$ distributed according to the exponential probability density given by Eq. (2). One obtains

$$\langle|S(\omega)|^2\rangle=2|\langle S(\omega)\rangle|^2=\frac{1}{\pi}\frac{\tau_g^2}{1+\omega^2\tau_g^2}. \tag{9}$$

If it is assumed, as in Ref. 21, that $\rho^*\gg 1$, then one also gets $\rho\approx\rho^*$. This assumption is justified by the fact that in general the optical gain is much larger than 1 and thus $\tau_e \gg \tau_g$. In particular, this is the case of the device discussed in the next section. We can also assume that

$$\nu_0\tau_0=\frac{\tau_e}{\tau_e+\tau_f}=\frac{n_{te}}{N_t}\ll 1, \tag{10}$$

which means to be far from saturation. Taking into account all these relationships, Eq. (4) simply becomes

$$\phi(\omega)=\frac{1}{\pi}\frac{n_{te}}{N_t}\frac{1}{1+\omega^2\tau_g^2}\left[g\tau_g\Delta g+\Delta g^2\frac{\tau_e}{1+\omega^2\tau_e{}^2}\right]. \tag{11}$$

We must now consider the contribution of all the traps N_t to the noise. By assuming that the trap ionization processes produced by light are independent and that the photoconductance varies linearly with n_{te}, then it is correct to sum up the power spectra produced by each trap. One gets

$$\Phi_{\mathrm{ph}}(\omega)=\frac{1}{\pi}\frac{1}{1+\omega^2\tau_g^2}\left[g\tau_g\Delta G+n_{te}\Delta g^2\frac{\tau_e}{1+\omega^2\tau_e{}^2}\right], \tag{12}$$

where $\Delta G=n_{te}\Delta g$ represents the contribution of light to the intergrain conductance of the elementary system of Fig. 1. Actually ΔG represents the conductance increment produced by light through the lowering of the intergrain barrier. Therefore the first term at right member of Eq. (12) corresponds to the g-r noise related to the excess carriers crossing the intergrain barrier in the presence of light. This term simply adds to the noise power spectrum of the dark current expressed by Eq. (3), giving the whole g-r noise power spectrum of the elementary system of Fig. 1 in the presence of light. The second term in square brackets of Eq. (12) represents the modulation noise component produced by the barrier fluctuation.

A few remarks are now required. Equation (12) holds also if the linearity of the photoconductance vs n_{te} is not fulfilled. Actually the excess noise due to the barrier fluctuation depends only on the average value of n_{te} and on the local derivative $\Delta g=dG/dn_{te}$. Therefore, if the fluctuation is small with respect to G, the second term in Eq. (12) is correct, as shown in Ref. 21. It is only necessary to take into account that the value of Δg depends on the operative conditions of the device. Concerning the first term, which corresponds to the noise spectrum in the absence of barrier fluctuations, it can be independently calculated for a Poisson distributed pulse train due to the average conductance increment ΔG produced by light. Thus, the power spectrum given by Eq. (12) remains unchanged. The assumption $\nu_0\tau_0\ll 1$ (far from saturation) and $\rho^*\gg 1$ (large optical gain) could be also removed, making the second term within square brackets in Eq. (12) more complicated but exact. Its expression, which will not be reported here, can be easily obtained from Eq. (4) by using Eqs. (5), (6), and (7), and vanishes, as expected, in the two limits $\rho^*\to 1$ and $\nu_0\tau_0\to 1$.

The final expression of the photoconductance noise power spectrum of a single grain pair thus becomes

$$\Phi(\omega)=\frac{1}{\pi}\frac{1}{1+\omega^2\tau_g^2}\left[g\tau_g G+\Delta g^2 n_{te}\frac{\tau_e}{1+\omega^2\tau_e{}^2}\right], \tag{13}$$

where the quantity $G=G_{\mathrm{dark}}+\Delta G$ is the conductance of the elementary system constituted by a grain and its interface barrier in the presence of light. In writing Eq. (13) it has been assumed that the pulse duration τ_g remains unchanged during illumination. This may be correct at room temperature and at low values of the light intensity, since in this case the increment of the conductance ΔG is mainly due to the lowering of the intergrain barrier, while carriers are produced by the thermal activation of the acceptor centers. However, when the light intensity is increased or the temperature lowered the optically generated carrier density becomes gradually larger and may be finally predominant over the dark carrier density. It is thus expected that τ_g depends on the light intensity and that it becomes smaller at high illumination values, both because of the increment of the carrier density and because of the predominance of the interband transitions. It will be shown in Sec. IV that the experimental results confirm these conjectures. Finally it must also be observed that Eq. (13) has been obtained by assuming a defined characteristic time τ_e for the intergrain trap transitions. A distribution $P(\tau_e)$ should however be expected either within a given intergrain barrier or within the ensemble of the grains making up the photoconducting film. This point will be discussed in the next section.

III. EXTENSION TO THE WHOLE SPECIMEN

In this section we shall discuss the main aspects of the noise power spectrum expected from Eq. (13) in order to compare them with the experimental results reported in Sec. IV. Let us first consider the extension of Eq. (13), valid for the noise generated by a single intergrain barrier, to the whole photoconducting device. In order to do this, two general expressions can be used, valid for any type of networks at any frequency ω with the only assumption that the elementary noise sources at the grain interfaces are uncorrelated:[28]

$$\Phi(\omega)=\frac{1}{V^4}\sum_{ij}\Delta V_{ij}^4\Phi_{ij}(\omega), \tag{14}$$

$$G=\frac{1}{V^2}\sum_{ij}\Delta V_{ij}^2 G_{ij}. \tag{15}$$

In the previous expressions G_{ij}, V_{ij}, and $\Phi_{ij}(\omega)$ are, respectively, the conductance, the potential drop, and the noise power spectrum between the contiguous grains i and j, while G,V are the whole conductance and potential drop between electrodes. If it is assumed that G_{ij} and $\Phi_{ij}(\omega)$ are the same for all the grain pairs and the potential drops ΔV_{ij} are either equal to each other or zero, from Eqs. (14) and (15) one gets

$$\Psi_G(\omega)=\frac{\Phi(\omega)}{G^2}=\frac{\Phi_{ij}(\omega)}{G_{ij}^2}\frac{\sum_{ij}{}'1}{\left(\sum_{ij}{}'1\right)^2}=\Psi_{ij}(\omega)\frac{1}{n_{ij}}, \tag{16}$$

where the $'$ in the sums means that the pairs having $\Delta V_{ij}=0$ should be neglected. n_{ij} is the number of the pairs with $\Delta V_{ij}\neq 0$, while $\Psi_{ij}(\omega)$ and $\Psi_G(\omega)$ are, respectively, the relative conductance noise power spectrum of the grain pairs and of the whole specimen. Furthermore, if the network is simply considered as a three-dimensional lattice with cubic elementary cells whose nodes are the grains, n_{ij} coincides with the number of the grains and, according to Eq. (16), the relative noise spectrum scales as the inverse of the sample volume. It should be noticed that this does not mean that, when grains become smaller and n_{ij} increases, the total noise of the whole specimen decreases. Actually according to Eq. (1), the height of the elementary conductance pulse g scales as the inverse of d_g^2 while their average number per unit time ν_0 varies as d_g^3. From Eq. (4) one thus obtains that $\Phi_{ij}(\omega)$ varies as d_g. Moreover the conductance G_{ij} is proportional to $\nu_0 g$ and thus turns out to be proportional to d_g. On account of this, one gets

$$\Psi_{ij}(\omega)=\frac{\Phi_{ij}(\omega)}{G_{ij}^2}\propto\frac{1}{d_g^3}\propto n_{ij}, \tag{17}$$

which proves that $\Psi_G(\omega)$ remains unchanged. This fact has the important consequence that Eq. (13) can be used to calculate the relative conductance noise power spectrum of the whole specimen, provided that the whole set of quantities $g,G,n_{te},\Delta g,\tau_g,\tau_{te}$ are measured on the whole specimen. In any case, if $\Phi_{ij}(\omega)$ is, except for an amplitude factor, equal for all the grain pairs, $\Psi(\omega)$ is a weighted average of the $\Psi_{ij}(\omega)$'s and can be calculated by means of Eqs. (14) and (15). In general it may be, however, assumed that different grain pairs have rather different intergrain barriers and are characterized by different sets of hole traps.

As already stated in the previous section and discussed in detail in the next section, light induces a $1/f$ sloped noise component, not a simple Lorentzian. This fact can be accounted for by assuming that the traps have a wide distribution of emptying-filling times τ_e, either within each intergrain barrier or within the intergrain barrier ensemble. In both cases, taking into account Eq. (17), the expression of $\Psi_G(\omega)$ becomes

$$\Psi_G(\omega)=\frac{1}{\pi}\frac{1}{1+\omega^2\tau_g^2}\left[\frac{g\tau_g}{G}+\frac{\Delta g^2 n_{te}}{G^2}\sum_j\frac{a^{(j)}\tau_e^{(j)}}{1+\omega^2\tau_e^{(j)2}}\right], \tag{18}$$

where $a^{(j)}$ is the relative weight of $\tau_e^{(j)}$ and

$$\sum_j a^{(j)}=1. \tag{19}$$

The second term within square brackets in Eq. (18) gives a $1/f$-*like* spectrum if a wide distribution of $a^{(j)}$ is assumed. However this $1/f$-*like* component, being multiplied by a Lorentzian spectrum having a cutoff angular frequency $\omega_g=1/\tau_g$, also has a cutoff frequency at $\omega=\omega_g$. This important result is consistent with the experiments reported in the next section.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

We shall now consider the main aspects of the noise spectrum given by Eq. (18) and compare them with the experimental results obtained on PbS infrared photoconducting devices. It will be shown that the theory can explain the strong variation that the slope of the noise power spectrum undergoes in the presence of light, particularly in the low-frequency range, where it changes from the Lorentzian to the $1/f$ type. Furthermore, the unusual behavior of the relative noise power spectrum density vs light intensity, which presents a maximum instead of monotonically decreasing, can also be accounted for.

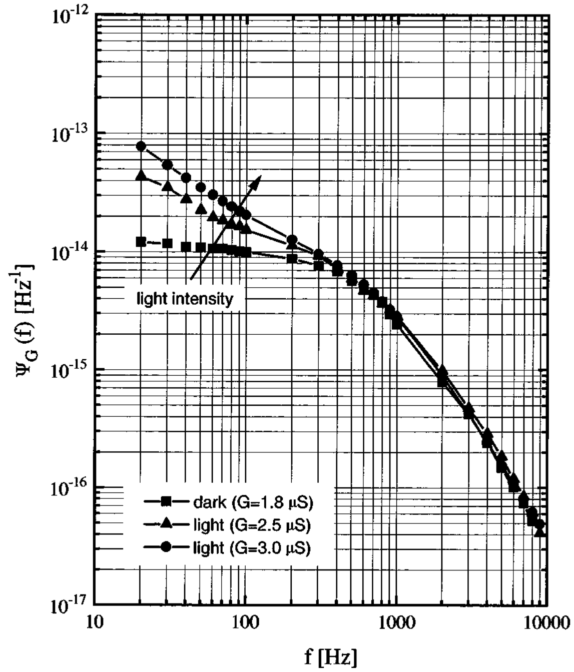

FIG. 2. Room-temperature power spectra of the relative conductance noise at low illumination values. Squares correspond to dark conditions. The other curves correspond to white-light irradiation. The onset of a $1/f$-*like* component having a cutoff frequency corresponding to the dark noise Lorentzian one can be observed in the presence of light. The reported quantity $\Psi_G(f)$ corresponds to $4\pi\Psi_G(\omega)$, being normalized in the domain of the frequency and only for positive values of this last quantity.

According to the present model, the light impinging on the device introduces a further noise component, represented by the second term within square brackets in Eq. (18). This component strongly enhances the low-frequency part of the spectrum, since the duration τ_e of a cluster of pulses is always larger than the duration τ_g of the elementary pulse. As stated in the previous section, a wide distribution of the trap emptying times τ_e justifies a $1/f$ sloped spectrum of the modulation noise induced by light. However a cutoff frequency corresponding to the one of the dark Lorentzian spectrum must be expected, owing to the Lorentzian term in front of the square brackets. This is what actually happens in the experimental spectra at low light intensities. Actually, in this case, the conduction process is still dominated by the thermally activated acceptor centers whose characteristic time τ_g remains unchanged. Figure 2 shows some typical experimental noise spectra obtained on a PbS-based photoconducting device (P394A of Hamamatsu Photonics[29]). These results, taken in dark conditions (squares) and at low illumination values (triangles, circles) show the onset of an $1/f$-*like* component under illumination, having a cutoff frequency corresponding to the dark Lorentzian spectrum.

Figure 3 shows the current noise power spectra at higher light intensity. The device conductance takes much larger values than in the dark. As discussed in the previous section, in this case it is expected that, in addition to the lowering of the barrier, the density of the optically excited carriers gen-

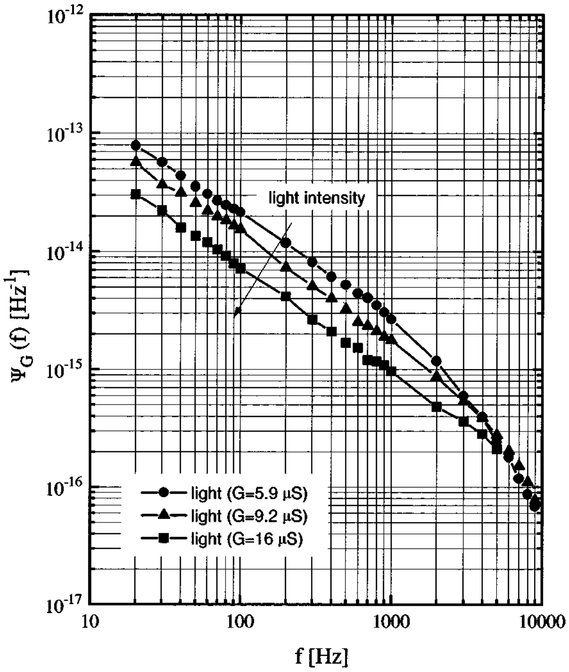

FIG. 3. Same as Fig. 2, but at higher light intensity. In this case the cutoff frequency of the $1/f$ component shows a gradual shift towards higher frequencies and the intensity of spectrum decreases. Both of these aspects are accounted for by the photoconductance noise theory here developed.

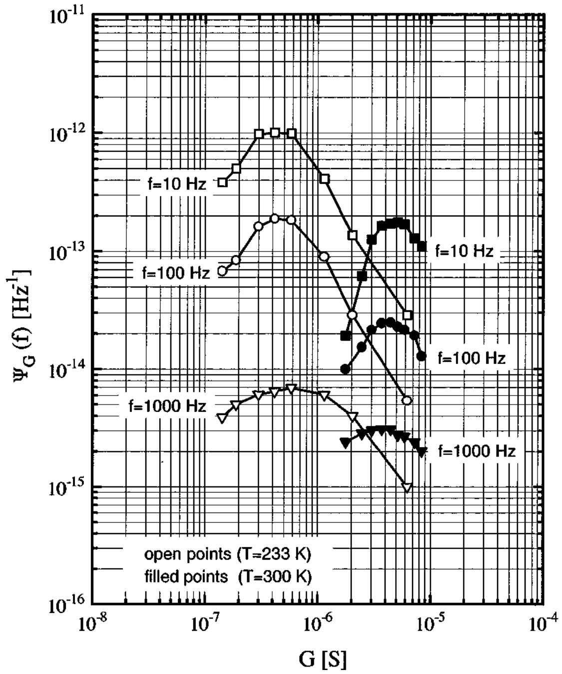

FIG. 4. Power spectral densities of the relative conductance noise as a function of the conductance G respectively at $T=300$ K (circles) and at $T=233$ K (squares). The first point of each curve corresponds to the dark conductance conditions. The curves have a maximum corresponding to a conductance value of about two times G_{dark}, as expected by the theory.

erated by interband transitions increases. One thus expects that τ_g becomes increasingly smaller and the cutoff frequency of the Lorentzians becomes increasingly larger. In these conditions the cutoff frequency of the $1/f$ component shifts towards higher frequencies.

The results of Fig. 2 and Fig. 3 are summarized in Fig. 4, showing the behavior of the relative conductance noise power spectral density vs the conductance (filled symbols) at room temperature. The relative conductance noise at lower temperature is also reported (open symbols). Within a fully Poissonian linear model of the fluctuations, $\Psi_G(\omega)$ should monotonically decrease as $1/G$. The unusual behavior of $\Psi_G(\omega)$ can be explained on the basis of Eq. (18). Let us consider the low-frequency spectral density, where this effect is more enhanced. Since the second term within square brackets in Eq. (18) dominates the power spectrum in the low-frequency range, we can limit our check to the behavior of this term as a function of the light intensity. It can be shown that $n_{te}\Delta g^2/G^2$ reaches its maximum value in correspondence of $2G_{\mathrm{dark}}$. Let the conductance G be linearly dependent on the photon flux n_f:[7,14,18,29]

$$G=G_{\mathrm{dark}}+k_f n_f=G_{\mathrm{dark}}+k_t n_{te} \tag{20}$$

with k_p and k_t constants. The second relationship derives from Eq. (8), taking into account that at room temperature the quantum efficiency η and the photoconductance relaxation time τ_e are practically independent of the light intensity.[7,14,18] Since the quantity Δg is the derivative of the average conductance with respect to n_{te}, one gets from Eq. (20):

$$\frac{n_{te}\Delta g^2}{G^2}=k_t\frac{(G-G_{\mathrm{dark}})}{G^2}, \tag{21}$$

which has a maximum at $G=2G_{\mathrm{dark}}$ and decreases as $1/G$ for $G \gg G_{\mathrm{dark}}$.

At lower temperatures, since a slight decrease of the relaxation time is observed when the light intensity increases,[7,14,18] the maximum value of the relative photoconductance noise is expected to occur at higher conductance values, as actually observed. Finally, it is worth remarking that a similar nonmonotonic dependence of the low frequency $1/f$ noise upon illumination intensity has also been observed in Si and GaAs semiconductors.[27]

For completeness, an estimate of the quantum $1/f$ noise is given in the physical conditions where its power spectrum is maximized, i.e., at room temperature, high light intensities and for the coherent quantum state. The effective number of carriers N has been evaluated from the value of the conductance G, being the carrier mobility $\mu=5$ cm^2 V^{-1} s^{-1} Ref. 18 and the specimen dimensions given in Ref. 29. The relative intensity of the noise turns out to be about two orders of magnitude lower than the experimental one in the range of the explored frequencies reported in Fig. 4. A still lower value of the power spectrum has been obtained by considering the incoherent quantum $1/f$ noise for the elementary system of Fig. 1, due to the recombination processes in the grain and in the intergrain region, and to the fluctuations of the crossing rate of the intergrain barrier.[26]

V. CONCLUSIONS

In this paper an approach to the calculation of the conductance noise power spectrum in polycrystalline infrared photoconductors is reported. The model is based on the multibarrier theory of photoconductivity and assumes that the excess noise in the presence of light is generated by the normal fluctuation of the intergrain photosensitive barriers. This brings us to a unified mechanism of noise generation, according to which, at low illumination values, the Lorentzian g-r noise produced by the thermally activated carriers is modulated by the barrier fluctuation, giving rise to a $1/f$-*like* component having a cutoff frequency determined by the g-r noise Lorentzian. At higher light intensities, where the carrier density increases by effect of the interband electron transitions produced by light and the average lifetime of the carriers decreases, the noise spectrum becomes gradually fully $1/f$-*like*. Both these aspects, together with the behavior of the relative conductance noise spectral density, which presents a maximum at $G \approx 2G_{\mathrm{dark}}$, are found in the experimental spectra, as shown in the previous section. The final expression of the theoretical power spectrum contains only quantities obtainable by means of suitable measurements. A correct order of magnitude of the noise is obtained with very reasonable values of the quantities entering Eq. (18), while the changes of the noise power spectrum corresponding to different physical conditions have been shown to be consistent with those observed in the experiments.

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