Current noise spectroscopy of deep energy levels in photoconductors

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According to a barrier photoconductance theory recently developed, two current noise sources can be envisaged, related respectively to the fluctuation of the barrier height (*photoinduced noise component*) and to the trapping–detrapping processes in shallow states within the photoconducting material ($g-r$ and $1/f$ *noise component*). It is shown that the first noise component, which can be separated by the second one, gives information on the energy gap and on the photoionization cross section of the deep energy levels of the photoconducting material. In particular for thin films it will be shown that the photoionization cross section of the deep energy levels varies inversely to the total number of photons impinging on the photoconductor and proportionally to the noise power spectral density as the photon energy changes. Such relationship suggests that the wavelength dependence of the noise power spectrum provides the correction to be taken into account if the constant photocurrent method is used and the variations of the minority carrier lifetime with the photon energy cannot be disregarded. Results concerning the energy gap and its temperature dependence, in the interval ranging from the room temperature to 200 K, are reported and compared with the results found in the literature for CdS based samples. The photoionization cross section of the deep centers as a function of the photon energy, at room temperature, is reported for the same sample. Such quantities have been obtained by measuring the spectral density of the photoinduced noise vs wavelength at constant photoconductance value. As for the other kinds of noise spectroscopy, the main advantage of the present method is to work out in the operative condition of the semiconductor device. © *1996 American Institute of Physics.* [S0021-8979(96)00315-5]

I. INTRODUCTION

The interest in the study of the spontaneous conductance fluctuations is mainly related to the attempt to improve the performances of an electronic device.[1] However, in many cases, the analysis of the conductance fluctuations is a powerful tool to obtain detailed informations about the physical mechanism to which they are related. In particular, for semiconductor materials, the fluctuation of the electrical conductance shows some features which are related to the processes of generation–recombination ($g-r$ *noise*) and trapping–detrapping ($1/f$ *noise*) of the carriers.[2] Since the pioneering work of McWorther,[3] the current noise spectroscopy has been therefore considered a powerful tool to analyze the electronic states in the forbidden energy gap of the semiconductor materials (see Ref. 4 for a review). It is commonly recognized that the absolute value of the noise power spectrum is in fact related to the total number of electronic states taking part to the fluctuation process, while, if the transitions from and to the localized levels are thermally activated, the cutoff frequency $1/(2\pi\tau_o)$ provides information about the activation energy and the capture cross-section area of the shallow energy levels. A wide literature exists, showing that the noise spectroscopy techniques can be used to study how shallow centers affect the performances of a solid-state device.[5] Actually, the noise spectroscopy is generally welcomed in the solid state physics with respect to other steady-state and transient techniques (deep level transient spectroscopy, junction techniques, thermally stimulated conductivity, optical techniques[6,7]). One of the advantages of the noise spectroscopy is the high sensitivity. In fact, a continuous signal produced by the spontaneous fluctuation of the occupancy of the levels in stationary conditions is detected. Moreover, it allows to characterize the semiconductor materials in the actual operative conditions rather than in a device *ad hoc* prepared for the measurements to be performed.

In this paper, we report on a noise spectroscopy technique for photoconducting materials. When light impinges on a photoconductor, generation of electron-hole pairs or ionization of deep donor centers occurs, according to the value of the light wavelength. Thus a further conductance fluctuation source adds to the generation–recombination and to the $1/f$ noise. The average time constant of the photoexcited transitions between deep energy levels and conduction band is in general longer than for the thermally activated transitions from the shallow levels. This allows to distinguish the corresponding fluctuations from the g–r and $1/f$ noise components in the noise power spectrum. Since these time constants depend on the intensity and on the wavelength of the exciting light, the photoconductance noise power spectrum will change accordingly.[8–10]

The goal of the papers[8–10] was mainly addressed to check the barrier photoconductance model and the photocurrent noise theory against several experimental results concerning the noise and other physical quantities characteristic of the photoconductive process. In particular, a large set of data concerning the dependence of the photocurrent noise on the light intensity and on the temperature have been reported respectively in paper[9] and.[10] In the present paper, it will be shown that the analytical results of the noise theory can be

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used to extract the value of (a) the energy gap and its temperature dependence and (b) the spectral dependence of the photoionization cross section of the deep impurity centers. In order to that, the behavior of the photocurrent noise when the light wavelength changes has been investigated every 5 nm in the range of visible spectrum, in several CdS_xSe_{1-x} based devices. The technique here presented is indeed based on the variation of the photocurrent noise power spectrum as photons with energy close to E_{gap} impinge on the photoconductor and the value of the device conductance is kept constant by varying the photon flux. It will be shown that the variation of the noise power spectral density with the photon energy yields directly the value of the energy gap E_{gap}. Furthermore, by using the results of the noise theory developed in Ref. 8, the value of the relative photoionization cross section of the deep donor centers or of the valence band states as a function of the photon energy can be obtained.

Steady state and modulated optical measurements are the standard method to analyze the electronic properties of the energy bands and to evaluate the energy corresponding to the minimum of the forbidden band gap. A deep insight into the structure of the forbidden energy bands can be achieved by processing the data obtained by the optical measurements on the basis of analytical relationships.[6]

A reliable estimate of the energy gap and of the optical properties of the semiconductors can also be obtained by the steady-state and the transient photoelectronic spectroscopy techniques: photocurrent spectral response, photocapacitance, photoconductivity decay, optical and thermal quenching of the photoconductance, constant photocurrent spectroscopy, dual and multiple beam modulation technique.[7,11] By comparison with other standard photoelectronic methods, the photocurrent noise spectroscopy turns out to be independent of the photocurrent decay times, whose determination requires delicate measurements and deconvolution techniques. This is an important aspect of the present method.

In the following section, the theoretical basis of the photocurrent noise spectroscopy is explained. In order to show the feasibility and the reliability of the method, experimental results for a CdS based photoconductor devices are reported in Sec. III and discussed in Sec. IV.

II. THEORETICAL BACKGROUND OF THE PHOTOCURRENT NOISE SPECTROSCOPY

As above mentioned, an analytical relationship describing the photoconductance noise power spectrum was obtained in Ref. 8 on the basis of a barrier model of the photoconductance. A brief summary of the theory and a few analytical relationships useful to a better understanding of the present paper are reported in the Appendix. It is shown that two noise components, defined respectively *intrinsic* and *photoinduced* on the basis of their different origin, can be distinguished in the power spectrum of the photoconductance fluctuations. The intrinsic noise component is related to the generation–recombination and to the trapping–detrapping processes of the free carriers in shallow centers (g–r and $1/f$ noise), while the photoinduced noise component is generated by the fluctuation of the number of photoionized centers (holes or deep donor levels, depending on the light wavelength). Actually, according to the model, the positive charge created by the photoionized centers lowers the potential barrier existing near the electrode–photoconductor interface, allowing the electron conduction process. For a given device, the average photoconductance G will thus depend only on the average number n_d of ionized centers or trapped holes. The fluctuation of the barrier is a stochastic process that modulates the electron injection from the electrode into the photoconductor and gives rise to the photoinduced noise component of the power spectrum. In this section, we shall show that the photoinduced component of the noise power spectrum can be used to get information on the value of the forbidden energy gap of the photoconductor as well as on the light quantum efficiency of the photosensitive centers.

As shown in the Appendix, the power spectrum of the photoinduced noise component can be written as

$$\Phi_G^{ph}(\omega)=\frac{1}{\pi}(\Delta g)^2 n_{fa}\sum_j \frac{\eta_\lambda^{(j)}\tau_d^{(j)^2}}{1+\omega^2\tau_d^{(j)^2}}, \tag{1}$$

where Δg is the photoconductance derivative with respect to the total number of ionized center n_d, n_{fa} is the number of absorbed photons, $\eta_\lambda^{(j)}$ and $\tau_d^{(j)}$ are, respectively, the contribution to the quantum efficiency and the lifetimes of the j centers.

At frequency values for which the following condition holds:

$$\omega^2\tau_d^{(j)^2}\gg 1, \tag{2}$$

Eq. (1) can be rewritten

$$\Phi_G^{ph}(\omega)=\frac{1}{\pi}\frac{(\Delta g)^2}{\omega^2}n_{fa}\sum_j \eta_\lambda^{(j)}. \tag{3}$$

Since the quantity $\Sigma_j\eta_\lambda^{(j)}$ corresponds to the total photoionization efficiency η_λ, the following equation is obtained:

$$\Phi_G^{ph}(\omega)=\frac{1}{\pi}\frac{(\Delta g)^2}{\omega^2}n_{fa}\eta_\lambda. \tag{4}$$

According to the Eq. (A5), this equation can be written as

$$\Phi_G^{ph}(\omega)=\frac{1}{\pi}\frac{(\Delta g)^2}{\omega^2}\frac{n_d}{\tau_d}, \tag{5}$$

where τ_d is the average lifetime of the positive charge and n_d has been defined above. In the ambit of the present model of photoconductivity, if the wavelength (or the temperature) are changed while the photoconductance G is kept constant by varying the light intensity, the quantities n_d and Δg must not change. On the contrary, the quantity τ_d shows an abrupt increase in correspondence of wavelengths longer than λ_{gap}.[9,10] Thus, if the condition (2) holds, the spectral density of the photoinduced noise component varies as the inverse of the quantity τ_d when the photon energy is changed and the average photoconductance is kept constant. In particular, $\Phi_G^{ph}(\omega)$ undergoes an abrupt variation in correspondence of λ_{gap}, thus allowing to determine the value of the energy gap of the photoconductor material, as it will be shown in the following sections.

By solving Eq. (4) with respect to η_λ, one obtains

$$\eta_\lambda=\frac{\Phi_G^{ph}(\omega_o)\omega_o^2\pi}{(\Delta g)^2 n_{fa}}. \tag{6}$$

where ω_o is a value of ω for which the condition (2) is satisfied.

Since, as stated above, Δg does not vary when the light wavelength changes, the relative variations of η_λ with the photon energy are determined only by the variations of the photoinduced noise spectral density $\Phi_G^{\mathrm{ph}}(\omega_o)$ and of the photon flux n_{fa}, needed to keep the photoconductance G constant.

According to the theory, since at high light intensity, the quantity Δg will tend to the constant g defined by

$$g=\frac{e\mu}{d^2}, \tag{7}$$

where e is the elementary charge, μ is the electron mobility and d the interelectrodic distance, the absolute value of η_λ can be obtained from Eq. (6) with a good approximation. It can be observed that, at high illumination value, the photoinduced noise component of the noise power spectrum varies proportionally to G, which, in its turn, varies linearly with the photon flux n_f.[8,9] The value of η_λ obtained from Eq. (6) is thus independent of the light intensity, as expected. The average quantum efficiency is also related to the total photoionization cross-section σ_{ph} by the following relationship:

$$\eta_\lambda=\frac{\sigma_{\mathrm{ph}}}{\sigma_o}, \tag{8}$$

where σ_o is the average optical cross section of the centers. Thus, Eq. (6) can be written in terms of the photoionization cross section as follows:

$$\sigma_{\mathrm{ph}}=\frac{\Phi_G^{\mathrm{ph}}(\omega_o)\omega_o^2\pi}{(\Delta g)^2 n_{fa}}\,\sigma_o. \tag{9}$$

As shown in the Appendix, since the quantity σ_o is proportional to the absorption coefficient α, the previous equation turns out to be practically independent of α if the condition $\alpha s \ll 1$ holds, where s is the film thickness. In this condition, from Eq. (9), since the quantity Δg is independent of the light wavelength, as discussed above, the spectral dependence of the photoionization cross section is given by the inverse of the photon flux multiplied by the noise power spectral density. We can thus conclude that the method here proposed presents several analogies with the constant photocurrent method (CPM), according to which the photoionization cross section is given by the inverse of the photon number at constant value of the photoconductance. As already cited the change of the noise power spectral density with the light wavelength at constant photoconductance value provides the correction to the CPM results, required when the minority carrier lifetime depends also on the photon energy.

In the next section, several experimental results concerning the measurements of photocurrent noise power spectra and of other quantities entering Eqs. (6) and (9) will be reported.

III. EXPERIMENTAL RESULTS

The photocurrent noise measurements have been carried out on commercial photoconductive CdS based devices.

The experimental setup and the scheme of the electrical circuit used to perform the photocurrent noise measurements are reported in Ref. 9. An halogen lamp is used as light source. The light is sent to a grating monochromator having a wavelength resolution of 3 nm. By means of a beam splitter and two optical fibers, the monochromatic light is sent to the cryostat containing the sample and to a calibrated photocell.

Photocurrent noise measurements have been carried out in the visible region of the light (from 450 to 800 nm) at different temperatures, ranging from liquid nitrogen to room temperature. The actual value of the temperature of the samples has been obtained by measuring the Nyquist noise power spectrum in quasithermal equilibrium under illumination as explained in Ref. 10. To obtain the photoconductance noise power spectra, the voltage noise power spectrum given by the signal analyzer were corrected according to the equivalent circuit reported in paper.[9] In Figs. 1(a)–1(c), some typical results concerning the photoconductance noise power spectra at different wavelengths of the incident light are shown. The device temperatures were respectively equal to 295, 235, and 205 K. Lower temperatures brought to the persistent photoconductance effect and were thus disregarded. The conductance G of the sample was kept constant and equal to 5×10^{-6} S for all the curves, by changing the light intensity when the wavelength was changed. A rapid change both of the shape and of the amplitude of the noise power spectra can be observed when the wavelength takes values near to λ_{gap}.

As it has been cleared up in the previous section, in order to obtain the photoionization quantum efficiency, measurements of the photoconductance noise power spectrum at high light intensity are required. In Fig. 1(d), the photoconductance noise power spectra are reported for a higher light intensity, corresponding to a conductance $G=2\times10^{-5}$ S.

The power spectral density of the photoinduced noise component $\Phi_G^{\mathrm{ph}}(\omega_o)$ can be obtained by subtracting the intrinsic noise component, given by the first term of the Eq. (A1), from the total noise power spectrum. In Fig. 2, this procedure has been applied to two power spectra corresponding to a conductance $G=2\times10^{-5}$ S. In this figure, points correspond to the total noise power spectra taken respectively at $\lambda=490$ nm and $\lambda=510$ nm. Continuous and broken lines correspond, respectively, to the photoinduced and to the intrinsic noise components. The experimental noise power spectrum given by the signal analyzer has to be corrected according to the $\Phi_G(\omega)=[1/(4\pi)]\Phi_G(f)$ before being introduced into the Eqs. (6) and (9). In Fig. 3, the spectral densities of the photoinduced noise component vs light wavelength are reported at a frequency of 400 Hz for different temperatures.

In Fig. 4, the curves of the photoconductance vs light wavelength (at a constant photon flux) and of the photoconductance noise power spectral density vs wavelength (at constant photoconductance) for a CdSSe compound are reported. These results show the remarkable improvement in the determination of the energy gap achievable by means of the noise technique with respect to the standard spectral response measurements. The reason is that the average photo-

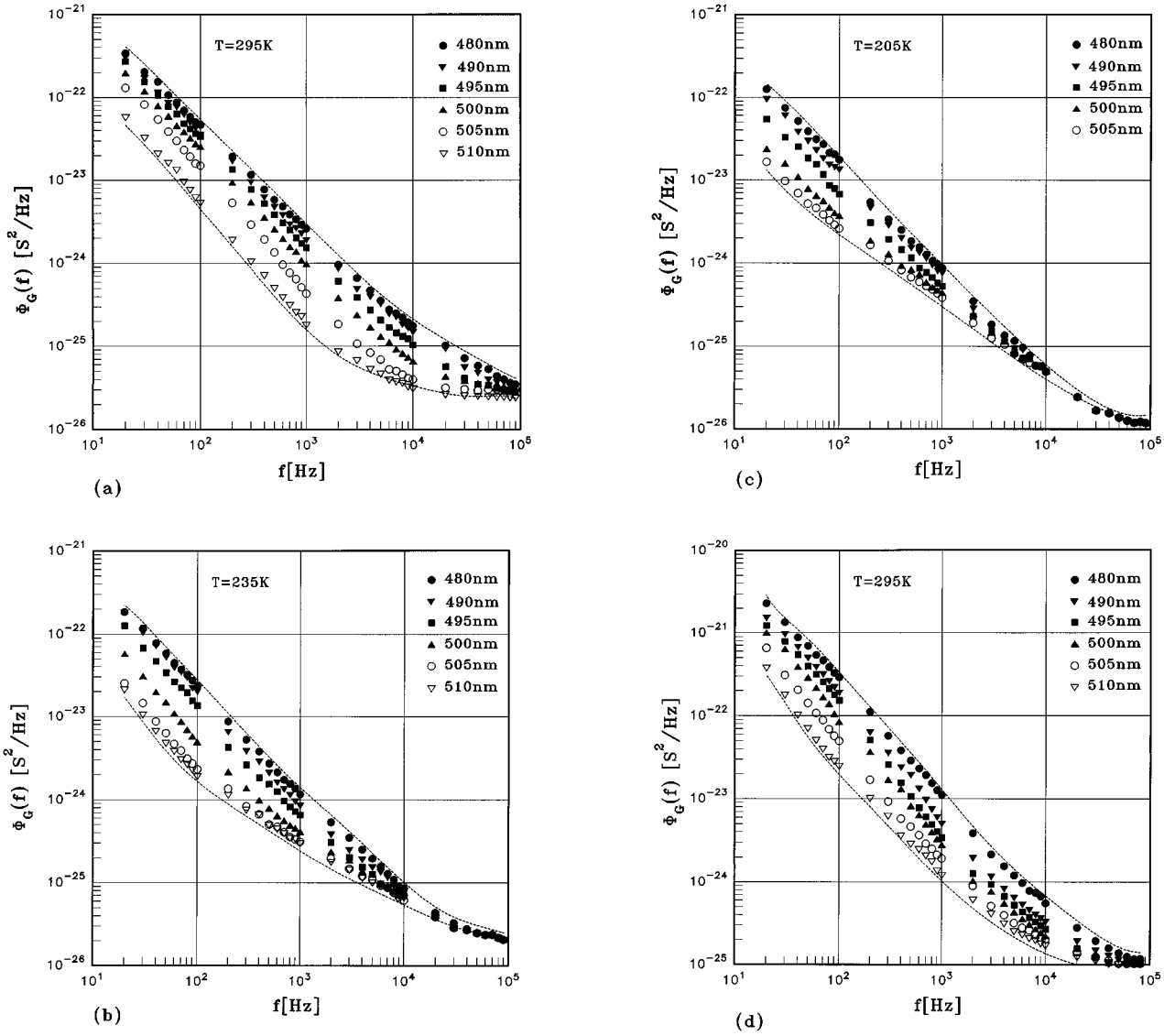

FIG. 1. Power spectra of the conductance fluctuation noise $\Phi_G(f)$ taken at different values of the wavelength λ of the incident light, as indicated by the legend. The average electrical conductance was kept constant for all the spectra, by varying the light intensity. The value of the conductance is 5×10^{-6} S. Broken lines represent the limits to which the noise power spectra tend, respectively, for $\lambda<450$ nm (upper curve) and $\lambda>800$ nm (lower curve) (see Fig.3). (a) Room temperature; (b) 235 K; (c) 205 K; (d) room temperature and conductance G equal to 2×10^{-5} S.

conductance depends on the light wavelength through two parameters: the quantum efficiency η_λ and the photoionization relaxation time τ_d, whose variations vs wavelength partly compensate each other. On the contrary, the spectral density of the photoinduced noise component, depends only on τ_d, as Eq. (5) shows.

Finally in Fig. 5, the inverse of the photon number per unit time n_f is reported as a function of the photon wavelength. Each curve has been obtained at constant photoconductance value G, corresponding to the value used for the noise power spectra above reported, respectively, $G=5\times10^{-6}$ S and $G=2\times10^{-5}$ S. These curves have been reported for two different reasons. The first one is that the inverse of photon number enters directly in the Eq. (9) giving the photoionization cross section. Furthermore, these curves correspond to the photoionization cross section according to the CPM technique providing that the minority carrier lifetime be independent of the photon energy. By comparing these results with those obtained in the following section according to the present technique, a noticeable improvement will be observed.

IV. DISCUSSION AND CONCLUSION

In this section, the energy gap and the photoionization cross section will be obtained from the experimental results reported in the previous section, and compared with the data already existing in the literature.

From the spectral densities reported in Fig. 3 the energy gap of the photoconducting material can be determined (for CdS $\lambda_{gap}\cong500$ nm). The shift of λ_{gap} toward the blue region of the visible spectrum as the temperature decreases is clearly deduced. It turns out to be in good agreement with the data reported in the literature, as can be deduced from the following relationship, describing the dependence of the band state energy on the temperature:[12]

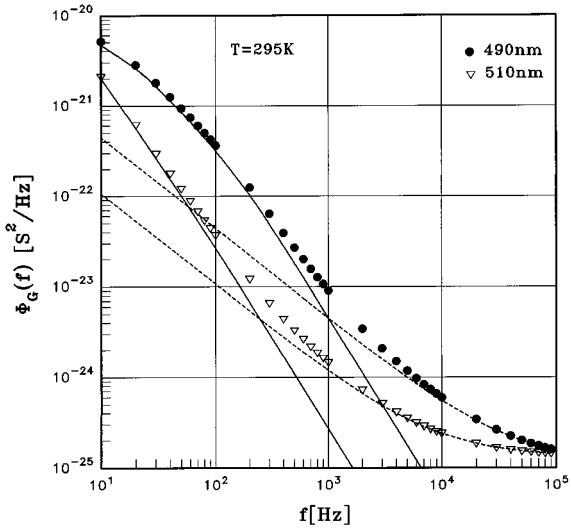

FIG. 2. Photoinduced noise component (continuous lines) and intrinsic noise component (broken lines) corresponding to the experimental photocurrent noise power spectra reported in the same figure (points). The upper curves correspond to $\lambda=490$ nm, the lower to $\lambda=510$ nm. Photoinduced noise components of the types shown in this figure are used to obtain the average photoionization efficiency at each value of λ, as explained in Sec. II.

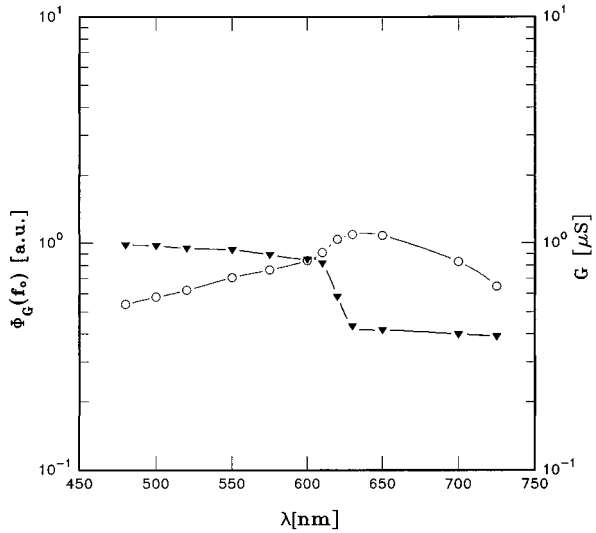

FIG. 4. Photoconductance vs light wavelength at constant photon flux (circles) and photoconductance noise power density at 400 Hz vs light wavelength at constant photoconductance (triangles) for a CdSSe compound (CdS photocell model P368 of the Hamamatsu Optical Detectors Catalogue). Comparison between the curves shows that the noise technique yields a more accurate and univocal determination of the energy gap ($\lambda_{gap}=610$ nm).

$$E_c(T)=E_c(0)+\beta T, \tag{10}$$

where the coefficient β takes the values $\beta=-5.2\times10^{-4}$ eV/K for the CdS.[13]

Let us now discuss the behavior of the average photoionization cross section σ_{ph} vs the photon energy. As explained in Sec. II, the determination of σ_{ph} is not directly obtained from the experimental data of the noise power spectrum, as for the energy gap. In fact the experimental data relative to the photocurrent noise have to be processed according to the Eq. (6), which requires that other physical quantities, characteristic of the material, must be known. In particular, it is necessary to determine the number of the absorbed photons n_{fa} by suitable optical measurements. However, if the absorption coefficient α or if the sample thickness s are such that $\alpha s \gg 1$, the number of absorbed photons can be reasonably approximated with the total number of photons impinging on the active area of the photocon-

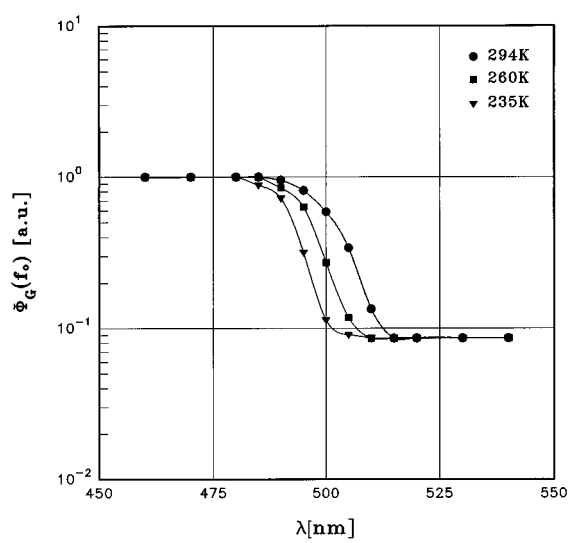

FIG. 3. Spectral densities of the conductance fluctuation noise $\Phi_G(f_o)$ taken at different temperatures as a function of the wavelength λ of the incident light. All the curves were taken at the same value of the electrical conductance $G=5\times10^{-6}$ S and correspond to a frequency $f_o=400$ Hz.

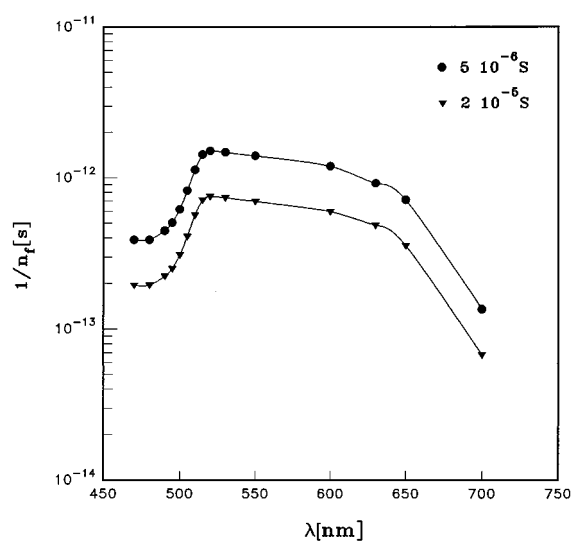

FIG. 5. Inverse of the photon flux n_f as a function of the light wavelength λ at constant photoconductance value [respectively, $G=2\times10^{-5}$ S (triangles) and $G=5\times10^{-6}$ S (circles)]. These data have been introduced in the Eqs. (6) and (9) to obtain the average quantum efficiency η_λ or the relative photoionization cross-section σ_{ph}, as explained in Sec. II. The inverse of the photon flux has been given instead of n_f in order to compare the photocurrent noise spectroscopy with the continuous constant photocurrent technique.

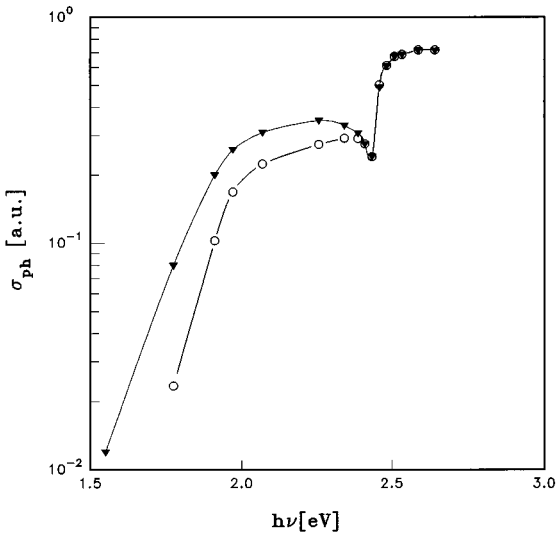

FIG. 6. Average photoionization cross-section σ_{ph} (circles) and average photoionization efficiency η_λ (triangles) vs photon energy in the region close to the valence band edge of a typical CdS sample.

ductor surface corrected only for the reflection coefficient. Furthermore, if the absolute value of σ_{ph} has to be determined, the electron mobility μ and the interelectrodic distance d of the sample are required.

In Fig. 6, the quantities η_λ and σ_{ph}, obtained from Eqs. (6) and (9), by using the experimental data reported in the previous section, are shown.

The value of ω_o has been chosen in correspondence of f_o=400 Hz where the photoinduced noise component becomes $1/f^2$ sloped. The photocurrent noise power spectrum densities are thus taken from the curves of Fig. 1(d). The value of g has been obtained taking into account that $d \cong 1$ mm for our CdS sample, and the electron mobility $\mu = 3\times10^{-2}$ m^2 V^{-1} s^{-1}.[14] It results $g = 5\times10^{-15}$ S.

The behavior of σ_{ph} vs photon energy is in good agreement with the data obtained by other photoelectronic techniques.[15–17] Very similar results concerning the photoionization cross section were obtained by Grimmeiss by using the photocapacitance technique in CdS:Cu samples. In Ref. 17, a similar distribution of the deep energy levels was obtained by theoretical consideration on the effect of the cadmium vacancies on the electronic structure of the energy bands in cadmium compounds.

Finally we want to point out that the photoionization cross section can be related to the energy E_d of the deep centers in the forbidden band gap. The first analytical relationship between σ_{ph} and E_d was obtained by Lucovsky[19] by considering a δ-function potential energy model. A modification of the Lucovsky model by Grimmeiss and Ledebo,[20] the hard-sphere model[21] and other quantum defects models have been later proposed.[22] In all cases, a threshold of the σ_{ph} at an energy value of E_d is obtained. On this account, the photoionization cross section of Fig. 6 should correspond to a deep energy level located at an energy of about 1.7 eV in the band gap. Further results concerning the photoionization cross section of several CdS_xSe_{1-x} compounds (obtained according the present technique), and the corresponding values of the deep energy levels (obtained according the Lucovsky model) will appear in a following paper.[23]

We can summarize the previous results as follows. As in the case of the constant photocurrent measurements (CPM), the noise spectroscopy technique requires to be carried out at constant average photoconductance G. The advantage of the present technique with respect to the CPM is related to the fact that it does not require the recombination time of the minority carrier to be constant. This constitutes the main difficulty of the CPM method, that have to be preferably performed with modulated or transient light to overcome this problem. The present technique exploits the spontaneous fluctuation of the photoconductance, and thus the measurements are carried out in quasiequilibrium conditions. The photocurrent noise spectroscopy thus turns out easier and more reliable, because it does not introduce out-of-equilibrium conditions in the samples to be analyzed. Furthermore, as already pointed out in the Introduction, another advantage of the noise spectroscopy technique lies in the possibility to obtain the results directly on the semiconductor device in its operative conditions, rather than in a suitable structure as for other high sensitive photoelectronic techniques (DLTS, photocapacitance) or for optical method.

APPENDIX: NOISE THEORY

As already mentioned, the current noise theory developed in Ref. 8 is based on a barrier-type photoconduction model. According to these models, the photoconducting behavior of a semiconductor device is strongly influenced by the presence of light sensitive potential barriers. The barrier mechanism assumed to be responsible of the photoconductivity in CdS and CdSe based devices has been quantitatively described in paper,[8] where a comparison with the experimental data has also been reported. A brief account of this process is given below. In the case of CdS and of CdSe based devices with indium electrodes, a potential barrier exists near the metal–semiconductor interface. The presence of this barrier prevents the electrical conduction in the dark. When photons with energy near to E_{gap} imping on the photoconductor, a positive static charge (deep donor centers or trapped holes according to the wavelength) is created. This positive charge lowers the potential barrier allowing the electron conduction. The fluctuation of the photoionization processes, creating the positive static charge, origins a fluctuation of the height of the barrier, that modulates the charge carrier injection into the photoconductor. The other noise sources are related respectively to the generation–recombination and trapping–detrapping processes in shallow centers. They give rise to the well-known $1/f$ and g–r noise component commonly found in the semiconductors.

Omitting the details of the analytical development of the theory, the final expression of the photoconductance noise power spectrum $\Phi_G(\omega)$ is reported below:

$$\Phi_G(\omega)=g\Delta g n_d \tau_g \frac{\langle |S(\omega)|^2\rangle}{\tau_g^2} + 2(\Delta g)^2 n_d \frac{|\langle S(\omega)\rangle|^2}{\tau_g^2} \sum_j \frac{a_j \tau_d^{(j)}}{1+\omega^2 \tau_d^{(j)^2}}. \quad \text{(A1)}$$

In this expression g is the contribution to the conductance G of the device of a single electron in the conduction band of the photoconductor; τ_g is the average free lifetime of this electron, in relation to the trapping processes in shallow centers; n_d is the average number of the ionized deep donor centers or trapped holes in the illumination condition determining the conductance G; Δg is the average increment of conductance related to the change of barrier height due to the excess ionization of a single deep donor center (or due to a trapped hole) during its lifetime τ_d and thus it is, by definition, the derivative of the conductance G with respect to n_d; $a^{(j)}$ is the relative weight of the ionized centers of type j, whose lifetime is $\tau_d^{(j)}$, in the same illumination conditions.

Finally the quantities $\langle |S(\omega)|^2\rangle$ and $|\langle S(\omega)\rangle|^2$ represent, respectively, the average of the square modulus and the square modulus of the average of the Fourier transform of a square conductance pulse of unitary amplitude and duration $\tau_g^{(i)}$. The distribution of the $\tau_g^{(i)}$, which are the individual electron lifetimes in the conduction band, is discussed in Ref. 8 and is commonly used in the literature to obtain the $1/f$ and the g–r noise components. $\langle |S(\omega)|\rangle^2/\tau_g^2$ is given by the sum of a $1/f$ and of a Lorentzian term, while $|\langle S(\omega)\rangle|^2/\tau_g^2$ is very nearly a constant, whose value is $(2\pi)^{-1}$. The plot of $\langle |S(\omega)|^2\rangle$ and $|\langle S(\omega)\rangle|^2$ vs frequency is reported in Ref. 8.

The first term of Eq. (A1) corresponds to the *intrinsic noise* generated by trapping–detrapping of free electrons in shallow centers within the photoconducting material, while the second term represents the *photoinduced noise* component produced by the barrier fluctuation. It has also been shown that the photoinduced component dominates the whole noise spectrum in the low frequency range and contains only quantities obtainable from experiments.

In order to analyze the photoelectronic properties of the deep energy levels, only the photoinduced noise component of the noise power spectrum has to be considered. Actually, the photoinduced noise component is strongly affected by the distribution of the deep energy levels. The intrinsic noise component depends very slightly on the photon energy of the incident light through the distribution of the electron lifetimes $\tau_g^{(i)}$, as explained in Ref. 8.

Taking into account that $|\langle S(\omega)\rangle|^2/\tau_g^2 \sim (2\pi)^{-1}$, the photoinduced noise component can be rewritten in the simplified form:

$$\Phi_G^{\text{ph}}(\omega) \cong \frac{1}{\pi}(\Delta g)^2 n_d \sum_j \frac{a_j \tau_d^{(j)}}{1+\omega^2 \tau_d^{(j)^2}}, \quad \text{(A2)}$$

where the terms a_j are defined by

$$a^{(j)} = \frac{n^{(j)}}{n_d}. \quad \text{(A3)}$$

In this equation, $n^{(j)}$ is the number of ionized centers of type (j), defined as follows:

$$n^{(j)} = \eta_\lambda^{(j)} n_{fa} \tau_d^{(j)}, \quad \text{(A4)}$$

where n_{fa} is the number of absorbed photons and $\eta_\lambda^{(j)}$ is the photoionization efficiency of the j centers.[24] The quantity n_d is the total number of ionized centers and has been defined as follows:

$$n_d = \eta_\lambda n_{fa} \tau_d, \quad \text{(A5)}$$

where η_λ and τ_d are the average value of the corresponding quantities in the Eq. (A4) all over the ionized center.

The photoinduced noise component thus results in

$$\Phi_G^{\text{ph}}(\omega) \cong \frac{1}{\pi}(\Delta g)^2 n_{fa} \sum_j \frac{\eta_\lambda^{(j)} \tau_d^{(j)^2}}{1+\omega^2 \tau_d^{(j)^2}}. \quad \text{(A6)}$$

Since the photoionization efficiency $\eta_\lambda^{(j)}$ is related to the photoionization cross-section $\sigma_{\text{ph}}^{(j)}$ by the following relationship:

$$\sigma_{\text{ph}}^{(j)} = n_\lambda^{(j)} \sigma_0, \quad \text{(A7)}$$

where σ_o is the total optical absorption cross section, Eq. (A6) becomes

$$\Phi_G^{\text{ph}}(\omega) \cong \frac{1}{\pi}(\Delta g)^2 \frac{n_{fa}}{\sigma_o} \sum_j \frac{\sigma_{\text{ph}}^{(j)} \tau_d^{(j)^2}}{1+\omega^2 \tau_d^{(j)^2}}. \quad \text{(A8)}$$

The quantities σ_o and n_{fa} in the previous equation are both dependent on the absorption coefficient α. The optical cross section is indeed related to the absorption coefficient α by the following relationship (see Ref. 7, Vol. 1, p. 323):

$$\sigma_o = \frac{\alpha}{N_v}, \quad \text{(A9)}$$

N_v being the concentration of the centers absorbing the light.

The quantity n_{fa} can be expressed in terms of the absorption coefficient α in the simple following form:

$$n_{fa} = n_f(1-r)(1-e^{-\alpha s}), \quad \text{(A10)}$$

where n_f is the total number of photons impinging on the photoconductor surface, r is the reflection coefficient and s is the sample thickness.

Taking into account Eqs. (A9) and (A10), and that the condition $\alpha s \ll 1$ is generally valid for thin films, the photoinduced noise component can be further simplified:

$$\Phi_G^{\text{ph}}(\omega) \cong \frac{1}{\pi}(\Delta g)^2 n_f (1-r) N_v s \sum_j \frac{\sigma_{\text{ph}}^{(j)} \tau_d^{(j)^2}}{1+\omega^2 \tau_d^{(j)^2}}, \quad \text{(A11)}$$

which turns out to be independent of the absorption coefficient α.

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