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Analysis of Defects in Metals, Semiconductors and Photoconducting Insulators through Current Noise Measurements

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Abstract. The use of current noise to characterize defects and impurity levels in several types of materials is described. After a brief review of the main results concerning defect kinetics in metals, the accent is given to the study of the effect of shallow and deep impurity levels on the current noise observed in semiconductors and photoconducting insulators.
Aim of the paper is to present a general overview of the information that can be obtained by means of current noise technique in different types of defect analysis in materials. As such only a few typical results and references are given for each topic. The paper should not be considered as a review of the extremely vast literature existing on this argument.

1. Introduction

Contrarily to the thermal voltage noise, which has a thermodynamic origin and depends only on temperature and on the real part of the device impedance, whatever its origin, the current noise, observed in a vast number of devices and materials when connected to a voltage generator, is an extremely useful source of informations about the process of electric transport. A classical case concerns the vacuum diode, where current noise analysis yields the electron charge and lifetime. Electrical conduction in solid state materials is a more complicate process, where different sources of noise can be envisaged. Conductance noise may arise from number or mobility fluctuations of the carriers. These fluctuations may be triggered by rather complex mechanisms, as trapping detrapping of carriers in different types of surface states or impurity levels in semiconductors, scattering from lattice vacancies or diffusing interstitials in metals, potential barrier fluctuations as in discontinuous metal films, cermets, barrier photoconductors and granular ceramic superconductors below the percolation threshold. In the following we shall give a brief description of these mechanisms of noise generation together with a few typical examples of application to actual physical systems. Recent results concerning the development of a theory of noise in insulating photoconductors and the use of this theory for studying deep levels in photoconducting insulators will be also given and commented. The purpose of the paper is to present an overview of the contribution that noise analysis can give to the study of defects in solid state materials. It should not be considered as a review paper of the extremely vast literature existing in this context.

2. Current noise generation processes

In this section we shall present an overview of the different mechanisms by which defects generate conductance fluctuations in metal films, semiconductors, photoconducting insulators and superconductors. Quantum 1/f noise, which, according to recent theories [1,2] has a rather fundamental origin and is unrelated to defects, will not be considered here. It is in general negligible when other noisy processes produced by defects are present.
In metals, current noise is extremely low and can be evidenced only in thin films, where current density can reach values of the order of $10^9 \frac{A}{cm^2}$ [3]. If the films are continuous, as it is assumed here, noise is produced by electron scattering from defects whose number spontaneously fluctuates in thermal equilibrium (lattice vacancies [4]) or during electrical transport (in the case of electromigration [5]). A third possibility is related to the diffusion and annihilation of defects during thermal annealing [6]. An interesting case is the noise produced by creation and annihilation of dislocations during plastic

deformation in thin metal films [7]. In this case the study of the noise intensity vs. temperature allowed to evidence that the increment with the temperature of the plasticity of metals is due to the enhancement of the creation-annihilation processes of dislocations.
In the case of lattice vacancies, the power spectrum of the noise has been used in [4] to get the vacancy lifetime in dependence of temperature together with the migration energy and the unit vacancy resistivity in aluminium films. As reported in that paper, the expected noise power spectrum produced by the vacancy creation and annihilation processes is lorentzian and is given by the expression:

$$\Phi_V(f) = \frac{4 \cdot 10^4}{C_A} \cdot \frac{l}{S} \cdot J_o^2 \cdot (\Delta\rho_V)^2 \cdot \frac{\eta_V \tau_o}{1 + 4\pi^2 f^2 \tau_o^2} \tag{1}$$

where J_o is the current density, l and S are respectively the length and the cross section area of the specimen, $\Delta\rho_V$ is the resistivity charge per unit vacancy concentration in atomic percent, C_A is the number of atoms per unit volume, η_V the vacancy concentration per atom and τ_o the vacancy average lifetime.
Noise spectra for aluminium are reported in Fig.1. They provide reliable values for the vacancy migration energy E_m and the unit vacancy resistivity $\Delta\rho_V$, as shown in [4]

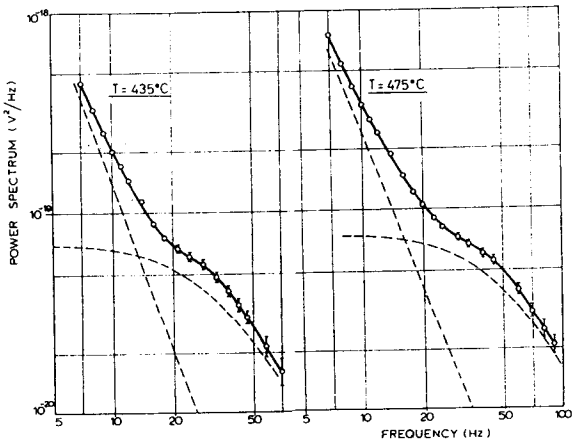

Fig.1 Power spectra of current noise in Al thin films taken at two different temperatures with a current density $J_o = 3.6 \cdot 10^9 \frac{A}{m^2}$. Dashed curves represent a best-fit decomposition of experimental data. Data fluctuations for a single spectrum point are represented by vertical bars. Points are averages over ten samples. (From Ref.[4])

A completely different mechanism rules the noise generation in ultrathin discontinuous metallic films, where electrical conduction is obtained by means of a tunneling or a thermoionic process of transport between metallic islands. In this case noise is generated by the spontaneous fluctuation of the potential barrier between islands, fluctuation which is produced by a thermodynamic equilibrium of the electrons trapped in surface states at the interface between metal and insulating substrate [8].Since barrier height noise strongly modulates the film conductance, this mechanism produces a rather strong current noise having a nearly $1/f$ power spectrum. At high temperatures, when the thermoionic process becomes predominant over tunneling in overcoming the barrier, a flatter spectrum of the noise is observed (see Fig.2).
A mechanism of noise generation similar to the one described above is also observed in cermets. For what concerns noise in semiconductors and photoconductors, it is treated in more details in the following section.

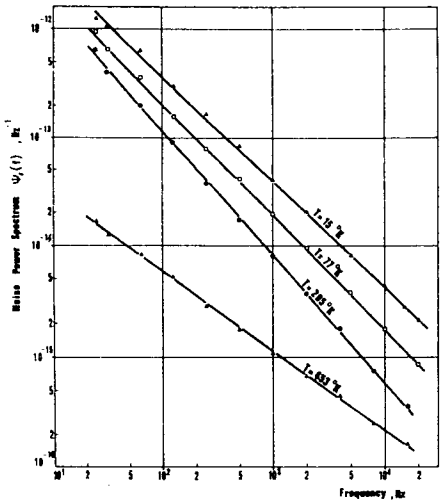

Fig.2 Experimental power spectra of relative conductance noise $\Phi_G(f)$ at different temperatures in Au film evaporated onto sapphire substrate. (From Ref.[8])

3. Noise spectroscopy in semiconductors

It is well established that many properties of semiconductor materials are drastically modified if impurity atoms are introduced in a perfect crystal lattice. The presence of a defect can indeed introduce one or more energy levels in the forbidden band-gap. Depending upon their energy position, the defects are divided in two main categories: shallow and deep defect levels. While the behaviour of a shallow impurity should be described in the ambit of a long range interaction, the deep impurities are expected to interact with the atomic system by a short range potential [9,10].
It is generally found that the deep energy levels act as trapping rather than recombination centers for minority carriers, thus increasing the electron-hole pair lifetime. The shallow impurity levels instead introduce an additional path to the charge carrier recombination processes thus reducing the carriers lifetime. One consequence of the increase of the electron-hole pair lifetime is the enhancement of the photoconductive gain (that is proportional to the ratio of the carrier lifetime to the transit time), that's why the deep energy levels are also referred to as photosensitizing centers [11].
On account of the strong influence that both the shallow and the deep impurity levels have on the charge carrier transport, a lot of effort has been made in order to attain a better insight into their physical properties.
Among other standard optical and electrical techniques, current noise analysis has been also used to this purpose, giving rise to the so called g-r noise spectroscopy, which is normally used to characterize energy levels, whose excitation is achieved through thermally activated processes. The fluctuations in the thermal transitions from and to shallow energy levels have been indeed related to the lorentzian and 1/f components of the current noise power spectrum of a semiconductor material. In particular, it is by now well-established that the lorentzian noise component is due to a two levels stochastic process, corresponding to the fluctuations in the processes of generation-recombination or trapping-detrapping of the charge carriers. In 1957 McWorther related the characteristics of the current noise power spectrum to the distribution of slow interface states in the n-channel of a Mosfet transistor. Since then, a lot of work has been done and at present the current noise spectroscopy is considered an effective technique to obtain information about the shallow impurity levels in the forbidden band-gap [12-14].
The fluctuations relative to the transitions involving deep impurity levels cannot be detected by the current noise spectroscopy as long as one works in thermal equilibrium condition. In order to characterize also the deep energy levels by current noise we have recently proposed a method based on a photocurrent noise theory [15].
Before reporting on this deep level noise spectroscopy, for the sake of completeness a very brief account of the link between the g-r noise power spectrum and some physical parameters of the defect will be given here following, without going into the details of the practical procedure of the noise spectroscopy

technique.
As already cited above, the mechanism for generation-recombination noise is related to the spontaneous fluctuations affecting the electronic transitions between discrete energy levels in the bands of a semiconductor material [16,17]. It has been shown, on the basis of different approaches, that the power spectrum density of such fluctuations is related to the number of free carriers N by the relationship:

$$\Phi_N(\omega) = 4 \cdot < \Delta N^2 > \cdot \frac{\tau}{1+\omega^2\tau^2} \tag{2}$$

where $< \Delta N^2 >$ corresponds to the variance of the variable N, that for a normal distribution is equal to N, and τ is a characteristic time depending on the transition involved in the fluctuating process.
In the case of a thermally activated process, the characteristic time τ is given by:

$$\tau = \tau_0 \exp\frac{E_a}{kT} \tag{3}$$

where τ_0 is a constant related to the capture cross-section σ_c of the trap by the relationship $\tau_0 = [v\sigma_c n]^{-1}$, v, and n being respectively the thermal velocity of the carriers and the number of the traps, E_a is the activation energy of the trap, k is the Boltzmann constant and T the temperature.
By means of the two previous relationships, the activation energy, the capture cross section and the number of the traps can be obtained by performing the current noise measurements at different temperatures.
Recently the g-r noise spectroscopy has been successfully employed in determining the parameters of defect levels in heterostructures or multi quantum well semiconductor devices, taking mainly advantage of the ability of the current noise spectroscopy to be performed under the actual device operation conditions. Other techniques as, for instance, the high sensitive capacitive DLTS technique, need a proper structure to work out. Typical results are reported in Fig.3, concerning the current noise related to DX centers in GaAs-$Al_xGa_{1-x}As$ heterostructures, from Ref.[18].

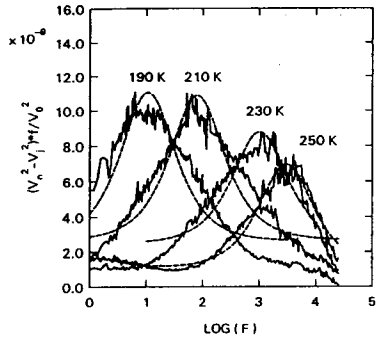

Fig.3. Reduced noise power spectra multiplied by frequency plotted as function of frequency for a sample with Al mole fraction x=0.37. The dashed lines are fits to the data. (From Ref.[18])

As already anticipated, current noise spectroscopy can be used to characterize deeper energy levels in the forbidden band gap, provided that it is carried out under stationary photoexcitation conditions. This method, that has been defined as constant photocurrent noise spectroscopy (to remind of the analogies with the constant photocurrent method proposed by Grimmeiss [19]) will be described in more details in the following.

Constant photocurrent noise spectroscopy

As briefly mentioned above, an increase of photosensitivity is commonly obtained by introducing in a material centers which capture minority carrier, but having a much smaller probability to capture majority carriers. If the density of free carriers in a material is greater than the density of impurity centers, the electron-hole pair lifetime will be equal to the free carrier lifetime. However if the density of deep impurity centers is increased, the minority carrier will be very likely trapped, thus the electron-hole pair lifetime increased. A further consequence of the minority carrier trapping will be the reduction of their mobility, which might result some orders of magnitude lower than that of the majority carriers.
Under photoexcitation, the generation of electron-hole pairs or the ionization of deep energy levels occur depending upon the value of the photon energy. Due to the presence of the deep impurities, the minority carriers will be trapped giving rise to a space charge, whose effect on the current fluctuation has been accounted for both experimentally and theoretically in papers [15,20,21]. Starting from the observation that a potential barrier can exist at the metal-insulator interface also if the contact is by definition ohmic, the amount of photogenerated trapped charge has been analytically related to the reduction of the height of such a potential barrier, thus accounting for the enhancement of the electrical conductance in presence of light. Since the number of photogenerated charges fluctuates spontaneously, the height of the barrier will fluctuate accordingly. The effect of the electrode barrier fluctuation will thus result in a modulation of the number of free carriers injected into the photoconductor. In paper [15], the modulation noise component due to the fluctuation of the potential barrier has been properly introduced in the total photocurrent noise power spectrum, in addition to the g-r and 1/f noise components. Here following the total photoconductance noise power spectrum is reported:

$$\Phi_G(\omega) = g \cdot \Delta g \cdot n_d \cdot \tau_g \cdot \frac{<|S(\omega)|^2>}{\tau_g^2} + 2 \cdot (\Delta g)^2 \cdot n_d \cdot \frac{|<S(\omega)>|^2}{\tau_g^2} \cdot \Sigma_j \frac{a_j \tau_d^{(j)}}{1+\omega^2 \tau_d^{(j)2}} \cdot \tag{4}$$

where 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. The quantity $a^{(j)}$ is given by:

$$a^{(j)} = \frac{n^{(j)}}{n_d} \quad . \tag{5}$$

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

$$n^{(j)} = \eta_\lambda^{(j)} \cdot n_{fa} \cdot \tau_d^{(j)} \tag{6}$$

n_{fa} is the number of absorbed photons and $\eta_\lambda^{(j)}$ is the photoionization efficiency of the j centers.

Finally the quantities $<|S(\omega)|^2>$ and $|<S(\omega)>|^2$ 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 [15] and is commonly used in the literature to obtain the *1/f* and the *g-r* noise components. $<|S(\omega)|>^2/\tau_g^2$ is given by the sum of a 1/f and of a lorentzian term, while $|<S(\omega)>|^2/\tau_g^2$ is very nearly a constant, whose value is $(2\pi)^{-1}$. The plot of $<|S(\omega)|^2>$ and

$|< S(\omega) >|^2$ vs. frequency is also reported in [15].
The first term of Eq.4 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 can been shown, both theoretically and experimentally, that the photoinduced component dominates the whole noise spectrum in the low frequency range and contains only quantities obtainable from experiments.
A discussion of the theory and a comparison with the experimental results can be found in [15,20,21], we shall now limit the following discussion to the photoinduced noise component appearing in the Eq.4, in order to explain the way to characterize the deep energy levels in photoconducting insulators by photocurrent noise measurements. The technical details of the way to perform the photocurrent noise spectroscopy will not be described, but they can be found in Ref. [22].
On the basis of the previous discussion, the quantity $|< S(\omega) >|^2 / \tau_g^2$ can be set equal to $(2\pi)^{-1}$ without appreciable error, moreover taking into account the definition (6), the power spectrum of the photoinduced noise component can be written as:

$$\Phi_G^{ph}(\omega) = \frac{1}{\pi} \cdot (\Delta g)^2 \cdot n_{fa} \cdot \Sigma_j \frac{\eta_\lambda^{(j)} \cdot \tau_d^{(j)2}}{1 + \omega^2 \tau_d^{(j)2}} \ , \tag{7}$$

If the condition $\omega^2 \tau_d^{(j)2} \gg 1$ holds and since $\Sigma_j \eta_\lambda^{(j)}$ is equal to the average photoionization efficiency η_λ, that is related to the average photoionization cross-section σ_{ph} by the following relationship:

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

where σ_o is the average optical cross-section of the centers, the spectrum of the photoionization cross-section can be rewritten as follows:

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

In the previous equation, the optical cross-section σ_o varies linearly with the absorption coefficient α and, for thin films, n_{fa} is proportional to αn_f where n_f is the total number of impinging photons. The quantity Δg is independent of the photon energy at constant photoconductance G, as reported in [15,20]. Therefore the wavelength dependence of $\sigma_{ph}(h\nu)$ will be determined only by that of the quantities $\Phi_G^{ph}(h\nu)$ and $n_f(h\nu)$, which can be obtained experimentally.
The photoionization cross-section $\sigma_{ph}(h\nu)$ depends on the position of the level in the forbidden band gap. The analytical relationship giving the energy dependence of $\sigma_{ph}(h\nu)$ for a given value of the energy position of the defect level E_d was first obtained by G.Lucovsky [23]. In its derivation, he took into account that, while for shallow defect levels the charge carrier is bent to the atomic system by an hydrogenic potential, for a deep energy level the ion core potential predominates giving rise to a short range interaction. By assuming a delta function for the dependence of such potential on the distance r, the following relationship was obtained:

$$\sigma_{ph}(h\nu) = const \cdot \left[\frac{4(h\nu - E_d)E_d}{(h\nu)^2} \right]^{\frac{3}{2}} \tag{10}$$

From the previous relationship, it can be deduced that the photoionization cross-section presents a threshold at a photon energy equal to E_d and rises to a maximum at a photon energy value of $2E_d$. Other more complicate models have been later proposed to derive the σ_{ph}, but the model of Lucovsky is still now the most effective in reproducing the experimental results.
As a conclusion the number of the photoionized centers and their position in the forbidden band gap can be obtained using the relationship 9 and 10, if the photocurrent noise measurements are performed at different values of the photon energy E_d and at constant value of the average photoconductance.
In Fig.4 typical results concerning the photoionization cross section for three commercial CdS_xSe_{1-x} samples, having different stoichiometry, are reported. Broken lines correspond to the theoretical photoionization cross-sections obtained according to the Eq.10, the positions of the deep level E_d used as fitting parameter are respectively equal to $1.7eV$, $1.6eV$ and$1.45eV$ with respect to the bottom of the conduction band (from Ref.[22]).

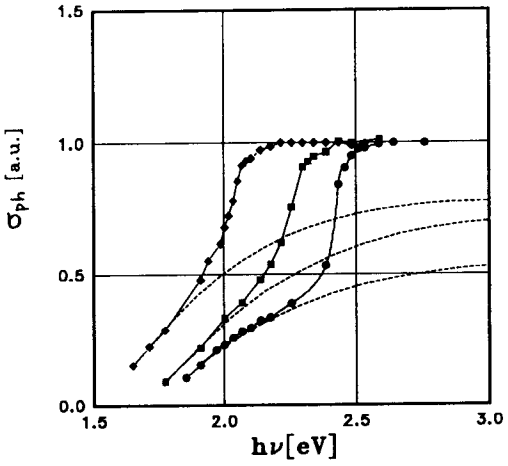

Fig.4 Relative photoionization cross-sections versus photon energy in the region close to the valence band-edge for three CdS_xSe_{1-x} samples, having different composition obtained from noise measurements using Eq.10. Broken lines correspond to the photoionization cross-section obtained according to the Lucovsky model [23]. (From Ref.[22])

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With this contribution we would like to remember Prof. F. Demichelis, passed away on last December, who collaborated in this field [24,25].

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