Fractal properties of the percolation conductivity of polycrystalline PbS films

O. A. Gudaev, V. K. Malinovskiĭ, and É. É. Paul'
Institute of Automation and Electrometry, Siberian Branch of the Academy of Sciences of the USSR

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Fractal properties of a percolation cluster may be manifested in a nonlinear relationship between the photoconductivity and the lifetime of photoexcited carriers. An effect has been observed experimentally in polycrystalline PbS films.

Percolation arguments are effective in analyzing charge transport in materials whose properties exhibit a pronounced spatial variation. It can be seen from an algorithm for the construction of percolation clusters that the latter should exhibit a fractal structure. One is led to ask just what observable consequences might result from considering the fractal properties of the percolation clusters which determine the charge transport in materials with highly inhomogeneous properties.

Let us consider the charge transport in a material for which the condition $l \sim a$ holds, where l is the mean free path, and a is the atomic spacing [$\mu \sim 1$ cm^2/(V·s)]. We will take the approach proposed by Cohen.[1] Cohen treated the motion as a diffusion or Brownian motion. In this case there is no localization, but the motion cannot be regarded as free.

Distinctive features of diffusion processes in the case of a fractal cluster were studied in Ref. 2. It was shown that the diffusion coefficient in a fractal is in general a function of the distance:

$$Dg(r) \sim r^{-\theta}, \quad \theta = 2(D/d - 1).$$

Here D is the fractal or Hausdorff dimension, and d is the spectral dimension. In the case of a random walk over a fractal, the distance r which the particle moves in a time t has a t dependence $\langle r^2 \rangle \sim t^{d/D}$. Let us examine the photoconductivity of a semiconductor in the case in which the transport of nonequilibrium carriers occurs along a percolation cluster having a fractal structure. For a nonequilibrium carrier, the time of the random walk over the fractal is equal to the lifetime of the carrier. In general, we should incorporate the statistics of the distribution of carrier lifetimes, but in a first approximation we will assume that the lifetime of all the nonequilibrium carriers is equal to the mean value τ. We then find the following expression for the diffusion coefficient:

$$Dg(r) \sim r^{-\theta} \sim r^{-2(D/d-1)} \sim \tau^{(1-d/D)}.$$

To estimate the mobility, we use the Einstein relation $\mu = eDg/(kT)$. The magnitude of the photoconductivity is determined by the product of the mobility and the concen-

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tration of the photoexcited carriers, $\sigma_p \sim \mu \Delta p$, where $\Delta p \sim \tau$. We finally find the following expression for the photoconductivity, which relates the photoconductivity to the lifetime of the nonequilibrium carriers:

$$\sigma_p \sim \tau^p, \quad p = (2 - d/D).$$

For percolation systems the parameter d has the universal value[2] $d = 4/3$. To estimate the fractal dimension, we need more information. We would thus expect that if the fractal properties of a percolation cluster were manifested during the transport of charge over it, the photoconductivity would be a nonlinear function of the lifetime of the photoexcited carriers: $\sigma_p \sim \tau^p$, where $p \geqslant 1$.

To test the conclusions above, one needs a photosensitive material in which the charge transport is determined by a motion of carriers along a percolation cluster. It

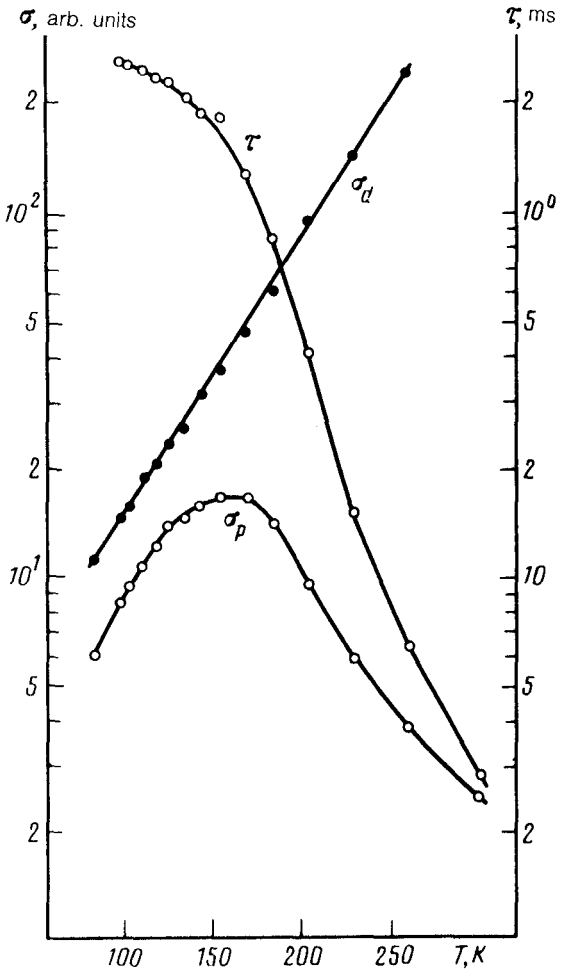

FIG. 1. Temperature dependence of the photoconductivity σ_p, the dark conductivity σ_d, and the lifetime of nonequilibrium carriers, τ.

was shown previously[3,4] that polycrystalline PbS films have such properties. The lifetime of nonequilibrium carriers in these films and the magnitude of the photoconductivity depend strongly on the sample temperature (Fig. 1). By measuring the values of σ_p and τ of the films at various temperatures and at intensities I, one can test the relationship between these parameters over a fairly wide range. As was shown previously,[5] the application of light to chemically deposited PbS films results in a change in the concentration of the majority carriers. The magnitude of the conductivity is determined by the following product of parameters: $\sigma_p = e\alpha I\mu(T,\tau)\tau$, where e is the charge of a carrier, I is the light intensity, and α is the absorption coefficient. So that we could ignore the temperature dependence of the absorption coefficient, we carried out the measurements at energies of the incident photons greater than the band gap of PbS (950 nm), i.e., in a region in which the temperature dependence of the absorption due to the shift of the fundamental absorption edge could be ignored. To eliminate the temperature dependence of the mobility, we normalized the value of σ_p at each given temperature to the dark conductivity σ_d. The quantity $\sigma_p^* = \sigma_p/(I\sigma_d)$ depends on only τ in this case.

The lifetime of the nonequilibrium carriers was determined from the decay of the photocurrent during pulsed excitation. Figure 2 shows σ_p^* as a function of τ for

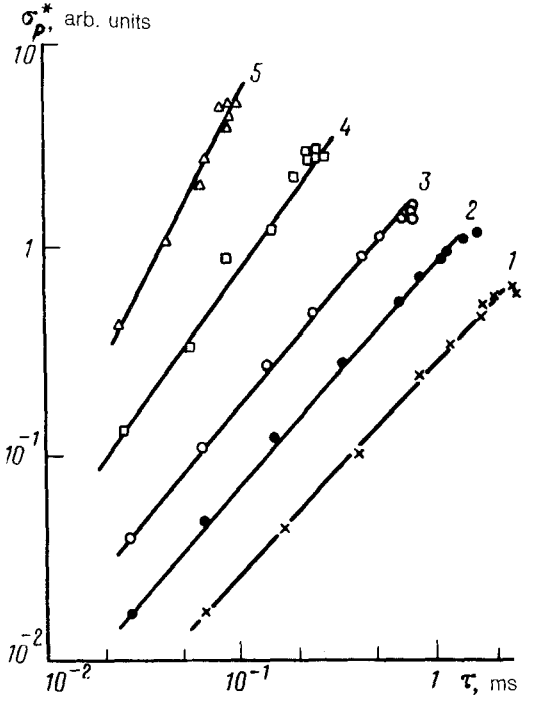

FIG. 2. Photoconductivity as a function of the lifetime of the nonequilibrium carriers for various light intensity levels: *1*—$1.4\times10^{-2}I_0$; *2*—$4.0\times10^{-2}I_0$; *3*—$9.2\times10^{-2}I_0$; *4*—$3.5\times10^{-1}I_0$; 5—I_0.

several intensities of the exciting light. It turns out that at comparatively low intensities the τ dependence of σ_p^* is linear ($p = 1$). This linearity corresponds to the usual picture in the theory of photoconductivity in semiconductors (curves *1*, *2*, and *3*, in Fig. 2). At higher intensities (curves *4* and *5* in Fig. 2); however, we found $p = 1.3$ and $p = 1.6$, respectively. These results indicate that the fractal properties of the percolation cluster are manifested in the conductivity under certain conditions (in the case at hand, at a sufficiently high excitation level).

Because of the particular features of the growth of polycrystalline PbS films during chemical deposition, the distribution of the more or less photosensitive regions (e.g., oxides) over the volume of the sample is randomly inhomogeneous. An increase in the light intensity apparently increases the difference between the resistances of neighboring regions, giving the charge transport a clearly expressed percolation nature.

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