Possible new type of photoconductivity in disordered semiconductors with random fields

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A new type of photoconductivity is indicated, which can be observed in disordered semiconductors at low temperatures. The effect is connected with the finite (independent of the temperature T as $T \to 0$) widths of the fluctuation levels situated above the Fermi level.

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It is known that in random fields of rather general type the spectrum of the discrete (fluctuation) levels is everywhere dense. This leads, in particular, to the fact that even at the temperature $T=0$ all the discrete levels situated above the Fermi level F (see Fig. 1; we refer to electrons for the sake of argument) turn out to be nonstationary. Indeed, owing to the spontaneous emission of phonons and/or photons etc. (as well as magnons in the case of magnetic materials), transitions are possible from these levels to vacant lower-lying states. The density of state $\rho(E)$ at energies $E>F$ is no longer given in this case (prior to averaging over the random fields) by the sum of δ functions corresponding to the strictly discrete levels, but becomes "smeared out." Thus, in the case of weak interaction between the carriers and the phonons etc. we have (in the first non-vanishing approximation)

$$\rho(E) = \frac{2}{\Omega}\sum_{\lambda} \frac{|\,\mathrm{Im}\, M_r(\lambda, E)\,|}{[E - W_\lambda - \mathrm{Re} M_r(\lambda, E)]^2 + [\mathrm{Im} M_r(\lambda, E)]^2} \tag{1}$$

$$(\hbar = 1)$$

Here Ω is the volume of the system, λ is the aggregate of the quantum numbers describing the unperturbed states of the electron (with wave functions ψ_λ), W_λ

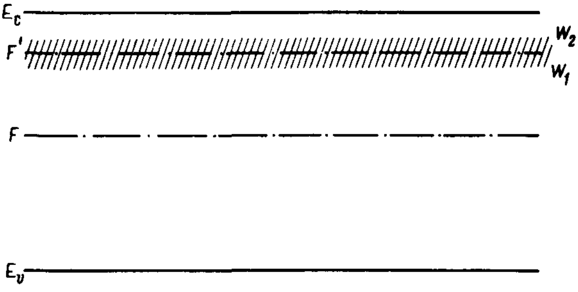

FIG. 1.

are the corresponding energies, and $M_r(\lambda, E)$ are the diagonal matrix elements of the mass operator and are set in correspondence with the one-fermion retarded Green's function. The function M_r can be easily calculated formally by standard methods. The result, however, depends on the form of the functions ψ_λ, on the type of phonons, etc., as well as on the statistical characteristics of the considered level system. For our purposes it suffices to know that at $E > F$ we have $|\mathrm{Im} M_r(\lambda, E)| \equiv \gamma(\lambda, E) \neq 0$ even at $T=0$ (with account taken of the continuous spectrum of the phonons), i.e., the density of states in this region is different from zero and is continuous. According to the general theorem on the correlation between the density of states and the static electric conductivity[1], this means that the electrons landing in the indicated energy region give a finite contribution to the static electron conductivity at $T=0$. In this case this is due to two mechanisms: first, the "smearing" of the levels makes classical hopping between the localization centers no longer mandatory; second, as a result of the perturbation of the wave function of the electron there appears an admixture of states with indices λ corresponding to the continuous spectrum1). Of course, under equilibrium conditions at $T=0$ there will be no electrons at all in the considered energy region. The electrons appear there, however, when the sample is exposed to light of frequency $\omega < (E_c - F)/h$. For a tentative estimate of the mobility of these electrons we make two assumptions: 1) let the illumination cause the electrons to land mainly in the layer shown shaded in Fig. I (the upper limit W_2 of this layer can also coincide with E_c, and the lower limit W, can be smeared); 2) let the transitions between the states of the layer be much more frequent than their departure from the layer to deeper levels. 2) The electrons in the layer can then be regarded as an autonomous system with its own Fermi level F' situated (at $T=0$) as shown in Fig. 1.

The sought mobility is $\mu = \mu_1 + \mu_2 + \mu_3$, where μ_1 and μ_2 describe, respectively, the contributions from the first and second mechanisms, and μ_3 describes the contribution from their interference.

We denote by $\mu_h \sim \zeta(T)$ the usual hopping mobility, which the electrons would possess in a given layer at a temperature T; (T) is the usual factor, equal, for example, to $\exp[-(T_0/T)^{1/4}]$ in the case of Mott's law. Then, neglecting the statistical correlation between the levels, we have

$$\mu_1 \sim \mu_h \zeta^{-1}.$$

The contributions μ_3 and μ_2 are proportional respectively to $\hbar\gamma/(E_c - F')$ and $(\hbar\gamma/(E_c - F'))^2$, where $\gamma = \gamma(W, F')$, and W is the characteristic energy in the continuous spectrum. In order of magnitude, γ is close to the reciprocal time of the recombination transition from the conduction band to the F' level. These are small quantities at not too small differences $E_c - F'$.

The phonon contribution to the line width can become comparable with the phonon contribution at a sufficiently large intensity of the light. Thus, for simplicity, the spectral density of the (non-thermal) radiation incident on the sample be uniformly distributed in the interval $W_2 - F \geq \hbar\omega \geq W_1 - F$.

Then the photon contribution becomes comparable with the phonon contribution at

$$\frac{I\pi^2 c^2}{\omega^3 (W_2 - W_1)} \sim \frac{g^2 \hbar c}{c^2}\ .$$

Here I is the intensity of the light, g is the dimensionless coupling constant of the electrons and phonons, and c is the speed of light in the medium. This yields $I = 3\times 10^2$ W/cm^2 at $g = 1$, $W_2 - W_1 = 10^{-2}$ eV, $W_1 - F = 10^{-1}$ eV, and if the refractive index of the medium is equal to 4. Under these conditions one should obviously observe superlinear photoconductivity: the light not only transfers the electrons to the corresponding levels, but also gives rise to the width of the latter as a result of stimulated emission.

1) The role of the nonstationarity and of the associated partial localization in the electric conductivity of one-dimensional disordered systems was investigated in[2], thoughts over which have stimulated the present paper. The idea of the role of the zero-point oscillations in the electric conductivity of a semiconductor at $T = 0$ has been advanced long ago.[3] The corresponding calculation in[3], however, seems to me at present to be unconvincing.

2) The first assumption is physically immaterial, so long as the second is satisfied: under these conditions the mobility should not depend on the method of illumination. The second assumption is evidently satisfied if $W_2 - W_1 \ll W_2 - F$; the exact meaning of the symbol "$\ll$" depends here on the statistical properties of the level system.

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