Hopping conductivity of disordered semiconductors in strong fields

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The hopping conductivity of disordered semiconductors in strong fields is calculated. It is shown that the exponential growth of the conductivity with increasing field is followed by a linear section due to hopping between the nearest neighbors with and without emission of phonons.

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The hopping motion of an electron over the localization centers in disordered structures in the presence of a strong electric field at low temperatures is effected by nonactivation hops of length $R(F)$, determined by the field $F=eE$, in accordance with the result of Shklovskii[1]

$$\Delta E = \epsilon_0 \left(\frac{R_0}{R}\right)^3 - FR = 0. \tag{1}$$

The first term here is the Mott difference between the levels of centers separated by a distance R,[2] while the second term is the energy in a constant field for hops along the field. ϵ_0 is the average difference between the levels of the nearest-neighbor centers, and R_0 is the average distance between centers.

We consider the behavior of hopping conductivity in fields stronger than in[1]. With increasing field strength F, the length $R(F)$ decreases and becomes equal R_0 at $F=F_0$. Further decrease is impossible because R_0 is the average distance to the nearest center. F_0 is determined by the condition

$$F_0 R_0 = \epsilon_0 . \tag{2}$$

With further increase of the field strength F, the energy FR_0 already exceeds the level difference ϵ_0. Hops to a neighboring center are possible only with emission of a phonon or with rotation of the direction of the hop towards the direction of the field.

The contribution σ_0 to the conductivity due to hops without participation of phonons, at an angle to the field direction, is given by the expression

$$\sigma = (e^2\hbar/9m)N_0(\hbar^2/Tma^2)(R_0/a)^4 e^{-2R_0/a} \int_0^\pi a\theta \sin\theta \; \delta(\epsilon_0 - FR_0\cos\theta). \tag{3}$$

Here $e^2R_0^2\exp(-2R_0/a)$ is the square of the matrix element of the dipole moment, T is the temperature in energy units, $4\pi R_0^2$ is the surface area of a sphere of radius R_0, and the δ function expresses the energy conservation law in hops of this type. The effective carrier density N_0 is equal to the product of the level density at the Fermi level N_F by the width of the energy layer FR_0 from which the electrons are detached.

We thus obtain for the contribution σ_0 of the phononless hops an expression that is independent of the field strength

$$\sigma_0 = (e^2\hbar/9m)\, N_F\, (\hbar^2/Tma^2)(R_0/a)^4 e^{-2R_0/a}. \tag{4}$$

To calculate the contribution of hops with phonon emission, it is necessary to obtain the imaginary part of the two-particle Green's function with account taken of the interaction of the electrons with the phonon field. The result of this calculation reduces to a smearing of the δ function in (3) by an amount γ proportional to the phonon emission probability. The contribution σ_1 made to the conductivity by hops of this type is

$$\sigma_1 = \sigma_0\, (N_1/N_F) \int_0^{\theta_0} (d\theta/\pi)\, \sin\theta \frac{\gamma(\theta)}{\gamma^2(\theta) + (\epsilon_0 - FR_0 \cos\theta)^2}\, ; \quad \cos\theta_0 = F_0/F\, . \tag{5}$$

The phonon width of the two-particle Green's function is equal to

$$\gamma = \gamma_0 [\,(F\cos\theta/F_0) - 1]^5; \qquad \gamma_0 = (E_1^2/24\pi)\,(R_0^2/\rho s^2)\,(\epsilon_0/\hbar s)^5. \tag{6}$$

Here E_1 is the deformation potential, s is the speed of sound, and ρ is the density of the material.

The effective carrier number N_1 is the product of the concentrations of electrons N_0 and holes N_h $(=N_0)$ participating in these hops, divided by the number of centers N_i over which the hops are made. N_i is the level density N_F multiplied by the energy width Δ. Thus,

$$N_1 = N_F \frac{(FR_0)^2}{\Delta}.$$

Calculating the integral, we obtain the following expression for the conductivity with allowance for both mechanisms of the motion

$$\sigma = \sigma_0 [\,1 + (FR_0/4\pi\Delta)\,\mathrm{arc\ tg}\,(\gamma_0/\epsilon_0)\,(F/F_0 - 1)^4\,]. \tag{7}$$

The formula (7) for the conductivity, in fields stronger than $3F_0$, becomes

$$\sigma = \sigma_0 \left(1 + b\frac{F}{F_0}\right);$$

where the constant b depends on the scatter of the level ϵ_0.

An exact formulation of the problem of the resistance of a three-dimensional network consisting of wires of length R and with resistance $\exp(2R/a)$ yielded[3,4] for R_0 the concentration dependence $R_0 = (0.87 \pm 0.01)N^{-1/3}$. The region of applicability of formula (7) is $F_0 < F < F_h$ (the localized levels break down at fields on the order of F_h).

The results of high-frequency measurements of the absorption in InSb[5] show that the damping γ has a power-law dependence on the phonon energy, with an exponent close to five in accordance with formula (6). According to the same measurements, ϵ_0 is of the order of 0.1—0.3 meV and $R_0 = 1300$ Å. Estimating the field F_0, we obtain $F_0 \sim 10$ V/cm, of the same order as the fields in which the conductivity slows down according to the data of[6]. There are no detailed measurements in the region of stronger fields. We note that the fields F_0 are relatively weak for narrow-band materials.

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