

Hall effect and electron mobility in inhomogeneous semiconductors

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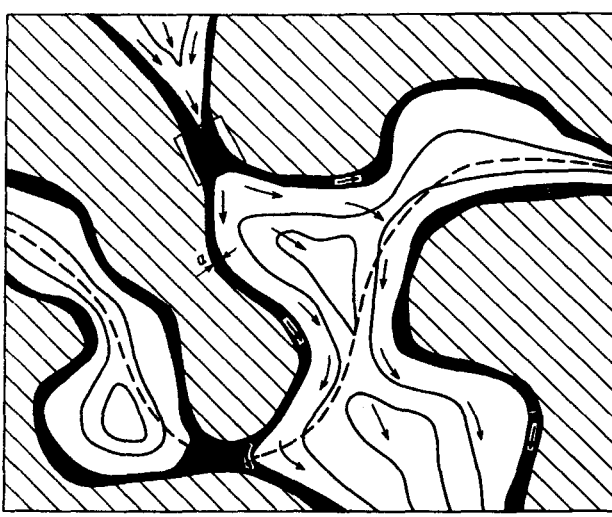
(Submitted April 27, 1973)

ZhETF Pis. Red. 20, 14-16 (July 5, 1974)

The features of the Hall effect in inhomogeneous semiconductors are investigated on the basis of the concepts of "percolation theory." The performed analysis explains the anomalous temperature dependence of the Hall mobility, which is frequently observed in experiments.

In experimental studies of the galvanomagnetic properties of semiconductors one observes in many cases an anomalous temperature dependence of the Hall mobility μ_H , whereby this mobility decreases abruptly when the temperature T is lowered. In the region $T \lesssim 100-200^\circ\text{K}$ the mobility is given by $\mu_H \sim T^\alpha$, where the exponent α

differs from experiment to experiment and can range from 2 to 10. These anomalies of $\mu_H(T)$ are observed either in compensated semiconductors with definite types of impurities^[1-4] or in irradiated samples^[5-7]; in all the cited papers, the anomalies are attributed to inhomogeneities in the samples.



Energy relief of inhomogeneous semiconductor. Phase 1 is shown black and phase 3 is shown shaded. The equal-energy surfaces are mapped in phase 2. The arrows indicate the current direction.

This statement, however, has not been proved, since calculations for the simplest inhomogeneity models (see, e.g., ^[8-10]) do not lead to an anomalous $\mu_H(T)$ dependence, and there is still no physical picture of the phenomenon for the more general case.

This paper is an attempt to present qualitatively this picture and to explain the temperature dependence of μ_H in a sample with a random potential relief $V(r)$. We shall describe this relief by means of the "percolation energy" ϵ_p ^[11] and assume that the level of the chemical potential ζ lies lower than ϵ_p , with $\epsilon_p - \zeta \ll T$ [this is possible if the amplitude of $V(r)$ is large or in the case of strong compensation]. We subdivide the semiconductor arbitrarily into three phases: 1 - three-dimensional lattice of regions with electron potential energy in a band of width $\sim T$ near ϵ_p ; 2 - individual unconnected regions with lower energy; 3 - regions with higher energy (see the figure). When the current flows through the sample, its resistance is determined by the saddle points of $V(r)$ with energy $\sim \epsilon_p$, where the entire current I flows through a section of phase 1 with linear dimensions $\sim \sqrt{(T/V_0)}L$ [V_0 and L are the characteristic amplitude and period of the potential $V(r)$]. The resistance of this section (it is bounded by the square in the figure), and hence of the entire sample, is

$$R_0 \sim \frac{1}{e n_0 \mu L} \sqrt{V_0/T} \exp\left(\frac{\epsilon_p - \zeta}{T}\right) \quad (1)$$

(n_0 is the average carrier density and μ is the mobility in the absence of a potential relief). In all the remaining places, the current is distributed among the phases 1 and 2. It can be shown that the fraction $\Delta = I_1/I$ of the current flowing through phase 1 namely is small in power-law fashion relative to α/L , where $\alpha \sim (L/V_0)T$ is the characteristic widths of the regions of phase 1 far from the saddle points.

A weak magnetic field H applied to the system does not change the current density distribution $j(r)$ in first-order approximation, and the Hall emf in the sample

can be calculated from the formula

$$U_H = (\mu/c) \int \rho(r) [j(r) \times H] dl, \quad (2)$$

where $\rho(r)$ is the local value of the resistivity. The integration path joins opposite faces of the sample, from which U_H is picked off, and since the electric field is potential, the path can be chosen arbitrarily. We draw it along the percolation path in the Hall direction (dashed curve in the figure). It crosses the current-carrying sections of both phase 1 and phase 2 far from all the saddle points, which determine the sample resistance (the probability of two percolation paths crossing in a saddle point is extremely small). Since the current-density ratio in the phases is a power-law function of the temperature, while the ratio of the resistances (of the concentrations) is an exponential function, it follows that the main contribution to the integral (2) is made at $\epsilon_p - \zeta \gg T$ by the sections of phase 1.

Thus, in inhomogeneous semiconductors the Hall emf is produced practically entirely by that small current fraction $I\Delta(T)$ which flows around sections of phase 2 in phase 1. Taking this into account, we obtain from (2)

$$U_H \sim \frac{I H \Delta(T)}{e c n_0 L} \exp\left(\frac{\epsilon_p - \zeta}{T}\right), \quad (3)$$

so that the Hall mobility is

$$\mu_H \sim \mu \Delta(T) \sqrt{T/V_0}. \quad (4)$$

Since $\Delta < 1$ and $T < V_0$, the presence of a potential relief lowers the Hall mobility. In addition μ_H acquires a strong temperature dependence of precisely the character observed in the experiments, since Δ decreases when α decreases (and the latter, in turn, is proportional to T).

The exact form of the $\Delta(T)$ dependence is determined by the shapes of the regions of phase 2. If we assume them to be spheres, then the corresponding Laplace equation, which determines the current distribution, can be solved exactly and yields $\Delta \sim (T/V_0)^2$. If the carriers are scattered by ionized impurities in the absence of inhomogeneities, then $\mu_H \sim T^4$. For a more realistic non-convex shape of the regions, the $\mu_H(T)$ dependence is apparently even steeper. In particular, for cruciform regions of phase 2, rough estimates lead to a relation close to $\Delta \sim T^3$.

The author thanks B.I. Shklovskii and A.L. Efros for discussions.

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