On the conception of minimal metal conductivity in metal-insulator phase transitions

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Abstract. The agreement between the conception of minimal metal conductivity and experiment has been shown. It is found, that the smoothness of metal-insulator transition observed in crystal semiconductors is caused either by disorder and then we need the percolation theory to be used for data interpreting at T=0 K, or by small value of critical concentration of carriers. The critical concentration depends on the compensation level, classical and “natural” widening of defect level or correlated distribution of impurities. According to experimental data, the characteristic parameters of transition in n-CdSnAs2, p-CdSnAs2<Cu> and p-Ge has been obtained by the extrapolation to T=0 K.

1. Introduction

While considering a metal-insulator phase transitions in Mott and Anderson crystal semiconductors, an interesting theoretical problem concerning to the type of phase transitions and to the electronic conductivity behaviour in the vicinity of transition point is appearing. Still in his early works, analyzing a nature of the metal conductivity, Mott had suggested that the metal-insulator transition is not continuous [1, 2]. His conclusion was based on Ioffe’s and Regel’s statement that a free pass length can not be less than electron wave length [3]. However, until today many aspects remain vaguely enough about the nature of metal-insulator phase transitions.

2. Results and discussion

2.1. In [4], the minimal metal conductivities in the conduction band (where the Anderson transition takes a place) and in the deep acceptor band (the Mott transition) have been obtained from pressure dependences of electric conductivity $\sigma(P)$ and Hall coefficient $R_{H}(P)$ in heavily compensated quasi-gapless semiconductor $p$-CdSnAs2<Cu>, extrapolating the temperature interval 2÷5 K to $T=0$ K [5]. However in some cases the idea of minimal metal conductivity has not been confirmed [6, 7].

In [8], the smoothness of the metal-insulator phase transition has been thought as a consequence of large scale fluctuations of the impurity distribution. A transition to the conducting state in bulk samples is defined as a coherence of metalized regions, i.e. when atoms of the metalized regions of a sample, form an infinite cluster penetrating the whole sample. It can be said, that the metal-insulator transition is determined by a solution of a continual problem of the percolation theory, according to which the conductivity as a function of governing parameter grows from zero value continuously. The transition occurs in weakly doped semiconductors with chaotically distributed impurities and in
heavily doped compensated semiconductors, while we have studied a transition peculiarities analysing data for the temperature dependence of electric conductivity $\sigma(T)$ at $T<4$ K and $T\to0$K. It should be noted, that the role of disorder in the whole physics of the phenomenon rises with the temperature decrease [9] and near $T=0$ K may become determinative.

Sometimes the smoothness of the transition may be caused by a smallness of electron critical concentration (as an instance the n-type of semiconductor is considered): $n_c=N_i(1-K_c)$, where $N_i$ is a concentration of primary impurity, $K_c$ is a critical coefficient of compensation. As it has been shown in [10], the coefficient $K_c$ is close to 1 in heavily doped semiconductors as well as in weakly doped semiconductors containing hydrogen-like impurities with $N_i$ near to $N_{\text{hd}}$. ($N_{\text{hd}}$ is a critical impurity concentration when impurity and intrinsic bands unite).

**Figure 1.** Dependence of conductivity from temperature in weakly doped and compensated GaAs crystals of n-type with shallow hydrogen-like donors. Hopes on the nearest centers [14-15]. Sample numbers correspond to concentrations: 1- $4.5\times10^{17}$; 2- $1.7\times10^{17}$; 3- $3\times10^{16}$; 4- $1.3\times10^{16}$; 5- $1.3\times10^{16}$; 6- $7.1\times10^{15}$; 7- $6.4\times10^{15}$; 8- $3.5\times10^{15}$ cm$^{-3}$ [14-15].

**Figure 2.** Dependence of resistivity from temperature in weakly doped and compensated GaAs crystals of n-type with shallow hydrogen-like donors [16]. Hopes with variable length, Efros-Shklovsky law.

Besides, as a result of smallness of the ionization energy for shallow donors in narrowband weakly doped n-InSb and n-InAs, the impurity band originated from fluctuating classical field is overlapped with the intrinsic band at $N_d<N_M$ ($N_M\alpha_B^2\varphi_0\approx0.02$, $\alpha_B$ is an effective Bohr radius). The impurity states closest to the edge of intrinsic band, merge with the states of intrinsic band continuum and become hybridized (so called “natural” broadening of the level) [10-13]. Appeared free extra carriers screen the potential of the impure center. The ionization energy of localized levels decreases. With increase in $N_d$, a process assumes an avalanche-like character, giving the fast transition from weakly doped state to the heavily doped state when the impurity band merge with the conduction band completely. It should be noted that “metal” conductivity in n-type narrowband semiconductors is revealed when impurity concentrations $N_d<N_M$. For instance, in n-InSb $N_d$ exceed $N_M$ by about two orders of magnitude. Thus, in narrowband n-type semiconductors the critical concentration of electrons is essentially underestimated at the absence of compensation.

At last, typical profile of the random potential is forming in heavily doped compensated semiconductors under the correlated distribution of the charged impurities, which decreases the carries critical concentration for several orders. Obviously, then we always have the inequity $N_c^\text{eff}<N_c$ to be
held. For example, in CdSnAs₂<Cu> \( N_c^{\text{eff}} \), and \( n_c \) is by two orders lesser than \( N_c \) during Anderson localization \([4, 12]\) (Table).

2.2. According to experimental data on hopping conduction in \( n \)-GaAs, \( p \)-Ge, \( p \)-CdSnAs₂<Cu> (Fig.1-4), the parameter \( T_0 \) in expression \( \sigma(T)=\exp[-(T_0/T)^p] \) tends to zero (see Fig.3, 4) at fixed temperatures when approaching to the transition point at temperatures close to \( T=0.04 \) K (Fig.2). Thus, the conductivity \( \sigma \) tends to 0 with \( T \to 0 \) K and if \( T_0>0 \), insensibly to the type of the hopping conductivity \([7, 8]\). If \( T_0=0 \), the minimal conductivity can be found from experimental data, extrapolating to \( T=0 \) K. The characteristic parameters of the transition are presented in the Table. Critical concentrations of electrons (holes) are obtained from the Hall coefficient \( n_c(p_c)=(|R_H|e)^{-1} \) data.

| Semiconductors | \( \sigma_{\text{min}} \), \( \Omega^{-1} \cdot \text{cm}^{-1} \) | \( p_c \), \( n_c \), \( \text{cm}^3 \) | \( \mu_{\text{Hmin}} \), \( \text{cm}^2 \cdot \text{V}^{-1} \cdot \text{s}^{-1} \) |
|----------------|-------------------|-------------------|-------------------|
| \( n \)-GaAs \([14,15]\) \( K_c \approx 0 \) | 9.5               | 3.0\cdot 10^{16}  | 2000              |
| \( p \)-Ge \([16]\) \( K_c = 0.4 \) | 4.2               | 1.5\cdot 10^{17}  | 175               |
| \( p \)-CdSnAs₂<Cu> \([4]\) \( K_c = 0.4 \) | 6.1\cdot 10^{-2}  | 2.5\cdot 10^{15}  | 155               |
| \( p \)-CdSnAs₂<Cu> \([4]\) \( K_c = 0 \) | 4.3\cdot 10^{-3}  | 10^{13}           | 2750              |

**Figure 3a.** Concentration \( N_A \) dependences of activation energy and hopping conductivity through the nearest shallow hydrogen-like acceptors of \( p \)-Ge crystals (\( T=1.25 \) K, see Table in \([17]\)).

**Figure 3b.** Conductivity versus temperature for \( p \)-Ge crystals with shallow hydrogen-like acceptors at \( T=1.25 \) K (see Table in \([17]\)).
Figure 4. Pressure dependences for: 1) conduction band electron mobility $\mu_e$, 2) deep acceptor band hole mobility $\mu_A$, 3) parameter of hopping conductivity with altering step (Mott’s law) of electrons $T_{0e}$, and (4) parameter of hopping conductivity of acceptor band holes $T_{0A}$ (T=4.2 K, sample #2 $p$-CdSnAs$_2<$Cu$>$ [4]).

3. Conclusion

The problem of minimal metal conductivity is stipulated by the complicated situation. On the one hand we do not have a strict, theoretically founded solution to this problem [18], but on the other hand every particular case requires a thorough analysis. A smoothness (“continuous”) of the electric conductivity change in the vicinity of the critical point may be due to: 1.) the smallness of carrier critical concentration at $T=0$ K, measured experimentally at nearly apparatus error limit, 2.) the large scale fluctuations of the impurity distribution, which can play a determinative role at $T\to0$ K. In latter case an interpretation of the experiment should be carried out in the frame of percolation theory. According to the theory, the electric conductivity increases from zero value after formation of an infinite cluster, made of “metalized” atoms and penetrating the whole bulk sample. It is worth to be noted, that experiments carried out at hydrostatic pressures also indicate the “continuity” of structural phase transition in solid states. The smoothness of the phase transition observed in these experiments also is caused by a disorder of the medium [19].

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