ELECTRON TRANSPORT PROCESSES IN SEMICONDUCTORS

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1. INTRODUCTION

This survey paper will not, naturally, involve, all the questions of electron transport processes in semiconductors; it will deal only with some questions related to doped and heavily doped semiconductors and with some problems of two-dimensional transport. The treatment will be more of an applicative rather than theoretical aspect, which means that less attention will be devoted to the low-temperature problems[1]. The N- type semiconductors will be considered.

2. IMPURITY SEMICONDUCTORS

The heavily doped semiconductors (HDS) have been less studied than the lightly doped ones (LDS) or intrinsic. This can be explained by the fact that impurities create impurity band (d-band), which, due to random space distribution of impurities cannot be treated by the quasi ideal lattice method. The impurity electrons affect the "conduction band" electrons - the conduction band is no more ideal; the density of state, ρ, is no more proportional to the square root of the energy $(E)^2$.

1. The topical problem here is also a correlated hopping motion of electrons, as a new transport mechanism in compensated semiconductors. See Prof. Gosar s communication at this Symposium.
2. The situation resembles the one in amorphous semiconductors: forbidden band is no more an energy gap in a proper sense (see the survey lecture of Dr.M. Peršin on amorphous layers at this Symposium.

The physical criterion determining the boundary between the light and the heavy doping is the degree of the electron localization at the Fermi level (E_F) in the range of very low temperatures ($T \to 0$, in that case the E_F tends to the donor´s level E_d). In the LDS these electrons are localized and the low-temperature conductivity has an activating character (the electron concentrations are $n \sim \exp(-E_d/kT)$, while in the HDS the electrons are delocalized and the conductivity is of the metal-type.

In the LDS the low-temperature conductivity is explained by the hopping conductivity mechanism which requires a definite degree of the impurity compensation[1]. This mechanism can be treated by a percolation theory, the application of which to the semiconductors was independently proposed by the authors in /1/ and /2/ (see monograph /3/ on the same topic, containing an exhaustive bibliography). Such a semiconductor could be called "a moderately doped", while the semiconductor where the hopping mechanism is either impossible or negligible, could be called quasi-intrinsic /4/,

The extention of the impurity band need not be the measure of the delocalization because it can occur not as a consequence of the Pauli principle, but as a consequence of the potential fluctuation of randomly distributed impurities. It means the delocalization criterion would be the over-lapping of wave functions, or the condition that the Bohr radius a ($\mathcal{E}$, m*) is:

(1a) $$a > or \gg R_0 = N^{-1/3} .$$

However, the experiments show that the Mott tranistion[3] in the

3. Apart from the Mott model, as known, there are others, also. See the survey of the Dr. P.Prelovšek on conductor-insulator phase transitions, too.

d-band from the metal to activation conductivity occurs already at /3/

/1b/ $$z \approx R_0/4 < R_0 \quad \text{or} \quad Na^3 \approx 0{,}02\,,$$

so that this semiconductor would be, with respect to delocalization, the HDS[4]. The basic difficulty in the VHDS is the ignorance of accurate impurity correlation dependences which becomes particularly serious when describing the metal-insulator transition due to the influence of compensation effect of the opposite-type impurities. At higher temperatures mobile excitations - fluctuons can exist, consisting ofelectrons and of impurities (see survey paper /5/).

The central place in these problems belongs to the determination of the density of state function, (ρ), and of the screening length, (λ), when often the theory of the linear screening is not satisfactory. If this problem is adequately set, the satisfactory semiquantitative answers could be given to the questions of interband light absoprption and the kinetic properties of heavy doped compensated semiconductors: the creation of electron drops separated by high barriers - see /3/. It should be stressed that the calculation of λ must be performed self-consistently, /6/, /7/, because the carrier concentration n depends on ρ, while ρ depends on λ.

One must start from the definition:

(2a) $$\frac{1}{\lambda^2} \sim \left|\frac{\partial n}{\partial E_F}\right| + \left|\frac{\partial p}{\partial E_F}\right|\,,$$

noting that $\frac{\partial n}{\partial E_F} \neq \int \frac{\partial f}{\partial E_F}\rho\, d\mathcal{E}$ because ρ depends on the impurity concentration N, i.e., on n. In the opposite case some higher values are obtained from the screening length (see for example /8/). Proceeding in such a way /7/, a surprising dependence on concentration is obtained for the Einstein relation:

4. According to classifications in /4/ it would be the HDS, while that according to (1a) would be very highly doped semiconductor - the VHDS.

$$\left(D/\mu\right)\frac{e}{kT} \equiv \psi(n) = \frac{n}{\partial n/\partial \eta}$$

As can be seen from Table 1 the ratio ψ decreases with the concentration increase n, whilefor the parabolic energy bands this ratio would increase according to:

(2b) $$\psi_{parab} = \mathcal{F}_{1/2}(\eta) \Big/ \mathcal{F}_{-1/2}(\eta), \quad (\eta = E_F/kT).$$

Table 1

$n(cm^{-3})$	$2.1o^{17}$	$3.1o^{18}$	$3.1o^{19}$	$1o^{20}$	$\to \infty$
$\psi_{acc.}$ /7/	0.91o	0.533	0.220	0.120	$\to 0$
(2b)	≈ 1	1.017	1.038	1.046	$\to \infty$

In the calculations of λ, i.e. of n, the exact form of the dependence $\rho(E)$ for low values of ρ_α is not essential because $\rho(E)$ is in the denominator: $n = \int \rho f dE$ .However, similarly to the idea in /9/ it could be shown that the relation for the conductivity or mobility /1o/

(3a) $$n\mu \sim \int \frac{\partial f_o}{\partial E} \tau \frac{J_\rho^{4/3}}{\rho} dE$$

for nonparabolic elipsoidal bands, such as c- and d-bands in heavy doped semiconductors; here

(3 b) $$J_\rho \equiv \int_{-\infty}^{E} \rho dE \qquad (= k/3\pi^2 \text{ for spherical bands})$$

is laways an increasing function with respect to E. Since ρ is in the denominator, the accurate knowledge of $\rho(E)$ is essential for low values (except when $\rho \sim \sqrt{E}$).

When the mobility in dependence of N' is calculated (at 300 K at the uncompensated case) taking ρ_c and ρ_α , similarly to /6/, i.e. to /11/ (in fact, these authors base their works on basic pa-

pers /12, /13/ and /14/), as well as the relations using the constant effective masses for the relaxation time, τ , the results communicated at the previous Symposium /15/ are obtained. However, in heavy doped semiconductors constant m* cannot be explained either for c- or d-bands so that the particular relaxation times should be calculated using the general definition of the transition probability,i.e. make a substitution $m^* \vec{k} \rightsquigarrow \rho$:

$$\frac{1}{\tau_i} = \rho(E) \cdot F_i(\vec{k}) , \tag{4}$$

where dependence F_i on wave vector $\vec{k}$ is different for different (i-th) scattering mechanisms. Unfortunately, in that case the preliminary results obtained for the dependence $\mu(N)$ are not satisfactory: for $N \geq 10^{18}$ cm^{-3} the mobility is three times greater than the real one, while for a lower N the great values of μ are obtained. Though such an approach would be conceptually more correct, these disagreements may be explained,in our opinion, by the negligence of the electrons localization for lower concentrations and for the lower densities of states in the doped zone.Apart from that, for $N \gg 10^{18}$ cm^{-3} the possibility of the cluster formation should be taken into account.

3. THE TWO-DIMENSIONAL TRANSPORT - THE EINSTEIN RELATION

The two-dimensional motion of electrons may occur, not taking into account the influence of a strong magnetic field, either due to the two-dimensionality of the lattice or due to the effect of the electric field ($\vec{\mathcal{E}}$), applied normally to the surface of the semiconductor (along the x-axis) when the quantization of state appears in the inverted layer of the surface well. This second two-dimensional problem has been dealt with in the fundamental paper /6/ as well as in several later works, containing the results and solutions of

the problem of subband creation, the screening problems, as well as the questions related to the scattering processes mechanisms (especially scaterings on ionized impurities and ionized interface states).

We shall present here only one aspect of this problem related to the application of the transport equations in the inverse quantizing layers. Namely, when writing the current expression of the i-th subband on the plane parallel to the surface (along x-axis):

(5a) $$J_{xi} \equiv J_i = -e\int v_x f_{1i} \frac{dS_k}{2\hat{\pi}^2}$$

due attention should be paid to the fact that the electron of the i-th subband is affected by the particular (quasi) electric field $e\vec{\mathcal{E}}_{xi} = \frac{\partial E_i}{\partial x}$ (E_i-the eigenvalue of the bottom energy of the i-th subband). Also it should be kept in mind that the quasi-Fermi level

(5b) $$W_{fni} = E_{fn} - E_i(x)$$

is also different for every subband, in the general case (similar to that in the MOSFET channel), i.e. that W_{fni} and W_{fnj} are not equidistant.From (5a) we get:

(5c) $$J_i = \mu_i N_i \left(e\mathcal{E}_{xi} + \frac{\partial W_{fni}}{\partial x} \right)$$

so that the Einstein relation[5] reads:

(5d) $$D_i/\mu_i = \frac{1}{e} N_i \Big/ \partial N_i / \partial W_{fni}$$

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5. It should be stressed that the partial derivative due to the surface density N_i should be taken according to W_{fni} and not according to E_{fn}, as was done in /17/.

The total current is $J=\Sigma J_i$, so that for the "total" diffusion coefficient D and mobility $\mu = \frac{\Sigma \mu_i N_i}{N_s}$ the following Einstein relation is reached:

(6a) $$D/\mu = \frac{1}{e} \cdot N_s \cdot \Sigma \frac{\mu_i N_i}{\partial N_s / \partial W_{fn_i}} \Big/ \Sigma \mu_i N_i$$

which is, in a general case, dependent on the scattering mechanism.

In /18/ it was shown that in the case of the quantum limit, meaning that only the basic level E_o is occupied, the Einsten relation has the form:

(6b) $$\left(D/\mu\right)_o = \frac{kT}{e} \cdot \frac{R}{1-e^{-R}}, \quad R = \frac{\pi \hbar^2 N_s^o}{n_v m_d kT}$$

which, in turn, means that self-consistent solving of the Schrödinger and Poisson's equation is unnecessary; also unnecessary is the knowledge of some parameters of the semiconductor as is for example the impurity concentration, dielectric constant, intrinsic concentration, etc.

4. FINAL REMARKS

In the present short survey the stress was laid on the problem of electron transport in heavy doped semiconductors at high (ambient) temperatures. It was shown that the basic difficulty is the ignorance of the correlations between impurities. When an attempt is made to determine the mobility, due attention is to be paid to this correlation, which means to the accurate determination of the density of state and to the degree of localization of the impurity electrons[6].

6. We are aware that only a many-electron treatment (by the Green function, for example as in /14/) and not one-electron treatment considered here could yield the most adequate solutions.

In the two-dimensional transport- the result of the field quantization it was stressed that a particular electric field and particular quasi Fermi level act for every subband.

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