PROCEEDINGS OF THE INTERNATIONAL CONFERENCE ON THE PHYSICS OF SEMICONDUCTORS, KYOTO, 1966
JOURNAL OF THE PHYSICAL SOCIETY OF JAPAN VOL. 21, SUPPLEMENT, 1966

XIV-2. Contact Effects in the Degenerate Semiconductors at Low Temperature

B. M. VUL and E. I. ZAVARITSKAYA

P. N. Lebedev Physics Institute, Academy of Sciences, Moscow, USSR

N. V. ZAVARITSKY

Institute for Physical Problems, Academy of Sciences, Moscow, USSR

It was found that at $T<25°K$, dV/dI characteristics of GaAs diodes has a maximum at $V=0$, the relative magnitude of which increases logarithmically with the decrease of temperature reaching a value 2~3 % at 1°K. The half-width δ of the maximum decreases steadily with temperature and approaches the limit determined only by the finite signal magnitude. At constant temperatures the half-width remains constant in all magnetic fields up to 22 kOe. It is suggested that the maximum is due to the peculiarity of electron energy distribution function near the Fermi level. It is shown that the results of the experiments can be strongly affected by the influence of tunneling from degenerate semiconductor to the superconductor at the "ohmic" contact.

In 1960 in studying the tunnel junctions, prepared from polar semiconductors, Hall found at $T=4.2°K$ the conductance dip centered at zero voltage. This result was interpreted as arising from the lowering of the electron and hole energies due to self-interaction with the phonon field (polaron formation).[1]

In 1963 Keldysh and Kopajev showed theoretically that such result may be due to the singularity in the density of states near the Fermi level.[2]

The present work extends Hall's observation to discover the real nature of the effect.

The measurements were made on GaAs tunnel diodes with hole concentrations from 4×10^{19} cm^{-3} up to 8×10^{19} cm^{-3}. The *p-n* junctions were made by tin alloying, and ohmic contacts by alloying of lead with appropriate impurities.

In the course of the experiment the dependences of $I-V$, $dV/dI-V$, d^2V/dI^2-V were recorded. Measurements were made in the temperature range between 1 and 30°K and in magnetic fields up to $H=22$ kOe.

In all the cases in which the extraneous effects at the contacts were not observed or eliminated by raising the temperature or by applying the magnetic field, the dependence $dV/dI-V$ exhibits a peak centered at zero voltage. At helium temperatures this peak was characteristically of two millivolt width and represents an increased resistance of order of 1%.

The effect remained up to $T\leq30°K$ and did not disappear in the magnetic fields up to $H=$ 22 kOe. At higher temperatures this peak becomes very small and one can notice it only at the d^2V/dI^2-V curve.

Typical d^2V/dI^2-V recordings obtained at several temperatures are shown in Fig. 1.

It is seen from Fig. 1 that the magnitude and the sharpness of the extrema, $(d^2V/dI^2)_{max}$ and $|(d^2V/dI^2)_{min}|$, increase with decreasing temperature, but the distance δ between these extrema decreases.

Figures 2 and 3 show the temperature dependence of the additional resistance at zero

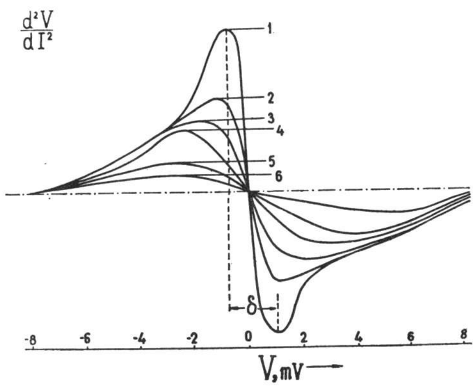

Fig. 1. The typical dependences of d^2V/dI^2-V at temperatures 1) 1.3; 2) 4.2; 3) 6.8; 4) 7.8; 5) 14; 6) 18°K.

voltage and the temperature dependence of the width of the resistance peak.

The value of ΔR in Fig. 2 was obtained by integration of d^2V/dI^2-V curve and the value of $R_0(0)$ was obtained by extrapolation of dV/dI to $V\to 0$ supposing that there is no extremum at $V=0$.

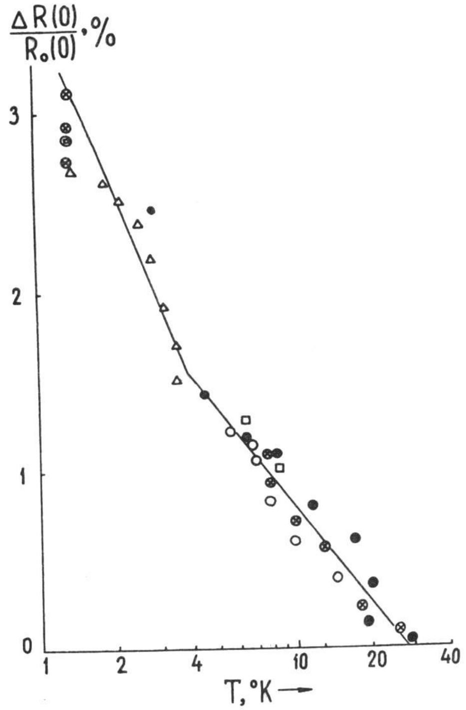

Fig. 2. The dependence of $\Delta R/R_0(0)=f(T)$ for several samples. (The different points are related to different samples).

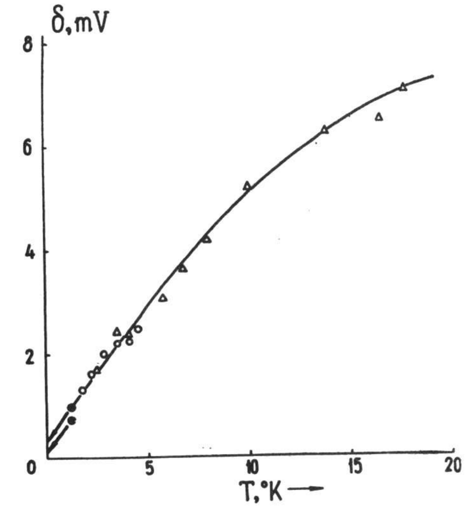

Fig. 3. The temperature dependence of δ. (Dotted lines are extrapolated to the signal magnitude).

The relative magnitude of the additional resistance $\Delta R/R_0(0)$ at zero voltage increases logarithmically with decreasing temperature, reaching a value of several percent. The magnitude of δ decreases gradually with temperature approaching the limit determined only by the finite signal magnitude.

Such a dependence of $\delta(T)$, when $\delta\to 0$ at $T\to 0$ does not agree with the conception of polaron's tunneling as, according to ref. 3) the relaxation energy in this case $\sim 2\times 10^{-3}$ volt; this shows that at $V=0$ takes place a singularity, but not an energy gap Δ, even a small width. Experimental dependence of $\Delta R=f(T)$ and $\delta=f(T)$ agrees qualitatively with the suggestion that there is a singularity in the density of electron states in GaAs at Fermi energy.

Keldysh and Kopajev have shown theoretically that such a singularity can exist in a degenerate semiconductor with ionic lattice.[2)] Taking into account the interaction between electrons and optical phonons, according to ref. 2) the energy dependence of the wave vector $\boldsymbol{k}$ is not given by standard expression, $E\sim \boldsymbol{k}^2$, but the energy E suffers a jump ΔE at the Fermi level, $\boldsymbol{k}=\boldsymbol{k}_F$. As a consequence the velocity of the electrons $v\simeq dE/d\boldsymbol{k}$ turns into infinity and the density of states $\rho\sim(\boldsymbol{k}^2/(dE/d\boldsymbol{k}))$ comes to nought at the Fermi energy.

Near the Fermi level the density of states is

$$\rho(E)=\rho_0\frac{1}{1-\frac{\alpha}{2\pi}\left(\frac{\hbar\omega_0}{\mu}\right)^{1/2}\ln\left[\left(\sqrt{\frac{E}{\mu}}-1\right)^2\right]}\,. \tag{1}$$

Here ρ_0 is the density of states in the absence of the interaction between electrons and longitudinal optical phonons, $\hbar\omega_0$.

α is the interaction constant of electrons with optical phonons, and is equal to

$$\alpha=\left(\frac{e^2}{\hbar}\right)\left(\frac{m^*}{2\hbar\omega_0}\right)^{1/2}(\varepsilon_\infty^{-1}-\varepsilon_0^{-1})\,, \tag{2}$$

where m^* is the effective mass, μ the Fermi energy, ε_0, ε_∞ dielectric constant for static and high-frequency field, respectively.

At the Fermi level

$$\rho(\mu)=\rho_0\frac{1}{1-\frac{\alpha}{\pi}\left(\frac{\hbar\omega_0}{\mu}\right)^{1/2}\ln\frac{\kappa T}{2\mu}} \tag{3}$$

and

$$\frac{\Delta\rho}{\rho}=\frac{\rho_0-\rho}{\rho}\sim-\frac{\alpha}{\pi}\left(\frac{\hbar\omega_0}{\mu}\right)^{1/2}\ln\frac{\kappa T}{2\mu}\,. \tag{3a}$$

In the case of GaAs $\alpha=0.06$; and at $T=1°K$ $\hbar\omega_0=0.036$ eV.

$\Delta\rho/\rho(\mu)$, %	10	8	6	4.5	4	3.5	2.5
at μ, eV	10^{-2}	2×10^{-2}	5×10^{-2}	0.10	0.15	0.20	0.50

(4)

As is seen from (4), the more is the anomaly at the Fermi level, the less is μ and so this effect is much more expressed in p-type. In our case the hole concentration was $(4\sim8)\times10^{19}\mathrm{cm}^{-3}$, therefore $\mu=(5\sim10)\times10^{-2}$ eV and $\Delta\rho/\rho(\mu)=(4.5\sim6)\%$.

The probability of tunneling is proportional to the density of states, and the current through a tunnel junction, as it is known, is given by the relation

$$J=C\int_{-\infty}^{\infty}\rho_1(E+eV)\rho_2(E)\left\{f\left(\frac{E+eV}{\kappa T}\right)-f\left(\frac{E}{\kappa T}\right)\right\}dE. \qquad (5)$$

Here ρ_1 and ρ_2 are the density of states at the one and the other side of the tunnel barrier. $f(E)=(\exp(E/\kappa T)+1)^{-1}$ is the Fermi distribution of carriers.

In case of p–n junction the anomaly near the Fermi level takes place in n-type as in p-type, but it is more in p-type. In first approxi-

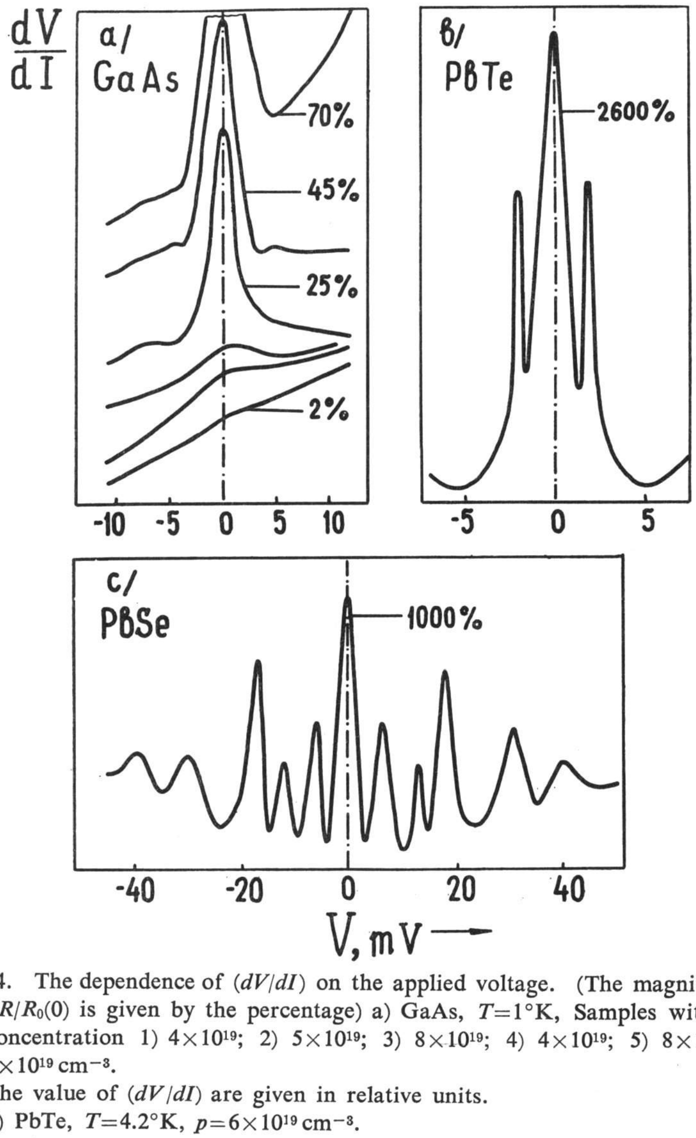

Fig. 4. The dependence of (dV/dI) on the applied voltage. (The magnitude of $\Delta R/R_0(0)$ is given by the percentage) a) GaAs, $T=1°K$, Samples with hole concentration 1) 4×10^{19}; 2) 5×10^{19}; 3) 8×10^{19}; 4) 4×10^{19}; 5) 8×10^{19}; 6) 6×10^{19} cm^{-3}.
The value of (dV/dI) are given in relative units.
b) PbTe, $T=4.2°K$, $p=6\times10^{19}$ cm^{-3}.
c) PbSe, $T=4.2°K$, $p\simeq10^{20}$ cm^{-3}.

mation we can consider that the density of states ρ_1 in *n*-type is equal to ρ_0, but that in *p*-type, ρ_2, varies with energy as (1).

Substituting this density of states (1) into eq. (5) and differentiating with respect to V we find theoretically the magnitude of the additional resistance at zero voltage.

The comparison of the threshold $\Delta R/R_0(0)$ estimated from the magnitude of the maximum in the experimental curve with that calculated from eqs. (1) and (5) shows that at very low temperature the experimental data are two-three times smaller than theoretical.

This discrepancy hardly has a principal significance. Most probably it is due to the fact that in the theory in ref. 2) the Coulomb screening has not been taken into account.

We may conclude that the singularity in the density of states in GaAs is useful for describing the resistance peak at zero voltage.

The results of the experiment, however, can be strongly affected by the extraneous effects at the contact.

Typical curves $dV/dI-V$ obtained for a number of the samples of GaAs at 1°K are presented in Fig. 4a.

It can be seen that the ratio $\Delta R/R_0(0)$ changes from sample to sample by more than an order of magnitude from 2% up to 70%.

The samples with larger value of $dV/dI(0)$ were obtained by making *p-n* junction in GaAs with arbitrary hole concentration between 4×10^{19} and 8×10^{19} cm^{-3} but mostly at $p\simeq4\times10^{19}$ cm^{-3}.

Among the data presented in Fig. 4a one can point out those concerning samples having the larger $\Delta R/R(0)$ % at maximum. For these samples at $T=1$°K besides the main maximum at $V=0$ one can see a system of satellites symmetrically located around those at $V=0$.

The magnitude and sharpness of the main maximum on the $dV/dI-V$ curves decrease considerably with increasing temperature to $T=7.2$°K, and change sharply in the magnetic fields, as it is seen in Fig. 5. It seems that one can suggest the existence of a "critical" field removing almost all peculiarities of the d^2V/dI^2-V curve.

In the case where an ohmic contact was made of lead, the temperature dependence of this "critical" field coincides with the temperature dependence of the critical magnetic field destroying the superconductivity of lead. The temperature, at which the sharply expressed peculiarity in d^2V/dI^2-V curves disappears, coincides with the temperature of transition of lead from superconducting state to the normal one.

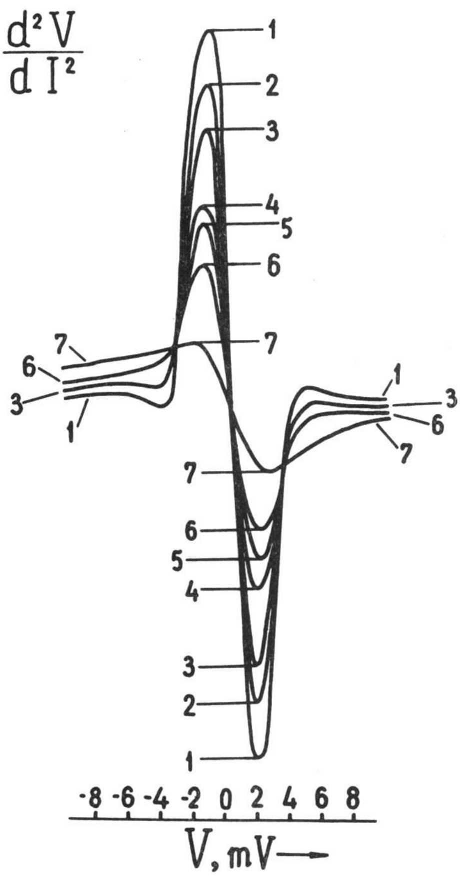

Fig. 5. The dependence of d^2V/dI^2-V at $T=1.3$°K in magnetic fields 1) 0~240; 2) 430; 3) 475; 4) 550; 5) 600; 6) 700; 7) 1000 Oe.

In tunnel diodes with ohmic contacts made of indium, the anomaly at $V=0$ as well as a superconductivity in indium disappears at $H_c=270$ Oe and $T_c=3.4$°K.

All our experiments show that the unusually large 100% value of $\Delta R/R_0$ for a number of the investigated samples is really due to the tunnel transition between a superconductor and a degenerate semicondutor at the "ohmic" contact.

It is thought that such effects distort the results of the investigations of details of tunnel transitions near $V=0$, when a superconducting metal is used for contact.

In particular, such tunnel junction between superconductor and semiconductor is formed often during alloying indium in *p*-PbTe and *p*-PbSe. On this account some peculiar structure may be observed, as it is seen from Figs. 4b and

4c. Sharply expressed peak at zero voltage in this figure is connected to the resistivity of the tunnel junction between superconductor and semiconductor after the superconducting transition at $eV<\Delta$, where Δ is the gap width in the energy spectrum of electrons of superconductor.

Additional peaks at $V\neq 0$ belong to partial transition into normal state in the separate part of the superconductor.

This superconducting structure at the $dV/dI-V$ curves sometimes remained up to $T_c=8°K$ and $H_c=20$ kOe.

The reason is that in compound semiconductors the indium alloying gives rise to formation of the superconducting alloys In_xPb_y with high critical temperature and high critical magnetic field.

References

1) R. N. Hall: *Proc. Int. Conf. Semiconductor Physics*, Prague (1960) p. 193.
2) L. V. Keldysh and Yu. V. Kopajev: Fiz. tverdogo Tela **5** (1963) 1411.
3) R. N. Hall, J. H. Racette and H. Ehrenreich: Phys. Rev. Letters **4** (1960) 456.

DISCUSSION

Burstein, E.: Similar structure due to superconductor metal-semiconductor contacts have been observed by Rowell and co-workers and also by the group at the University of Pennsylvania (Payne, Salonek and Burstein).

In the studies at Pennsylvania, structure was actually observed which coincided with the phonon effective density of states reported for Indium from measurements on superconductor oxide metal junctions. We also attribute the superconductor effects to tunneling from the metal through a space charge layer in the superconductor into the degenerate region.

I would like to ask whether the paper by Keldysh *et al.* referred to has corrected some errors which were presented in Keldysh's first paper on the singularities in the density of states due to optical phonons. These errors were first pointed out by Schrieffer at the time that Keldysh's first paper appeared in translation.

Zavaritskaya, E. I.: We also observed structure which coincided with the phonon effective density of states known for Indium and Lead when we had the extraneous effects at the "ohmic" contact.

For explanation our results observed in the case when the extraneous effects at the contacts were not observed, we used Keldysh's formula for qualitative comparison only.