TEMPERATURE DEPENDENCE OF THE REFLECTION COEFFICIENT OF ELECTRONS ON THE INTERFACE BETWEEN SUPERCONDUCTING AND NORMAL PHASES

I.L. Landau
Institute of Physics Problems, USSR Academy of Sciences
Submitted 25 March 1970
ZhETF Pis. Red. 11, No. 9, 437 - 440 (5 May 1970)

If the mean free path ℓ of the carriers is comparable with or exceeds the period a of the structure of the intermediate state of a sample, then the electric conductivity of the sample depends strongly on the character of the interaction between the charge-carrying excitations and the interface between the superconducting (s) and normal (n) phases. When $T \ll T_c$, the energy of the excitations is smaller than the energy gap in the superconductor, and the excitations are completely reflected from the boundary of the s-phase, the momentum being conserved and the signs of the mass and charge of the particle being reversed [1, 2]. This character of the reflection causes the conductivity of the thin n-layers to be equal to the electric conductivity σ_0 of the bulky metal in the n-state, and the electric conductivity of the entire sample is $\sigma = \sigma_0/C_n$, where C_n is the concentration of the n-phase.

When $T \sim T_c$ there is no longer total reflection of the excitations from the ns boundary, and an appreciable fraction of the excitations can move through the s-region. Then the scattering processes occurring in the s-layers should increase the resistance of the n-layers. As shown by Nozieres (private communication), in the limiting case when the reflection coefficient $R = 0$ and $\ell \gg a$, the resistance of the sample does not depend on C_n at all when $C_n > 0$, and vanishes only when $C_n = 0$.

An exact calculation of the electric conductivity when $\ell \sim a$ is made difficult by the fact that the electric field in the n-layers is not uniform. However, when $a/\ell < a_{max} \sim (1 - C_n)^{-1/2}$, the change of the electric field over the extent of the n-layer is small, $\Delta E \lesssim 0.1E$ (this estimate was obtained for $R = 0$, and the introduction of $R > 0$ leads to an additional smoothing of the electric field), and the calculation simplifies greatly. In this case the electric conductivity of the n layer can be written in the form $\sigma_0 \sim \ell_e/\ell$, where ℓ_e is that part of the mean free path due to the n-phase, averaged over all the electrons of the n-layers. For the excitations reflected from the ns interface we have $\ell_e = \ell$. In the case of excitations that are not reflected, calculation for an isotropic metal yields

$$\frac{\ell_e}{\ell} = C_n e^{\alpha(C_n - 1)} \left[1 + \alpha e^{\alpha} \int_{C_n\alpha}^{\alpha} \frac{e^{-x}\,dx}{x} \right], \quad \alpha = a/\ell .$$

In the derivation of this formula it is assumed, as in [3], that the mean free paths are the same in the n- and s-regions; the influence of the magnetic field, being small, was disregarded. The electric conductivity of the entire layer is in this case

$$\sigma = (\sigma_0/C_n)[R + (1 - R)\ell_e/\ell]. \tag{1}$$

The experiments were performed on a cylindrical single crystal of indium with C_4 axis aligned with the sample axis. The cylinder diameter was 3 mm and the resistance ratio was $\rho(300°)/\rho(0°) = 4.65 \times 10^4$. The intermediate state was produced by a transverse magnetic field. The electric conductivity was measured by passing through the sample a current $I - 0.1I_c$. The potential difference was measured with a superconducting modulator.

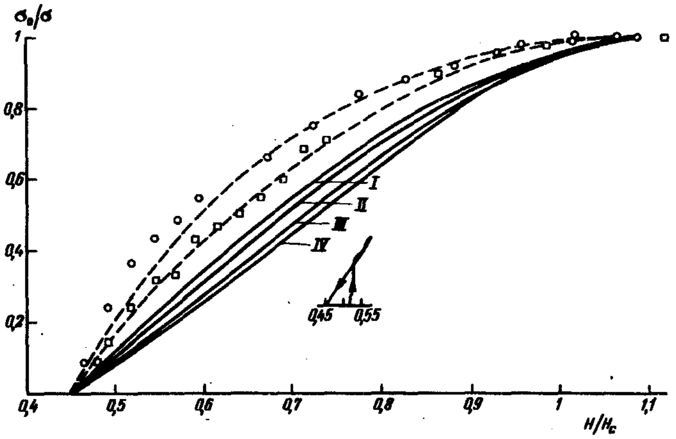

Fig. 1. Circles - T = 3.377°K, squares - T = 3.3°K; the solid curves were obtained with the PDS-021 automatic plotter: I - T = 3.247°K, II - T = 3.164°K, III - T = 3.09°K, IV = curve obtained from measurements at 2.8, 2.73, 2.31, and 2.12°K.

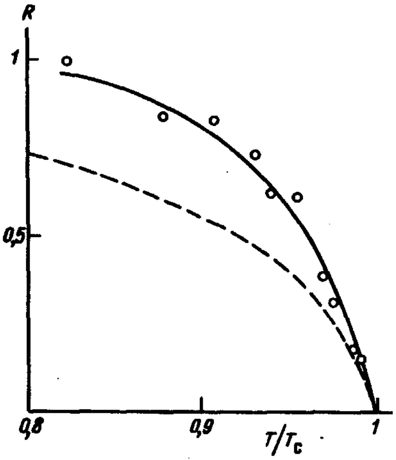

Fig. 2. Temperature dependence of the coefficient of carrier reflection from the phase boundary. The dashed curve shows for comparison the temperature dependence of the number of excitations in the normal metal with energy lower than the energy gap, referred to the total number of excitations.

Figure 1 shows a number of plots of σ_0/σ against H/H_c at different temperatures. Below 2.8°K, the curves practically coincided. The destruction of the s-state was accompanied by a slight hysteresis, shown in the lower part of Fig. 1 (T = 3.164°K). H_c was determined from the instant of vanishing of the resistance with decreasing magnetic field[1]. This agreed, within the limits of errors, with measurements of B(H) performed on the same sample by a ballistic method in a longitudinal magnetic field.

From the transition curves it is possible to estimate with the aid of (1) the reflection coefficient R (Fig. 2). In the calculations, C_n was assumed equal to σ_0/σ for the corresponding H/H_c at low temperatures (curve IV). We determined in passing the quantity $\ell/\sigma = (2 \pm 0.5) \times 10^{-11}$ ohm-cm^2, the low accuracy being connected here with the weak dependence of the results on the mean free path in the case of large ℓ. The dashed curves of Fig. 1 are based on the calculated values of R.

The discrepancy between the experimental points at small values of C_n and the calculated curve at T = 3.377° is apparently due to the fact that the validity of formula (1) at the highest temperature is limited to the region of not too small C_n. At T = 3.377°K we have $\ell \simeq a \simeq 7 \times 10^{-2}$ cm at $C_n = 0.4 - 0.5$, and $\ell < \underline{a}$ at other values of C_n. However, $\underline{a}$ decreases rapidly when the temperature is lowered, and this, together with the increase of R, extends the region of validity of formula (1) to include the entire transition curve.

It is seen from Fig. 2 that an appreciable contribution is made to R by the effect of over-the-barrier reflection. Our measurements are in satisfactory

---

[1] We have assumed that in the presence of a measuring current $I = 0.1I_c$ total destruction of the superconductivity occurs at $H = 1.1H_c$ and the total restoration of the s-state occurs at $H = 0.45H_c$.

agreement with the theoretical estimates of the over-the-barrier reflection, given in [1].

Generally speaking, the system of layers perpendicular to the current is not static in an uncompensated metal, and moves along the current direction in pure indium [4, 5]. Such a motion, however, should not lead to a change of the sample resistance [4]; indeed, the stopping of the layers on going from $T = 2.12^\circ$ to $T = 2.8^\circ$ does not lead to a change of the transition curves.

I am grateful to Yu.V. Sharvin for constant interest in the work and for many valuable remarks, to A.F. Andreev for a discussion of the results, and to F. Nozieres for interest in the questions touched upon in this paper.

[1] A.F. Andreev, Zh. Eksp. Teor. Fiz. 46, 1823 (1964) [Sov. Phys.-JEPT 19, 1228 (1964)].
[2] A.F. Andreev, ibid. 51, 1510 (1966) [24, 1019 (1967)].
[3] J. Bardeen, G. Rickayzen, and L. Tewordt, Phys. Rev. 113, 982 (1959).
[4] A.F. Andreev and Yu.V. Sharvin, Zh. Eksp. Teor. Fiz. 53, 1493 (1967) [Sov. Phys.-JETP 26, 861 (1968)].
[5] Yu.V. Sharvin and I.L. Landau, ibid. 58, No. 6, (1970) [31, No. 6 (1970)].

EXPERIMENTAL INVESTIGATION OF THE APPEARANCE OF SCREENING IN LEAD AND ALUMINUM VAPOR

Ya.N. Gnoevoi, A.I. Petrukhin, Yu.E. Pleshanov, and V.A. Sulyaev
O.Yu. Shmidt Earth Physics Institute, USSR Academy of Sciences
Submitted 27 March 1970
ZhETF Pis. Red. 11, No. 9, 440 - 443 (5 May 1970)

Evaporation of matter under the influence of laser radiation can occur in two essentially different modes. In the first, the vapor has a temperature close to the phase-transition temperature, is weakly ionized, and is practically transparent to the incident radiation (evaporation wave without screening of the evaporating surface [1 - 3]). In the other the vapor is heated to much higher temperatures, it is strongly ionized, and absorbs the incident radiation completely (the surface is screened [4 - 6]). Since the distribution of the parameters in the vapor layer, the laws governing the time variation of these parameters, and the most characteristic values of the parameters (temperature, velocity, etc.) are essentially different in these two modes, it is of interest to determine the conditions for the transition from one mode to the other.

A theoretical analysis of the conditions under which the screening takes place [7] entails considerable difficulties, connected with the nonstationary character of the phenomenon and the lack of detailed information on the optical properties of heated vapor and on the evaporation mechanism. Most experimental investigations were devoted to evaporation without screening [1, 3] or to evaporation with developed screening [5]. There was no detailed investigations of the transition mode.

We have measured certain parameters of the transition mode of evaporation of lead and aluminum under the influence of radiation from a ruby laser. The laser consisted of a Q-switched master generator and an amplifier. To ensure uniform illumination over the entire affected target area, a ground-glass plate was placed ahead of the input face of the amplifier crystal. The output face of the amplifying crystal was projected with the aid of a lens on the surface of the target. Special measurements have shown that the inhomogeneity of the area illumination did not exceed 20%. The radiation pulse from the laser was bell-shaped and its duration at the half-power level was 30 - 40 nsec. The laser pulse energy could be varied in a wide range with the aid of absorbing