Field Emission from Niobium in the Normal and Superconducting States

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(Received June 29, 1961)

The change of field emission current from a superconductor as a result of a transition to the normal state under constant field and temperature conditions was calculated. The derivation is based on the Bardeen-Cooper-Schrieffer formulation of the density of states and band gap model for a superconductor. The experimental method for determining the current change consisted in measuring the current increment between a niobium field emitter in the superconducting state at 4.2°K and in the normal state at a temperature T above the transition. After correcting for the current increase occurring as a result of the temperature increase alone, the residual would be that associated with the superconducting-normal transition. This was less than the detectability of the measurements, although the calculations indicated an expected increase in current easily measurable if the superconducting-normal transition had occurred at the emitter surface. It is speculated that under high-field conditions, the superconducting state is quenched at the surface.

I. INTRODUCTION

THE recent verification of the energy gap in superconductors by low-voltage tunneling[1] suggested that the effect of the superconducting-normal transition on field emission be reinvestigated. In a previous measurement[2] no change, at least to within 0.2%, in the total emission current at constant voltage, was found between the normal and superconducting states of tantalum. In addition, no change was detected in the current from this same tantalum emitter at 300°K as compared to 4.2°K, whereas a change of 2% was expected on theoretical grounds. Since the energy band gap associated with the superconducting state is proportional to the transition temperature well below this temperature,[3] some advantage is gained through the use of niobium (T_c=9.2°K) rather than tantalum as the field emitter. Therefore, a tube to observe field emission from niobium was prepared, and the current from the emitter in both the superconducting and normal states was measured.

II. THEORY

The temperature dependence of field emission has been discussed previously.[4] Some modification is required in treating a niobium emitter initially in the superconducting state at 4.2°K. It will be assumed that an increment of current Δi_t is associated with the superconducting-normal transition at 4.2°K and constant field.

$$i_s(4.2)=i_n(4.2)-\Delta i_t. \tag{1}$$

The subscripts s, n, and t refer to superconducting, normal, and transition, respectively. According to the measurement in the experiment

$$\Delta i_m=i_n(T)-i_s(4.2), \tag{2}$$

where Δi_m is a measured current increment. Using Eq. (11) of the preceding paper[4] we can now write

$$\Delta i_m=\frac{i_s(4.2)K^2}{6}[T^2-(4.2)^2]+\Delta i_t, \tag{3}$$

where $K=\pi k/d=2.77\times10^4(\phi^{\frac{1}{2}}/F)$. Here, ϕ is the work function and F is the field strength in volts/cm. Δi_m is linear with T^2 so that a plot of Δi_m vs T^2 extrapolated to 4.2°K gives Δi_t, the current difference associated with the elimination of the energy band gap in the superconducting-normal transition.

The value of Δi_t may be calculated on the basis of the field emission theory and the Bardeen-Cooper-Schrieffer density-of-states function. The latter gives $N(0)E/(E^2-\epsilon_0{}^2)^{\frac{1}{2}}$ for the density of states in the superconducting state,[3] where E is measured from the Fermi level and ϵ_0 is half the energy gap. $N(0)$ is the normal density of states. The change in emission current for the normal-superconducting transition, at constant temperature, is

$$\Delta j_t=e\int_{-W}^{\infty}[P_n(E)-P_s(E)]dE, \tag{4}$$

where e is the electron charge and $P_n(E)$ and $P_s(E)$ are the total energy distributions for the normal and superconducting states, respectively. $P(E)$ includes the supply function at the surface and the barrier penetration probability.[5] The supply function follows the usual Fermi-Dirac distribution. Now[5]

$$P_n(E)\cong A\frac{e^{E/d}}{e^{E/kT}+1}, \tag{5a}$$

$$P_s(E)\cong A\frac{e^{E/d}}{e^{E/kT}+1}\,\frac{E}{(E^2-\epsilon_0{}^2)^{\frac{1}{2}}}, \tag{5b}$$

$$A=(4\pi md/h^3)e^{-c}, \tag{6a}$$

$$c=\frac{(32m\phi^3)^{\frac{1}{2}}}{3\hbar eF}v(e^{\frac{3}{2}}F^{\frac{1}{2}}/\phi), \tag{6b}$$

[1] I. Giaever, Phys. Rev. Letters **5**, 147 (1960).
[2] R. Gomer and J. K. Hulm, J. Chem. Phys. **20**, 1500 (1953).
[3] J. Bardeen, L. N. Cooper, and J. R. Schrieffer, Phys. Rev. **108**, 1175 (1957).
[4] R. Klein and L. B. Leder, preceding paper [Phys. Rev. **124**, 1046 (1961)].
[5] R. D. Young, Phys. Rev. **113**, 110 (1959).

m is the electron mass and d, ϕ, and F have been defined earlier. E is measured from the Fermi level. The function v is approximately equal to unity for the conditions of this experiment. In the expression for Δi_t we will use $-\infty$ for $-W$ as a limit of the integral. This can be done with negligible error. The integral $e\int_{-\infty}^{\infty}\rho_s(E)dE$ is equivalent to

$$A\int_{-\infty}^{\infty}\frac{\exp[\beta(E'^2+\epsilon_0^2)^{\frac{1}{2}}]}{\exp[\alpha(E'^2+\epsilon_0^2)^{\frac{1}{2}}]+1}dE',$$

where $\beta=1/d$ and $\alpha=1/kT$. The current increment is now

$$\Delta j_t=Ae\int_{-\infty}^{\infty}\left[\frac{e^{\beta E}}{e^{\alpha E}+1}-\frac{\exp[\beta(E^2+\epsilon_0^2)^{\frac{1}{2}}]}{\exp[\alpha(E^2+\epsilon_0^2)^{\frac{1}{2}}]+1}\right]dE, \quad (7)$$

the primes having been dropped. At $T=0$°K the normal state emission current is Ae/β. Evaluation of Eq. (7) by contour integration gives

$$\Delta j_t\cong\frac{Ae\epsilon_0^2\alpha}{2\pi}\sin\frac{\pi\beta}{\alpha}\left[\frac{1}{2}\ln\left(1+\frac{\alpha^2}{\pi^2\beta^2}\right)\right], \quad (8)$$

or

$$\Delta j_t\cong\frac{Ae\epsilon_0^2\beta}{2}\ln\frac{\alpha}{\pi\beta}. \quad (9)$$

This approximation is valid only when $\pi\beta\exp(2/\epsilon_0^2\beta^2)>\alpha$. It is noted that the current increment due to the transition at a given temperature well below the transition temperature is not particularly sensitive to temperature, although it does increase slowly with decreasing temperature.

III. EXPERIMENTAL METHODS AND RESULTS

The construction of the field emission tube and much of the experimental procedure has been described in the accompanying paper.[4] The temperature-resistance relationship for the niobium loop was obtained at four temperatures, 20.4, 77.4, 194.6, and 300. A calibration point at 4.2°K could not be obtained in the absence of the critical magnetic field. The shape of the temperature-resistance curve was taken from Rosenberg[6] and fitted to the calibrated points. The transition from the superconducting state was accomplished by conductive heating of the loop from the tungsten leads to which it was welded. The heating current level was too low for the Silsbee effect to be operative. It was found that a loop current of 0.445 ampere was required to effect the transition. To make measurements at lower currents it was necessary to first apply the higher current. A rotary switch, well insulated from ground, with three positions, open circuit, required current, and high current, was used. The required current was that necessary to produce a given temperature. Changing the switch position from open circuit to required current gave no temperature change in the case of niobium if the required current was below the critical current for changeover from the superconducting to the normal state. However, momentarily switching to the high-current position and then returning to the required-current position permitted the called-for temperature to be established.

[6] H. M. Rosenberg, Trans. Roy. Soc. (London) **A247**, 441 (1955).

The initial value of the emission current was 2.6×10^{-10} amp, established at 4.2°K with the niobium emitter in the superconducting state. The emission current as a function of temperature over the range 19°K to 110°K is shown in Fig. 1. Figure 2 is a plot of Δi vs $[T^2-(4.2)^2]$ with a least-squares line fitted to the data. The relationship given in Eq. (3) is confirmed. The extrapolation of this line to $T=4.2$°K gives for Δi_t the value $(-2.7\pm3.0)\times10^{-13}$ amp. This value can be compared to the expected Δi_t calculated by Eq. (9). The base current is $i_s(4.2)\cong i_n(0)=A'e/\beta=2.6\times10^{-10}$ amp, where A' includes an area term.

The energy gap in niobium has been found[7] to be $2\epsilon_0=3.02$ ev, $\beta=1/d=18.4$ ev^{-1}, and $\alpha=1/kT=2800$ ev^{-1}, so that $\Delta i_t=3.8\times10^{-13}$ amp. This value was confirmed by machine calculation of Eq. (7).

Although the standard deviation is large it is nevertheless apparent that the calculated emission current increment was not observed. At 19°K (this temperature was known within 0.5° since it is close to a fixed temperature calibration point, 20.4°K) the Δi was 1.7×10^{-13} amp. Below this temperature no change in the current was observed since the noise level was approximately 1×10^{-13} amp. The sum of the current change at 19°K due to the thermal effect plus the calculated transition

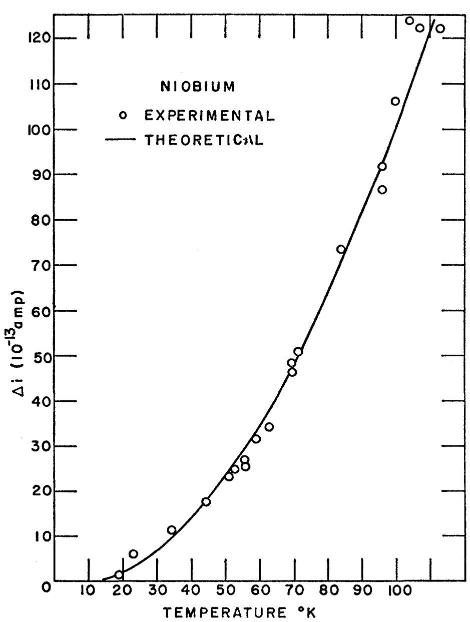

FIG. 1. Change in emission current with temperature at constant field.

[7] M. D. Sherrill and H. H. Edwards, Phys. Rev. Letters **6**, 460 (1961).

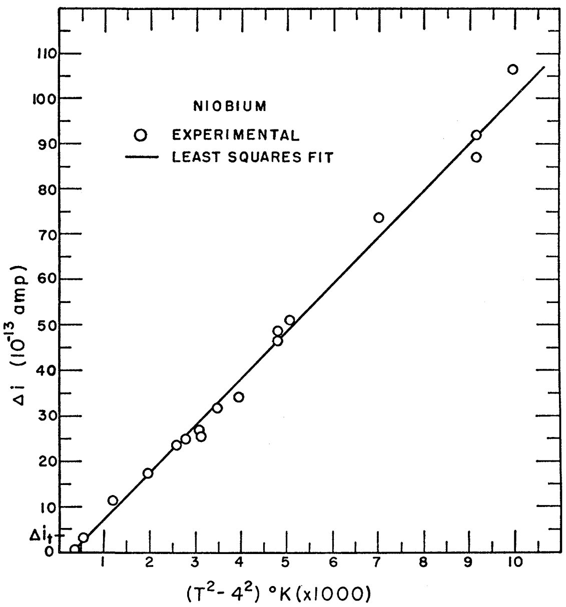

FIG. 2. Change in emission current with the square of temperature at constant field. The theoretical value of Δi_t, the current increment due to the superconducting-normal transition at 4.2°K, is indicated on the ordinate.

effect is 7.3×10^{-13} amp. The observed current change of 1.7×10^{-13} amp was, within the experimental uncertainty, equivalent to the thermal effect alone. The failure to detect the energy gap in these experiments, although calculation indicates that the effect should have been readily observable, suggests at least two possibilities. The first is, that the surface region of the emitting tip remains in the normal state even at 4.2°K, well below the transition temperature characteristic of niobium. This does not appear probable since the point had been well annealed under ultra-high vacuum conditions (tube immersed in liquid helium). The second is that under the high-field conditions associated with field emission, a mechanism exists whereby the effect of the superconducting state at the surface is suppressed. It has been proposed, for example, that field penetration to the extent of about 1 A occurs at the surface of a metal when field-emission fields are present.[8] It has not been determined whether such an effect imposed on a superconducting surface could account for the suppression of the energy gap at the surface, as indicated by the present experiments.

ACKNOWLEDGMENT

We express our thanks to Dr. Julius Jackson of the National Bureau of Standards staff for the solution of Eq. (7).

[8] G. M. Avak'iants, Trudy Fiz.-Tekh. Inst. Akad. Nauk Uzbek. S.S.R. **6**, 43 (1955).