TEMPERATURE AND VELOCITY DEPENDENCES OF ELECTRONIC DISLOCATION STOPPING POWER IN A SUPERCONDUCTOR

M. I. KAGANOV and V. D. NATSIK

Institute of Physics Problems, USSR Academy of Sciences; Physico-technical Institute of Low Temperatures, Ukrainian Academy of Sciences

Submitted July 28, 1970

Zh. Eksp. Teor. Fiz. 60, 326–329 (January, 1971)

We investigate the temperature-velocity dependence of the force of electronic dislocation stopping power due to scattering of normal electrons by the dislocation and to generation of electron-hole pairs. It is shown that a plot of the stopping power against the velocity V has a kink at $V = 2\Delta(t)/\hbar q_m$, where $\Delta(T)$ is the energy gap of the superconductor at the temperature T, and $q_m \approx a^{-1}$ (a—dimensions of the nucleus of the dislocation). The temperature dependence of the stopping power is analyzed and it is shown that it reduces to the temperature dependence of the energy gap $\Delta(T)$ and of the number of normal electrons $N(T)$.

RECENTLY, Pustovalov and Fomenko[1] investigated experimentally the temperature dependence of the jump of the deformation stress $\Delta\sigma$ when a metal goes over from the superconducting into the normal state. At the present time it is customary to attribute this jump to the change in the electronic stopping power of individual dislocations in such a transition. It is shown in[1] that the dependence of $\Delta\sigma(T)$ on the temperature T is very close to the temperature dependence of the energy gap of the superconductor $\Delta(T)$.

We[2], and also Hoffman and Louat[3], obtained a general expression for the force of electronic stopping of a dislocation in a superconductor $F_s(T, V)$ (V is the dislocation velocity). Previously, however, this expression was not analyzed for all the limiting cases, and this makes comparison with the experimental results difficult. In the present communication we present the results of a detailed investigation of the dependence of the stopping power $F_s(T, V)$, based on formula (6) of[2], on the temperature T and on the velocity V. The results of the investigation are conveniently represented in the form of the ratio F_s/F_n, where $F_n = (m^2b^2\lambda^2 q_m/3\pi^3\hbar^3)V$ is the electronic stopping power for a dislocation in a normal metal[1)]. An expression for F_n can be obtained by putting $\Delta = 0$ for the energy gap in formula (6) of[2]. This expression coincides with the expression obtained by Kravchenko[4] and Holstein[5], if allowance is made for some uncertainty in the choice of the constant in the deformation potential. This uncertainty disappears if the ratio F_s/F_n is investigated.

We note first that in the case of extremely small velocities the ratio of the stopping powers in the superconducting and normal states behaves in accordance with the hypothesis by Mason[6] (see also[3]) like the ratio of the ultrasound absorption coefficients:

$$\frac{F_s}{F_n} = \frac{2}{1 + e^{\Delta(T)/T}}, \quad V \ll \frac{\Delta(T)}{\hbar q_m}, \frac{T}{\hbar q_m}. \tag{1}$$

It should be noted that the interval of applicability of formula (1) depends strongly on the temperature.

With increasing dislocation velocity, the temperature-velocity dependence of the force $F_s(T, V)$ becomes much more complicated and its character can be explained only at a temperature close to the critical temperature of the superconductor T_c ($T_c - T \ll T_c$) or close to absolute zero $T \ll T_c$.

In the case of low temperatures $T \ll T_c$, with increasing velocity ($T \ll \hbar q_m V \ll T_c$), the linear dependence of $F_s(T, V)$ on the velocity V gives way to a square-root dependence, and the character of the temperature dependence also changes somewhat

$$\frac{F_s}{F_n} \approx 2\sqrt{\frac{\pi T}{\hbar q_m V}} e^{-\Delta_0/T}, \quad T \ll \hbar q_m V \ll T_c, \tag{2}$$

where $\Delta_0 = \Delta(0)$ is the value of the gap at absolute zero. Further increase of the dislocation velocity $\hbar q_m V \gg T_c$ leads to a turning on of the threshold stopping mechanism, namely generation of electron-hole pairs[2,3]; at such velocities, the electronic stopping power of the dislocation in the superconductor differs only slightly from the stopping power in the normal metal:

$$\frac{F_s}{F_n} \approx 1 - \frac{2\Delta_0}{\hbar q_m V}\left(1 - \sqrt{\frac{\pi T}{2\Delta_0}} e^{-\Delta_0/T}\right) \ln\frac{\hbar q_m V}{2\Delta_0}; \tag{3}$$

$$\hbar q_m V \gg T_c; \quad T \ll T_c.$$

We now proceed to the case of temperatures close to T_c. In the narrow velocity interval

$$\hbar q_m V \ll 2\Delta(T) \approx \approx 6{,}4\, T_c\sqrt{1 - (T/T_c)}$$

formula (1) is valid. At higher velocities $2\Delta(T) \ll \hbar q_m V \ll T_c$ we have

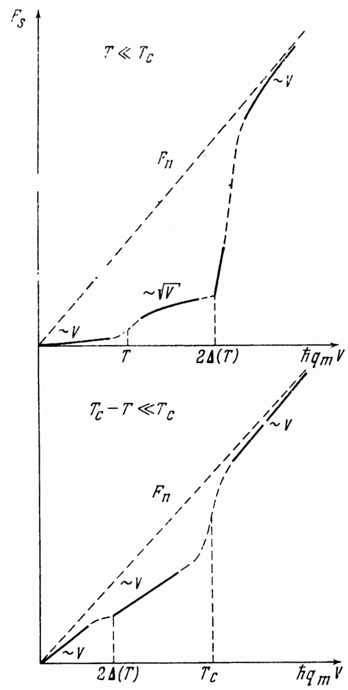
$$F_s/F_n \approx 1 - \Delta(T)/T_c. \tag{4}$$

With further increase of the velocity ($V\hbar q_m \gg T_c$) we have

$$\frac{F_s}{F_n} \approx 1 - \frac{2\Delta(T)}{\hbar q_m V} \ln\frac{\hbar q_m V}{T_c}. \tag{5}$$

It must be emphasized that when $V = V_{cr}(T) = 2\Delta(T)/\hbar q_m$ the curve representing the dependence of F_s on the velocity has a kink due to the inclusion

1) We use the notation of [2].



of the aforementioned threshold mechanism of deceleration. The magnitude of the kink is characterized by a jump of the perimeter

$$\delta\left(\frac{\partial F_s}{\partial V}\right) = \left(\frac{\partial F_s}{\partial V}\right)_{v=v_{cr}+0} - \left(\frac{\partial F_s}{\partial V}\right)_{v=v_{cr}-0}$$

and can be calculated at an arbitrary temperature:

$$\delta\left(\frac{\partial F_s}{\partial V}\right) = \frac{\pi}{2} B_n \,\mathrm{th}\frac{\Delta(T)}{2T}, \qquad (6)$$

where $B_n = F_n/V$ is the coefficient of deceleration in the normal metal. The kink is maximal at $T = 0$, and naturally, vanishes when the metal goes over into the normal state ($\Delta \to 0$). The value of the stopping power F_s at the point $V = V_{cr}$ has in the limiting cases the form

$$\frac{F_s}{F_n} \approx \begin{cases} \pi\sqrt{\dfrac{\pi T}{2\Delta_0}}\, e^{-\Delta_0/T}, & T \ll T_c, \\ 1 - 3\left(\dfrac{3}{4} - \ln 2\right)\dfrac{\Delta T}{T_c}, & T_c - T \ll T_c. \end{cases} \qquad (7)$$

Schematically, the dependence of the dislocation stopping power in a superconductor on the velocity is shown in the figure.

The foregoing formulas enable us to compare the temperature dependence of the jump in the stopping power $\delta F = F_n - F_s$ with the temperature dependence of the gap $\Delta(T)$ 2). At the lowest velocities, as seen from (1), the temperature dependence of δF does not reduce to that of $\Delta(T)$. At intermediate velocities ($\hbar q_m V \ll T_c$), in accordance with (2) and (4), we have

$$\frac{\delta F}{F_n} \approx \begin{cases} 1 - \sqrt{\dfrac{2\Delta_0}{\hbar q_m V}}\left[1 - \dfrac{\Delta(T)}{\Delta_0}\right], & T \ll T_c, \\ \Delta(T)/T_c, & T_c - T \ll T_c. \end{cases}$$

Finally, at the highest velocities ($\hbar q_m V \gg T_c$) it follows from (3) and (5) that

$$\frac{\delta F}{F_n} \approx \begin{cases} \dfrac{\Delta_0}{\hbar q_m V}\ln\left(\dfrac{\hbar q_m V}{2\Delta_0}\right)\left[1 + \dfrac{\Delta(T)}{\Delta_0}\right], & T \ll T_c, \\ \dfrac{2\Delta_0}{\hbar q_m V}\ln\left(\dfrac{\hbar q_m V}{T_c}\right)\dfrac{\Delta(T)}{\Delta_0}, & T \lesssim T_c \end{cases}$$

Thus, in limiting cases the temperature dependence of δF coincides with the temperature dependence of $\Delta(T)$. However, there exists no single linear dependence of δF on $\Delta(T)$ within the framework of the mechanism under discussion. It is possible that the temperature variation of the jump of the deforming stress, which coincides according to[1] with the $\Delta(T)$ dependence in a broad temperature interval, is the consequence of averaging over a large number of dislocations moving with different velocities.

We take the opportunity to thank V. V. Pustovalov and V. I. Startsev for numerous stimulating discussions.

2) At low temperatures we have $\Delta(T) \approx \Delta_0 - \sqrt{2\pi T\Delta_0}\, e^{-\Delta_0/T}$.

1 V. V. Pulstovalov and V. S. Fomenko, ZhETF Pis. Red. 12, 15 (1970) [JETP Lett. 12, 10 (1970)].
2 M. I. Kaganov and V. D. Natsik, ibid. 11, 550 (1970) [11, 379 (1970)].
3 G. Hoffman and N. Louat, Phys. Rev. Lett., 24, 1055 (1970).
4 V. Ya. Kravchenko, Fiz. Tverd. Tela 8, 927 (1966) [Sov. Phys.-Solid State 8, 740 (1966)].
5 T. Holstein (see Appendix to: B. Tittman and H. Bömmel, Phys. Rev., 151, 178 (1966).
6 W. Mason, Appl. Phys. Lett., 6, 111 (1965).

Translated by J. G. Adashko
37