Critical pair-breaking currents of thin superconducting films in a perpendicular magnetic field

N. Ya. Fogel', A. A. Moshenskiĭ, A. M. Glukhov, and I. M. Dmitrenko

Physico-technical Institute of Low Temperatures, Ukrainian Academy of Sciences

(Submitted September 25, 1975)
Pis'ma Zh. Eksp. Teor. Fiz. **22**, No. 9, 450–454 (5 November 1975)

It is observed that the critical current of thin superconducting In and Pb films in perpendicular fields close to H_{c2} is determined by the mechanism of Cooper-pair breaking. The critical current and its field dependence are well described within the framework of a simple phenomenological energy model.

PACS numbers: 73.60.Ka, 74.40.Jw

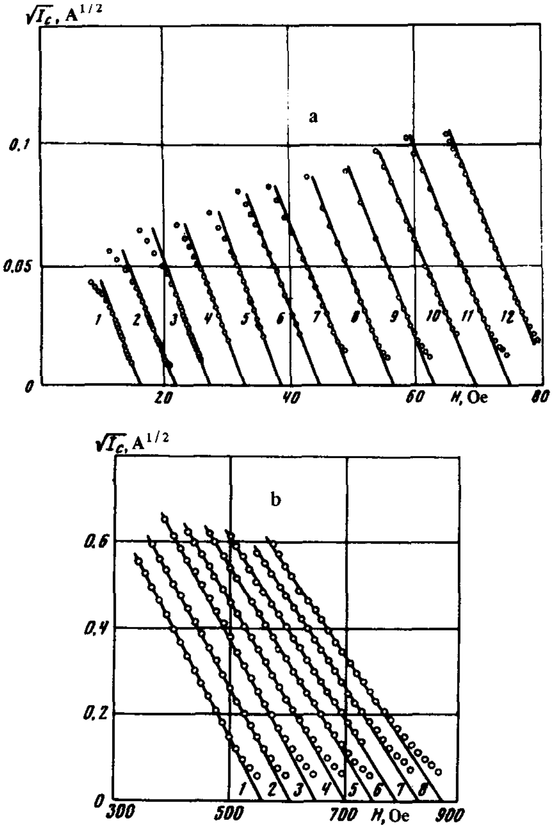
If transport current is made to flow through a type-II superconductor (SC II) in the mixed state, then the superconductor goes over into the resistive state after a certain critical current is reached. Two resistivity mechanisms are possible: energy dissipation by the moving vortices, and Cooper-pair decay when the superconducting condensate reaches critical velocity. The superconductivity-destruction mechanism that should be realized in experiment is the one corresponding to the lower value of the critical current. In the overwhelming majority of cases the critical pinning current in the mixed state is much smaller than the pair-breaking current. However, in bulky SC II the inverse situation was also observed. In Nb-Ti alloys, under conditions when the vortex lattice is rigidly fastened to the pinning centers, one measures the critical pair-breaking current near H_{c2}.

In a perpendicular magnetic field, thin superconducting films behave like SC II. We have observed that in this case, too, in fields close to H_{c2}, the critical current is connected with the pair-breaking mechanism.

The critical current I_c was investigated in polycrystalline wide In and Pb films of thickness $d = 450-1000$ Å. The edges of the films, which were of uneven thickness, were cut off. I_c was determined from the appearance of a fixed voltage across the potential leads of the film. The $I_c(H_\perp)$ characteristics of many samples were measured at various temperatures. In fields up to $0.5H_{c2}$ the critical current is determined by the pinning of the vortices.[2] In stronger fields, the $I_c(H_\perp)$ characteristics exhibit a small kink, beyond which the field and temperature dependences of I_c undergo an appreciable change. The field dependence obtained for the critical current near H_{c2} is conveniently represented in the form of plots of $I_c^{1/2}$ against $H_\perp$ (see the figure). The intercepts of the lines with the abscissa axis yield the values of H_{c2}, which agree well with those determined from the $V(H)$ transition curves at fixed current. It follows from the plots in the figure that near H_{c2} the critical current of the films is described by the following empirical expression:

$$I_c = \gamma H_{c2}^2(t)(1-h)^2, \tag{1}$$

where $h = H/H_{c2}(t)$ and γ is a coefficient that is practically independent of temperature. Similar results were obtained also with other samples. For the In films, the $I_c(h)$ dependence described by expression (1) was observed in the field interval $0.8 < h \lesssim 1$, whereas the relative field h_1, starting with which this dependence is observed, is the same at all temperatures. The small deviation of the points from straight lines in the figure in the immediate vicinity of H_{c2} is apparently due to the fluctuation smearing of the phase transition in the magnetic field. The field dependence observed in the



Plot of $I_c^{1/2}$ against $H_\perp$ at various temperatures. a) In film 460 Å thick: 1—t=0.96, 2—0.94, 3—0.92, 4—0.90, 5—0.88, 6—0.86, 7—0.84, 8—0.82, 9—0.80, 10—0.78, 11—0.76, 12—0.74. b) Pb film 7 Å thick: 1—t=0.584, 2—0.542, 3—0.502, 4—0.460, 5—0.418, 6—0.377, 7—0.334, 8—0.290.

In and Pb films agrees with the field dependence of I_c observed in[1] for the critical pair-breaking current.

According to contemporary notions,[3] the change of the superconducting-electron energy in the presence of current in the superconductor is determined by the quantity $p_F v$, where p_F is the Fermi momentum and v is the drift velocity. The change of the kinetic-energy density of the superconducting electrons, due to the presence of the current, is of the order of $n_s p_F v$ (n_s is the density of the superconducting electrons in a layer $\sim\Delta$ near the Fermi surface). Calculations in[4] and at $T=0$ yielded $n_s(0)=\Delta(0) m p_F/2\pi^2\hbar^3$. To obtain the dependence of the critical pair-breaking current on the magnetic field, it is necessary to equate the change of the electron kinetic-energy density to the difference between the free-energy densities in the normal and superconducting states[5] in a magnetic field[1,6]:

$$\frac{2\kappa^2 H_{\text{free}}^2(1-h)^2}{8\pi\{[2\kappa^2-f(\eta)]\beta_0+1\}}=n_s p_F v_c\,. \tag{2}$$

The critical density of the pair-breaking current is given by

$$j_{sc}=N_s e v_c\,. \tag{3}$$

When calculating the critical current density j_{sc} it is necessary, in contrast to[6], to take into account the fact that N_s in (3) is the total concentration of the superconducting electrons. The concentration of the superconducting electrons, both the total one and the one in the strip near the Fermi surface, decreases with increasing magnetic field in the mixed state as the vortex density is increased.

We confine ourselves to the simplest case $T=0$. From (2) and (3) with allowance for the expression for $n_s(0)$ we obtain for $j_{sc}(0)$ in a perpendicular field

$$j_{sc}(0)=\frac{\pi\hbar^3 e\kappa^2 H_{\text{free}}^2(0)(1-h)^2 N_{s0}}{4\Delta(0)m^3 v_F^2\{[2\kappa^2-f(\eta)]\beta_0+1\}}, \tag{4}$$

where $N_{s0}=mc^2/4\pi e^2\lambda_L^2(0)$. Comparing (4) with the experimentally observed empirical law (1), we can conclude that the considered model describes well the field dependence of I_c. Recongnizing that the slope γ in (1) is practically independent of the temperature, we can, by equating (1) and (4), determine v_F from the experimental values of γ and compare the obtained quantity with the known published data on In and Pb. The results of such a comparison for a number of films are given in the table. In the calculation of γ, the density of the critical current is calculated on the basis of the transverse dimensions of the samples. In the calculations for In we used the values $\lambda_L(0)=390$ Å, $2\Delta(0)/kT_c=3.64$, $m_{\text{eff}}=1.35m_0$, while for Pb we used $\lambda_L(0)=315$ Å, $2\Delta(0)/kT_c=4.34$, and $m_{\text{eff}}=2.1m_0$.[7] The values of m_{eff} and v_F were taken from[8] for polycrystalline In and Pb samples. It is seen from the table that the experimentally determined critical current agrees quite well in absolute value with its theoretical value in the considered model.

Additional evidence in favor of the pair-breaking mechanism is also provided by preliminary results of analogous investigations on In films with implanted helium particles. The values of I_c and γ remain practically constant following bombardment with a large dose, whereas in weak fields, where the critical current is determined by the vortex-pinning mechanism, the value of I_c changes after bombardment by one order of magnitude.[2]

On the basis of all the foregoing we can state that in thin In and Pb films, near H_{c2}, the critical current is connected with the breaking of the Cooper pairs. This mechanism seems to "go into operation" near H_{c2} ahead of the vortex instability, owing to the strong decrease

In	d	460Å	460Å	480Å	960Å
	v'_F/v_F	0.82	0.87	0.72	1.04
Pb	d	700Å	400Å	–	–
	v'_F/v_F	1.68	1.96	–	–

v'_F is the Fermi velocity obtained from the experimental data with the aid of (4); v_F is the Fermi velocity from the published data.[8]

of the concentration of the superconducting electrons at a large vortex density. One can expect to observe a similar behavior in strong fields in thin superconducting films of other materials.

In conclusion, the authors thank V. P. Galaǐka for a discussion of questions touched upon in the article.

[1] Yu. F. Bychkov, V. G. Vereshchagin, M. T. Zuev, V. R. Karasik, G. B. Kurganov, and V. A. Mal'tsev, ZhETF Pis. Red. **9**, 451 (1969) [JETP Lett. **9**, 271 (1969)]; Zh. Eksp. Teor. Fiz. **56**, 505 (1969) [Sov. Phys.-JETP **29**, 276 (1969)].

[2] N. Ya. Fogel', A. A. Moshenskii, L. P. Tishchenko, T. I. Pergon, Ya. M. Fogel', and I. M. Dmitrenko, Phys. Lett. **53A**, 52 (1975).

[3] J. Bardeen, Rev. Mod. Phys. **34**, 667 (1962).

[4] R. H. Parmenter, RCA Rev. **23**, 323 (1962).

[5] K. Maki, Ann. Phys. (N. Y.) **34**, 363 (1965).

[6] S. Takacs, Phys. Lett. **46A**, 121 (1973).

[7] I. Giaever and K. Megerle, Phys. Rev. **122**, 1101 (1961); H. R. Kerchner and D. M. Ginzberg, Phys. Rev. **B10**, 1916 (1974); J. G. Adler, J. E. Jackson, Phys. Lett. **24A**, 407 (1967).

[8] W. L. McMillan and P. W. Anderson, Phys. Rev. Lett. **16**, 85 (1966); P. Morel and P. W. Anderson, Phys. Rev. **125**, 1263 (1962).