RELATION BETWEEN CURRENT AND VOLTAGE IN TYPE-II SUPERCONDUCTORS IN THE FLUX-FLOW REGIME*

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It has been found that the relation $\ln I \propto V^{1/2}$ accurately describes flux flow in superconductors in both the "linear" and "nonlinear" portions of the I-V curves. The validity of this relation is sample independent.

When a current is passed through a type-II superconductor in the mixed state in a transverse magnetic field, a voltage is observed when the current exceeds a certain critical value, I_p, for the sample. It has been reported[1] that the voltage appears to be linearly related to the current for $I > I_p$; however, near I_p, the graph of V as a function of I is curved so that it appears to join the I axis tangentially. Kim, Hempstead, and Strnad[1] suggested that this curved part is no more than a departure from ideal conditions, and recently Jones, Rhoderick, and Rose-Innes[2] suggested that this is due to inhomogeneities in the sample. We present here evidence that V and I satisfy the relation $\ln(I/I_p) \propto V^{1/2}$ over the whole range of I and that the division of the I-V curves into "linear" and "curved" parts is no more than an optical illusion.

In Fig. 1 we have displayed the flux-flow data of Kim, Hempstead, and Strnad[1] on bulk $Pb_{0.83}In_{0.17}$, the data of Farrell, Dinewitz, and Chandrasekhar[3] on bulk $Pb_{0.80}In_{0.20}$ and some of our own data on magnetically coupled[4] $In_{0.97}Pb_{0.03}$ films, wherein the voltage shown is that across the secondary film. As much of the data as was displayed in Refs. 1 and 3 was used in Fig. 1. The secondary voltages taken from the magnetically coupled film studies were plotted right up to the current at which the secondary decoupled from the primary. The primary voltages were also found to follow the relation $\ln(I/I_p) \propto V^{1/2}$ up to the point at which they were driven normal by the combined effect of field and current. We note the small amount of scatter in the data and the fact that the slopes appear to be characteristic of the sample. However, the effect of field is merely to shift the intercept of the curve with the $\ln I$ axis. The validity of this relation is sample independent and holds for values of the depinning current density which span more than two decades. Furthermore, it is applicable in the case of (i) linear flux flow, (ii) nonlinear flux flow, and (iii) induced flux flow[4] (magnetically coupled films).

In order to demonstrate the suggestion that the origin of the "nonlinear" portion of the flux-flow curves may be sample inhomogeneity, Jones, Rhoderick, and Rose-Innes[2] prepared a $Nb_{0.5}Ta_{0.5}$ sample which was shown to be inhomogeneous in an experiment in which flux-flow voltages could be observed in different sections of the sample. Their data for this

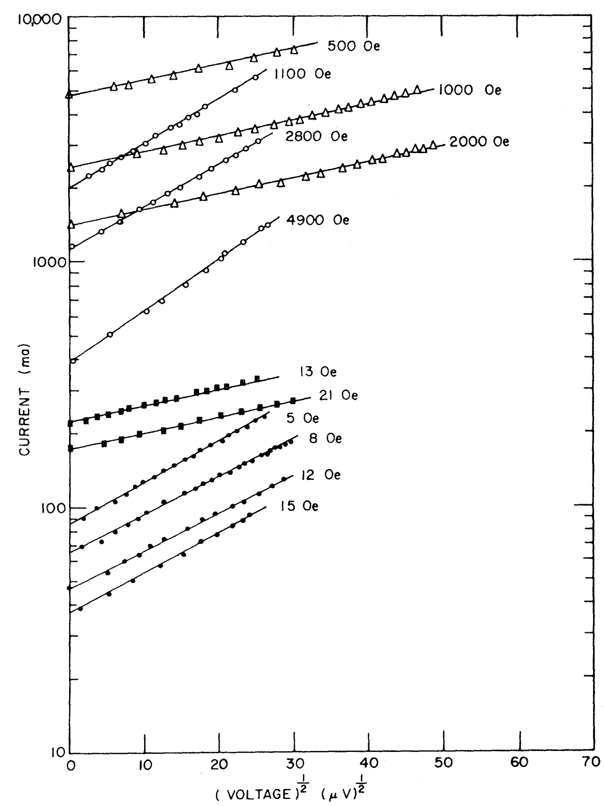

FIG. 1. LnI is plotted as a function of the square root of the flux-flow voltage for a variety of samples. Open triangles: data of Kim, Hempstead, and Strnad[1] on bulk $Pb_{0.83}In_{0.17}$ ("linear flux flow"); open circles; data of Farrel, Dinewitz, and Chandrasekhar[3] on bulk $Pb_{0.80}In_{0.20}$ ("nonlinear flux flow"); solid squares: data from this work on $In_{0.97}Pb_{0.03}$ films in a dc transformer configuration,[4] V being the voltage across the secondary ($t = 0.8$). Solid circles: the same as preceding entry, except that $t = 0.9$.

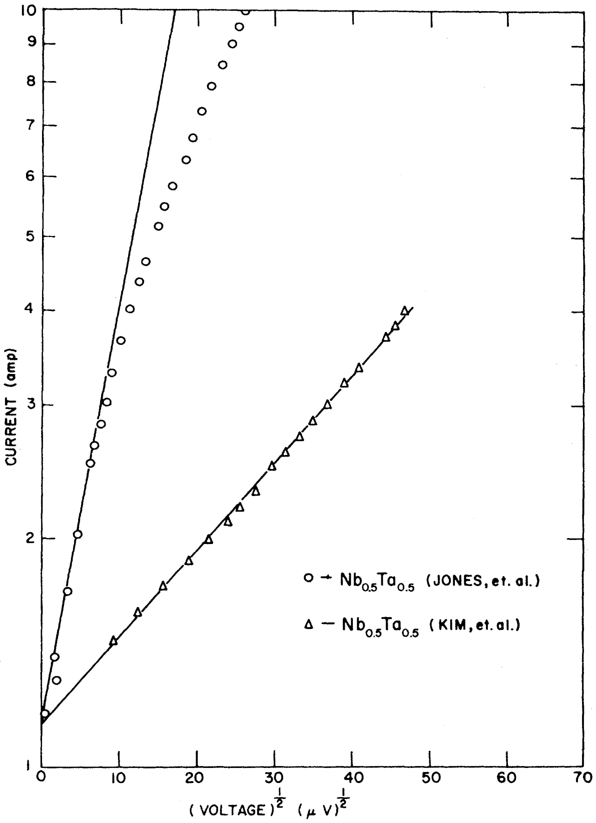

FIG. 2. Circles: data of Jones, Rhoderick, and Rose-Innes[2] for an inhomogeneous $Nb_{0.5}Ta_{0.5}$ alloy. Triangles: data of Kim, Hempstead, and Strnad[1] for a similar (but perhaps homogeneous) sample.

sample (the entire sample) are shown in Fig. 2. It can be seen that the data from this (an inhomogeneous sample) do not fit our relation. The lack of fit, however, does not seem to be an intrinsic characteristic of $Nb_{0.5}Ta_{0.5}$, as we have also plotted the data from one of the $Nb_{0.5}Ta_{0.5}$ alloys used in the pioneer work of Kim, Hempstead, and Strnad,[1] and this can be seen to fit quite well. The data (not shown) for a second $Nb_{0.5}Ta_{0.5}$ sample used in the studies by Kim et al. do not fit our relation—in fact, the deviation is similar to that of the data for the inhomogeneous sample used in the study by Jones et al.

We have also discovered the importance of sample geometry effects in determining the shape of the I-V curves. This is illustrated in Fig. 3, where two representative sample arrangements are shown. A 1000-Å $In_{0.97}Pb_{0.03}$ film sample with the voltage-lead geometry (tabs 1 and 2) illustrated in (a) exhibited flux-flow curves which were similar in appearance

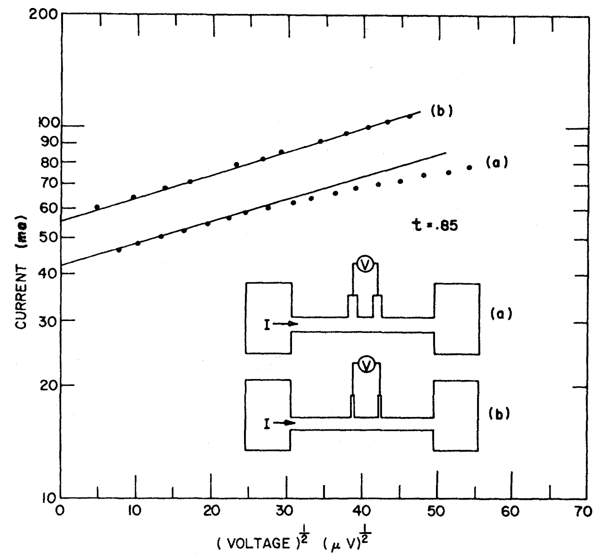

FIG. 3. Flux-flow data for 1000-Å $In_{0.97}Pb_{0.03}$ film. Upper curves: data for sample configuration (*b*) shown in inset. Lower curve: data for sample configuration (*a*).

to those obtained with the "inhomogeneous" $Nb_{0.5}Ta_{0.5}$ samples. When the voltage tabs were made narrower (on the same sample), the I-V characteristics obeyed the relation $\ln(I/I_p) \propto V^{1/2}$, thus illustrating the importance of having a uniform current distribution, and therefore "controlled" sample geometry.

The reason for the I-V flux-flow "characteristics" being formally the same as for the I-V characteristics of field emission[5] from a metallic surface is still obscure. It is as if the "transport electrons" interact with the "normal" electrons in the vortex core with a Coulombic $1/r$ potential superimposed upon a potential from a constant electric field. The constant field is presumably just the electric field that is said to arise because of vortex motion.[1,6-8]

Thus we conclude that whereas sample inhomogeneity may contribute to the "curved part" of the flux-flow characteristics, the fact that the same relation [viz. $\ln(I/I_p) \propto V^{1/2}$] holds for such a variety of samples leads one to suspect that the "curved part" may be as significant as the "linear part." Exactly why $\ln I$ should be proportional to $V^{1/2}$ is not understood.

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[1]Y. B. Kim, C. F. Hempstead, and A. R. Strnad, Phys. Rev. 139, A1163 (1965).

[2]R. G. Jones, E. H. Rhoderick, and A. C. Rose-Innes, Phys. Letters 24A, 318 (1967).

[3]D. E. Farrell, I. Dinewitz, and B. S. Chandrasekhar, Phys. Rev. Letters 16, 91 (1966).

[4]I. Giaever, Phys. Rev. Letters 15, 825 (1965); P. Solomon, Phys. Rev. Letters 16, 50 (1966).

[5]F. Seitz, The Modern Theory of Solids (McGraw-Hill Book Company, Inc., New York, 1940), p. 162.

[6]P. W. Anderson, N. R. Werthamer, and J. M. Luttinger, Phys. Rev. 138, A1157 (1965).

[7]B. B. Schwartz, Bull. Am. Phys. Soc. 11, 106 (1966).

[8]J. Bardeen and M. J. Stephen, Phys. Rev. 140, A1197 (1965).

SUPERCONDUCTIVE PAIRING ACROSS ELECTRON BARRIERS*

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We consider the possibility of superconductive pairing of two electrons separated by a barrier. We argue that such pairing is possible in principle for all metals and may lead to high transition temperatures.

Systems comprised of two superposed metal films S_1 (thickness t_1) and S_2 (thickness t_2) separated by an insulating barrier B (thickness t_B), as in Fig. 1(a), have been intensively studied in connection with superconductive tunneling.[1-3] It has been assumed that both electrons of the Cooper pairs in such systems lie either in S_1 or S_2. In this Letter we consider the possibility of superconductive pairing across B, i.e., Cooper pairs with one electron in S_1 and one in S_2. We find that such pairing is possible in principle and would lead to novel effects including the possibilities of higher transition temperatures for known superconductors and of superconductivity in previously nonsuperconducting materials, e.g., the magnetic metals.

Apart from partial reflection at the S_1B and BS_2 interfaces, B does not present a barrier to phonons. An electron in S_1 can emit a phonon which subsequently travels across B and is absorbed by an electron in S_2, Fig. 1(b), resulting in an attractive, phonon-induced interaction $V_{\rm ph}^{12}$ comparable in magnitude with the interaction within a single film $V_{\rm ph}^{11}$. The Coulomb interaction across the barrier V_C^{12}, on the other hand, differs greatly from that within a single film V_C^{11}. Because the screening cloud around an electron is of radius λ_{TF}, the static screening length, electrons on opposite sides of the barrier interact via a dynamically screened Coulomb interaction similar to that in the bulk. The closest distance of approach, however, is only t_B. Provided t_B, t_1, and t_2 exceed λ_{TF}, V_C^{12} is reduced essentially to zero for low-energy transfers, leaving a residuum at higher energies which acts as an attractive interaction.[4] Dynamical effects such as the exchange of low-frequency surface plasmons[5,6] could provide an additional attractive interaction. These crude arguments suggest that the net interaction across the barrier, $V_T^{12} = V_{\rm ph}^{12} + V_C^{12}$, could be attractive for all choices of metals S_1 and S_2. Such an attractive interaction would give rise to pairing across the barrier as a possible new channel whereby superconductivity could be

(a)

(b)

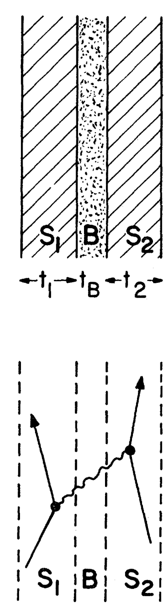

FIG. 1. (a) Metal (S_1)-insulator (B)-metal (S_2) sandwich. (b) Feynman diagram for phonon-induced electron-electron interaction across the barrier $V_{\rm ph}^{12}$.