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VOLTAGE ASSOCIATED WITH THE COUPLED MOTION OF FLUX IN TYPE-I SUPERCONDUCTORS

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Potential differences across current-carrying type-II superconductors in the mixed state and type-I superconductors in the intermediate state have previously been observed.[1-8] Recently Giaever[9] reported an experiment supporting the interpretation which attributes the potential difference across a type-II superconductor in the mixed state to the fields produced by quantized flux lines (Abrikosov vortices) moving through the material.[10-14] This Letter reports an analogous experiment which was performed on a type-I superconductor in the intermediate state. It confirms that the potential difference across a type-I superconductor in the intermediate state is also due to the motion of vortices. Our results indicate that, as expected, the vortex structures for a type-I superconductor in the intermediate state depend on sample geometry and can be much larger and contain many more flux quanta than the vortices of a type-II superconductor in the mixed state. These results are important in view of the many recent papers on the motion of vortex structures in the intermediate state.[15]

The experiment was performed with sandwiches consisting of two superconducting strips separated by a thin insulating layer. A typical sample geometry is shown in Fig. 1. The lower superconductor is called the primary and the upper superconductor is called the secondary. A magnetic field was applied perpendicular to the broad surface of the sample and a current, I_p, was passed through the primary. If the two superconductors were in close enough proximity, then a potential difference, V_p, across the primary was sometimes accompanied by a potential difference, V_s, across the secondary.

The results are explained by assuming that the potential differences, V_s and V_p, are produced by the motion of vortices across the respective superconductors and that the vortices in the secondary are moved by forces exerted on them by the vortices moving through the primary. To understand how a potential difference is produced by the moving vortices, consider the motion of a single vortex.[16] When a vortex is created or destroyed at the edge of the superconductor, solenoidal electric fields are induced within the superconductor. In order to make the total electric field within the superconductor equal to zero, charges are distributed on the surface of the superconductor producing an irrotational electric field which exactly cancels the solenoidal electric field everywhere within the superconductor except within the penetration depth and the area around the vortex. The electric fields do not cancel outside the superconductor, and it is the integral of this electric field along the voltmeter leads which produces the observed potential difference. To understand how the vortices in the

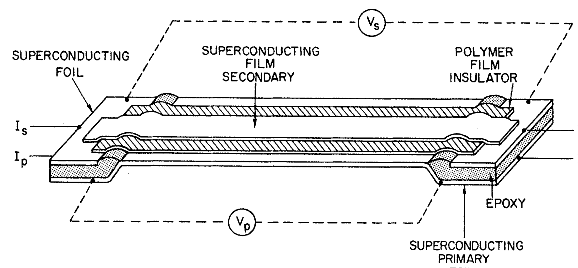

FIG. 1. Typical geometry for a superconducting sandwich.

secondary are moved by vortices in the primary, consider the extreme case of two completely isolated vortices in the primary and secondary which are lined up so that the magnetic field lines pass directly through the two vortices. If the two vortices are moved apart, the magnetic field lines will have to make a bend in the insulating layer. The bending of the field lines produces an increase in the energy of the system and, hence, forces which tend to keep the vortices lined up. This process yields some maximum force, F_m, which can be exerted by one vortex on the other. In the other extreme where the vortices are closely packed, the field lines in the insulator have almost uniform intensity, and negligible force will be exerted to keep the vortices lined up. When the vortices are loosely packed the maximum force that can be exerted will be between zero and F_m. The vortex in the secondary will move if this force is large enough to overcome the forces of pinning and viscous drag. This picture leads to the criterion suggested by Giaever,[9] that in order to get coupled motion of the vortices the spacing between the two superconductors must be small compared to the spacing between the vortices.

To investigate the coupled motion of vortices, measurements of V_s and V_p were made in a variety of samples as a function of I_p for various values of magnetic field and temperature. In all samples on which measurements were made, the resistance between the primary and secondary was observed to be in excess of 10^3 Ω, and V_s was observed to be zero for all values of V_p when both the primary and the secondary were normal. Three samples had the geometry shown in Fig. 1. Sample A had a 0.25-mm-thick Pb foil primary [residual resistance ratio, $R_{300°\mathrm{K}}/R_{4.2°\mathrm{K}}(H=H_c)$, of about 10^4], a 2000Å polymer insulator, and a 10 000Å Pb film secondary. Samples B and C had similar primaries and secondaries separated by 4000 and 20 000Å-thick polymer insulators, respectively. Sample D consisted of a 50 000Å-thick Pb film primary, a 10 000Å-thick Pb secondary, and a 2000Å-thick polymer insulator. Coupling was observed in samples A, B, and C but not in sample D. At small values of V_p the ratio of V_s to V_p (which will be called the coupling parameter) was independent of I_p for fixed magnetic field and temperature. When I_p was increased and V_p became larger, V_s was sometimes observed to level off. This is reasonable since an increase in V_s requires that the vortices in the secondary move faster, and this in turn requires that a larger force be exerted on them to overcome the viscous drag. When V_s levels off, the moving vortices in the primary were presumably exerting their maximum force on the vortices in the secondary. In Fig. 2 the coupling parameter for sample B for small V_p is plotted as a function of magnetic field for several temperatures. The coupling parameter has a maximum value of 0.8 at low magnetic fields. The striking feature of the curves is the sharp drop of the coupling parameter to zero with increasing field. This occurs when the magnetic field is roughly $\frac{2}{3}$ of the critical field at that temperature. The curves for sample A are similar while for sample C the coupling parameter has a maximum value of only 0.25 and falls to zero at slightly lower fields.

The explanation for the above results is related to the criterion for coupling which requires that the moving magnetic field produced by the vortices in the primary be sufficiently inhomogeneous to exert a force on the vortices in the secondary to overcome the pinning and viscous drag forces. The pinning forces on the vortices in the secondaries of samples A, B, C, and D are similar and so the differences in the coupling parameter reflect the differences in the applied forces. It should be noted that for a given magnetic field, the size of the vortices in samples A, B, and C should be identical since they all have primaries of the same thickness. The fact that no coupling is observed in sample D which has the same spacing between

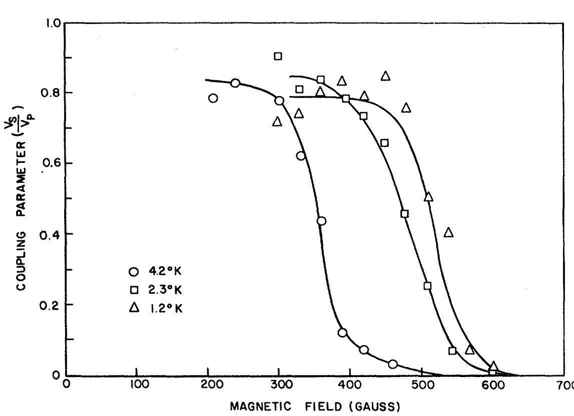

FIG. 2. Coupling parameter in sample B for small values of V_p as a function of magnetic field at various temperatures.

primary and secondary as sample A suggests that for a given magnetic field, the vortices in the 0.25-mm-thick primary of sample A are farther apart and are, therefore, bigger and contain more flux quanta than the vortices in the 50 000Å-thick primary of sample D. The variation in the maximum value of the coupling parameters for samples A, B, and C suggests that at $\frac{1}{2}$ the critical field, the typical dimension for the structure of the intermediate state is on the order of 20 000Å. The sharp drop in the coupling parameter at increased magnetic field must also be related to the size of the vortex structure, the distance between vortices, and the distance between the superconductors. It appears, therefore, that measurement of the coupling parameter could be a useful tool to investigate the structure of the intermediate state.

A potential difference across the secondary was also observed in sample E in which the secondary was wider than the primary. This is in contradiction with one of the conditions proposed by Giaever[9] as necessary for the observation of coupling between superconductors. While the above geometry is not the most advantageous for the observation of coupling it is not prohibitive. The only condition necessary for the observation of a potential difference across the secondary is that vortices move across the secondary. Assume that the center section of the secondary is close enough to the surface of the primary for vortices moving in the primary to exert forces sufficient to overcome pinning on the vortices in that section and start them moving. Then vortices will be removed from one edge of the secondary and piled up on the other. This process will continue until one of two things happens: Either the gradient in the density of vortices at the edge of the film becomes sufficiently steep to push vortices out of one edge and pull them into the other, or else the gradient becomes so steep that the increased force required to push the vortices through the central region against the gradient cannot be exerted by the vortices moving in the primary. The former condition allows motion of vortices through the secondary and hence a potential difference while the latter situation allows no motion of vortices and hence no potential difference. It is interesting to note that the coupling parameter for sample E was very anisotropic, having a maximum value of 0.20 for the motion of flux in one direction and a value close to zero for the motion of flux in the other. This point will be the subject of further investigation.

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