Observation of penetration of Abrikosov vortices into superconducting niobium films with the help of a Josephson tunnel junction

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The penetration of Abrikosov vortices into niobium films and the pinning of the vortices in these films have been observed and studied with the help of a Josephson tunnel junction in the temperature interval $0.5 \lesssim T/T_c \lesssim 1$.

Abrikosov vortices pinned in the electrodes of Josephson tunnel junctions strongly influence the Josephson critical current I_c (Ref. 1). This property of Josephson tunnel junctions has recently been utilized[2] to study the elementary force which pins the Abrikosov vortices. In the present letter we report the use of an *S-I-S* Josephson tunnel function to study the penetration of Abrikosov vortices into superconducting niobium films and the pinning of the vortices in these films at various temperatures.

In the experiments we used an Nb–AlO_x–Nb Josephson tunnel junction. The thicknesses of the lower and upper electrodes were $d_l \sim 200$ nm and $d_u \sim 400$ nm, respectively. The weak-link region had transverse dimensions of 12×12 μm^2. The inset in Fig. 1 shows the configuration of the Josephson junction. The procedure by which the junction was fabricated is described in Ref. 3. For niobium films synthesized by a similar procedure, the London penetration depth is $\lambda_L(4.2\text{ K}) \approx 85$ nm (Ref. 4), and the coherence length is $\xi(4.2\text{ K}) \approx 13$ nm (Ref. 5).

If the electrodes of the junction do not have pinned Abrikosov vortices, the experimental plot of I_c versus the magnetic field component parallel to the plane of the junction, $B_\parallel$, has a shape approximately that of an ideal Fraunhofer curve, indicating that the critical current density is distributed uniformly over the cross section of the contact.[6]

Let us outline the experimental procedure. A magnetic field directed perpendicular to the plane of the junction is increased from 0 to a certain value $B_\perp$ and then turned off. We then measure $I_c(B_\parallel)$. During these events, the sample is at constant temperature $T < T_c$, where T_c is the superconducting transition temperature. It was found that for fields $B_\perp^+$ (the + means that the magnetic field is oriented as in the inset in Fig. 1) there exists an interval of field values between 0 and $B_\perp^*$ in which the curve of $I_c(B_\parallel)$ remains the same and corresponds to a "vortex-free" Fraunhofer curve (the solid line in Fig. 1). When $B_\perp^+ = B_\perp^*$ is reached, however (at 4.2 K, $B_\perp^* \approx 10$ G), the shape of the $I_c(B_\parallel)$ curve changes abruptly; in particular, the maximum Josephson critical current decreases, and the current near the first minimum increases (the dashed line in Fig. 1). According to the conclusions reached in Ref. 2, these changes in the $I_c(B_\parallel)$ curve indicate the appearance of the first Abrikosov vortices in

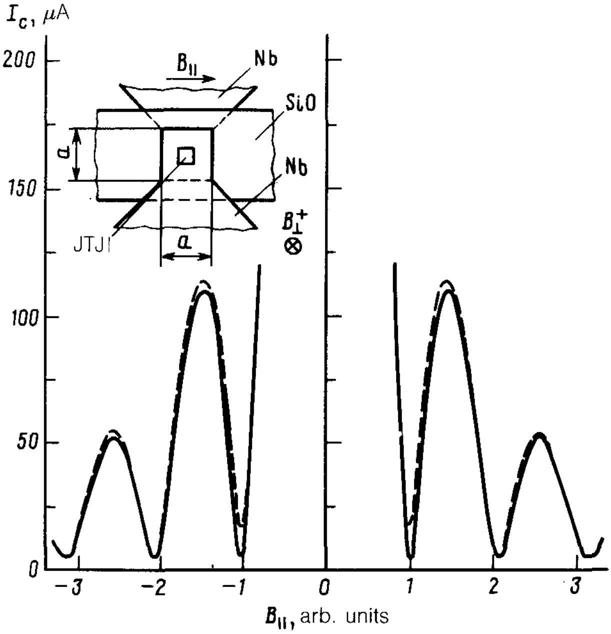

FIG. 1. Fragment of an $I_c(B_{\parallel})$ curve. Solid line—Results of measurements for a Josephson junction whose electrodes contain no pinned Abrikosov vortices; dashed line—the same behavior, but after the imposition of a field $B_\perp^+ = B_\perp^*$. The temperature is 4.2 K. The inset shows the configuration of the Josephson junction and the orientation of the magnetic fields; here $a = 40$ μm.

the junction and the pinning of these vortices at pinning centers when the field $B_\perp^+ = B_\perp^*$ is reached. The niobium films forming the Josephson junction are bulk type-II superconductors ($d_l, d_u > \lambda_L$ and $\kappa = \lambda_L/\xi \approx 6$ at 4.2 K), and at such weak magnetic fields the vortex penetration may occur by virtue of a demagnetizing factor $n \approx 1$ and the granular structure of the films.[7] The field at which the vortices begin to penetrate into the film is weaker than $B_\perp^*$, because the junction is at the center of the niobium electrodes (see the inset in Fig. 1).

When a perpendicular magnetic field of the opposite polarity ($B_\perp^-$) is applied, the nature of the $I_c(B_{\parallel})$ curve does not change immediately after $B_\perp^+ = B_\perp^*$ is reached, up to fields $|B_\perp^-| < |B_\perp^{**}|$. This result is evidence that there are vortices in the junction region. Upon the attainment of $B_\perp^{**}$ ($|B_\perp^{**}| \approx 6$ G for $T = 4.2$ K, $|B_\perp^{**}| \sim B_\perp^*$) the curve of $I_c(B_{\parallel})$ abruptly reverts to its vortex-free shape.

The penetration of the vortices into the junction region at $B_\perp^+ = B_\perp^*$, and the escape of these vortices at $B_\perp^- = B_\perp^{**}$, are detected simultaneously on the $I_c(B_\perp)$ curve. When $B_\perp^*$ is reached, a hysteresis appears in the $I_c(B_\perp)$ curve, reflecting the penetration and pinning of the first vortices in the junction region. The $I_c(B_\perp)$ curve recovers its original shape at $B_\perp^- = B_\perp^{**}$. Figure 2 shows the temperature evolution of the $I_c(B_\perp)$ curves. We see that as the temperature is raised, the values of $B_\perp^*$ and $B_\perp^{**}$ move closer together [the hysteresis loop on the plots of $I_c(B_\perp)$ shrinks]. At a relative

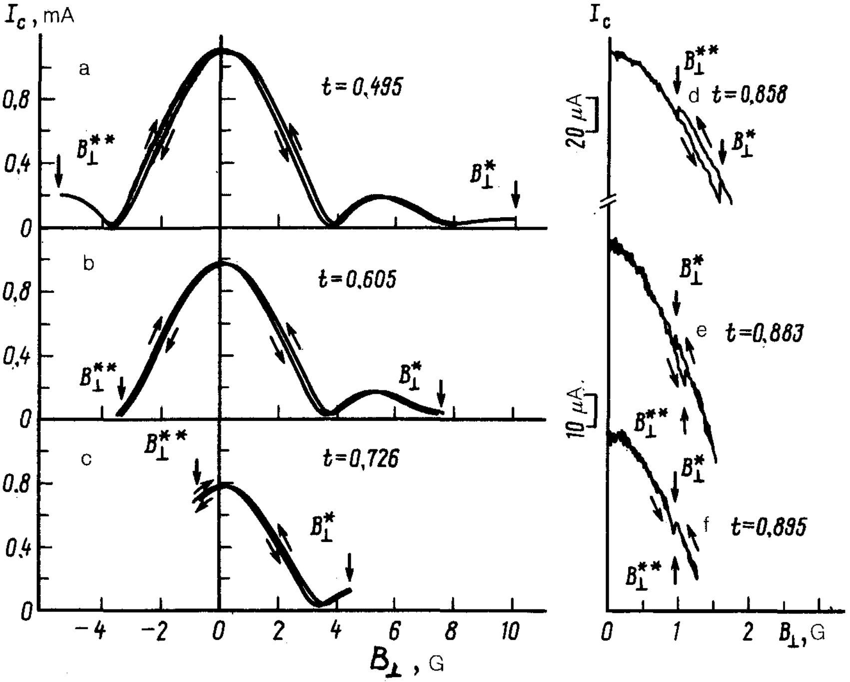

FIG. 2. Temperature evolution of the $I_c(B_\perp)$ curves. Curves *d*, *e*, and *f* are shown in enlarged scale along the current and field axes.

temperature $t = t_1 \approx 0.75$ ($t = T/T_c$), the quantity $B_\perp^{**}$ changes sign, and at $t > t_1$ it acquires the same polarity as that of $B_\perp^*$ (i.e., at temperatures near T_c, it is not necessary to apply a field of the opposite polarity in order to restore the vortex-free state of the junction). When the temperature $t = t_2 \approx 0.89$, the hysteresis loop collapses, and $B_\perp^{**}$ becomes equal to $B_\perp^*$. Figure 3 shows the temperature dependence of $B_\perp^*$ and $B_\perp^{**}$ according to the experimental results shown in Fig. 2.

Our results can be interpreted in the following way. In the temperature interval $t < t_1$ the vortices which go into the film are pinned at pinning centers in the junction region when the field $B_\perp^*$ is reached, and they remain in a static state after the field $B_\perp^+$ is turned off. The vortices can leave the junction at a field $B_\perp^- = B_\perp^{**}$, without a change in polarity, because of (on the one hand) the entrance of vortices of the opposite polarity and (on the other) the repulsion by the Meissner currents which arise in the film when there is an external magnetic field $B_\perp^-$. Together, these two processes apparently account for the fact that $|B_\perp^{**}| < B_\perp^*$. As the temperature is raised, at $t > t_1$, the conditions for a static state of the vortices which have reached the junction region are satisfied only if the magnetic field $B_\perp^+$ is turned on. By virtue of the Meissner currents, this field prevents the vortices from escaping from the film. At $t_2 \approx 0.89$ the curves of $B_\perp^*(t)$ and $B_\perp^{**}(t)$ merge. This result is evidence that at $t > t_2$ the vortices in the junction region are no longer held at pinning centers, because of a thermally activated creep.

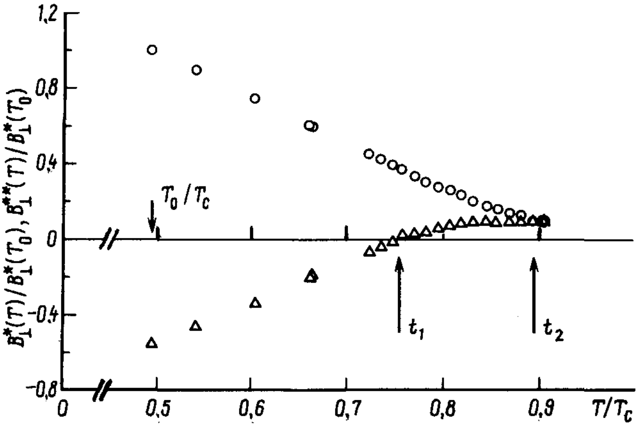

FIG. 3. Temperature dependence of $B_\perp^*$ and $B_\perp^{**}$, normalized to the value of $B_\perp^*$, according to measurements at $T_0 = 4.2$ K. O—$B_\perp^*(T)/B_\perp^*(T_0)$; △—$B_\perp^{**}(T)/B_\perp^*(T_0)$.

The quantity $B_\perp^*$ can thus be linked with the magnetic induction at which the vortices reach the junction region and are pinned at pinning centers. In our experiments, this quantity is a characteristic feature of a given junction with a certain geometry, with superconducting films with certain properties. Our results indicate that it would be possible in principle to carry out a detailed study of the penetration of magnetic flux into superconducting films by using a Josephson tunnel junction to detect single Abrikosov vortices.

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