

Observation of a nonmonotonic transverse voltage induced by vortex motion in a superconducting thin film

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A vortex-induced transverse voltage in a superconducting film, previously predicted theoretically, has been seen experimentally for the first time. The magnitude of this voltage and its nonmonotonic current dependence are explained on the basis of a curvature of the trajectory of vortices resulting from their interaction. A good agreement between theory and experiment is found.

An interaction between magnetic flux vortices of opposite signs in a current-carrying superconducting thin film can result in the appearance of a voltage in the direction transverse with respect to the transport current. This effect was discussed theoretically by Glazman.¹ In this letter we are reporting an experimental confirmation of this effect.

Glazman's theory can be outlined as follows: The magnetic field of the transport current penetrates into a strip of film in the form of vortices of opposite sign, because of the different field directions at the opposite edges of the film. The attraction of the vortices to each other causes their trajectories to become curved if they enter the film

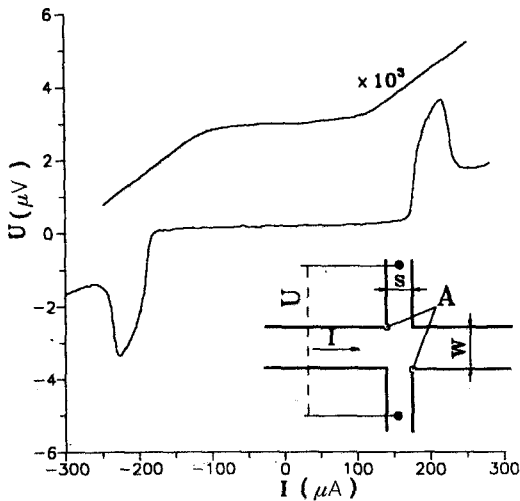


FIG. 1. Longitudinal (upper curve) and transverse current-voltage characteristics. The longitudinal characteristic has been displaced upward for clarity, and the corresponding voltage scale is in millivolts. The inset shows the central part of the sample.

from the opposite edges in regions displaced along the current. The result is the appearance of a transverse voltage. The transverse current-voltage characteristic is not monotonic.

The sample preparation procedure consisted of the following basic steps: (1) vacuum deposition of tin to a thickness $d = 400\text{--}700 \text{ \AA}$ on silicon substrates; (2) the formation of a pattern in the resist by electron lithography; (3) etching of the film in an argon plasma. The inset in Fig. 1 shows the central part of a sample. The sample is a film strip of width $w = 4\text{--}8 \text{ \mu m}$ with transverse potential contacts. The penetration of flux vortices into the film is facilitated by some notches A displaced along the current direction by the width of the potential contacts, $s = 3\text{--}5 \text{ \mu m}$. The size of these notches is $0.2\text{--}0.7 \text{ \mu m}$.

Longitudinal and transverse dc current-voltage characteristics are recorded in a superconducting shield, cooled in such a manner that the geomagnetic field is expelled from the shield when it goes superconducting. A magnetic field perpendicular to the film is produced by a copper solenoid inside the superconducting shield. The temperature is determined from the helium vapor pressure and is regulated by a membrane evacuation regulator. The derivative of the I-V characteristic is measured by means of a sonic-frequency modulation of the current.

Figure 1 shows some typical I-V characteristics, longitudinal (the upper curve) and transverse, recorded in a zero magnetic field. On the transverse curve we see the voltage surges predicted in Ref. 1. There are some differences between the experimental and theoretical curves. First, the voltage peaks arise at currents well below the I_c of the film, while according to Ref. 1 these peaks should appear at current near I_c . The other regions of the film apparently have a lower critical current. The reason may lie in an inhomogeneity of the film or in a current spreading in the crossing region, since the width of the potential contacts is on the order of the film width. Second, it was

predicted in Ref. 1 that the voltage would drop to zero after a surge on the theoretical transverse current-voltage characteristic. We see a different picture: The voltage drops to a certain level and then exhibits a linear behavior with increasing I . We believe that the reason for this discrepancy is the nonaxial arrangement of the potential contacts, due in particular to the presence of notches A . To test this interpretation, we measured a transverse I-V characteristic with the sample in its normal state, at $T > T_c$. The curve turned out to be linear, with a resistance $\sim 10^{-2} \Omega$ for this particular structure. This result corresponds to a $0.25\text{-}\mu\text{m}$ misalignment of the potential contacts.

We can work from the experimental data to estimate the size of the voltage surge which we would expect on the transverse current-voltage characteristic as the result of the motion and annihilation of a vortex-antivortex pair. The curves in Fig. 1 were found for a structure with $w = 7 \mu\text{m}$, $s = 4 \mu\text{m}$, $d = 600 \text{ \AA}$, $R_{\square} = 0.28 \Omega$, and $T_c = 3.94 \text{ K}$ at $T = 3.89 \text{ K}$. We use the expression from Ref. 1, which takes into account the displacement of the vortex entry points, s :

$$V \simeq h\Phi_0^2/8\pi^2 w e \eta d \lambda_{\perp} s. \quad (1)$$

Here e is the charge of an electron, $\Phi_0 = hc/2e$ is the flux quantum, and $\lambda_{\perp} = 2\lambda^2/d$, where λ is the magnetic-field penetration depth. The viscosity η can be estimated from $\eta \simeq \Phi_0 H_{c2}/\rho c^2$. Using $H_{c2} = \Phi_0/2\pi\xi^2$ and $\rho/d = R_{\square}$, we then find the product

$$\eta d \simeq \Phi_0^2/2\pi c^2 \xi^2 R_{\square}. \quad (2)$$

The electron mean free path l can be estimated from the resistance at liquid-helium temperature under the assumption³ $\rho l \simeq 6 \times 10^{-12} \Omega \cdot \text{cm}^2$. This estimate yields $l \simeq 360 \text{ \AA}$. Since the coherence length for tin is⁴ $\xi_0 = 2300 \text{ \AA}$, the subsequent calculations are carried out for the case of a dirty superconductor:⁵

$$\xi(T) = 0.85(\xi_0 l)^{1/2}(1 - T/T_c)^{-1/2}. \quad (3)$$

The penetration depth can be estimated from the value of R_{\square} (Ref. 6):

$$\lambda_{\perp} (\mu\text{m}) \simeq 0.83 R_{\square} (\Omega\text{m}) / (T_c - T). \quad (4)$$

The calculations yield $\lambda_{\perp} \simeq 5 \mu\text{m}$ and $\eta d \simeq 5 \times 10^{-15}$ cgs units. We thus find $V \simeq 3 \mu\text{V}$. These rather simple estimates agree well with the experimental results (Fig. 1). Equating the Lorentz force to the friction force (ignoring pinning), we can estimate the vortex velocity: $v = \Phi_0 I / c w d \eta \simeq 5 \times 10^5 \text{ cm/s}$. This value is on the order of the sound velocity in the material.

Figure 2 shows the derivative of the transverse voltage, dU/dI , versus I , according to measurements in various magnetic fields. At $H = 0$ the curve is symmetric. With increasing field, an asymmetry with respect to the direction of the transport current arises, and in a field $H = 2, 3 \text{ Oe}$ the structural features in the transverse voltage disappear completely. We believe that this symmetry occurs because notches A are not exactly equivalent.

In summary, the effect predicted by Glazman¹ has been observed, and there is a quantitative agreement between theory and experiment.

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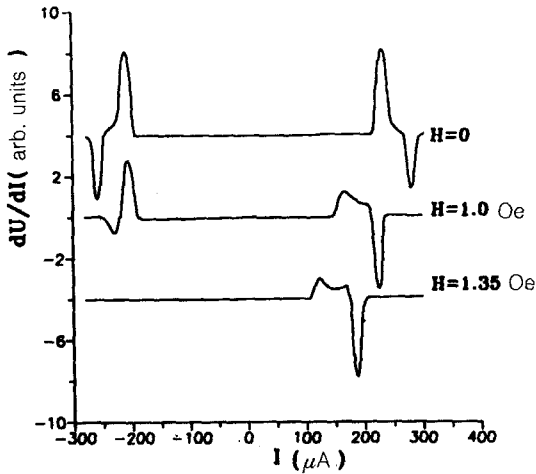


FIG. 2. Derivative of the transverse current-voltage characteristic recorded at 3.89 K in various magnetic fields. The curves have been displaced vertically for clarity.

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