Interaction between Moving Flux Lines and a Two-Dimensional Electron Gas

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A novel method is presented to study the dynamics of vortices in superconducting films at fields close to the upper critical magnetic field. It is shown that moving flux lines in the gate of a superconductor-oxide-semiconductor field-effect transistor are magnetically coupled to a two-dimensional electron gas, leading to an induced voltage. The major part of this voltage is proportional to the magnetoresistance, which is varied by changing the Landau-level filling. A second part is independent of the electron density and is tentatively attributed to the Hall component of the resistivity tensor.

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The recent discovery of high-critical-temperature superconductors has led to a dramatic increase of interest in vortex dynamics. Various models have been developed to understand the collective behavior of a vortex lattice under the influence of external driving forces and/or in the presence of thermal activation [1]. For temperatures close to the critical temperature (T_c), or magnetic fields close to the upper critical field (B_{c2}), possible transitions from the well-known hexagonal lattice to a glasslike or liquidlike state have been predicted. Although these concepts strongly influence our understanding of the vortex dynamics, few techniques are available to resolve these issues experimentally. Most researchers focus on a study of the magnetization supplemented with a careful study of current-voltage characteristics. Further progress in the understanding of the dynamics of flux lines, either collectively or individually, may greatly benefit from new experimental information.

The most convincing proof of flux flow has been provided by Giaever [2], who studied flux flow in two superposed superconducting films. He showed that current-induced flux flow in one of the films (primary) induces a voltage in the magnetically coupled secondary film. In this Letter we describe a related system (inset, Fig. 1) in which the secondary superconducting film is replaced by a two-dimensional electron gas (2DEG). The 2DEG is formed at the interface between silicon and silicon dioxide by applying a voltage between the superconducting gate and the silicon. Compared to the original system studied by Giaever this has two important advantages. First, the magnetically coupled films are different in nature and the viscous forces on the vortices in the primary film are independent of the dissipation in the secondary. Second, the dependence of an induced voltage in the secondary on the electronic properties of the 2DEG can be studied by varying the voltage between the gate and the silicon. As expected [3,4], we find that moving flux lines in the (low-T_c) superconducting film induce a voltage in the 2DEG. Two contributions to this voltage are found, one proportional to the magnetoresistance, which is varied through the electron density, and one roughly independent of electron density. Apart from their use in the study of vortex dynamics, these observations will also raise interesting new questions with respect to the response of a two-dimensional electron gas to a moving inhomogeneous magnetic field, in particular at fields where the quantum Hall effect is present.

It has been shown by Meincke [3] that magnetic coupling in the superconductor-oxide-superconductor system studied by Giaever [2] is a special case. In principle, a voltage will be induced in any metallic secondary film provided that the material has magnetoresistance. From this perspective a superconductor forms an extreme case of magnetoresistivity. Meincke analyzes an idealized system consisting of a conducting medium exposed only locally to a magnetic field. The region where the magnetic field is present is moving with respect to the conductor. Assuming that the local current density is in the direction of the time derivative of the vector potential, he shows that the electric fields induced by a moving magnetic field cause local noncancellation of current density. To preserve charge conservation, the secondary film responds by the buildup of a charge distribution leading to an induced voltage:

$$V_{\mathrm{ind}} = \frac{\rho_1 - \rho_2}{\rho_2} BvL \sin\theta , \qquad (1)$$

where ρ_1 and ρ_2 are resistivities outside and inside the

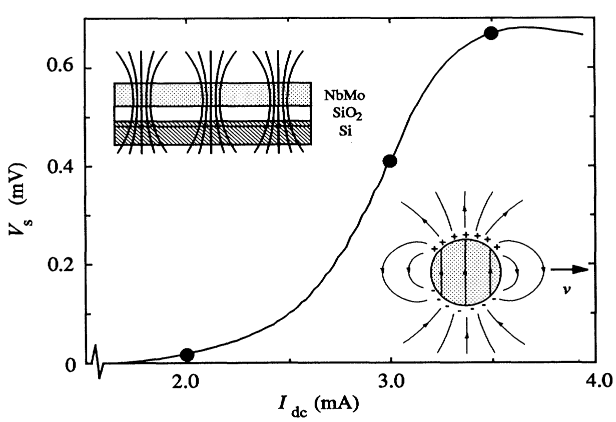

FIG. 1. ac flux-flow voltage V_s as a function of dc current I_{dc} (I_{ac}=0.1 mA, T=1.1 K, B=2.1 T). For the three points indicated with a dot the induced voltage in the 2DEG is given in Fig. 2(b). Upper left inset: The superconductor-oxide-semiconductor stack with penetrating vortices. Because of the thin oxide the magnetic field is inhomogeneous in both superconductor and 2DEG. Lower right inset: The electric-field pattern and the charges around a moving flux bundle in the 2DEG.

magnetic-field region, B the strength of the magnetic field, v the velocity of the moving magnetic-field domain, θ the angle between the vector potential and the potentiometric contacts, and L the width of the magnetic-field region. Obviously a voltage will only be present if ρ_1 and ρ_2 differ. Also the potential drop is largest when the magnetic-field domain moves perpendicular to the line connecting the voltage contacts.

The crossover from the semi-infinite geometry of Meincke towards a localized magnetic field of a moving vortex changes this picture only slightly. A pattern of quasicircular electric-field lines is induced along which the electrons move (inset of Fig. 1). Merely motion of electrons along these field lines does not give rise to a macroscopic voltage drop, since no net charge is being transferred. However, since the electrons experience a change in resistivity as they cross the edge of the magnetic-field region, the induced current density will differ inside from outside. To preserve current continuity, charge builds up resulting in an additional dipole field directed perpendicular to the velocity direction of the magnetic field. Hence if flux flow is induced in the primary film, i.e., an array of vortices moves in the superconductor, an array of moving dipoles is induced in the secondary film. The electric field of this charge distribution is measured as a voltage drop across the 2DEG. Note, however, that the boundary conditions for the electric fields associated with a moving flux bundle in a 2DEG are different from those in a superconductor [5], because the supercurrent is absent.

For magnetic fields close to B_{c2}, the modulation of the magnetic field is small. The magnetic field around a vortex extends to a depth of the penetration length λ of about 100 nm, while the mutual separation of the vortices a_0 is about 30 nm. With these parameters the small modulation of the magnetic field due to the vortex lattice allows us to rewrite Eq. (1) as

$$V_{\text{ind}} = \frac{1}{\rho}\frac{d\rho}{dB}\delta B V_s \,. \tag{2}$$

Equation (2) predicts that the voltage induced in a magnetoresistive film V_{ind} is proportional to the flux-flow voltage V_s in the superconducting film. The proportionality factor is determined by the modulation of the field strength δB and the strength of the magnetoresistance $\rho(B)$ in the 2DEG.

We use in essence conventional metal-oxide-semiconductor field-effect transistors to study the magnetic coupling (Fig. 1, inset). The metal gate is replaced by a superconductor, which still permits the use of the system as a field-effect transistor by applying a voltage across the oxide and measuring the conductivity between source and drain contacts (not shown). The gate consists of 300-nm-thick e-beam-evaporated $Nb_{1-x}Mo_x$ alloy (with resistivity $\rho = 1.4\times10^{-7}$ Ω m and $T_c = 7.6$ K). The molybdenum concentration is approximately 5% as determined from the evaporation rates. No post-metallization anneal has been applied. The width of the gate is 20 μm and the oxide thickness is 36 nm. The 2DEG, acting as a secondary film, has two sources of magnetoresistivity: suppression of the weak localization (WL) contribution to the resistivity at low magnetic field, and the Shubnikov–de Haas (SdH) oscillations at high magnetic field due to the formation of Landau levels. The influence of the inhomogeneity in the magnetic field on the suppression of WL has been studied recently [6–8]. In this regime of magnetic fields very large currents are needed to induce controlled flux motion in the gate and the superposition of an applied and a current-induced magnetic field makes the interpretation of the experimental results difficult. However, the transport mobility of the electrons ($\mu_t \approx 1$ m^2/Vs) is high enough to observe SdH oscillations well below the upper critical field of the superconductor ($B_{c2} \approx 3$ T at $T = 1.1$ K). As we will show, in this regime for small currents flux flow can be induced in the superconducting film.

Figure 2(a) shows the SdH oscillations as a function of gate voltage V_g. No current is fed through the superconducting gate. The data have been expressed as $d\rho/\rho\, dB$ to facilitate comparison with Eq. (2). Since the resistivity ρ of the 2DEG is only a weak function of V_g in this region, the data can be described by a sinusoidal dependence [9]:

$$\frac{1}{\rho}\frac{d\rho}{dB} = K \sin\left[\frac{2\pi(V_g - V_t)}{\Delta V}\right], \tag{3}$$

where V_t is the threshold voltage. The Landau-level degeneracy ΔV is 0.34 V at a magnetic field of 2.1 T (spin and valley degeneracy are both unresolved). The experimentally determined value of K is 2.0 T^{-1}. These results are fully consistent with those obtained with a normal-metal gate. Since the SdH amplitude depends on temperature, it can be used to detect the rise in temperature due to dissipation in the gate. We find, with a gate driven normal by a magnetic field above B_{c2}, that at the power levels used to study flux flow the temperature rise at the 2DEG is below 50 mK.

Because the coupling of the flux-flow voltage to the 2DEG is expected to be weak, the measurements have been performed differentially with standard lock-in techniques ($f = 9.5$ Hz). To measure the flux flow in the gate, a dc current I_{dc} with an ac modulation $I_{\text{ac}} = 0.1$ mA is passed through the film. Figure 1 gives the ac flux-flow voltage V_s as a function of dc current I_{dc}. As usual for thin films at high magnetic fields, the flux-flow resistance V_s/I_{ac} is not a constant but approaches the normal-state resistance gradually.

The coupling is studied by passing a constant dc current with an ac modulation through the gate, while the voltage V_{ind} generated in the 2DEG is recorded as a function of gate voltage V_g [Fig. 2(b)]. The current is kept sufficiently low to ensure that the flux-flow voltage is low with respect to the Landau-level degeneracy. The phenomena reported here have been observed in four different samples. For clarity we focus on results recorded for one specific sample. Figure 2(b) shows the in-

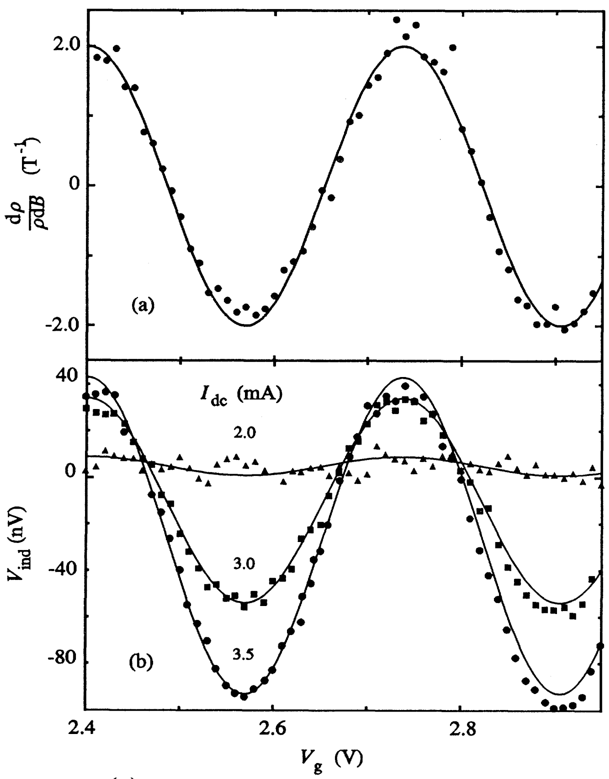

FIG. 2. (a) Magnetoresistance of the 2DEG. For ease of comparison, the data have been expressed as $d\rho/\rho dB$. The solid line through the data is a sinusoidal approximation according to Eq. (3). (b) The voltage induced in the 2DEG, V_{ind}, as a function of gate voltage V_g for the three values of dc current indicated in Fig. 1. The solid lines are fits according to Eq. (4).

duced voltage for three values of the dc current I_{dc}, marked in Fig. 1 by dots. No out-of-phase component is observed, and capacitive or inductive pickup appears to be absent. To reduce low-frequency noise, three measurements have been averaged. Clearly, the induced voltage is related to the electronic properties of the 2DEG that vary with the gate voltage. Apart from the oscillatory behavior, a (negative) background signal is present. Additional damping of the vortex motion in the superconductor by the 2DEG should, in principle, influence the flux-flow voltage observed in the superconducting film. In practice, no difference can be observed between flux flow with and without a gate voltage applied. This is consistent with the large difference between the normal-state resistivity ρ_n of the gate and the resistivity of the 2DEG.

The oscillations in the induced voltage show the same periodicity as the SdH oscillations in the longitudinal resistivity of the 2DEG. However, they are 90° out of phase, and therefore do not reflect the resistivity ρ, but rather its derivative with respect to the magnetic field, $d\rho/dB$. Hence, we seek a description of the measurements through

$$V_{\text{ind}} = A\left(\frac{1}{\rho}\frac{d\rho}{dB}\right) + C, \tag{4}$$

where the independently measured sinusoidal approximation [Eq. (3)] is used to describe the magnetoresistivity. The constants A and C will be used as fit parameters. In Fig. 2(b), the solid lines represent the fits to the data according to Eq. (4). The dependence of the parameters A and C on dc current is given in Fig. 3(a). Since the value of A should be determined by the flux-flow voltage and the magnetic-field inhomogeneity [Eq. (2)], i.e., $A = V_s \delta B$, the combination of the measured V_s (Fig. 1) and A [Fig. 2(a)] can be used to calculate δB [Fig. 3(b)].

Before we discuss the size of this inhomogeneity we would like to point out that the chosen temperature (1.1 K) and magnetic field (2.1 T) represent experimentally found optimum values for the present system. An increase in temperature is found to reduce the amplitude of the induced voltage. This is to be expected since for a fixed current both the magnetoresistance and the inhomogeneity are reduced. The magnetic-field strength is chosen high enough to guarantee a flux-flow regime without voltage jumps. At higher fields the signal diminishes until it disappears completely on approaching B_{c2} proving that the observed coupling is absent when the gate is in the normal state.

For a comparison of the measured inhomogeneity with theory, we need to calculate the magnetic field in a vortex

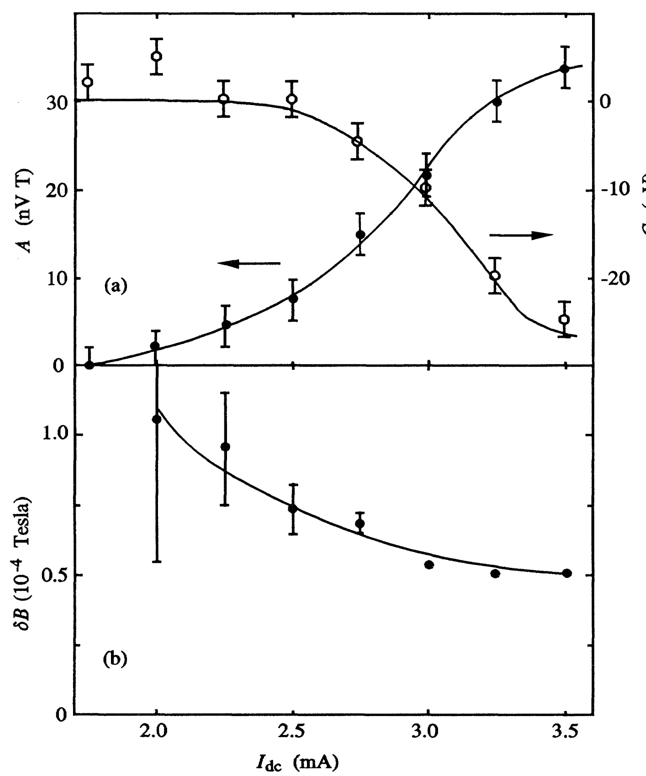

FIG. 3. (a) The fit parameters A (axis to the left) and C (axis to the right) as a function of dc current I_{dc}. (b) The combination of A with the measured flux-flow voltage V_s yields the inhomogeneity of the magnetic field δB, which is as shown. Solid lines in both figures are guides to the eye.

lattice. An accurate theoretical calculation will require a solution of the Eilenberger equations [10] for the present thin-film superconductor. For simplicity we estimate the inhomogeneity by superposing the magnetic-field contributions of the surrounding vortices. The field of a vortex is described by the second modified Bessel function outside the vortex core, and is constant within the vortex core [11]. The spacing between the vortices $a_0=33$ nm for $B=2.1$ T and the effective penetration depth $\lambda=\hbar\rho/\mu_0\pi\Delta_0=143$ nm. If we assume that the alloy $Nb_{1-x}Mo_x$ has the same electron density as Nb, the coherence length ξ is 10 nm. With these parameters the calculated inhomogeneity in the superconductor is $\delta B=5\times10^{-4}$ T. Outside the superconductor the inhomogeneity dampens [4] with a factor $\exp(-2\pi t_{\mathrm{ox}}/a_0)$, leading to an inhomogeneity in the 2DEG of $\delta B=1\times10^{-6}$ T. The experimentally found values fall between these two estimates.

We stress that the derived expression (3) contains no adjustable parameter other than the inhomogeneity of the field. No assumptions have to be made about the number or the velocity of the vortices, since this information is contained in the experimentally determined flux-flow voltage V_s. Although the error in the determination of δB is large, a general trend is observed that δB decreases as the velocity of the vortices increases. We consider a substantial change in magnetic penetration depth due to an increase in temperature unlikely in view of the observed small rise in temperature of the 2DEG. Instead the observed decrease in δB may indicate a situation in which the vortices move closer together when their average velocity increases. This would, for example, occur when the vortices move in the plastic-flow regime instead of the elastic-instability regime [12]. In the latter case, the whole arrangement of vortices would move without changing their mutual separation. This illustrates that new information on vortex dynamics may be obtained unaccessible to any other technique known to study flux flow.

In addition to the magnetoresistivity-induced coupling, another contribution is present that is independent of gate voltage V_g. It has been accounted for in the fit by introducing the parameter C, and is given in Fig. 3(a) as a function of dc current. This contribution is also only observed when the flux lattice moves. The sign of the coupling is negative, but its value seems correlated with the flux-flow voltage V_s. To find the cause of this second contribution, we recall that it was assumed that the electrons move in the direction of the electric-field lines. For the conditions used in the present experiment, the product of the cyclotron frequency with the scattering time $\omega_c\tau$ is approximately 2, which means that the electron motion in the 2DEG, unlike that in the superconductor, should be regarded as a mixture of motion along and perpendicular to the electric-field lines. The resistivity ρ must be treated as a tensor with components ρ_{xx} and ρ_{xy}. To show the intricate nature of the problem we recall a number of relevant parameters. The separation of the vortices a_0 is 33 nm, whereas in the 2DEG the wavelength of the electrons $\lambda_F=2\pi/k_F=30$ nm, the elastic length $(\hbar/eB)^{1/2}=17$ nm, and the elastic mean free path $v_F\tau=100$ nm. They are all of the same order of magnitude, and indicate that electrons should not be treated within a classical theory [4], while also nonlocal properties become important. Of special interest is the quantum Hall regime, where electron motion is only perpendicular to the electric field.

The first coupling mechanism that we have discussed is associated with the magnetic-field dependence of the longitudinal resistivity. The second mechanism is not dependent on the magnetoresistivity, and we tentatively ascribe this to the magnetic-field dependence of the Hall resistivity. Obviously, an extension of the available theory [3–5] is needed to reach a full understanding and to guide further experiments.

In summary, we have shown that in a superconductor-oxide-2DEG stack, a dc transforming behavior is obtained resembling the Giaever coupler. The coupled motion yields a new method to study flux flow in the superconductor. Its sensitivity to the inhomogeneity reveals information about the vortex dynamics that cannot be obtained with any other technique. It gives simultaneously important information on the local transport properties in the 2DEG.

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