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Superconducting vortices and the two-dimensional electron gas

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Moving flux lines in the gate of a superconductor-oxide-semiconductor field effect transistor are magnetically coupled to a two-dimensional electron gas. A voltage is induced of which the major part is proportional to the magnetoresistance of the 2DEG, 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.

The most convincing proof of flux-flow has been provided by Giaever [1], 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. We have studied a novel system in which the secondary superconducting film is replaced by a two-dimensional electron gas (2D EG). The 2D EG 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 an important advantage i.e. the dependence of an induced voltage in the secondary on the electronic properties of the 2D EG can be studied by varying the voltage between the gate and the silicon. As expected [2,3], we find that moving flux lines in the (low T_c) superconducting film induce a voltage in the 2D EG.

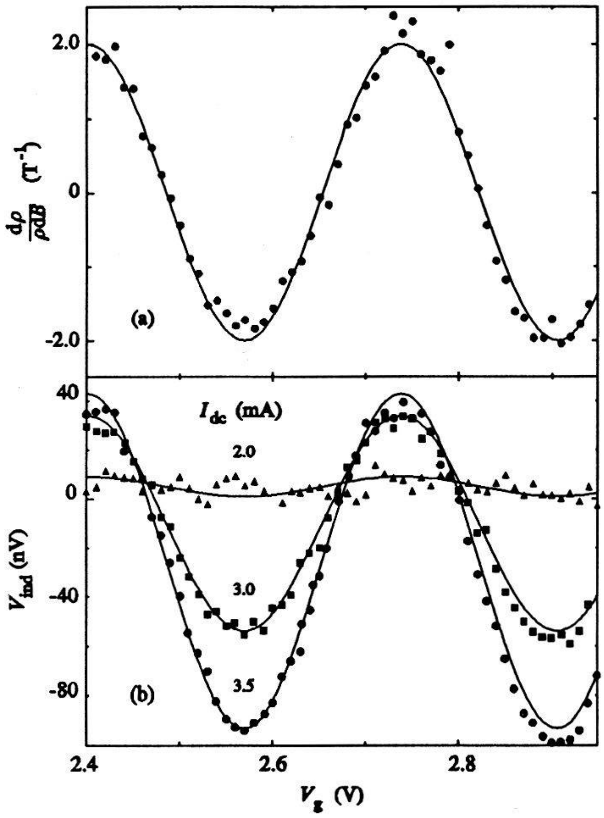
For magnetic fields close to B_{c2}, the modulation of the magnetic field is small. The magnetic field around a vortex extends to a depth of the penetration length λ of about 100 nm, while the mutual separation of the vortices a_0 is about 30 nm. With these parameters the small modulation of the magnetic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

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

Equation (1) 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 2D EG.

We use in essence conventional metal-oxide-semiconductor field effect transistors to study the magnetic coupling. 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. The gate consists of 300 nm thick e-beam evaporated $Nb_{1-x}Mo_x$ alloy (with resistivity $\rho = 1.4 \times 10^{-7}$ Ωm and $T_c=7.6$ K). The molybdenum concentration is approximately 5% as determined from the evaporation rates. The width of the gate is 20 μm and the oxide thickness is 36 nm.

Figure 1(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.(1). Since the resistivity ρ of the 2D EG is only a weak function of V_g in this region, the data can be described by a sinusoidal dependence. The Landau-level degeneracy, is 0.34 V at a magnetic field of 2.1 T (spin and valley degeneracy are both unresolved). These results are fully consistent with those obtained with a normal metal gate.



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 2D EG is recorded as a function of gate voltage V_g [Fig. 1(b)]. The current is kept sufficiently low to ensure that the flux-flow voltage is low with respect to the Landau-level degeneracy. Figure 1(b) shows the induced voltage for three values of the dc current I_{dc}. Clearly, the induced voltage is related to the electronic properties of the 2D EG, that vary with the gate voltage. Apart from the oscillatory behavior, a (negative) background signal is present. The oscillations in the induced voltage show the same periodicity as the SdH-oscillations in the longitudinal resistivity of the 2D EG.

Additional to the magnetoresistivity-induced coupling, a contribution is present that is independent of gate voltage V_g. 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 in deriving Eq. 1 it is tacitly 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 2D EG, 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_o is 33 nm, whereas in the 2D EG the wavelength of the electrons $\lambda_F=2\pi/k_F=30$ nm, the magnetic length $(h/eB)^{1/2}=17$ nm, and the elastic mean free path $v_F\tau=100$ nm. Of special interest is the quantum Hall regime, where electron motion is only perpendicular to the electric field.

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