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Experiments on Vortex Damping in Novel Superconductor–2D-Electron-Gas Hybrid Structures

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We have measured the power dissipation in thin Pb/In superconducting films which are coupled to an adjacent two-dimensional electron gas formed in a modulation-doped GaAs/AlGaAs heterostructure. An enhancement of vortex-motion damping at the superconductor is obtained by increasing the density of the electron gas using a gate voltage. Quantitative agreement is found with calculations based on a viscous model of vortex damping which considers the generation of eddy currents in the electron gas by moving flux lines. Eddy-current damping is much more pronounced in the regime of filamentary and channel vortex flow, as compared to the free-flux flow case, leading to striking reductions in dissipation due to stopping of entire vortex channels.

Introduction In the past few years, superconductor-semiconductor hybrid structures have attracted much attention due to their peculiar electronic properties resulting from interactions between both systems (for recent contributions and references, see [1]). Generally speaking, one can distinguish between two classes of experiments on hybrids depending upon whether the emphasis is put on the study of the superconductivity or on the transport properties of a two-dimensional electron gas (2DEG) placed close to the superconductor. To the first category belong experiments on Josephson-type junctions with Nb electrodes coupled by a high-mobility 2DEG in InAs layers. These hybrid devices exhibit phase-sensitive transport due to Andreev reflections of quasi particles at the interfaces between normal metal and superconductor [2 to 4]. Other experiments concentrate on commensurability and interference effects on electron ballistic transport in the 2DEG, which occur when a perpendicular magnetic field is spatially modulated by the vortices of an adjacent superconducting film. In this case, a pronounced suppression of the Hall effect was observed and ascribed to electron diffraction by flux quanta [5].

Very few investigations, however, are concerned with the influence of a high-mobility normal metal close to a type-II superconductor on the vortex dynamics under a transport current [6]. Nevertheless, the device under study in Ref. [6], a NbMo superconduc-

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tor on top of a Si/SiO_2 field-effect transistor, was intentionally designed for having no viscous coupling between its constituents. In contrast, our hybrid system can be thought off as a modified Giaever's dc transformer [7], in which one of the superconducting films has been replaced by a 2D electron gas. Under the action of a Lorentz force the vortices move at constant velocity due to viscous damping. For an isolated superconductor, this damping originates from the voltage induced across the normal core of each moving vortex. By bringing a highly mobile electron gas close enough to the superconducting film, i.e. at a distance of the order of the London penetration depth, an additional dissipation mechanism is introduced through coupling between vortex system and metal but without having any electron tunneling. In this case, one expects an increase in viscosity for the hybrid system. An issue of particular interest is to what extent the interaction with the electron gas would affect filamentary and channel vortex flow, for which dissipation jumps are observed in the current–voltage characteristics of thin-film superconductors [8 to 10]. Since in this regime the vortex lattice is torn apart resulting in channels of vortices flowing past pinned regions, the study of vortex damping in hybrids may provide further insight into vortex–vortex interactions and pinning effects.

Here we report on the damping enhancement of vortex motion due to the presence of a high-mobility electron gas in superconductor–semiconductor hybrids. The samples used in our experiments consist of thin Pb/In films evaporated on top of modulation-doped GaAs/AlGaAs heterostructures. The evidence is found in the decrease of dissipation voltage measured at the superconducting film caused by the higher viscosity for vortex flow of the hybrid system, as compared to the case without the normal conducting layer beneath. The method used here consists of varying the normal metal conductivity for one and the same sample by increasing the carrier density using a gate voltage applied between the 2DEG and a back contact. Our results are in good quantitative agreement with the predictions of a model which accounts for the generation of eddy currents in the electron gas by flowing vortices. For the currents and magnetic fields at which filamentary vortex flow occurs, however, striking dissipation reductions in excess of 10% are readily achieved.

Experimental Details A cross sectional sketch of one of the samples measured here is depicted in Fig. 1. The semiconductor component of the hybrid system is either a 25 nm wide GaAs/AlGaAs single quantum well (SQW) or a single heterointerface (SHI) structure grown by molecular beam epitaxy. A high-mobility two-dimensional electron gas is realized by modulation doping and is buried at a distance $D = 75$ nm and 50 nm from the surface for the SQW and SHI structure, respectively [11]. Figure 1 gives de-

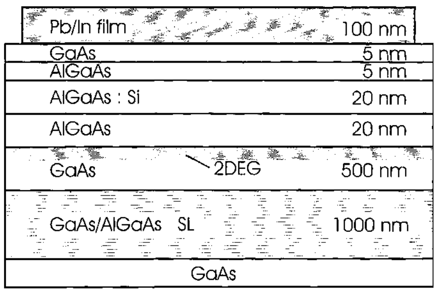

Fig. 1. Cross section of the PbIn/SHI hybrid sample showing the growth sequence. The position at which the electron gas (2DEG) forms, is indicated

tails of the growth sequence for the SHI sample. The nominal mobilities and carrier densities of both samples at 4.2 K and under illumination are $\mu \approx 8 \times 10^5\,\text{cm}^2/\text{Vs}$ and $n \approx 5.6 \times 10^{11}\,\text{cm}^{-2}$. The electron gas is contacted from the surface by In alloying in order to apply a gate voltage U_g between it and a metallic back contact. The variation of the 2D density was examined previously in photoluminescence experiments [12]. A linear increase in the carrier density n_{2D} between its nominal value and at most $\approx 6.5 \times 10^{11}\,\text{cm}^{-2}$ can be achieved by applying a gate voltage between 0 and 200 V. Hence the estimated maximum possible increase of density is less than 20%.

Superconducting films of Pb with nominally 14 at.% In were evaporated on the semiconductor surface ($4 \times 4\ \text{mm}^2$ in size) with film thicknesses d ranging from 60 to 300 nm, as determined using atomic-force microscopy. The superconducting transition in zero field occurs at 7.2 K. For transport experiments, Au leads were pressed against the superconductor film. Current–voltage measurements were performed with standard four-terminal configuration using dc currents up to 2 A. Experiments were carried out at 4.2 K and low perpendicular magnetic fields $B < 0.2$ T using a split-coil magnet in combination with a He-bath cryostat.

Results and Discussion

Theoretical model The coupling between vortex lattice and electron gas in our hybrid samples is modeled by considering the effect on the normal metal of the magnetic field B of a vortex moving with speed v. The experimental situation is schematically illustrated in Fig. 2. The time-varying stray magnetic field of the flowing vortices induces an electric field in the 2DEG that generates eddy currents leading to an additional dissipation which, in turn, forces the fluxoids to slow down. We are confronted with two limiting cases depending upon if either (i) $D \ll \lambda^2/d$ or (ii) $D \gg \lambda^2/d$, i.e. the superconductor–2DEG distance is much smaller or much larger than the effective London penetration depth, respectively. In case (i) the magnetic field of a vortex is essentially that of a monopole with $\mathbf{B} \sim \Phi_0 \hat{r}/2\pi r^2$, with r the distance to the vortex core and $\Phi_0 = h/2e$ the flux quantum [13]. On the other hand, for case (ii) the field can be approximated as $\mathbf{B} \sim (\Phi_0/2\pi\lambda^2)\, K_0(r/\lambda)\, \hat{z}$, where K_0 is the zeroth-order Bessel function of imaginary argument. For our samples the effective penetration depth is five to eight times D [8]. The vector potential in the plane of the 2DEG can be written as

$$\mathbf{A}(\rho) = \frac{\Phi_0}{2\pi\rho}\, F_\chi(\rho/\chi)\, \hat{e}_\varphi, \tag{1}$$

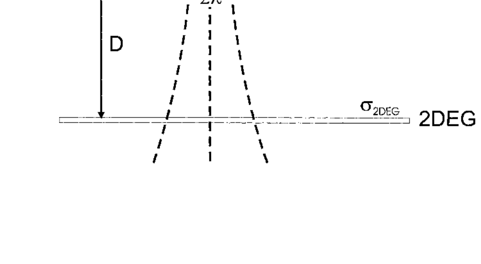

Fig. 2. Schematic representation of the superconductor–2DEG hybrid device. A transport current J flows through a superconducting film (SC) of thickness d and normal-state conductivity σ_{NC}. It couples to a 2DEG at a distance D through the magnetic field B of the vortices

where ρ is the polar radius from the vortex core, and $F_\chi(x) = \int_0^x \mathrm{d}y\, yK_0(y)$ is a function that decays with a characteristic length χ (D for case (i) and λ for case (ii)).

The time-varying vector potential produced by a flowing vortex induces an electric field $\mathbf{E} = v\,\frac{\partial}{\partial x}\mathbf{A}(x - vt, y)$, which causes Joule dissipation in the 2D gas. The energy loss per unit time is calculated according to

$$\frac{\mathrm{d}\varepsilon}{\mathrm{d}t} = \sigma_{2DEG}v^2 \int \mathrm{d}^2x \left[\frac{\partial}{\partial x}\,\mathbf{A}(\rho/\lambda)\right]^2 \approx \frac{\Phi_0^2}{2\pi\lambda^2}\,\sigma_{2\mathrm{DEG}}v^2 \equiv \eta_{2\mathrm{DEG}}\,v^2, \tag{2}$$

where $\sigma_{2\mathrm{DEG}}$ is the conductivity of the 2D electron gas and the dimensionless integrals are assumed to be of the order of unity.

We arrive at the general result that eddy current generation in the hybrid system manifests itself in a contribution to the viscosity $\eta_{2\mathrm{DEG}} = \sigma_{2\mathrm{DEG}}\,\Phi_0^2/2\pi\lambda^2$ describing the enhanced damping of vortex motion. In order for this effect to be observable, $\eta_{2\mathrm{DEG}}$ has to be comparable to the viscosity of type-II superconducting material, $\eta_{\mathrm{SC}} = \sigma_{\mathrm{NC}} d\,\Phi_0^2/2\pi a^2$ [14], where σ_{NC} is the normal state conductivity of the superconductor and a the vortex core radius. The electron gas acts as a shunt conductor, thus, increasing the system viscosity $\eta_{\mathrm{tot}} = \eta_{\mathrm{SC}} + \eta_{2\mathrm{DEG}}$ by

$$\frac{\eta_{2\mathrm{DEG}}}{\eta_{\mathrm{SC}}} = \begin{cases} \left(\dfrac{a}{\lambda}\right)^2 \dfrac{\sigma_{2\mathrm{DEG}}}{\sigma_{\mathrm{NC}} d}, & D \ll \dfrac{\lambda^2}{d}, \\ \left(\dfrac{a}{D}\right)^2 \dfrac{\sigma_{2\mathrm{DEG}}}{\sigma_{\mathrm{NC}} d}, & D \gg \dfrac{\lambda^2}{d}. \end{cases} \tag{3}$$

Hence the dissipation voltage under a transport current is $U_\mathrm{d} \propto v$ [14] and the vortex velocity is determined by the balance between the driving force jB and the viscous drag ηv. Eddy-current damping grows in proportion to σ_{2DEG}, i.e. to the carrier density n_{2D} of the electron gas.

Experimental results The dissipation due to flowing vortices in the PbIn superconducting film is significantly reduced by increasing the charge density in the neighboring electron gas. Figure 3 shows typical dissipation voltage (U_d) versus gate voltage (U_g) curves of a PbIn/SHI and a PbIn/SQW hybrid sample measured at a constant transport current of 700 mA and 2 A, respectively. For the SHI sample (see Fig. 3a), sweeping U_g from 0 to 170 V causes an almost linear de-

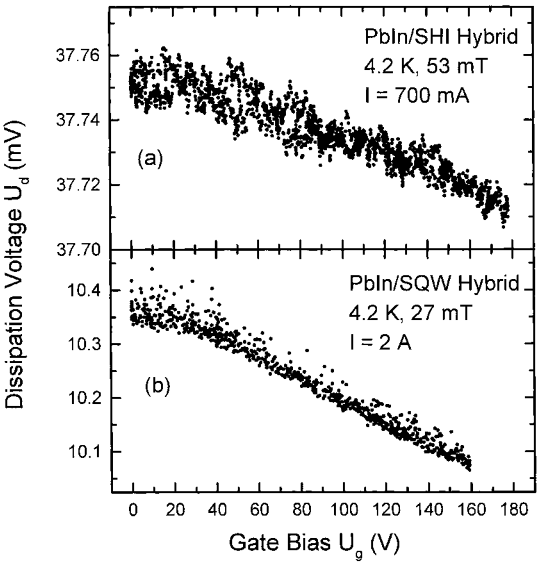

Fig. 3. Dissipation voltage as a function of gate bias of a) a PbIn/SHI and b) a PbIn/SQW hybrid structure at 4.2 K and in a perpendicular magnetic field of 53 and 27 mT using a transport current of 700 mA and 2 A, respectively

crease in dissipation of $\Delta U_d = 0.022$ mV, i.e. $\approx 0.1\%$ of the initial value. The dissipation change is even stronger (about 2%) for the PbIn/SQW hybrid (Fig. 3b). This is partly due to the fact that at this transport current of 2 A the vortex flow in the film has not completely reached massive regime but vortex channels are still being formed. As we show below, for filamentary and channel vortex flow the changes in dissipation attained by varying the density of the 2DEG can be more pronounced than for free flux flow. Here we give the gate voltage as a measure of the electron density because optical and transport experiments could not be carried out simultaneously. We assume that the 2D density varies linearly with U_g above 20 V, as inferred from optical measurements [12]. We emphasize that in spite of the relatively small change in 2DEG density the coupling within the hybrid appears to be effective enough to show up in its dissipative behavior. We also notice that during the experiment no leakage current between superconductor and electron gas was ever detected, thus we rule out any spurious bias to be at the origin of the observed effect.

We interpret the dissipation change in the superconductor with rising charge density in the 2DEG as the effect of eddy currents in the electron gas which slow down the vortices causing the voltage across the superconductor to decrease. Using Eq. (3) we can now estimate the magnitude of this effect. Typical sample parameters are $d \approx 100$ nm, $\lambda \approx 200$ nm and $D = 50$ and 75 nm, which puts us in case (i). Taking $a \approx \lambda$, $\sigma_n \approx 1.4 \times 10^5\,\Omega^{-1}\text{cm}^{-1}$ as obtained from resistance measurements, and $\sigma_{2\text{DEG}} \approx 0.08\,\Omega^{-1}$ with the 2DEG parameters given above, this yields $\eta_{2\text{DEG}}/\eta_{\text{SC}} \approx 5\%$. This change in dissipation voltage corresponds to the difference between having and not having the electron gas next to the superconductor. In our experiments, however, we start from a finite density and produce a variation of about 10 to 20%. The expected dissipation change is thus around 0.5 to 1%, in very good agreement with the experimental results.

The effects of eddy-current damping can be significantly enhanced in the regime of filamentary and channel vortex flow. They can lead to a striking fall of dissipation voltage by more than one order of magnitude, as shown in Fig. 4. Here, U_d was measured at a current close to the repinning transition of a large vortex channel. The inset to Fig. 4 displays the I–V characteristic of the superconducting film measured for a field of 53 mT and at 4.2 K but without gate bias. The abrupt jumps and large hysteresis

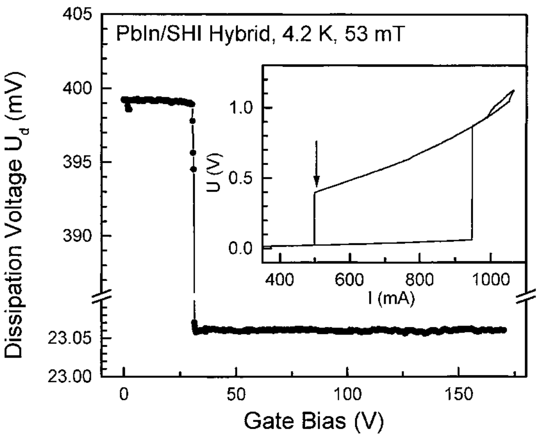

Fig. 4. Dissipation voltage as a function of gate bias of a PbIn/SHI hybrid structure in a perpendicular magnetic field of 53 mT, with 500 mA current and at 4.2 K. The inset shows the corresponding current–voltage characteristic. The point where the measurement of dissipation versus gate voltage was taken is marked with an arrow

apparent in the $I-V$ curve are the signature of channel vortex flow [8]. As indicated by the arrow, the point where the measurement of dissipation versus gate voltage was carried out is close above the critical current at which the downward jump occurs. In this case, the vortex speed is just high enough for the channel to keep flowing. Energy loss due to eddy currents slows the vortices further down, so that the whole channel will eventually be repinned. When the vortex channel stops, dissipation suddenly drops. This effect is highly reproducible even after heating the sample over T_c and re-cooling. Furthermore, these steep dissipation drops indicate that the vortex flow pattern itself can be drastically altered due to the combined effects of damping and pinning, such that in a hybrid device power dissipation can be switched off by slightly increasing the electron density.

Vortex damping due to eddy currents strongly correlates with the transport behavior at given magnetic field. As a measure of the damping strength, the maximum dissipation change ΔU_d for a gate voltage interval of $\Delta U_g = 170$ V is normalized by the dissipation voltage U_{d0} at zero bias. In Fig. 5a, $\Delta U_d/U_{d0}$ is plotted against the current I at which the dissipation change was measured. Figure 5b shows the corresponding $I-V$ curve with two regions of linear dissipation ($I < 400$ mA and $I > 1000$ mA) and a transition region exhibiting a small hysteresis. Here a large number of small vortex filaments depin in quick succession, leading to a softened dissipation rise that consists of many small steps rather than one large voltage jump. In the linear dissipation regimes, the damping effect remains small ($\Delta U_d/U_{d0} < 0.5\%$). A pronounced damping maximum of 9% is attained near the center of the transition region at $I = 700$ mA.

This different behavior of eddy-current damping in the transport regime dominated by filamentary vortex flow as compared to massive flux flow can be understood in terms of *fluctuations* in the number of moving vortices contributing to dissipation. In the regions of linear dissipation, the flux flow pattern is stable and the number of flowing vortices remains unchanged by damping. The decrease of dissipation is purely due to eddy-current damping. On the contrary, where the $I-V$ curves exhibit hysteretic

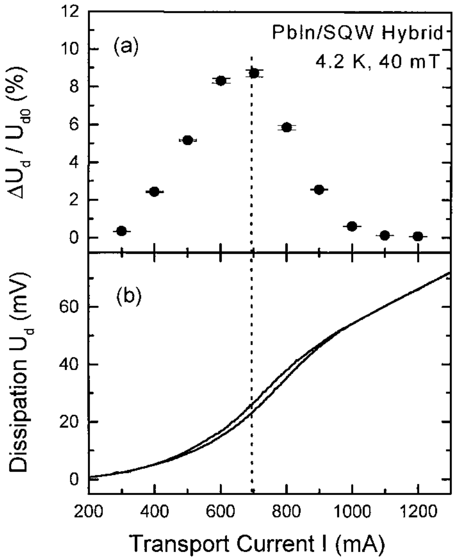

Fig. 5. a) Percentage change in dissipation versus current of a PbIn/SQW hybrid at 4.2 K and 40 mT. The percentage is calculated as the maximum dissipation change in a gate voltage interval of 170 V, divided by the initial dissipation value. b) The corresponding I–V characteristic; the dashed line marks the position of the damping maximum

behavior, entire channels of vortices can stop under the influence of damping resulting in a much larger reduction of dissipation with increasing gate voltage.

Conclusion In summary, we have observed significant additional damping of vortex motion in superconductor–semiconductor hybrid systems. A theoretical model is used to calculate the damping effect from eddy currents generated in the 2D electron gas showing quantitative agreement with the experiment. Under conditions of filamentary vortex flow, the energy loss due to eddy currents leads to the stopping of entire channels, giving rise to steep dissipation drops in the superconductor. Our results provide further insight into the issue of vortex dynamics with dissipation and open up a new class of devices for the study of correlations between adjacent non-tunneling systems with dissimilar electronic and magnetic properties.

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