Transport measurements on magnetically coupled superconductor-2D-electron-gas hybrids

H Scheel, A R Goñi, C Kristukat, C Thomsen
Institut für Festkörperphysik, TU-Berlin , Berlin, Germany

K Eberl
MPI für Festkörperforschung, Stuttgart, Germany

Abstract.
We report transport measurements on superconductor-2D-electron-gas (2DEG) hybrid structures performed on both the superconducting and the semiconducting part of the structure to study the magnetic coupling between two systems with dissimilar electronic properties. We observe an enhancement of power dissipation in the hybrid by generation of eddy currents in the nearby 2DEG due to moving vortices in the superconductor. The variation of the 2DEG carrier density with gate voltage, the latter used to tune dissipation, is verified by measuring Shubnikov-de Haas oscillations. Our results show a strong suppression of filamentary and channel vortex flow in the hybrid device, which indicates a strong influence of the normal metal underneath the superconductor on the static and dynamic properties of the vortex lattice.

1. Introduction

In the past years there has been a variety of different proposals for the study of hybrid structures combining a two-dimensional electron gas (2DEG) and a superconductor, in which the inhomogeneous field distribution that is created by a type-II superconductor couples to the nearby 2DEG. The experimental and theoretical research in this field can be categorized in two main areas depending upon if the main focus is set on the transport properties of the 2DEG or the superconductor. For example, Geim *et al.* [1] detected an excess longitudinal resistance of a 2DEG due to small-angle scattering of ballistic electrons by the magnetic-field inhomogeneities induced by a type-II superconductor. The versatility of superconductor-2DEG hybrid structures for device applications has been also demonstrated by Bending *et al.* [2], as they used a Hall-bar with a superconducting gate as a flux detector. On the other hand, there are a series of experimental [3, 4] as well as theoretical [5] investigations of the enhancement of vortex-motion damping under a transport current due to eddy currents created in the metal underneath the superconductor. Magnetic coupling between vortex lattice and electron gas has also been used to induce an ac voltage across the semiconductor by the moving flux lines in the superconductor [6].

In this paper we report new experimental results on vortex damping in type-II superconductors due to the presence of a nearby high-mobility metal. The model of viscous damping by generation of eddy currents is applied to interpret the results [3, 5]. In recent measurements on superconductor-2DEG hybrids which consist of thin Pb films evaporated on a GaAs/AlGaAs single heterointerface (SHI) structure, an oscillatory behavior of the magnitude of vortex damping has been observed as a function of superconductor transport current [7]. The oscillations showed to be independent of the external magnetic field and the thickness of the Pb film in a range from 70 to 140 nm. This speaks strongly for the oscillations being a property of the semiconducting part of the hybrid. In order to rule out an electric coupling between superconductor and semiconductor, experiments were performed in which the superconducting film was evaporated on a glass plate and then brought in contact with the SHI to form the hybrid, instead of direct evaporation on top of the semiconductor. In addition, we have investigated hybrids with an *undoped* semiconducting part, i.e. without the electron gas formed in the quantum well. These measurements demonstrate that filamentary and channel vortex flow, as observed on glass plates [8], is strongly suppressed due to the existence of the nearby doping layer. In a different approach, we performed transport measurements on the 2DEG to be able to quantify *in-situ*, that is while monitoring the dissipation in the superconductor, the change in electron density (n_{2DEG}) by applying a gate voltage. Photoluminescence and inelastic light scattering experiments on GaAs SQW structures already demonstrated the variation of n_{2DEG} by approximately 20%, which is here verified by measuring Shubikov-de Haas oscillations.

2. Experimental Details

The semiconducting part of the hybrid consists of either a modulation-doped GaAs/AlGaAs single quantum well (SQW) or a single heterointerface (SHI) structure grown by molecular beam epitaxy. By doping of the top AlGaAs barrier with Si, a two-dimensional electron gas of $\mu \approx 8 \times 10^5$ cm^2/Vs mobility and a density of $n \approx 5.6 \times 10^{11}$ cm^{-2} forms at a distance of 75 and 45 nm beneath the surface of the SQW and SHI, respectively. The electron gas is contacted from the top surface by In alloying and its density is varied by applying a gate voltage between the In point and a metallic back contact, as examined by photoluminescence (PL) [9]. Measurements where also performed on an identical quantum well structure without doping layer, therefore omitting the 2DEG. Ohmic contacts for Shubnikov-de Haas measurements consist of AuGe/Ni/Au pads tempered at 440°C for 60 s. The Shubnikov-de Haas oscillations were measured using a two-terminal configuration and a software lock-in technique [10], where an ac voltage signal is generated by the computer which is then transformed into an ac current of roughly 10 nA. The current and the voltage drop over the sample are then mixed by the computer with the reference frequency of the current source and Fourier analyzed. The dc components of the fast Fourier transformations are thereafter divided one by the other to generate a resistance. Further details will be given elsewhere [11].

The superconductors are thin Pb films with roughly 14 at% In and were thermally evaporated onto the surface of the semiconductor samples being typically 3×4 mm^2 in size. The thickness of the lead films ranges from 75 to 125 nm. For transport experiments thick In contact pads were evaporated on top of the Pb film and Au leads were pressed against them. Current-voltage measurements were performed in standard four-terminal configuration using dc currents up to 3 A. Samples were immersed in liquid helium at 4.2 K and subjected to low perpendicular magnetic fields by placing them in the cold bore of a 5 T split-coil superconducting magnet.

3. Results and Discussion

Figure 1 shows current-voltage (I-V) characteristics at different magnetic fields ranging from 50 to 125 mT for a PbIn/SHI hybrid, in which the superconductor was evaporated on a glass plate instead of on the semiconductor surface. The glass with the Pb film was gently pressed against the semiconductor to form the hybrid. All curves show hysteresis loops which are traced in counterclockwise direction. The 50 mT curve shows a jump to a small plateau at 900 mA, which indicates the onset of movement of a big part of the vortex lattice from now

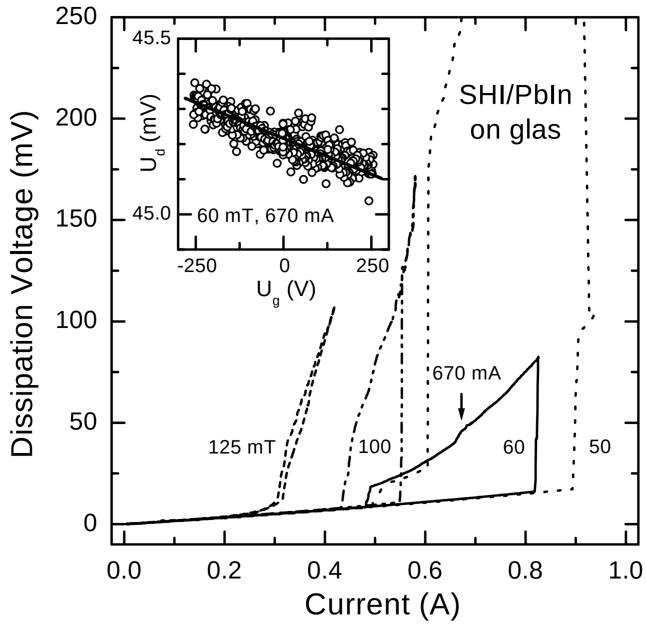

Figure 1. Current-voltage characteristic of a PbIn film pressed on a GaAs single heterointerface (SHI) structure for different magnetic fields. The inset shows the dissipation voltage (U_d) as a function of positive and negative gate voltages (U_g). The arrow indicates the position where the U_d-versus-U_g curve was measured.

on called a channel. If the current is further increased, the entire lattice starts to move leading to an even larger jump in the I-V curve. The same channel is set to movement at a lower current if the magnetic field is increased to 60 mT. On the upper branch of this hysteresis loop a small discontinuity is observed, which is associated with the repinning of a number of vortices or a filament. This filament can be slowed down or even stopped by increasing the carrier density in the adjacent 2DEG by applying a gate voltage. The inset to Fig. 1 shows the dependence of the dissipation voltage U_d on gate voltage U_g at the point on the 60 mT transport curve indicated by an arrow. An appreciable value for the slope of the U_d-versus-U_g curve is obtained only in the current range in the vicinity of the discontinuity. The amount of eddy-current damping, as measured by the slope, is similar but smaller than for hybrids with the Pb film evaporated directly on the semiconductor [3, 4]. This is, nevertheless, an important result which indicates that in order to achieved eddy-current vortex damping it is only necessary to attain magnetic coupling between vortex lattice and electron gas by bringing both close together.

For stronger magnetic fields, e.g. 100 and 125 mT, the entire vortex lattice moves after overcoming the pinning force, as is typical behavior for type-II superconductors. These features in the current-voltage curves, which are characteristic of filamentary and channel vortex flow for low dissipation, are observed only when the superconductor was evaporated on glass but not for the hybrids with the Pb deposited on the semiconductor. We can think of two possible explanations for this effect. On the one hand, the quality of the evaporated film depends much on the properties of the surface onto which is being deposited. On the other hand, the presence of the 2DEG or the doping layer might have an influence on the vortex-lattice pinning potential of the superconductor. To further investigate that issue we compared current-voltage characteristics of two similar semiconductor samples, one with and one without doping layer.

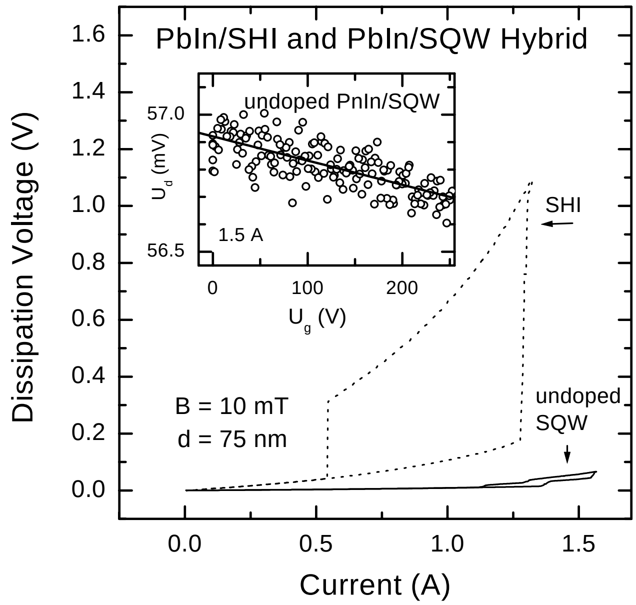

Figure 2. Current-voltage characteristic of a PbIn/SHI hybrid (dashed curve) and an one with an undoped SQW structure (solid line) measured at 4.2 K for 10 mT. The inset shows the dissipation voltage (U_d) as a function of the gate voltage (U_g) for the undoped-SQW hybrid obtained with a superconductor-transport current of 1.5 A.

Figure 2 shows the I-V curves of a PbIn/SHI hybrid (dashed curve) and the one made of an undoped SQW structure (solid curve) for a magnetic induction of 10 mT. The 75 nm thick lead films were evaporated simultaneously onto the semiconductor surfaces to provide identical thicknesses and processing parameters. The two curves exhibit remarkable differences in their shapes. The SHI-hybrid shows one large jump to high dissipation values. Prior to the jump the dissipation is already higher as in the undoped SQW hybrid, indicating overall lower pinning forces. Moreover, the typical features of filamentary vortex flow are absent in the I-V traces, what speaks for a smaller shear modulus C_{66} of the vortex lattice as compared with the compression modulus C_{11} [8]. For a certain Lorentz force (at approximately 1.3 A) almost the entire flux lattice starts moving. The current of the large jump does not seem to be connected to the critical current of the PbIn film at 10 mT because the PbIn/SQW hybrid does not show any transition into the normal state under the same conditions. The undoped SQW sample shows, in contrast, small jumps and pronounced hysteresis, just as observed for thin Pb films on glass substrates [8]. These results demonstrate the strong influence of the doping layer on the pinning forces and vortex-lattice dynamics, whereas the surface quality appears to play a minor role.

The dependence of the dissipation voltage (U_d) on gate bias (U_g) at a constant current of 1.5 A measured on the hybrid with the undoped SQW is depicted in the inset to Fig. 2. The decrease in dissipation is attributed to the slowing down of moving vortices caused by an increase in viscosity originating from the generation of additional eddy currents in the 2DEG [4, 7]. Again the slope of the linear relation fitted to the data points is taken as a measure of the magnitude of the vortex-damping mechanism. Thus, the observed gate-voltage dependence indicates the formation of an electron gas in the undoped structure, whose density can be varied with the applied gate voltage. We notice that PL measurements on a doped PbIn/SQW hybrid showed a pronounced increase in 2D carrier density underneath the superconducting

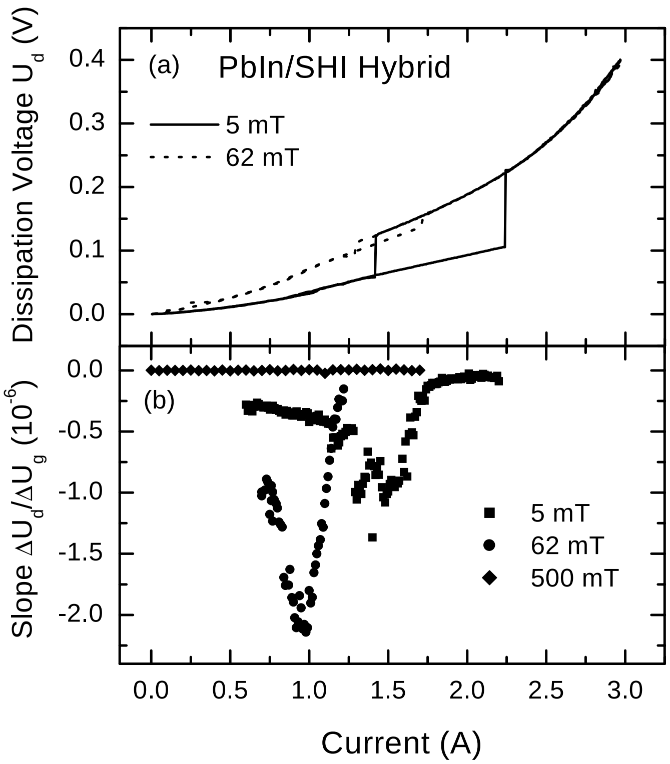

Figure 3. (a) Current-voltage characteristics of a 125-nm-thick PbIn/SHI hybrid for 5 and 62 mT at 4.2 K. (b) Dependence on transport current of the slope of the straight line obtained from the U_d-versus-U_g curves, as shown in the Inset to Fig. 2, for different magnetic fields.

film due to the very presence of the metal on the semiconductor surface, which leads to a saturation of surface states and the consequent increase of the Fermi level [12].

In previous measurements on the upper branch of IV curves on PbIn/SHI hybrids we have observed an oscillatory behavior of the eddy-current damping with transport current [7]. Since the oscillations are independent of magnetic field and PbIn-film thickness, we think that they must originate from a property of the semiconducting part of the hybrids. In that case, the dissipation level at the upper branch was very high and close to that expected for the Pb film in the normal state. Therefore, we have investigated the occurrence of the dissipation oscillations on the parts of the I-V curves, which are dominated by channel-vortex flow. Figure 3a shows current-voltage curves of a 125-nm-thick PbIn/SHI hybrid for 5 and 62 mT and at 4.2 K. The curves display a hysteresis loop whose size decreases with increasing magnetic field. The 500 mT curve has been omitted for clarity, as the hysteresis loop vanishes for high fields. In Fig. 3b we have plotted the slope of the measured U_d-versus-U_g relations recorded for different currents on the lower branch of the I-V curves in (a). As already pointed out, in the hybrids with modulation-doping, filamentary vortex flow seems to be suppressed and instead of a series of small, distinct jumps one rather observes a change in curvature and an increased noise on the lower branch trace. In these regions the slope of the U_d-versus-U_g curve gets very steep indicating an efficient eddy-current damping, which is a result of the number of moving flux lines changing abruptly due to vortex filaments depinning in quick succession. In this situation, an increase in viscosity leads to the slowing down and repinning of these filaments resulting in a large decrease in dissipation voltage. It is clear from the data of Fig. 3b that the maximum of the eddy-current damping shifts to smaller values of the

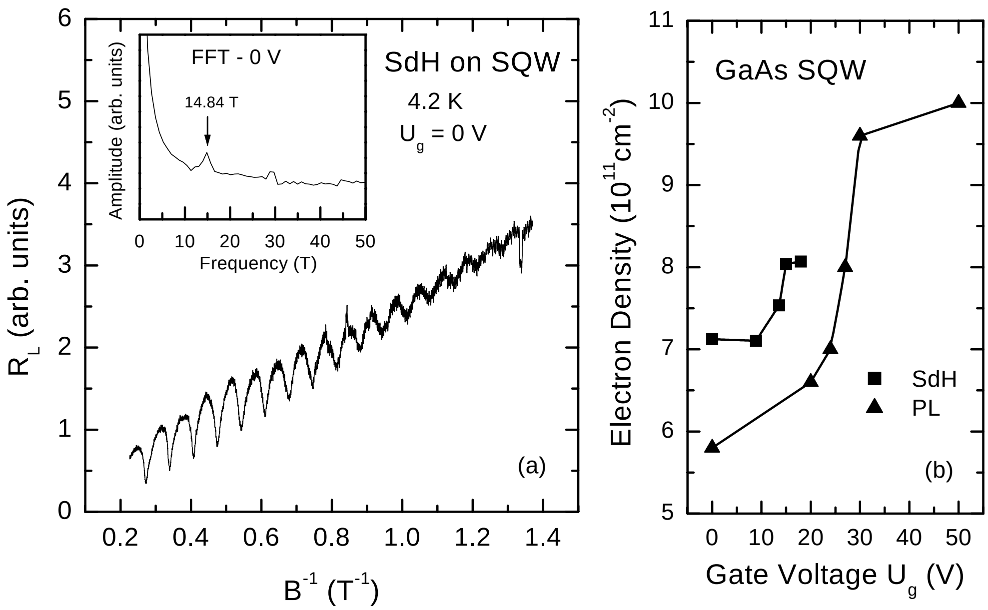

Figure 4. (a) Longitudinal resistance RL versus inverse magnetic field B^{-1} showing Shubnikov-de Haas oscillations. Measurements where performed without gate voltage at 4.2 K. The inset shows the fast Fourier analysis. (b) Variation of the 2DEG carrier density n_{2DEG} by applying a gate voltage between an In point and a metallic back contact. Squares represent the variation of the density measured with Shubnikov-de Haas (SdH); triangles correspond to results from photoluminescence (PL) [9].

transport current with increasing magnetic field. This is because the magnitude of $\Delta U_d/\Delta U_g$ is determined by the curvature of the I-V curve, as if the former were related to the derivative of the voltage-dissipation trace. For large fields the effect of eddy-current damping vanishes, which can be explained as due to the growing homogeneity of the field pattern of the vortices while approaching the upper critical field B$_{c2}$ and/or reaching the upper critical field B$_{c2}$. At lower fields moving vortices generate a magnetic field variable in time at the position of the 2DEG, which creates eddy currents [3].

For further investigation of the origin of the striking variations in power dissipation and to quantify the change in electron density with gate bias while we measure transport through the superconductor, we monitored the Shubnikov-de Haas (SdH) oscillations of the magnetoresistance of the 2DEG. Figure 4a shows the longitudinal resistance R$_L$ plotted versus inverse magnetic field obtained in a standard magnetoresistance experiment with the field perpendicular to the plane of the 2DEG. The result of a Fourier analysis, as displayed in the inset to Fig. 4a, yields a frequency of F=14.84 T for the SdH oscillation. From this frequency we calculate the 2DEG carrier density which is given by

$$n_{2DEG} = 2eF/h,$$

where e is the elementary charge and h is the Planck constant. We obtain a carrier density of $n_{2DEG} = 7,16 \times 10^{11}$ cm^{-2}. The results for different gate voltages (squares) are plotted in Fig. 4b together with the density values determined using luminescence (triangles) [9]. The determined change in the 2DEG carrier density by Shubnikov-de Haas is in good agreement with the PL data. Nevertheless, the variation of n_{2DEG} measured by optical spectroscopy depends much on the distance from the In point, where the gate voltage is applied. With applied bias the electron density becomes more inhomogeneous across the sample with the Pb film evaporated on top. These are the results of a recent PL study using a microscope setup for high spatial resolution to determine the lateral variation of the electron density in a SQW structure which was covered with PbIn. We were also able to detect a large increase of n_{2DEG} under the lead film without gate voltage relative to uncovered sites of the sample. The Shubnikov-de Haas technique, however, is only capable of measuring a mean carrier density, hence, the results would depend much on the position of the ohmic contacts with respect to the In point.

Finally, to explain the dissipation oscillations we have looked for means of producing a variation of the 2DEG resistance, since it would lead to a different efficiency for eddy-current generation, thus having an effect on the velocity of the moving vortices. We considered the superconducting current to be the source of magnetoresistance oscillations in the 2DEG, in view that a transport current of a few amperes would induce magnetic fields in the range of Tesla, if assuming a wire like current distribution. In this case, the field would lie in the plane of the 2DEG. Magnetoresistance measurements on the electron gas with in-plane field, however, showed no oscillatory behavior within experimental uncertainty. On the other hand, this is not surprising if a planar current distribution is assumed. This would produce a magnetic field independent of the distance to the 2DEG but which is three orders of magnitude smaller, for which magnetoresistance oscillations are not expected.

In summary, we have studied the dependence of the vortex dynamics in thin type-II superconductors on the existence of an adjacent electron gas. We found that filamentary and channel vortex flow is largely suppressed by the nearby doping layer and the entire flux lattice depins at once if a 2DEG is present. In addition, the variation of the 2DEG carrier density with a gate voltage was verified by monitoring Shubnikov-de Haas oscillations in the magnetoresistance of the 2DEG. The origin of the observed oscillatory variations of the magnitude of eddy-current damping as a function of the transport current through the superconductor has not been clarified yet. Further experiments using specially designed semiconductor heterostructures will be necessary. In particular, we aim at controlling filamentary and channel vortex flow in PbIn/2DEG hybrids using the gate voltage as adjustable parameter.

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