Andreev Reflection at High Magnetic Fields: Evidence for Electron and Hole Transport in Edge States

J. Eroms* and D. Weiss

Universität Regensburg, Institut für Experimentelle und Angewandte Physik, D-93040 Regensburg, Germany

J. De Boeck and G. Borghs

IMEC, Kapeldreef 75, B-3001 Leuven, Belgium

U. Zülicke

Institute of Fundamental Sciences and MacDiarmid Institute for Advanced Materials and Nanotechnology, Massey University, Private Bag 11 222, Palmerston North, New Zealand

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We have studied magnetotransport in arrays of niobium filled grooves in an $InAs/Al_xGa_{1-x}Sb$ heterostructure. The critical field of up to 2.6 T permits one to enter the quantum Hall regime. In the superconducting state, we observe strong magnetoresistance oscillations, whose amplitude exceeds the Shubnikov–de Haas oscillations by a factor of about 2, when normalized to the background. Additionally, we find that above a geometry-dependent magnetic field value the sample in the superconducting state has a higher longitudinal resistance than in the normal state. Both observations can be explained with edge channels populated with electrons and Andreev-reflected holes.

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The analysis of superconductor-semiconductor structures has been an active field of research in recent years (see, e.g., Ref. [1] and references therein). The versatility of semiconductors and the high mobilities attainable in heterostructures in combination with the retroreflecting and phase coherent process of Andreev reflection [2] have allowed one to observe a number of unique phenomena. By now, experiments in the regime of low magnetic fields, i.e., no larger than a few flux quanta per junction area, are well established. Gateable Josephson currents [3], quasiparticle interference [4], phase coherent oscillations [5], and an induced superconducting gap [6] have been observed, to name a few.

In the high-field regime, experimental evidence is much less abundant. A number of theoretical papers have dealt with Andreev reflection at high fields [7–10]. Notably, Ref. [7] describes how edge channels in the quantum Hall regime are formed of electron and hole states. To enter the regime of a fully developed quantum Hall effect, external fields of several tesla are required. Experiments have been performed with high critical field superconductors, such as NbN [11,12] or sintered SnAu [13], each of which suffer from technological difficulties, making the interpretation of the experiments in the quantum Hall regime difficult. In this work, however, we report clear evidence of the influence of Andreev reflection on transport in edge states using the well established Nb-InAs system. The critical field of up to 2.6 T permits one to enter the quantum Hall regime at high filling factors.

For the sample geometry we have chosen an array of Nb-filled grooves in an InAs-AlGaSb heterostructure containing a high-mobility two-dimensional electron gas (2DEG). A similar arrangement has been studied previously [14,15] in low magnetic fields. An important difference to single superconductor-2DEG-superconductor (*S*-2DEG-*S*) junctions is that the voltage probes are located in the 2DEG.

The samples were fabricated from a high-mobility $InAs/Al_xGa_{1-x}Sb$ quantum well, which was grown by molecular beam epitaxy on a GaAs substrate [16]. Mesas of 50 μm width and Ohmic contacts were prepared using optical lithography. After this step an electron density of $n_s = 1.25 \times 10^{12}$ cm^{-2} and a mobility of $\mu = 200\,000$ cm^2/V s were found. The mean free path in this material was therefore 3.8 μm, allowing for ballistic transport in nanostructures. The Nb-filled grooves were defined with electron beam lithography, selective reactive ion etching of the top AlGaSb layer, Nb sputter deposition, and lift-off. An *in situ* argon ion etch prior to the Nb sputtering ensured a high transparency of the Nb-InAs interface ($Z = 0.63$ in the Octavio-Blonder-Tinkham-Klapwijk model [17]), which allowed one to observe several subharmonic gap structures in the differential resistance at low magnetic fields. More fabrication details can be found in [18]. Lattice periods were ranging from $a = 400$ nm to $a = 3$ μm with different Nb-stripe widths.

The magnetoresistance (MR) measurements were done in a four-point configuration (see Fig. 1), but given the periodic geometry of the sample we effectively measured a series connection of many *S*-2DEG-*S* junctions. The critical temperature T_c of the Nb stripes was ranging from 6.9 to 8.3 K, depending mainly on the stripe width. Figure 2 shows the magnetotransport curves of two samples with lattice periods $a = 700$ nm and $a = 3$ μm. The Nb stripes were 120 nm wide and 70 nm thick in both cases.

Except for very low fields where the proximity effect dominates, the curves lie on one of two branches, depend-

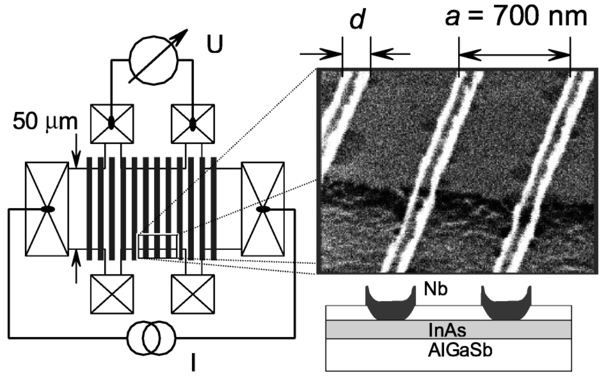

FIG. 1. Left: Geometry for the four-point measurements. Right: A scanning electron micrograph of the sample taken at the mesa edge. A cross section of the sample is also shown.

ing on whether the Nb stripes are in the normal or superconducting state. A transition between both branches is observed in Fig. 2 when the critical field of the Nb stripes at a given temperature is surpassed. Both branches cross at a certain magnetic field (arrows in Fig. 2). At low fields, the resistance on the superconducting branch is lower than on the normal branch, as expected for high quality contacts. For high fields, however, the magnetoresistance in the superconducting state is higher than in the normal state. This behavior is not due to a low contact transparency, resulting in a reduced Andreev reflection probability. In that case the resistance below T_c would *always* be higher than above T_c. A crossing point would not be observed. In a reference sample where the contact transparency was deliberately reduced, the resistance in the superconducting state was indeed higher than in the normal state throughout the entire field range.

At $B > 1$ T, oscillations appear in the magnetoresistance. In a 2DEG, magnetotransport oscillations are observed as soon as the magnetic field is strong enough to resolve Landau level quantization. Since the critical field of the Nb lines is much higher than the onset of the oscillations, we observe the impact of Andreev reflection on transport in the quantum Hall regime. On the superconducting branch, the oscillation amplitude is much more pronounced than on the normal branch. This can be seen more clearly in Fig. 3, where the data from Fig. 2, right, has been replotted versus $1/B$, after subtracting the slowly varying part of the MR. The increase in amplitude is indeed quite striking. The two main experimental findings in our samples are therefore the higher resistance at high fields and the strong increase in the amplitude of the $1/B$-periodic oscillations.

Let us first consider the MR oscillations in more detail. We evaluated the increase in amplitude for samples with a lattice period a of 1, 2, and 3 μm (data of the latter sample are shown in Fig. 2, right). The oscillation amplitude in the superconducting case was higher by a factor of 1.45, 4.1, and 6.4, respectively, when the amplitudes slightly above and below B_c were compared at $T = 3$ K. Thus, the further the stripes were apart, the more striking the increase in amplitude. The higher oscillation amplitude is not simply due to the larger nonoscillatory resistance in the superconducting state, caused, e.g., by the higher conductivity of the Nb stripes in the superconducting state. Normalized to the increase of the background, the oscillation amplitude still increased by a factor of up to 1.9 in the superconduct-

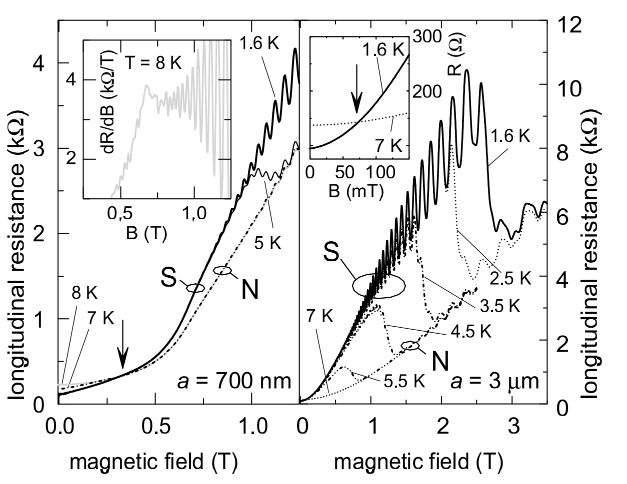

FIG. 2. T-dependent magnetotransport curves for two different samples. Arrows: crossing points of the graphs above T_c and below T_c. Left inset: The peak in dR/dB corresponds to a change in slope of the resistance trace. Right inset: Enlarged view of the crossing point for the sample with $a = 3$ μm. The critical temperatures were 7.4 K (left) and 6.9 K (right). Letters N and S denote the normal and superconducting branches, respectively.

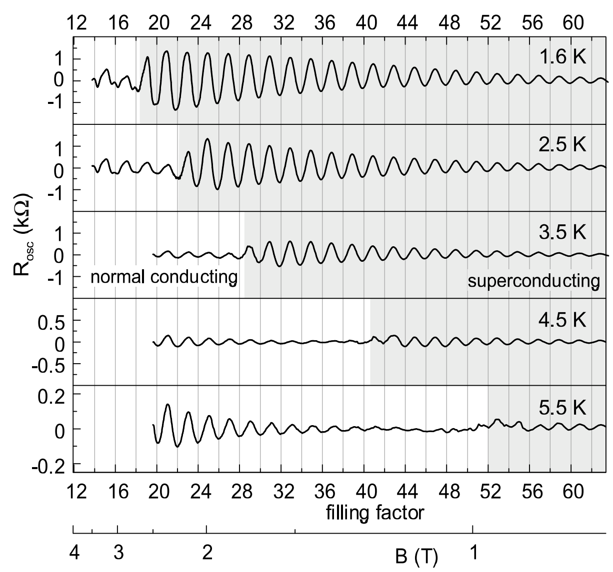

FIG. 3. Same data as in Fig. 2, right, after subtracting the slowly varying background and plotted against the filling factor. For ease of comparison, the value of B is also given. Shaded regions: Nb stripes are superconducting, as extracted from Fig. 2. Note the strong increase of the amplitude at the superconducting transition.

ing case [19], and the dependence on the stripe separation was maintained.

We also fitted the temperature dependence of the oscillation amplitude [20]. In the normal-conducting case the amplitude was well described by thermal activation over the Landau gap and gave an effective mass of $m_{\mathrm{eff}} = 0.04m_0$, where m_0 is the free electron mass. The same effective mass was found in a sample with the same geometry, but Au stripes instead of Nb. This value is comparable to what is found in InAs-based 2DEGs with a high carrier density [21]. In the superconducting case, however, the fit was poor and yielded an effective mass of up to $0.1m_0$, which is far from the real value. Therefore, Landau level splitting alone cannot be the underlying mechanism (and the effective mass extracted from such a fit is meaningless). Instead, edge channels containing electrons and Andreev-reflected holes can lead to the enhanced oscillations, as we discuss now.

Figure 4 illustrates the edge-channel picture for normal and superconducting stripes, both for a full and a half-filled Landau level. A normal-conducting metal stripe acts as an ideal contact for electrons propagating in edge channels once the stripe length greatly exceeds the cyclotron radius. This is indeed the case for our experiment. When the stripe is superconducting, the gap for quasiparticle excitations prevents the absorption of a single electron and leads to Andreev reflection instead. As both electrons and Andreev-reflected holes are forced on cyclotron orbits having the same chirality (see Fig. 4, inset), an edge channel is formed along a superconducting contact, consisting of a coherent superposition of electron and hole states [7–9], which is stable along its entire length. The charge current in such an Andreev edge channel is proportional to the difference between the moduli of electron and hole amplitudes in that superposition [7]. For an ideal 2DEG-S-interface, Andreev reflection is perfect and the Andreev edge channel is composed of electrons and holes in equal proportions. In that case, no net current is flowing along the superconductor edge and the mesa edges remain decoupled, i.e., the behavior of a normal quantum Hall sample is recovered. However, when an interface barrier and/or a Fermi-velocity mismatch leads to a finite amount of normal reflection, interference between normal and Andreev-reflected quasiparticles results in $1/B$-periodic oscillations of the electron and hole amplitudes [7,8]. For nonequal electron and hole amplitudes, a finite current is flowing parallel to the superconducting stripe, which is fed into the normal edge channel at the opposite mesa edge and gives rise to backscattering between the normal edge channels. Formally, these amplitudes can be calculated by matching appropriate solutions of the Bogoliubov–de Gennes equations [22] at the interface [7]. A parameter w was defined in Ref. [7] for characterizing the interface barrier, which corresponds to $2Z$ in the Blonder-Tinkham-Klapwijk model [23]. The hole probability—and therefore the strength of the backscattering—oscillates strongly when $w > 0$, with the same periodicity as Shubnikov–de Haas oscillations. This is what we would expect to occur in our samples, because even though the interface is highly transparent, there is still a residual barrier.

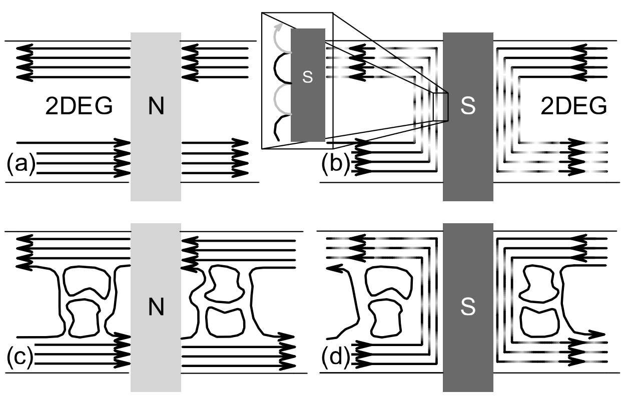

FIG. 4. Edge channels in a 2DEG hosting a normal (left) or superconducting (right) electrode. (a),(b) Integer filling factor (i.e., resistance minimum). (c),(d) Between integer filling factors. With a normal electrode, only the innermost channel is backscattered due to impurities in the 2DEG. In the superconducting case, edge channels hitting the electrode are Andreev reflected (see inset) and contain electrons and holes (gray). The amount of current that is backscattered depends on the hole probability, which oscillates in a magnetic field.

How can the formation of Andreev edge channels at an imperfect interface explain the enhanced MR oscillations observed in our measurements? In a quantum Hall sample with normal electrodes, the amplitude of the SdH oscillations is determined by backscattering of the innermost edge channel only, i.e., the one that is formed by the bulk Landau level closest to the Fermi energy. Therefore the conductivity of the sample can oscillate only by one conductance quantum. If the electrodes are superconducting, *all* edge channels are subject to Andreev reflection when they hit the electrode. The oscillation amplitude is therefore not limited to one conductance quantum. For example, for $w = 1$ and $\nu = 18$ (which would correspond to the critical field of the Nb stripes at 1.6 K), an amplitude of about six conductance quanta was obtained in Ref. [7]. The presence of the screening current in the superconductor [24] and disorder [25] does not change this behavior qualitatively for edge channels whose corresponding cyclotron radius is larger than the penetration depth but smaller than the mean free path. These conditions are satisfied for the range of filling factors where the enhanced MR oscillations are observed in our sample.

In the model treated in Ref. [7], the edge channels moving along the mesa edge and hitting the 2DEG-S interface consist of electrons only, since they originate from a normal-conducting electrode. Our samples incorporate many S-2DEG-S contacts in series. For short stripe separation, the edge channels impinging on the 2DEG-S boundary thus contain both electrons and holes. The situation of Ref. [7] is therefore not realized ideally, backscattering is less effective, and the oscillations are not as pronounced.

With increasing distance between the Nb stripes, more and more holes in the edge channel along the mesa edge recombine with the electrons, resulting in an edge channel containing only electrons as treated in Ref. [7]. This explains qualitatively why the oscillation amplitude increases with increasing stripe separation.

Now we turn to the nonoscillatory part of the MR. The magnetic field position of the crossover point (arrows in Fig. 2) for 16 samples was well described by the condition $R_c = 0.8b$, where $b = a - d$ is the distance between the stripes and $2R_c$ is the cyclotron diameter in the 2DEG. No satisfactory dependence on either the lattice period a or the stripe width d was found. Additionally, the slope of the MR trace (left inset of Fig. 2) changes at $2R_c = b$ (i.e., one cyclotron orbit fits between two stripes), which marks the transition to the regime of edge-channel transport. The latter is found both above and below T_c; hence this feature is unrelated to superconductivity. Note that this ballistic picture is justified as the mean free path is much larger than the perimeter of a cyclotron orbit at that field. Since both the crossing point and the change in slope are linked to the distance between the stripes, we conclude that both features are caused by the transition to the edge-channel regime.

In the given geometry, we measure a series connection of many two-point resistances (metal 2DEG), shunted to an unknown fraction by the semiconductor underneath the Nb stripes. Although it is therefore difficult to make quantitative statements about the resistance, we can explain qualitatively why the high-field resistance in the superconducting case is higher than in the normal case.

The Hall voltage is shunted by the metallic stripes connecting both sides of the Hall bar. This leads to a quadratic MR, which is less pronounced in the normal state when the Nb stripes have a finite resistance. This description is valid at low fields. At high fields, however, the MR appears to be linear in B, as one would expect for the two-point resistance in the edge-channel regime. The two-point resistance is determined by the number of edge channels (which decreases as B increases) and their conductivity, which is constant ($2e^2/h$) in a conventional quantum Hall sample. As we have seen above, the edge channels emitted by the superconducting electrodes consist of electrons and holes traveling in the same direction. Therefore, the conductivity of an edge channel is reduced compared to the normal case, which also leads to an increased resistance.

To summarize, we have examined arrays of Nb-filled grooves in an InAs-AlGaSb heterostructure at high magnetic fields using magnetotransport measurements at various temperatures. We observe strong $1/B$-periodic resistance oscillations when the Nb stripes get superconducting. They are due to edge channels containing both electrons and holes. We also find that above a geometry-dependent magnetic field, the overall sample resistance is higher in the superconducting case than in the normal case. This finding is consistent with the picture of edge channels containing Andreev-reflected holes. Our experiments therefore explore the impact of Andreev reflection on transport in the quantum Hall regime.

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*Present address: Kavli Institute of Nanoscience, Delft University of Technology, Lorentzweg 1, 2628 CJ Delft, The Netherlands.
Electronic address: eroms@qt.tn.tudelft.nl

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