PHYSICAL REVIEW B VOLUME 59, NUMBER 11 15 MARCH 1999-I

Andreev reflection at high magnetic fields

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(Received 3 December 1998)

Electron transport through a two-dimensional electron gas between superconducting contacts was studied in perpendicular magnetic fields of up to 6 T. Alloyed contacts with a high-critical field were used with a high-mobility GaAs:$\mathrm{Al_xGa_{1-x}As}$ heterostructure, allowing the first observation of Andreev reflection at fields of up to 3 T and into the quantum Hall regime. An increase in the probability of Andreev reflection was seen with increasing field to 1.2 T, and excess conductance is seen in the range 60 mT–3 T. Above 0.85 T, spin splitting in the semiconductor channel inhibits Andreev reflection. [S0163-1829(99)04211-3]

Much attention has been devoted to the study of superconductor- semiconductor hybrid systems, especially to the process of Andreev reflection (AR), whereby two electrons from the semiconductor pair upon crossing the interface.[1] In particular, the superconductor two-dimensional electron-gas junction is of interest because of the high-electron mobility and density in the channel. Many experiments have been performed, typically using Nb contacts to InAs-based channels,[2–5] because a transparent contact can be made between InAs and the superconducting electrodes. A smaller number of studies have used the GaAs:$\mathrm{Al_xGa_{1-x}As}$ heterostructure because of the higher mobilities obtainable[7–9], but the buried channel makes contact formation very difficult.

The effect of a magnetic field on Andreev reflection is currently of much interest,[6,10–13] including high-field effects such as the behavior of a superconductor-semiconductor junction in the quantum Hall regime.[11] The low-field response is now well understood, with a wealth of experimental evidence, mostly based on the clean Nb:InAs structure.[3,14] However, these contacts tend to have a low-critical magnetic field (H_c), with the result that the regime above 50 mT has been little studied experimentally. The one report of a high-field experiment, in Ref. 13, gives no details.

It has previously been demonstrated that a connection between a high-mobility two-dimensional electron gas and high H_c superconductor can be achieved with a GaAs/$\mathrm{Al_xGa_{1-x}As}$ heterostructure and a sintered alloy superconductor.[15] A careful choice of material and annealing conditions creates a contact containing interconnected regions of superconductor in a normal-metal matrix. This paper reports a study of the magnetoresistance of such a superconductor-semiconductor structure at relatively high applied field, and into the integer quantum Hall regime. Electron transport through the system is found to have an unusual field dependence, which disappears when the superconductor is driven into its normal state. Rather than decreasing, as had been expected, the probability of Andreev reflection is found to *increase* with increasing magnetic field.

Figure 1 shows the experimental structure, which is a refined version of a GaAs/tin contact,[15] produced using electron-beam lithography, lift-off, and rapid electron-beam annealing. The channel is formed from a standard high-mobility GaAs:$\mathrm{Al_xGa_{1-x}As}$ heterostructure, with an electron density of $3.32\times10^{11}\ \mathrm{cm}^{-2}$, a low-temperature mobility of $3.34\times10^{6}\ \mathrm{cm^2V^{-1}\ s^{-1}}$, length 2 μm and width 200 μm. Tin is evaporated and capped *in situ* with gold to prevent oxidation during specimen transfer. Silicon nitride is then sputtered, a refractory layer of chromium and gold evaporated, and the structure sintered using rapid electron-beam annealing with a time at peak temperature of $\sim$10 ms. The silicon nitride is a diffusion barrier to prevent chromium mixing and alloying with the tin and the semiconductor during annealing. A thin layer of aluminum oxide, not wetted by tin, is used to prevent contact flow across the gap during sintering.

This fabrication strategy optimises the repeatability of the electrical characteristics of the sintered contacts. The combination of refractory chromium and silicon nitride above the tin, and aluminum oxide between the contacts, keeps the tin in place during annealing and ensures uniformity of alloying. The microscopic structure has been investigated,[16] and is a multiplyconnected three-dimensional filamentary superconductor (predominantly $\mathrm{Sn_4Au}$) in a normal matrix, with a typical filament width and spacing of 100–500 nm. Contact is made to the two-dimensional electron gas(2DEG) via inclusions, which are morphologically similar to those seen in standard ohmic contacts to GaAs. The alloy is pseudo-type-II

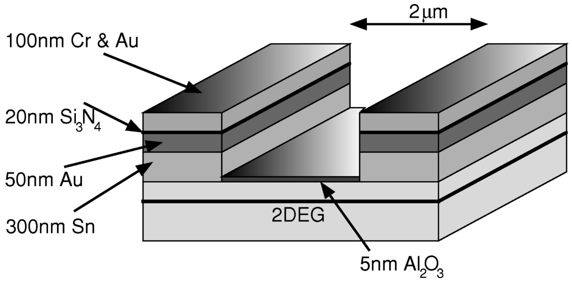

FIG. 1. Schematic figure of the junction.

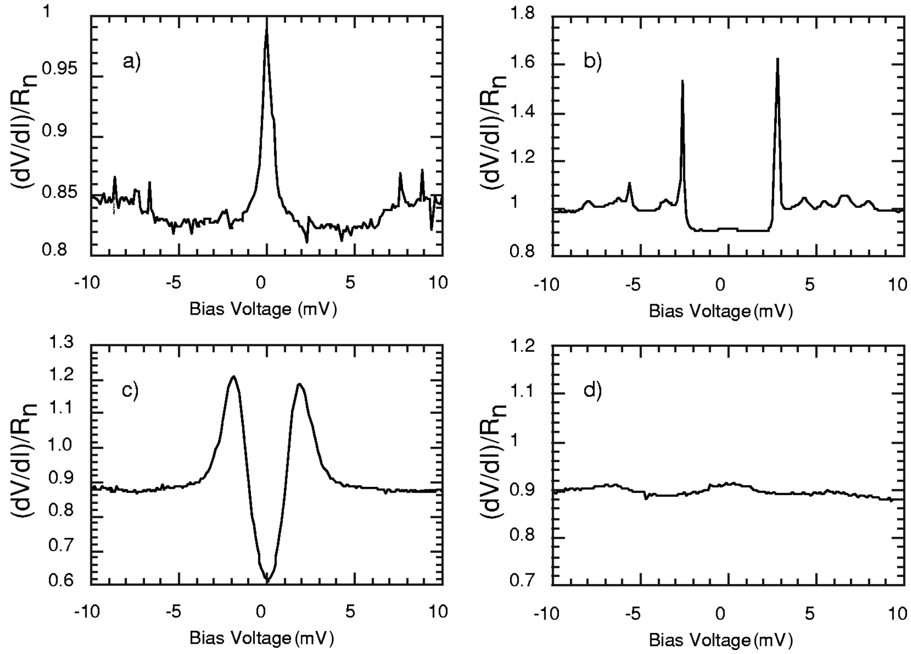

FIG. 2. Differential resistance traces at magnetic fields of (a) 0 T, (b) 200 mT, (c) 2 T, (d) 6 T. (b) and (c) are characteristic of Andreev reflection. The lower-field traces have repeatable finite-bias structure, which is absent at higher fields.

in that the field can penetrate the structure as a whole via the normal matrix, whilst being excluded from the superconductor. The critical temperature T_c and the critical magnetic field H_{cII} of the superconducting alloy contact material vary between specimens, lying in the ranges 4–7.5 K and 3–6.5 T, respectively. Values of $T_c=4.9$ K and $H_{cII}=4$ T were found for the device reported here, which corresponds to a superconductor gap 2Δ of 1.49 mV. A more detailed discussion of the microstructure of these contacts will be given elsewhere. Electrical contacts were made to the tin layer to allow four-terminal transport measurements. These were made at temperatures down to 300 mK in a He III refrigerator, using standard lock-in techniques, with a perpendicular magnetic field of up to 6 T.

The differential resistance as a function of applied bias shows a marked change of character with field. Figure 2 shows representative traces taken at 0 T, 200 mT, 2 T, and 6 T: At zero field, shown in Fig. 2(a), the resistance is sharply peaked at zero bias, falling as the voltage is increased. This is characteristic of a superconductor-semiconductor tunnel junction with a low AR probability, where charge transport through the junction is predominantly by single-particle tunneling to and from quasiparticle states in the superconductor at biases above Δ.

With a field applied, the response changes in an unexpected manner. The peak reduces as the field increases, inverting to become a dip, as can be seen in Fig. 2(b) and 2(c), at fields where an excess current is seen. This is characteristic of transport across a superconductor-semiconductor junction with a finite probability of Andreev reflection, resulting in a relatively low resistance (excess current) at low biases. A change in resistance is then observed when the bias across an interface reaches Δ. The dip increases in depth, (implying an increase in AR probability at zero bias), until around 1 T, then progressively reduces in depth. In Fig. 2(b), the cyclotron radius is ~ 500 nm, and the flat-based dip resembles the characteristic of a resistively shunted ballistic junction. In Fig. 2(c), however, the radius is ~ 50 nm, and the appearance is of a diffusive junction. In the range 1–2 T, the derived AR probability approaches unity, and the characteristics are those of diffusively coupled junctions. The inelastic scattering length in the channel is estimated at 33 μm, and the path length between current injection and removal points at these fields is ≈ 200 μm.

Figure 3 shows the magnetoresistance of the device at 0.3 K compared with that at 6 K. Superficially, the magnetoresistance appears to be as expected for a device of this geometry, with a progressive rise in resistance with increasing field and the onset of Shubnikov–de Haas/quantum Hall

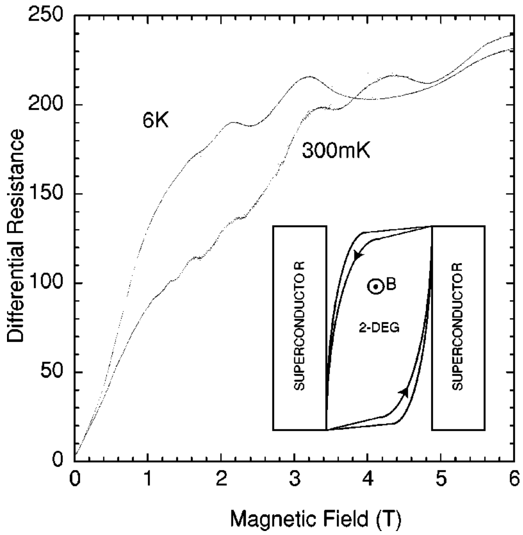

FIG. 3. Magnetoresistance of the structure at 300 mK and 6 K. The curves diverge and then reconverge as the field increases. The inset shows schematic current paths across the device at finite magnetic fields.

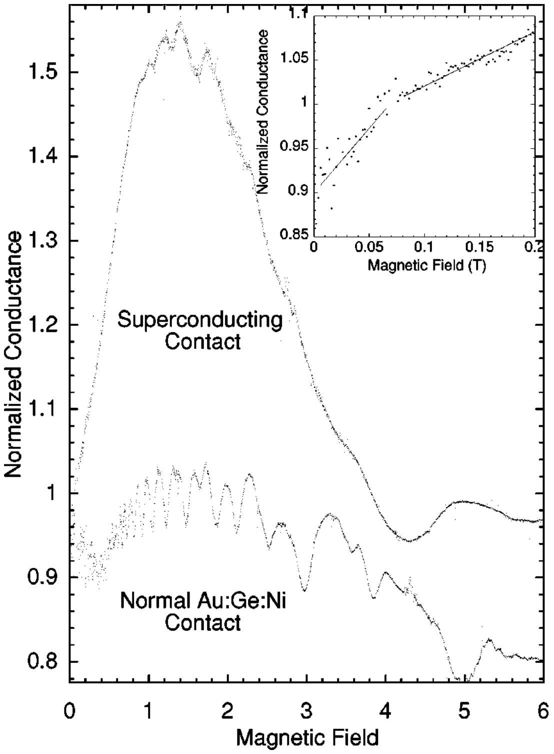

FIG. 4. Normalized zero-bias conductance as a function of applied magnetic field for structures of identical geometry, but with superconducting and normal-metal contacts. The inset shows the low-field behavior with superconducting contacts, where a distinct change in gradient is seen as the conductance passes through 1 at ~60 mT.

oscillations at higher fields. The measured magnetoresistance is two-terminal across the two-dimensional channel and so contains elements of both logitudinal and transverse conductance: $\rho_{xx}=\sigma_{yy}/(\sigma_{xx}\sigma_{yy}+\sigma_{xy}^{2})$. Such two-terminal measurements have been extensively studied and show positive magnetoresistance with steps and superposed oscillations, the character of which is strongly dependent on geometry.[17,18] However, the region below 3 T in the devices with superconducting contacts show an unusual curvature and a lower resistance relative to that at higher temperature or bias than is seen in control devices with normal contacts. The model of Takagaki,[13] of a superconductor in series with a two-dimensional electron gas in the quantum Hall regime, shows a very similar magnetoresistance, but not an increase in the Andreev reflection probability with field. The ratio of the superconductor/channel Fermi energies in these experiments, $\mu_S/\mu_N=6.8$, is higher than the range studied by Takagaki, $\mu_S/\mu_N=1-4$, and the device width is much larger. The bias dependence is very different from the model, showing a dip around zero bias rather than a dip at Δ, which is due to the presence of a disordered region near the interface, not included in the model.[1]

A plot of normalized conductance (G_S/G_N) vs perpendicular magnetic field, which gives a measure of the proportion of transport occuring by Andreev reflection, is shown in Fig. 4, for a sample with superconducting contacts, and a control sample of the same geometry but with normal gold:germanium:nickel contacts. The difference in behavior is immediately apparent. The conductance of the structure with superconducting contacts shows several distinct regimes: For very low fields, the normalized conductance is less than unity, and rises to one at a field of ~60 mT, due to the breaking of weak localization in the narrow region of disorder near the interface. This implies a phase-breaking length of ~65 nm in this region, which is estimated to be 80–90-nm thick from microscopic characterization. At higher fields, the conductance rises linearly and then oscillates and falls, reaching values around unity near 4 T.

Other differences are seen between the superconducting and normal contacts. With superconducting contacts, the absolute resistance of the structure and the change with field dR/dB, are both lower. Also, the magnetoresistance oscillations are considerably less well resolved than with normal contacts. This is due to the presence of the superconducting contacts, which impose a local lateral electrical equipotential, dampening the establishment of a Hall voltage across the channel.

Both the normalized zero-bias conductance and the character of the differential resistance at finite bias indicate that the proportion of the electron transport that takes place by Andreev reflection is first increasing with applied magnetic field, up to a field of around 1 T, then decreasing. This is against a background of generally decreasing conductance with magnetic field. The overall evidence therefore, is that from 0–60 mT, the conductance is dominated by single-particle tunnelling across the interfaces and weak localization in the channel. In this region, the fluctuations in conductance are larger than at higher fields. Between 60 mT and 0.85 T the AR probability increases linearly with field, reaching a maximum of around 0.7. Above 0.85 T, the proportion of AR begins to decrease with increasing field, being extinguished at approximately 4 T.

The unexpected rise in AR probability with magnetic field merits discussion. As the field increases, the number of conduction channels decreases and transport begins to take place via edge states. This gives the positive two-terminal magnetoresistance seen with both normal and superconducting contacts. With superconducting contacts, for transport across the interface to occur at subgap biases via Andreev reflection, the conditions of energy, $(E_1+E_2=2E_S)$ wave vector and spin, $k_{1,\uparrow}=-k_{2,\downarrow}$, matching must occur for the electrons in the channel to enter the superconductor as a spin-singlet pair. With no applied field, the range of states available near the interface and the high μ_S/μ_N mean that the probability of two incoming electrons satisfying these conditions is low (unless interference contributes strongly).

At finite magnetic field, flux is excluded from the superconducting regions of the contact, but penetrates the contact through the normal regions, so there will be no field enhancement in the channel. The superconductors are then in series with a field-quantized two-dimensional electron gas, with a thin-disordered region at each interface. Transport at low bias is by Andreev reflection in and out of the edge channels.

One explanation of the increase is that if edge-state transport is dominant, the wave vectors of incoming and outgoing electrons are closely constrained in the quasi-one-dimensional states and the matching probability for Andreev reflection is correspondingly raised. Although the application of the field reduces the overall conductance, the increasing probability of Andreev reflection lowers the rate of that reduction.

Alternatively, the effect may be due to the increased attempt rate due to skipping orbitals at the interface.[13,19] This implies an increase in AR probability, which is linear with field, proportional to the number of skips in the semiclassical picture. The increase does appear to be linear with field in the range 60–800 mT, but a simple analysis using this model, with the maximum AR probability of 0.95 near 1 T gives a zero-field probability of the order 10^{-3}. A more detailed analysis would need to include disorder near the interfaces, which is known to have a dramatic effect on Andreev reflection.

As the field is raised further, spin splitting means that the matching conditions are no longer satisfied. When the available channels are spin polarized, although the wave vector and energy conditions may be met, spin flip is needed for Andreev reflection to occur,[11] and so the probability decreases. The field at which the conductance turns over corresponds to the field at which spin splitting of the levels is seen. This can be seen in the longitudinal resistance of a standard Hall bar made from the same wafer; shown in Fig. 5 with the normalized conductance of the device with superconducting contacts. The turnover in excess conductance occurs at a field where spin splitting starts to be resolved in the longitudinal resistance. At higher fields, the superconductor gap decreases, which will also reduce Andreev reflection, but the coincidence of the turnover in excess conductance with the onset of spin splitting implies strongly that this dominates, at least to fields of the order of 2–3 T.

The experiments were repeated with the magnetic field applied parallel to the two-dimensional electron gas, and no Andreev reflection was observed, further indicating that this is an orbital effect. Similar behavior has been observed in several devices with this structure and in devices with other tin-based alloyed contact materials with markedly different alloy compositions, but similar superconducting microstructure, demonstrating that the effect is not material dependent. The contacts made to the Hall-bar control device were made using the same heat treatment as the superconducting device, and the longitudinal magnetoresistance shown in Fig. 5 confirms that the annealing does not deminish the channel mobility.

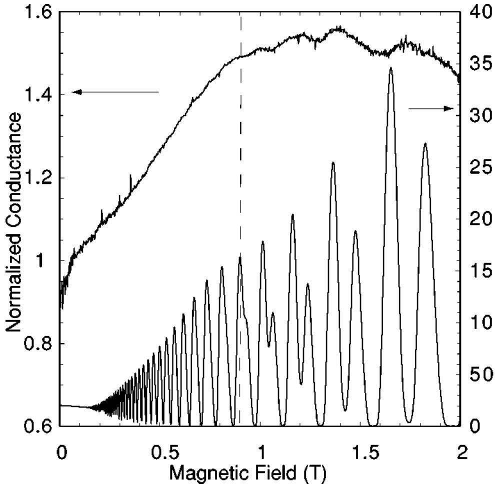

FIG. 5. Comparison of the excess conductance and the longitudinal resistance in a standard Hall bar made from the same wafer. Spin splitting starts to be resolved at 0.85 T, where the Andreev reflection starts to reduce.

In conclusion, we have observed Andreev reflection at high-magnetic fields. We find an increase in the Andreev reflection probability with increasing field for low fields, which is quenched when Zeeman splitting of the Landau levels becomes significant. There is currently no quantitative model for this effect, which is the inverse of the expected behavior. Several aspects of this response need further investigation, and the temperature dependence is currently being investigated in detail. This system potentially opens the possibility of studying Andreev reflection between a superconductor and a Luttinger liquid.[20] Very recently, a similar effect has been seen in the NbN:InAs system.[21]

The authors thank H. Ahmed, B.W. Alphenaar, D. Khmelnitskii, and B. Simons for useful discussions.

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