Hysteretic magnetotransport in *p*-type $Al_xGa_{1-x}As$ heterostructures with In/Zn/Au Ohmic contacts

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The two-terminal magnetoconductance of a hole gas in C-doped AlGaAs/GaAs heterostructures with Ohmic contacts consisting of alloyed In/Zn/Au displays a pronounced hysteresis of the conductance around zero magnetic field. The hysteresis disappears above magnetic fields of around 0.5 T and temperatures above 300 mK. For magnetic fields below 10 mT, we observe a pronounced dip in the magnetoconductance. We tentatively discuss these experimental observations in the light of superconductivity of the Ohmic contacts.

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Transport measurements in semiconductors require Ohmic contacts between the external metallic leads and the carriers in the semiconductor. At the interface between a semiconductor and a metal, usually a Schottky contact forms giving rise to nonlinear current-voltage (*I*-*V*) characteristics. In order to obtain linear *I*-*V* traces, this Schottky barrier has to be overcome, which is usually achieved by highly doping the semiconductor in the contact region. For *n*-type AlGaAs heterostructures, this is routinely achieved by using Au/Ge/Ni alloys. For *p*-type AlGaAs heterostructures, one usually uses layers of AuZn, AuBe, or InZn.[1] Especially at liquid He temperatures and below, the quality of the contacts to hole systems is inferior to the Ohmic contacts on electron gases. As long as the *I*-*V* characteristics are linear, high contact resistances can be experimentally overcome by using four-terminal measurements. However, for high impedance devices such as quantum dots, one has to perform voltage-biased measurements, and the contact quality becomes crucial.

Here we report on a peculiar hysteresis effect observed in two-terminal magnetoconductance measurements on a two-dimensional hole gas contacted by In/Zn/Au alloys. For voltage biased devices, the current signal shows a pronounced dip-like feature around zero magnetic field and hysteretic behavior up to magnetic fields, where Shubnikov–de Haas (SdH) oscillations become relevant. The feature disappears for high magnetic fields and high temperatures. We tentatively ascribe these observations to the contacts becoming superconducting. This way, we extract an estimate for T_c, the superconducting transition temperature, as well as for critical magnetic fields of the In/Zn/Au alloy, which are in tune with values reported in the literature. The purpose of this paper is to show experimental details of unusual Ohmic contacts possibly related to a superconducting phase transition.

Our experiments have been performed on AlGaAs heterostructures doped with carbon (C) acting as an acceptor on (100) substrates.[2,3] The integer, as well as the fractional quantum Hall effects, have been observed in such samples[4,5] testifying to the electronic quality of these structures. The material quality has strongly improved over the last couple of years[6,7] with mobilities now exceeding 10^6 cm^2/Vs.[8] Also, single electron transistors,[9] as well as high-quality Aharonov–Bohm rings,[10] have been realized. The effects, which we describe in the following, have been observed in two-terminal measurements on four different samples. We present data from one sample. The wafer consists (from surface to bottom) of 5 nm GaAs, 15 nm $Al_{0.35}Ga_{0.65}As$ with *C* doping, 25 nm $Al_{0.35}Ga_{0.65}As$, and 650 nm GaAs grown on a semi-insulating substrate. At 4.2 K, the carrier density is $n=3.8\times10^{11}$ cm^{-2}, and the mobility is $\mu=120\,000$ cm^2/Vs. The sample is patterned into a square mesa (20×20 μm^2) geometry by standard photo lithography and etching procedures. Before each evaporation of Ohmic contact metallization, the sample surface is cleaned for 2 min with oxygen plasma ashing (power 200 W), and the sample is then immediately placed in an evaporation machine.

Our experience shows that making Ohmic contacts to two-dimensional hole gases (2DHGs) deeper than 100 nm below the surface is relatively straightforward and can be achieved by using only Zn/Au metallization. In the case of shallow 2DHG heterostructures (45 nm below the sample surface), using only Au and Zn did not give satisfactory results. Therefore, we also added In in the contact metallization. We emphasize that the effects reported in this paper were observed only for In/Zn/Au and not for Zn/Au contacts. This suggests that the presence of In is responsible for the observed effects. We also found that for a thick initial layer of gold (40 nm) usually used as a sticking layer, the contacts did not work, and we had to reduce this thickness to 2 nm. Therefore, we use the following contact metallization for shallow 2DHG samples: 2 nm Au, 40 nm Zn, 40 nm In, and 200 nm Au annealed at 480–500 °C in 95% N_2 and 5% H_2 atmosphere for 2 min. The two-terminal resistances of these contacts are 300–500 kΩ at room temperature, and they drop very fast to values around 10–20 kΩ upon cooling the sample to 4.2 K. It is important to point out that the room temperature value of the two-terminal contact resistance cannot give a clear answer whether the contacts are good at low temperature. For some samples with similar values at room temperature, the contact resistance increased upon cooling to 4.2 K. Therefore, it is crucial to check if the contacts are good at 4.2 K before proceeding with the fabrication of nanostructures. It is important to note that indium becomes superconducting at $T_{c,\mathrm{In}}=3.4$ K and zinc at $T_{c,\mathrm{Zn}}=0.85$ K. Therefore, for experiments in a dilution fridge at temperatures in the mK range, the possible transition of the Au/Zn/In

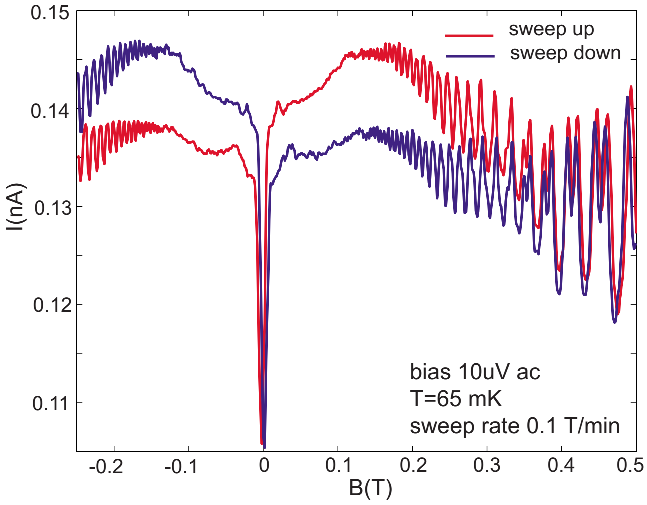

FIG. 1. (Color online) Current through a pair of Ohmic contacts at $T=65$ mK as a function of magnetic field at fixed ac bias of 10 μV and B-sweep rate 0.1 T/min. The red/gray trace corresponds to B-field up-sweeps and the blue/black trace to a down sweep. As the B-field approaches a value around 0.5 T, the hysteresis disappears.

contact metallization into a superconducting state might be relevant for transport measurements.

Figure 1 shows a typical two-terminal voltage biased transport measurement in the linear regime on a sample with Au/Zn/In contacts. Figure 2 displays the dependence of the hysteresis on temperature and sweep rate. The observed effects are described in the following:

(1) A hysteresis is observed for up and down sweeps of the magnetic field. A pronounced minimum occurs in the current around $B=0$ with a width of about 10 mT. The conductivity (current) next to the minimum is low before the minimum is reached and high after the minimum has been passed.

(2) The hysteresis persists into the regime of Shubnikov–de Haas oscillations and peters out at magnetic fields around 0.5 T.

(3) The current dip around $B=0$, as well as the hysteresis, weaken with increasing temperature and disappear around 230 mK.

(4) The difference between up and down sweeps becomes smaller as the sweep rate is reduced and almost disappears for a sweep rate of 0.01 T/min. The depth of the minimum around $B=0$ does not depend on the sweep rate.

Samples without In in their contacts did not display any of these features. These effects are present only in two-terminal measurements, and they are absent in four-terminal measurements. This indicates that these features originate from the contacts and not from the 2DHG. In particular, the zero-field behavior is completely opposite for these two cases. While the two-terminal conductance displays a dip, the four-terminal resistance displays a minimum due to weak antilocalization,[11] which corresponds to a maximum in the four-terminal conductance.

We have tested In-only contacts directly on the 2DHG, and they did not work at all (infinite contacts resistance). Therefore, we think that the presence of Zn, which is a

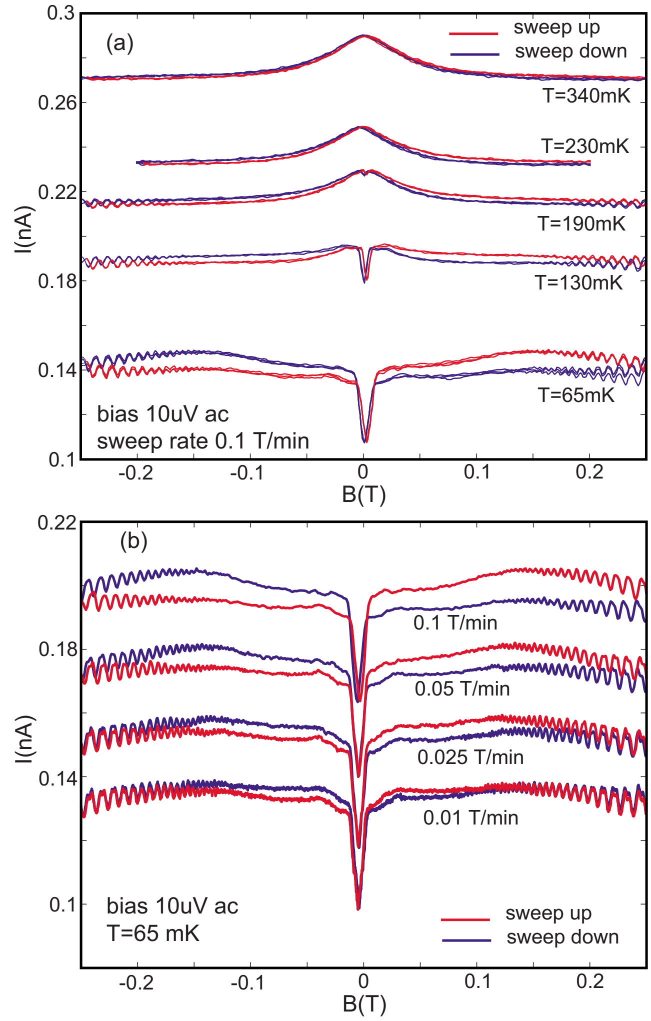

FIG. 2. (Color online) (a) Hysteretic magnetoconductance for different temperatures. Red/gray traces correspond to up-sweeps and blue/black traces to down-sweeps of the magnetic field. The sweep rate is 0.1 T/min, and an ac bias of 10 μV is applied across the contacts. The measurements are performed at different temperatures indicated on the right side. Note that the vertical offsets between the traces for different temperatures are not artificially introduced but originate from the change of contact resistance with temperature. At each temperature, six B-field sweeps are performed (three up and three down). The sweeps corresponding to the same sweep direction lie perfectly on top of each other demonstrating the reproducibility of the measurement. (b) Magnetoresistance for different sweep rates. The traces are vertically offset by 0.02 nA for clarity.

p-type dopant on GaAs, is crucial for formation of contacts to 2DHG. It was necessary to add In to reduce the melting temperature of the InZn alloy (compared to Zn alone) and improve the diffusion of Zn into the structure. We did not investigate In/Zn/Au on a two-dimensional electron gas.

Finally, we have measured the I-V characteristics of the Ohmic contacts at different temperatures [Fig. 3(a)]. At $T=65$ mK, a nonlinearity around zero bias is observed, which becomes weaker as the temperature increases and almost completely disappears above 340 mK. In order to visualize these data in a clearer way, we plot in Fig. 3(b) the differen-

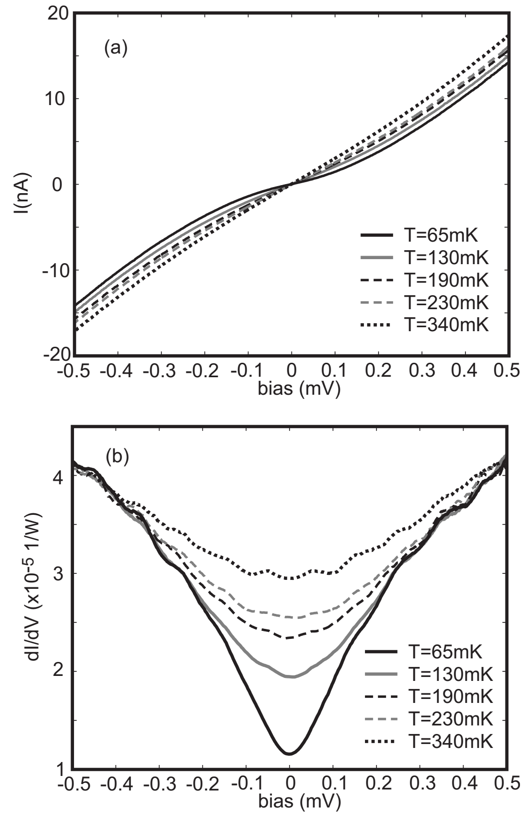

FIG. 3. (a) Temperature dependence of the *I*-*V* characteristics of In/Zn/Au Ohmic contacts at $B=0$. (b) Temperature dependence of the differential conductance dI/dV, obtained by numerical differentiation of the traces shown in (a).

tial conductance dI/dV, obtained by numerical differentiation of the measured *I*-*V* curves, as a function of bias. It can be seen that at $T=65$ mK, a very expressed dip in the differential conduction develops around zero bias with a minimum around 1×10^{-5} $1/\Omega$. This dip weakens as the temperature increases to 340 mK. If we analyze this change quantitatively, we see that at $T=340$ mK, the low-bias differential resistance is around 30 kΩ, and it increases to around 100 kΩ as the temperature is reduced to 65 mK. Such a strong increase in the low-bias two-terminal contact resistance as the temperature is lowered below 100 mK can be very harmful for low-noise transport measurements, which require low contact resistances and linear *I*-*V* characteristics of the contacts.

We would like to note that the temperature dependence of the conductance is pronounced for all magnetic fields investigated. The curves in Fig. 2(a) are not vertically offset. Rather, the background conductance changes from about 1/70 to $1/37$ kΩ^{-1} when the temperature is increased from 65 to 340 mK. In the same temperature range, the resistance around $B=0$ changes from 90 to 35 kΩ, which is consistent with the data of Fig. 3(b). We conclude that there are two different contributions to the temperature dependence of the resistance: one which is present for the entire magnetic field regime investigated and another one which is particularly pronounced around $B=0$.

These experimental features are linked to the presence of In in the contact material. Motivated by the temperature and magnetic field dependence of the observed effects, we discuss in the following possible relations to type II superconductivity in the In/Zn/Au contact pads.

Proximity effects extending between semiconductor contacts[12] have been investigated in InAs-Nb systems, where great care was taken to optimize the interface between the superconductor and the semiconductor. Indium Ohmic contacts were deposited on an *n*-type AlGaAs heterostructure at a distance of 1 μm, and the flow of a supercurrent was demonstrated[13] and explained in the framework of phase-coherent Andreev reflections.[14] Once the mobility of the electron gas was reduced by electron-beam irradiation, a zero-bias dip in the differential conductance was observed, which was strongly reduced as the magnetic field was increased above 40 mT. Superconducting Sn/Ti contacts were fabricated close to a quantum point contact in a high-mobility two-dimensional electron gas in a AlGaAs heterostructure.[15] The authors reported an enhanced weak localization signal around zero gate voltage. The experimental signatures of this dip in the magnetoconductance have a similar temperature dependence as the effects, which we report about in this paper. Indium contacts to AlGaAs heterostructures were investigated by both differential conductance spectroscopy and transmission electron microscopy.[16] It was found that metallic contacts deposited on a (100) AlGaAs/GaAs heterostructure grow down into the heterostructure upon thermal annealing. Pyramidlike point contacts form along crystallographic planes. Each superconducting point contact displayed a different interface transmission caused by random surface nucleation and growth. The observation of hysteresis in the conductance upon sweeping the magnetic field was not reported in these publications.[12,13,15,16]

Since the contacts are annealed into the GaAs host material, we do not expect a sharp and well-defined interface between the superconductor and the hole gas in the semiconductor. Also, there is a comparatively large distance (about 250 μm) between the contacts, much larger than the mean free path, the inelastic scattering length of the holes in the carrier gas, and the pair coherence length in the superconductor. The experiments were done on a square mesa, and the observed features did not depend on the contact pair used for the two-terminal experiment. Similar observations were also obtained on another sample with Hall-bar geometry.

Several experimentally observed features such as two typical magnetic field scales and a critical temperature indicate a possible relation to the contacts becoming superconducting. In the following, we discuss possible scenarios and their limitations to explain the experimental observations. It is conceivable that a potential barrier exists for Cooper pairs in the contact region with a low transmission to the hole Fermi gas. One may then attempt to interpret the above findings by assuming a superconductor-insulator-metal contact with quenched Andreev scattering: Charge transmission below the superconducting gap is suppressed, leading to a small contact conductance at zero magnetic field. In the presence of a magnetic field, vortices enter the superconductor, driving the material normal within the core regions of the flux lines. As a result, the contact conductance is expected to increase rapidly as vortices flood the superconducting contacts, in agreement with the experimental observation. A particular feature is the recovery of the zero-field dip in the current flow upon field decrease, signaling that vortices leave the contact region as the external magnetic field approaches zero. This feature is particular to surface pinning through Bean–Livingston barriers[17] or due to geometrical barriers[18]—in both cases, vortices do leave the superconductor smoothly as the field vanishes. Beyond this sharp minimum, which is nearly reversible, the magnetoconductivity becomes strongly hysteretic, as displayed in Figs. 1 and 2. It is here that the above scenario fails: for a given magnetic field, one expects that the number of vortices and, therefore, the current is smaller/larger for increasing/decreasing fields, a simple consequence of the magnetic behavior of a type II superconductor with surface pinning, cf. Ref. 19. This is opposite to the experimental observation.

If, on the other hand, the contacts between superconductor and electron gas are assumed to be of good quality without an insulator in between, then the high current state would be related to the situation with few vortices. Such a scenario would better explain the hysteretic behavior at finite magnetic fields but fails to account for the current minimum at $B=0$.

The sweep rate dependence of the hysteresis indicates the presence of vortex creep. Relaxation to the equilibrium magnetization should then be asymmetric,[19] with the high current branch (many vortices) decaying slower than the low current one (fewer vortices). From Fig. 2(b), we learn that the curves swept from high fields toward $B=0$ (red curves for $B<0$ and blue curves for $B>0$) are equidistantly spaced in the vertical direction, i.e., they are independent of sweep velocity. On the contrary, the sweeps from low fields to high fields (blue curves for $B<0$ and red curves for $B>0$) depend strongly on the sweep rate and approach their lower-lying counterpart as the sweep rate is reduced. This experimental observation is in contrast to the theoretical scenario described before.

Since all of the observed effects disappear above about 300 mK, this temperature can be interpreted as the critical temperature of the superconductor. The values for the critical fields as well as for the critical temperature T_c are not unreasonable, considering the numbers in the literature.[20,21] While the likelihood that the observed effects are related to the superconductivity of the contacts is large, we conclude, however, that the microscopic understanding of the contact region and the transport mechanism is lacking.

The flat region of the *I-V* curve in Fig. 3(a) probably arises from two different effects. One is a simple heating effect, which we have also observed for other *p*-type nanostructures. This effect appears to be very significant in the case of holes. Heating effects may explain the bias dependence of the conductance over the entire magnetic field range investigated. Another weaker bias dependence of the conductivity [Fig. 2(a)] could be related to the superconductivity of the contacts. Because the two effects occur simultaneously, it is not possible to estimate a gap energy from the nonlinear *I-V* characteristics at low temperatures.

We refrain from a more detailed and elaborate interpretation of the data in view of many experimental uncertainties. The superconductivity of the contacts has been discussed as a possible origin for the observed features. For experimentalists working with nanostructures in semiconductors, it is crucial to recall the importance of Ohmic contacts in general and, in particular, for two-terminal transport measurements.

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