Magnetic-field-induced metal-insulator-transitions in disordered constrictions

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Abstract The electronic transport properties of disordered constrictions have been studied in a perpendicular magnetic field. The disorder strength was variied by applying different backgate voltages. We observed magnetic-field induced metal-insulator transitions down to a critical backgate voltage. Below that value the constriction remains insulating independent of the magnetic field. Based on our findings we propose a phase diagram for a mesoscopic two-dimensional electron system and relate it to the global phase diagram in the quantum Hall effect.

1 Introduction

The properties of disordered systems have attracted a lot of interest in the past years and many recent experiments are still related to this subject. However, most experiments are dealing with macroscopic two-dimensional systems, hence there is little known about mesoscopic systems with disorder. Here we present results of magneto-transport experiments on narrow constrictions which can be viewed as disordered mesoscopic structures [1].

2 Experiment and results

The samples in this experiment are based on modulation-doped GaAs/AlGaAs-heterostructures grown by molecular-beam epitaxy (MBE). The constriction was mechanically patterned with an atomic force microscope (AFM) using controlled nanomachining presented in [2]. The resulting structure consists of a constriction which is coupled at both ends to two-dimensional electron gases (2DEG). Fig. 1a shows an AFM micrograph of a typical sample. The constriction size of $\approx 2\ \mu m\ x\ 2\ \mu m$ corresponds to a few times the mean free path in the 2DEGs. Due to the electronic depletion in the vicinity of the grooves the energetical spacing between the conduction-band edge and the Fermi energy in the constriction area is reduced compared to that in the 2DEG (see Fig. 1b), resulting in a lower electron density n inside the constriction [3].

We have investigated the dc-current through the constriction at fixed bias in a varying magnetic field perpendicular to the plane of the 2DEG. The bias voltage has been chosen fairly high (a few mV) in order to suppress possible disorder-related Coulomb-blockade effects in the constriction. The electron density inside the constriction could be variied by applying a backgate voltage on the back side of the GaAs-substrate. Note that a density change modifies the srceening capability of the electronic system leading to a change of the disorder strength inside the constriction. The experiments were perfomed at different temperatures, ranging from 1.4 K up to 20 K and in magnetic fields up to 14 T.

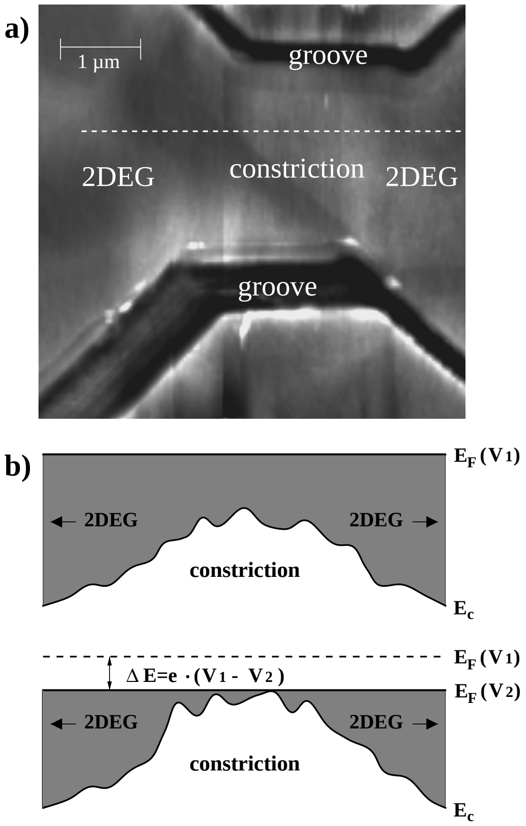

Fig. 1 a) AFM micrograph of a typical constriction. b) Sketch of the bandprofile along the dashed line in a) for two different backgate voltages V_1 and V_2.

At zero magnetic field the constriction exhibits insulating behaviour characterized by an increasing resistance with decreasing temperature. Fig. 2 shows the temperature dependent zero-field resistance for various backgate voltages. For the higher backgate voltages the resistance is described best by a logarithmic dependence $R \propto -\alpha \cdot ln(T)$ corresponding to the weak localization regime. With decreasing backgate voltage, i.e. increasing disorder, the constriction gradually changes from weak to strong localization.

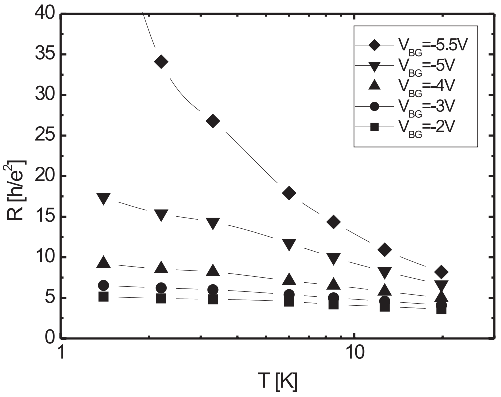

Fig. 2 Zero-field resistance for various backgate voltages as a function of temperature.

Our main interest focusses on the temperature dependence of the current through the constriction in a varying magnetic field as shown in Fig. 3. The magnetocurrent has been measured at a fixed backgate voltage of $V_{BG} = -2\ V$ and for different temperatures from T=1.4 K to T=19.8 K. Below a certain field (marked B_{c1} in the figure), the constriction shows insulating behaviour in a sense that the current increases with increasing temperature. At B_{c1} a transition occurs and the constriction enters the metallic phase characterized by a decreasing current with increasing temperature. The metallic regime extends up to a second transition field $B \approx B_{c2}$ where a reentrance into the insulating phase is observed.

In order to vary the strength of disorder we took measurements at different backgate voltages. With decreasing voltage, the transition fields B_{c1} and B_{c2} approach each other until finally a critical backgate voltage is reached ($V_{BG} \leq -5\ V$). At more negative voltages the constriction remains purely insulating for all magnetic fields. This strong dependence of the transitions on backgate voltage and magnetic field allows us to construct a phase diagram, which is shown in Fig.4. The pure insulating phase is observed for values below $V_{BG} \approx -5\ V$, while above that value two backgate-voltage dependent transitions from insulator-to-metal and metal-to-insulator emerge. Therefore, we propose a phase diagram for a disordered mesoscopic 2DES according to the global phase diagram (GPD) [4] based on the levitation of critical states [5,6]. Several experiments, e.g. [7,8], already verified the existence of the GPD for macroscopic 2DES.

3 Conclusions

In conclusion we have presented experimental results on the transport properties of disordered constrictions in a perpendicular magnetic field. The strength of disorder was altered by varying the backgate voltage. Below a critical amount of disorder the constriction undergoes magnetic-field induced metal-insulator transitions, whereas it remains insulating for all magnetic fields above that critical disorder strength. This result suggests a phase diagram for a mesoscopic 2DES very similiar to the global phase diagram of macroscopic 2DES.

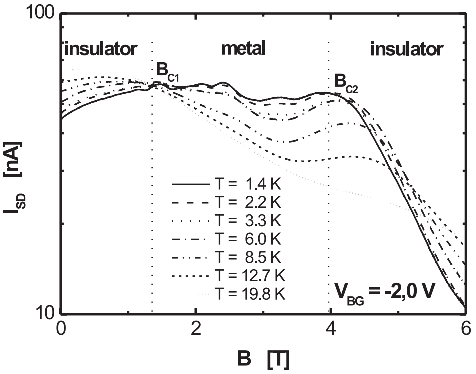

Fig. 3 Current versus magnetic field at fixed backgate voltage of $V_{BG} = -2\ V$ for different temperatures. The fields B_{c1} and B_{c2} mark the field-induced insulator-to-metal transition at B_{c1} and the reentrance into the insulating phase around B_{c2}

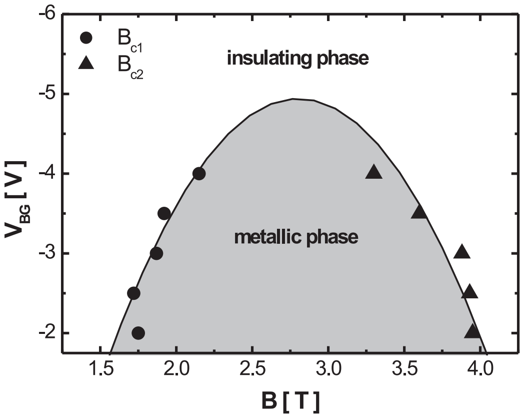

Fig. 4 Resulting phase diagram of the transitions. B_{c1} and B_{c2} mark the transition points as defined in Fig 3.

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3. Note that in a 2DEG: $\Delta E_F = \Delta n \cdot (\pi\hbar^2/m^*)$.
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