Fabrication of AlGaAs Nanostructures

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In order to investigate the electrical conductivity of nanostructures at low temperatures, different types of nanostructures were fabricated in the AlGaAs material system. The narrow lateral regions were either defined by deep etched grooves or by split gate structures on top of the samples. The electron density in the structures were additionally changed either by illumination or a large top gate Schottky contact. The formation of a 1D electron gas channel was observed.

1. Introduction

The driving force behind the investigation of solid state nanostructures is twofold. On the one hand side, the continuing miniaturization in microelectronics calls for investigation of the lower size limits for devices, on the other hand, nanostructures allow access to new fields in basic physics.

Today's miniaturization in microelectronics can be characterized by Moor's law – every 3 years, the single-chip memory size is increased by a factor of 4. The smallest structure size in this type of semiconductor devices is the gate length, which is 0.18 µm nowadays. This development in miniaturization is expected to continue at least for several years. But finally some hard physical limits will be reached. At least, when one memory unit would have the size of a single atom, a further continuation of miniaturization in the common way is hard to imagine. But other limits will be reached much earlier. If one continues to works with doped semiconductor structures, at much larger length scales one will reach the limit where only a few electrons will be in a single device, which makes the control of such a structure unreliable. Another limit is set by the wavelength of free electrons. As soon as the electrons wavelength becomes comparable with the structure size, interference and quantization effects will occur and strongly influence the functionality of such a device.

The latter limit is the starting point for a manifold of new physical phenomena. The confinement of electrons in nanostructures leads to a quantization in energies and wavefunctions. This allows, at least at low temperatures, the exact control of the state of the electrons and even allows to manipulate them individually. In quantum dots with two connecting tunneling contacts, single electron transmission due to Coulomb blockade can be achieved. Even the realization of quantum computation in solid state structures is considered nowadays.

In order to contribute to research and development in the above mentioned fields, we have established the techniques for the fabrication of nanostructures in the cleanroom facility in Linz. All necessary steps can be undertaken, including the critical electron beam lithography and etching steps. We have chosen AlGaAs heterostructures a the starting point for the nanostructures fabrication. Figure 1 shows the internal layer structure of a typical sample. The high mobility two-dimensional (2D) electron gas is formed in the GaAs buffer layer at the interface towards the above lying AlGaAs spacer. The doping region is typically 20 nm away from the interface in order to reduce the scattering efficiency and increase accordingly the mobility of the 2D electron gas.

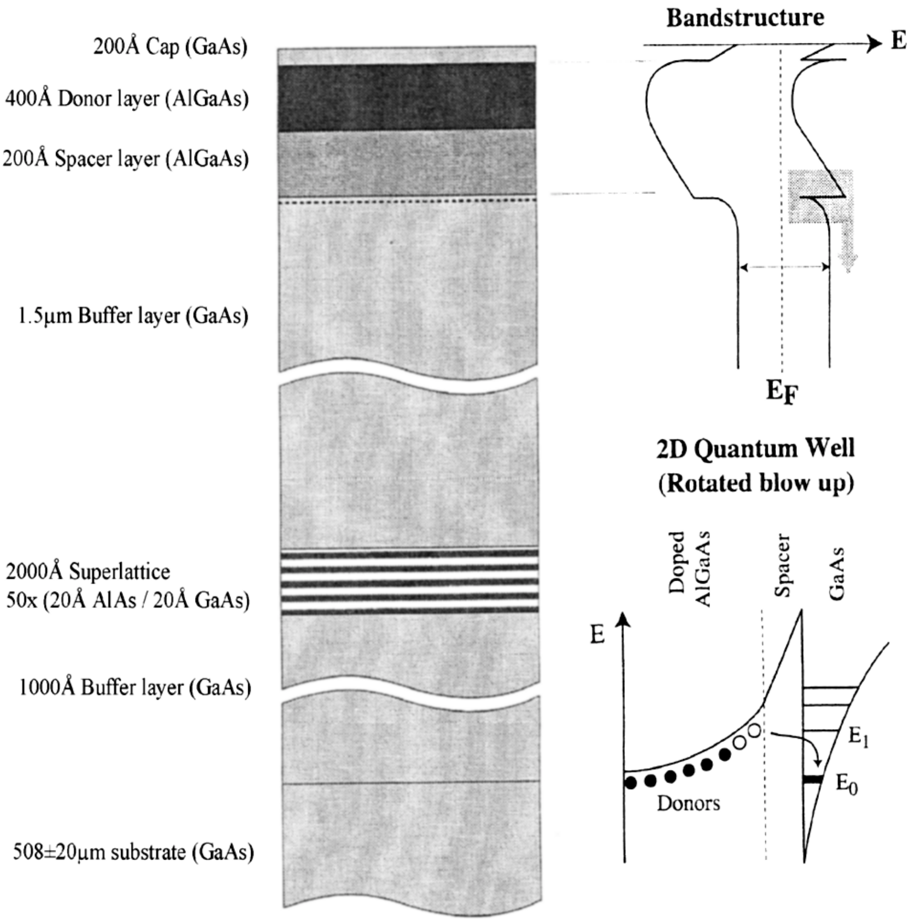
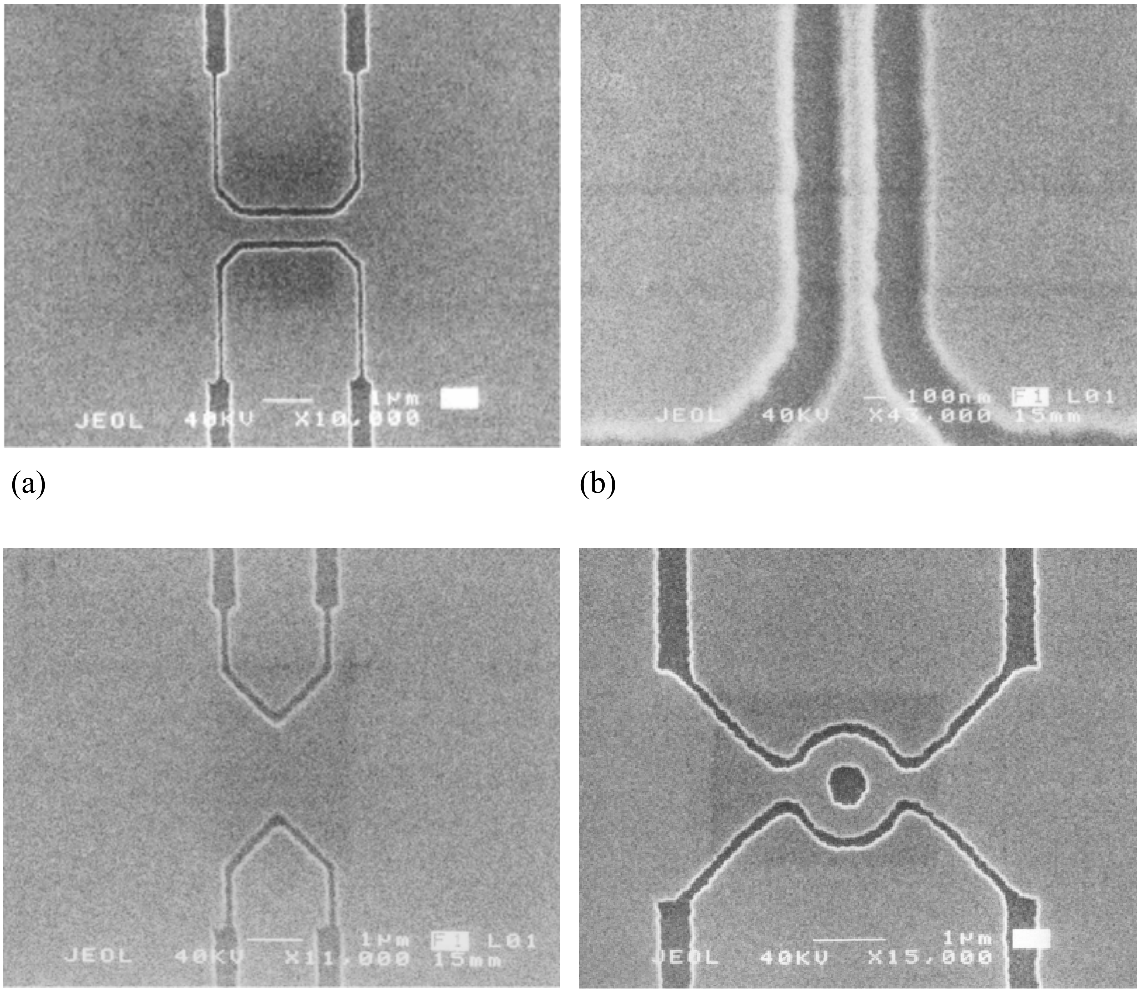


Fig. 1: The scheme on the left hand side shows a typical layer sequence of an AlGaAs heterostructure for achieving a high-mobility two-dimensional electron gas system. The upper diagram on the right hand side shows the band diagram of the heterostructure, the lower diagram displays the energy diagram in the vicinity of the electron gas on an expanded scale.

In order to be able to perform electrical measurements on nanostructures, some geometry for the electrical connections, the ohmic contacts and possible gates have to be prepared. We use a Hall bar geometry, which allows the determination of electron densities and mobilities on the same piece of heterostructure. The ohmic contacts are formed by a sequence of Cr/Ge/Au/Ni/Au which is evaporated onto the sample and annealed for 1.2 minute at 450°C. The Hall bar geometry was defined by a reversal photoresist AZ5218 and etched with CH_4 and H_2 in an “Oxford 80Plus” reactive ion etching system or in a wet chemical etch process. The different nanostructures are then prepared out of the Hall bar structures.

2. Etched Nanostructures

One kind of nanostructures is prepared by etching deep grooves into the heterostructure, which divide the 2D electron gas layer into different isolated regions. The groove structures were defined on the Hall bar by electron beam lithography with a JEOL 6400 microscope in a PMMA/MA photoresist. The etching of the structures was performed in the reactive ion etching system with CH_4/H_2 gas. The photoresist is then removed in a TEPLA asher. Wire structures with different widths between 100 and 1200 nm were produced, see Fig. 2a and 2b for 500 and 100 nm wide wires. In addition point contacts and ring structures were prepared (Fig. 2c and 2d).



(a) (b)

(c) (d)

Fig. 2: (a) 2 µm long wire structure; (b) detail of a 100 nm wide wire; (c) etched point contact; (d) etched ring structure.

The electrical properties of theses nanostructures were investigated. Most of the narrow structures were not conducting. This is caused by the defect states at the GaAs surface, which have a very high density close to midgap. Free electrons from the neighborhood go to those defect states leading to a depletion layer. Narrow etched nanostructure channels are thus usually not conducting in the GaAs material system. Only wider structures remain conducting despite the surface depletion.

Figure 3 shows resistivity measurements on a 400 nm wide, 2 µm long wire structure versus applied perpendicular magnetic field at a temperature of 1.5 K. As this sample had no gate, the electron density was varied via illumination with an infrared light emitting diode. Different curves in Fig. 3 correspond to different illumination intensities, where lower resistivity means higher intensity. Several curves show a step-like increase in resistivity at a magnetic field of about 0.6 T. The steps occur approximately between 1/10 and 1/6 of h/e^2 and between 1/6 and 1/4 h/e^2 and thus seem to correspond to transitions between different occupations of electron channels in the one-dimensional (1D) wire [1].

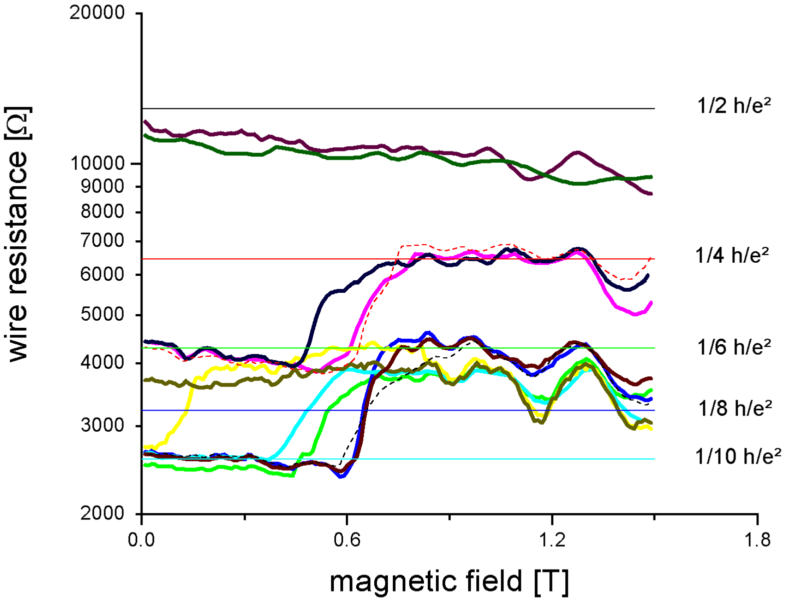


Fig. 3: Wire resistance versus magnetic field for a 400 nm wide, 2 µm long wire structure. Different curves correspond to different illumination intensities of the nanostructure with a infrared light emitting diode.

Due to the persistent photoconductivity effect, caused by DX-centers in AlGaAs structures [2], it is possible to increase the density of 2D electrons with illumination, but the density does not decrease to its previous value after switching off the illumination. Therefore it is difficult to change the density arbitrarily and the use of gated structures is desired.

3. Top Gate

By using a top gate, which covers the whole area of the 2D electrons gas together with the deep etched grooves, the electron density can be varied within a certain range. We have fabricated both a Schottky gate and an insulated metal gate on top of the structures. The area of the Schottky gate is defined in the usual way by photolithography, an Al metal layer is evaporated and the rest of the photoresist and the metallic layer is removed in the lift-off step. Figure 4 shows a sample where the surface is covered by an Al top gate. The Al layer forms itself a Schottky contact to the GaAs surface. With the

Schottky gate, the electron density *n* could be varied typically between 1.2x10^{11} and 4.2x10^{11} cm^{-2} before the leakage currents became too large. At low electron densities, where the resistivity is strongly increasing, we have observed several steps in the conductance versus gate voltage behavior, which can be attributed to transport in 1D channels.

As the Schottky gate starts to leak when the applied voltage becomes too high, we have also tested a metal gate on top of an insulating layer. As insulating layer, a PMMA/MA photoresist was used as this material is quite stable against thermal stress during cool down of the samples in a cryostat. A Ti/Au or Cr/Au layer was deposited on top of the insulation layer, the Ti (Cr) acts as an adhesive layer, the thicker Au is used as a contact layer for bonding beside the Hall bar. The samples with this kind of gate contact showed only a very small change of the electron density with applied voltage. It seems that lateral currents below the insulating layer shield the gate voltage, and the electron gas is nearly not affected.

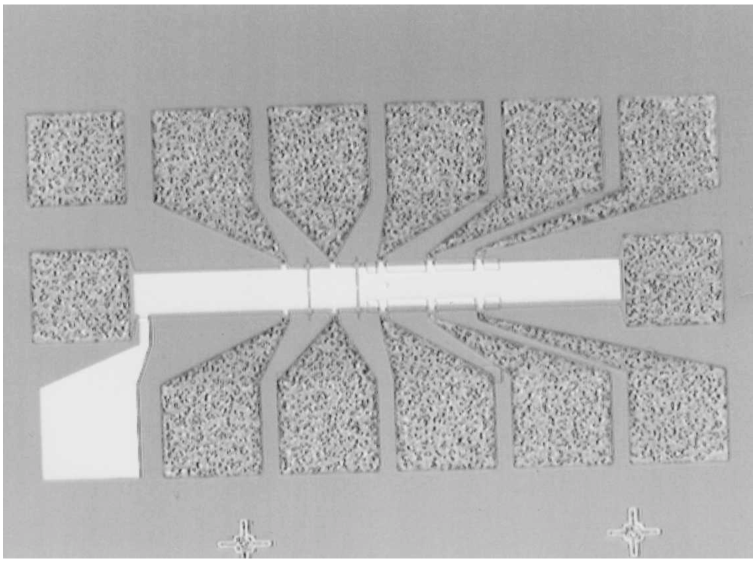
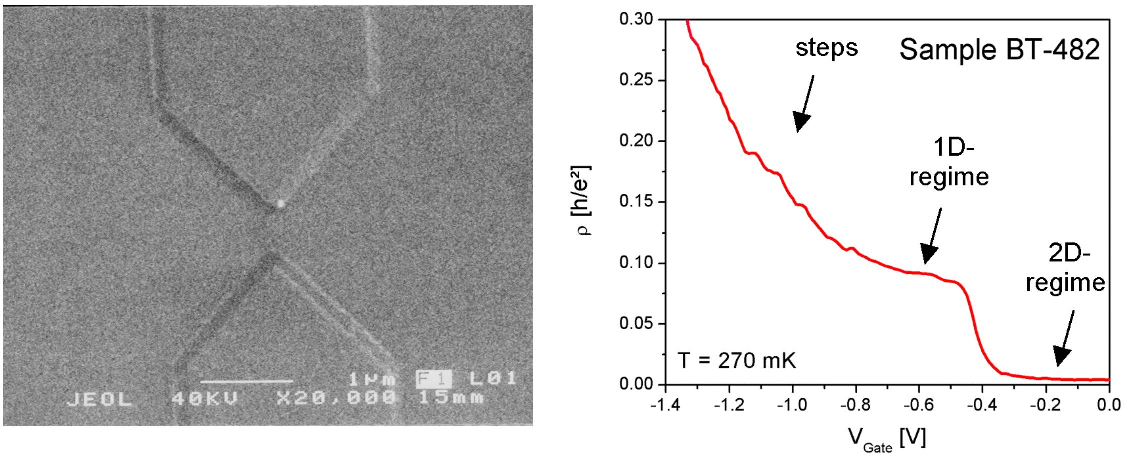


Fig. 4: Hall bar sample, where the 2D electron gas region together with the deep groove etched nanostructures is covered by an Al-Schottky gate.

4. Split Gate Nanostructures

Last but not least, split gate nanostructures were fabricated from the AlGaAs heterostructures. In these samples, a Schottky gate crosses the Hall bar from one side to the other, but leaving a narrow gap of several hundred nm width open. The narrow lateral gap in the gate was defined by electron beam lithography in the two-layer PMMA photoresist. The Al gate was produced in a lift-off step and is shown in a raster electron micrograph in Fig. 5(a).

By applying a negative voltage to both parts of the split gate, the electron density underneath can be reduced until the 2D electron gas is completely suppressed and the two conducting regions are separated. Only in the narrow restriction below the gap in the split gate, the two regions of the 2D gas are electrically connected via a 1D channel. This can be seen in Fig. 5(b) in the resistivity versus gate voltage curve as a plateau. By further increasing the negative gate voltage, also the lateral potential of the 1D channel shrinks, and the resistivity increases further. Small steps, probably due to the quantized conductance in the 1D wire, can already be seen in Fig. 5(b). This resistivity range is most interesting as it contains the conduction through only a few 1D channels and will be investigated in more detail in the future.



(a) (b)

Fig. 5: (a) Split gate geometry formed by Schottky gate fingers on top of an AlGaAs heterostructure. The restriction has a lateral width of 400 nm. (b) Resistivity versus gate voltage behavior of the top gate structure.

5. Conclusion

We have fabricated several types of nanostructures on high mobility AlGaAs heterostructures. The samples with deep etched grooves suffer from the surface depletion of the GaAs material system, and it is difficult to control the conductivity for narrow lateral structures. Top gate structures worked, but the range in which the electron density can be varied is restricted due to the leakage of Schottky gates. Split gate structures were best suited to change the electron density in a narrow point contact.

Acknowledgements

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