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Submicron conducting channels defined by shallow mesa etch in GaAs-AlGaAs heterojunctions

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A new approach to the lateral confinement of electrons in the two-dimensional electron gas of GaAs-AlGaAs heterojunctions has been developed. The electrons are electrostatically confined by a shallow mesa structure etched in the upper *n*-doped AlGaAs layer. This structure is fabricated using electron beam lithography and reactive ion etching. The undoped AlGaAs spacer layer is not removed in order to avoid mobility degradation and channel depletion. Long narrow channels have been made for the study of electrical transport properties. The effective channel width in the submicron range is smaller than the width of the mesa structure. Preliminary low-temperature magnetoresistance data are presented.

The two-dimensional electron gas (2DEG) in a heterostructure is an excellent model system for the study of low-temperature transport phenomena. In GaAs-AlGaAs heterostructures high values for the mobility are currently achieved, mainly because the GaAs-AlGaAs interface is nearly perfect on an atomic scale, and because the remote impurity scattering due to the positively charged donors in the AlGaAs is suppressed by the use of an undoped AlGaAs spacer.[1]

Narrow conducting structures in such materials are of great interest for the study of fundamental effects, such as low-temperature quasi-one-dimensional transport properties. Such structures can be fabricated by use of a gate or by etching of a mesa structure. Thornton *et al.*[2] have recently reported on a variant of the first approach. Their method consists of depletion of the 2DEG by a negatively charged gate with a 0.6-μm-wide slit. The etching of a deep mesa structure is commonly used for the fabrication of wide structures, such as Hall bars. Choi *et al.*[3] have studied the width dependence of low-temperature transport properties in such devices down to a width of 1.1 μm. This latter approach has the large inherent disadvantage that the electron channel is bounded by an etched surface, so that narrower channels will strongly deplete to the side surfaces and the mobility of the electrons will degrade.

This letter describes a new fabrication technique, where these disadvantages are mostly avoided. The confinement of the electrons is achieved without etching right through the electron gas. In order to remove the 2DEG it is sufficient to etch away only a shallow slice of the upper doped AlGaAs layer (see Fig. 1). It is especially important that the undoped AlGaAs spacer and part of the doped AlGaAs remain in order to limit sidewall depletion and mobility degradation.

The fabrication technology consists of the following steps. The starting point is a standard heterostructure. Our first samples have been made on material grown by metalorganic chemical vapor deposition (MOCVD) (see Fig. 1) with a mobility of 10 $m^2/V\,s$ at 77 K. AuGeNi alloyed ohmic contacts are made to the 2DEG, by standard lithographic techniques. As mask material for the definition of the shallow mesa etch a 25-nm layer of Al_2O_3 has been chosen since it is insulating and because it can withstand the reactive ion etch. This mask is defined by liftoff in two steps in order to avoid problems with proximity effects. First, two broad regions of Al_2O_3, each covering two contacts, are defined by optical lithography. These regions are then connected by a narrow line of Al_2O_3 defined by electron beam lithography and a two-layer resist technique. The narrowest structures which we have been able to fabricate so far are 40 nm wide.

Before etching the shallow mesa structure the AuGeNi contacts are protected by means of a 2-μm layer of photoresist baked at 120 °C. The samples are then anisotropically

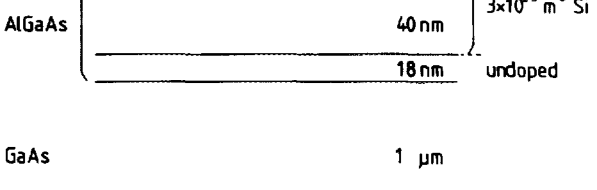

FIG. 1. Schematic drawing of the shallow mesa structure etched in a GaAs-$Al_xGa_{1-x}As$ ($x = 0.35$) heterostructure. A conducting electron layer, narrower than the mesa width, is formed at the GaAs-AlGaAs interface.

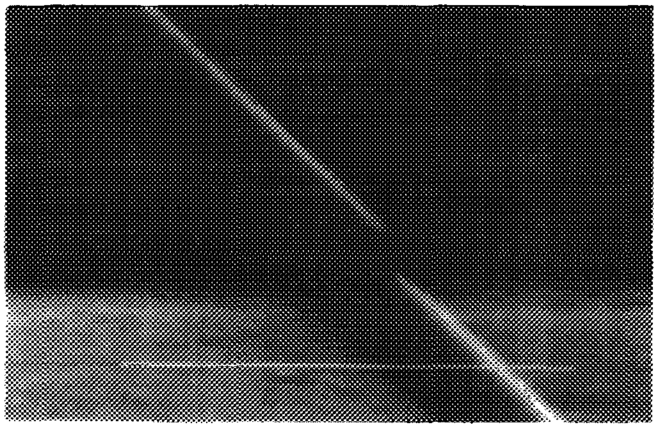

FIG. 2. Detail of completed structure (marker is 1 μm), showing connection between narrow channel (100 nm) with broader region leading to the contacts, covered by the Al_2O_x etch masks.

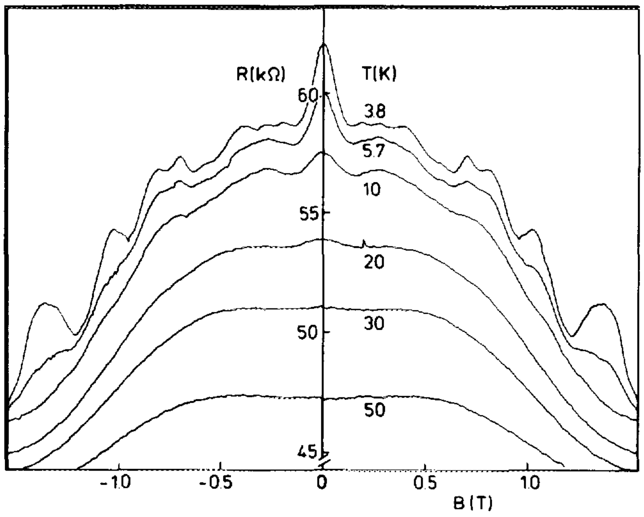

FIG. 4. Negative magnetoresistance for a nominally 500-nm-wide sample at several temperatures showing reproducible aperiodic fluctuations.

etched by reactive ion etching (RIE) in a Cl_2 and Ar (1:3.5) mixture at a pressure of 2 Pa. The etch rates for GaAs and AlGaAs are crucial parameters since it is desired to remove only 20–40 nm of the heterostructure. The GaAs capping layer enabled us to etch the AlGaAs without etch onset problems caused by oxidation of AlGaAs. The samples were heat sunk to the SiO_2 electrode (at 50 °C). This etch method yields very high aspect ratio (as judged from deeper etched samples) and a smooth surface.

In Fig. 2 a detail of the resulting structure is shown. Here 30 nm of the heterostructure has been removed, including the 10 nm GaAs capping layer. The remaining 40 nm doped AlGaAs is entirely depleted due to pinning of the Fermi level in the band gap at the AlGaAs surface and to the presence of deep traps in the layer.[4] No 2DEG is therefore formed at the heterojunction underneath. (The depletion width is estimated at 60 nm for a band bending of 0.9 V and a donor concentration of 3×10^{23} m^{-3}.) This is experimentally demonstrated by the very good isolation between devices on the same wafer after etching.

In Fig. 3 the resistivity per square (evaluated from conductance data assuming a channel width equal to the width of the mesa) is shown for three channel widths (10, 1.5, and 0.5 μm). The resistivities of the 10 μm and of the 1.5 μm channels thus obtained are nearly the same which may be regarded as further evidence that the 2DEG only remains below the narrow mesa. Further narrowing of the channel leads to a pronounced resistivity increase. This is attributed to depletion of the channel to the sides of the mesa structure, leading to a lower effective channel width, and possibly to a slight mobility degradation. Channels of 250 nm width proved to be insulating. By increasing the donor concentration in the AlGaAs layer it will probably be possible to fabricate narrower conducting channels. The large resistivity rise at lower temperatures for the narrow channel is likely related to quasi-one-dimensional localization and electron interaction effects.[5] From Shubnikov–de Haas (SdH) measurements at 4.2 K the 2D electron density n_s was found to be $n_s = 5.1\times10^{11}$ cm^{-2} for wide channels and $n_s = 3.8\times10^{11}$ cm^{-2} for a 500-nm sample. The resistivity of the narrow samples decreased up to 30% after cycling between 4 K and room temperature, but no drift was observed at low temperature.

Preliminary low field magnetoresistance measurements reveal an interesting range of phenomena, especially for the narrowest channel studied (500 nm). Some results are shown in Fig. 4. A strongly temperature-dependent negative magnetoresistance is found, which is attributed to suppression of the weak localization effect by a weak magnetic field[2,5] and to suppression of the electron-interaction effect at stronger field.[3] At fields above 0.1 T nonregular oscillations are seen at the lowest temperatures. This structure cannot be explained by SdH oscillations, which can be seen at higher fields, but may be the recently discussed universal conductance fluctuations in small samples at low temperature.[6] The onset of this effect was also noted by Choi *et al.*[3] in their narrowest sample (1.1 μm).

In summary, we have fabricated submicron conducting channels in the 2DEG of a GaAs-AlGaAs heterostructure using a novel shallow mesa etch technique. Preliminary low-temperature magnetoresistance data indicate quasi-one-di-

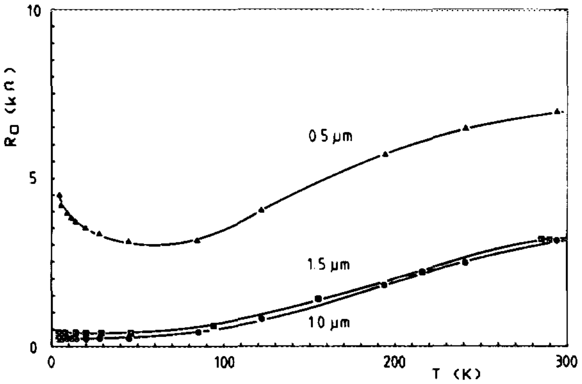

FIG. 3. Temperature dependence of the resistivity per square for three channel widths (taken equal to the etched mesa width). Solid lines are to guide the eye.

mensional localization and interaction effects. Future extensions of the method described will include a Schottky gate on top of the mesa structure, and the realization of different geometries, such as ring-shaped samples for the study of Aharonov–Bohm effects.

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