Ultranarrow conducting channels defined in GaAs-AlGaAs by low-energy ion damage

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We have laterally patterned the narrowest conducting wires of two-dimensional electron gas (2DEG) material reported to date. The depletion induced by low-energy ion etching of GaAs-AlGaAs 2DEG structures was used to define narrow conducting channels. We employed high voltage electron beam lithography to create a range of channel geometries with widths as small as 75 nm. Using ion beam assisted etching by Cl_2 gas and Ar ions with energies as low as 150 eV, conducting channels were defined by etching only through the thin GaAs cap layer. This slight etching is sufficient to entirely deplete the underlying material without necessitating exposure of the sidewalls that results in long lateral depletion lengths. At 4.2 K, without illumination, our narrowest wires retain a carrier density and mobility at least as high as that of the bulk 2DEG and exhibit quantized Hall effects. Aharonov–Bohm oscillations are seen in rings defined by this controlled etch-damage patterning. This patterning technique holds promise for creating one-dimensional conducting wires of even smaller sizes.

Modulation-doped GaAs-AlGaAs heterostructure two-dimensional electron gas systems open a new regime for the investigation of low-temperature transport phenomena in structures of reduced dimensionality. This is possible because of the high electron mobility, long scattering lengths, and small electron effective mass in this material. The ability to fabricate small structures in III-V compound semiconductors by electron beam lithography and dry etching processes has been demonstrated previously.[1,2] The creation of conducting structures with widths less than one micrometer, however, has been difficult.[3] Fermi level pinning by states at the exposed sidewalls of narrow etched structures causes depletion of the carriers within the small structure. A method has recently been described that significantly reduced this carrier depletion problem. By patterning only the doped AlGaAs layer of the two-dimensional electron gas (2DEG) structure, conducting paths were defined without exposing the electron gas interface at the sidewalls of the wire.[4] By this technique, however, channels narrower than 250 nm proved to be nonconducting. There exists a strong incentive to make even narrower wires, since quantum confinement effects become pronounced when the wire width becomes comparable to λ_f, the Fermi wavelength, which characterizes the spatial extent of the electron wave function. For a typical 2DEG with a electron density in the 10^{11} cm^{-2} range, $\lambda_f = 2\pi/k_f$ is on the order of 100 nm.

In this letter we describe a method of defining narrow conducting channels in a 2DEG structure by removing only a small amount of material from the surface of the material by ion etching. It appears that electrical damage, induced by 150–500 eV ions, is sufficient to destroy the conductivity of the 2DEG in unmasked areas. We have demonstrated this by controlled etching of large areas of material by ion beam assisted etching (IBAE) with Ar ions in the presence of Cl_2 gas. We observe a progressive deterioration of carrier mobility with increasing etch time. The mobility is clearly reduced as result of ion damage since similar amounts of material removed by chemical etching do not significantly alter the mobility of the 2DEG. Using this technique, we have patterned wires with mask widths as narrow as 75 nm. At liquid-helium temperatures, in the dark, these conducting channels exhibit no degradation in the original mobility and carrier density of the 2DEG.

The material used in our study was molecular beam epitaxially grown GaAs-AlGaAs with the dimensions shown in Fig. 1. The doped layer was $Al_{0.28}Ga_{0.72}As$ with a Si doping concentration of $\sim 2 \times 10^{18}$ cm^{-3}. The mobility at 4 K was 5.4×10^5 cm^2/V s, with a carrier density of 5.3×10^{11} cm^{-2}.

The electron beam lithography was done in a computer-controlled scanning transmission electron microscope (STEM) at an electron energy of 250 keV to expose a single layer of polymethylmethacrylate (PMMA) resist. The high-energy electron beam eliminates concerns of proximity correction in this type of isolated device, and we demonstrated that there was no measurable effect upon the electrical properties of the 2DEG at the electron doses used for exposure. A mask of 120 nm of SrF_2 was formed by deposition and lift-off. The fluoride was used because of its high resistance to etching by halogen-containing plasmas.[5] This was important for our original work where we etched entirely through the

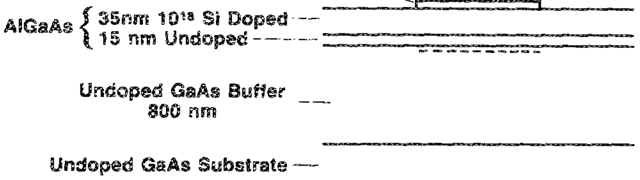

FIG. 1. Cross-sectional diagram of the GaAs-AlGaAs 2DEG material structure with the ion mask used for wire patterning. The dashed line represents the patterned 2DEG.

2DEG interface to create mesas. It was also significant in subsequent work where, as have others, we etched only the doped AlGaAs layer by reactive ion etching. With our present technique the strong fluoride etch resistance is less important since only shallow etching is done. It is convenient, however, that the fluoride etch mask is nonconducting and can remain on the surface during the measurements, simplifying the processing steps.

The etching was done by ion beam assisted etching with Ar ions in the presence of Cl_2. A 150-eV ion beam with a specimen current density of $30\,\mu A\ cm^{-2}$ was directed at the sample with Cl_2 gas introduced near the etched surface. The total system pressure was 3×10^{-4} Torr. These conditions lead to a GaAs etch rate of about 5 nm/min. This system has been developed for high aspect ratio etching of GaAs.[6] This high aspect ratio is not needed for this method of patterning, but we find that the available range and control of ion energies is appropriate for inducing damage to the necessary depths.

Initially we determined the etching conditions that were sufficient to entirely deplete the 2DEG. This was done with large area, chemically etched, Hall geometry samples that were then uniformly etched by IBAE. After etching the electron mobility and carrier density were ascertained from low-temperature magnetotransport measurements. We examined 2DEG material having two different structures, and for each we determined the etch conditions that were required to significantly reduce the 2DEG conductivity. This depended on the material layer thicknesses as expected. For the structure shown in Fig. 1, appropriate etch conditions were those described above using an etching time of 2 min. This removed essentially all of the 10-nm-thick GaAs cap layer. At room temperature the sheet resistance of the 2DEG increased by a factor of 35 after only 30 s of etching. After the full two minutes the sheet resistance was immeasurably large. This high resistance was not reduced after annealing at 500 °C for 1 min. Removing the cap layer with a chemical etch had no effect on the mobility or carrier density in the 2DEG material. With the same large area sample we also determined the thickness of the ion mask required to protect the underlying 2DEG from mobility degradation. We also confirmed using similar measurements that electron beam exposures above 10^{-3} C/cm^2 at energies from 150–250 keV did not cause any measurable decrease in the mobility or carrier density at 4 K.

The introduction of electrical damage in GaAs by low-energy ion bombardment has been observed previously. Capacitance-voltage (C-V) measurements show that ion milling with 100 eV ions electrically damaged the material to a depth of 90 nm.[8] These measurements are consistent with our sheet resistivity data, where similar ion energies were used. The ion penetration depth at 100 eV is much less than this 90 nm and gross structural changes as observed by transmission electron microscopy are on the order of a few nm for this type of ion species and energy.[9] The exact nature and mechanism of electrical damage introduction is not entirely understood. The case of ion beam assisted etching of 2DEG structures has been even less widely studied. We have done measurements that establish how to exploit the effect of ion damage for patterning of nanometer scale 2DEG structures, but we have not established the exact nature of the changes introduced by the processing.

Conducting wires and other channel geometries were created by the above conditions. Figure 2 shows a scanning electron micrograph of a 5-μm-long wire with ten Hall voltage probes along the length. The electron micrograph shows the shallow etch into the GaAs cap layer with the 120-nm fluoride mask. The fine electron beam written pattern connects to the larger gold ohmic contact pads seen as the larger features in this figure.

Figure 3 shows the measured magnetoresistance data from a ~100-nm-wide wire. All measurements were performed in the dark. The behavior seen from the quantum Hall plateaus is indicative of geometrically well defined 2DEG conduction paths. We observe a slight, but undramatic smearing of the zeros in the quantum oscillations of longi-

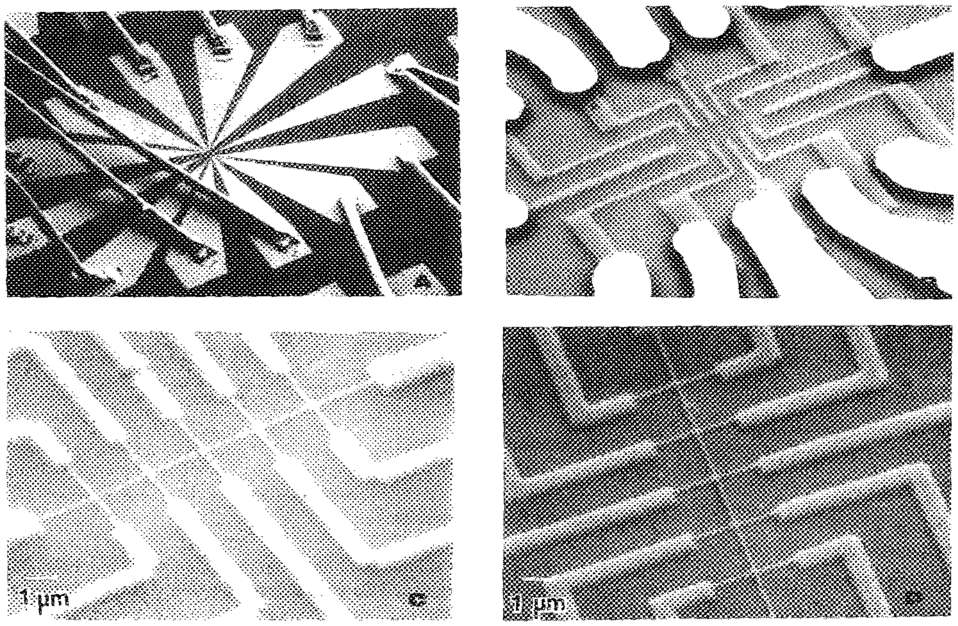

FIG. 2. Scanning electron micrographs of increasing magnification taken from a 75-nm quantum well wire structure. A—SEM of ohmic contact pattern with wire bond connections to the chip carrier. B—SEM of electron beam written connections from contact patterns to active area. C—The 75-nm Hall bar pattern which exhibits well-behaved quantum Hall behavior in the dark at 4.2 K. D—A 250-nm Aharonov—Bohm loop connected to a 100-nm Hall bar pattern.

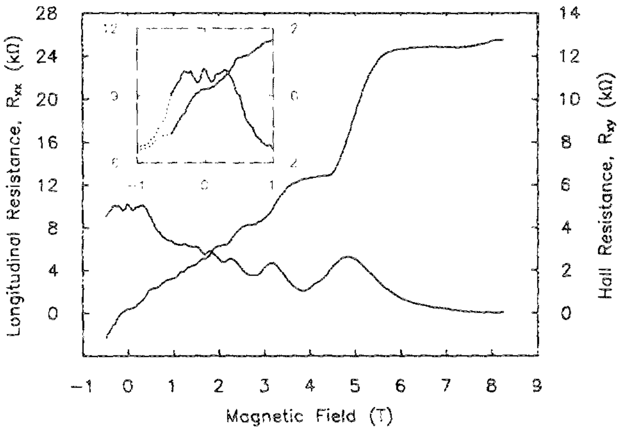

FIG. 3. Transverse and longitudinal magnetoresistance for a 100-nm quantum well wire, measured in the dark at 4.2 K. The inset shows data from $-0.5\ \mathrm{T} < B < 1.0\ \mathrm{T}$ centered about zero field. (The dotted lines are data from $+5\ \mathrm{T} < B < 1.0\ \mathrm{T}$ reflected to negative field to serve as a guide to the eye.)

titudinal magnetoresistance. We believe the oscillatory behavior as a function of low magnetic field (< 1 T) to be a quantum effect.[12]

The period of the Aharonov–Bohm oscillations as a function of magnetic field, which should have a magnetic flux periodicity h/e, provides a measure of the wire loop area.[10] In our case this appears, within experimental uncertainty, to equal the geometrical area of the mask. This additional evidence demonstrates that our patterning technique has created a well defined, multiply connected, conducting channel of unperturbed electron gas with a width nearly equal to the geometrical width of the mask. It suggests that the electron density profile in the patterned 2DEG beneath the mask falls off abruptly in unprotected regions. This is quite different from narrow wires defined by edge depletion in much wider etched "fins," where the exact geometry of the electrical channel is not well controlled.

The electron mobility estimated from the high field measurements is at least as great as the original unpatterned 2DEG. The existence of a slight enhancement of the mobility in these quasi-one-dimensional wires is possible.[11] The measurements on these narrow wires display effects at low fields due to their one-dimensional nature.[12] With the ability we now have to create arbitrary geometries of fine wires we are exploring further the conduction properties of these small systems.

Some of the considerations of this technique are similar to those in the high resolution definition of GaAs structures by implant-induced disordering of heterostructures.[13] Much narrower conducting channels can be defined by locally changing the electrical properties than by etching and exposing untreated surface. Until surface passivation[14] and regrowth techniques are perfected these selected area modification techniques such as that described here, appear the most promising for creating ultrasmall quantum structures. Our present size limit of 75 nm is not a fundamental one. It is limited by the difficulty in fabricating high aspect ratio and continuous ion masks. The narrowest wire we have been able to create has conducted without illumination. We see no reason that with further work and advances in the mask fabrication that even narrower wires are possible with this selective low-energy ion damaging. This is in contrast to other methods involving etching where the limits of lateral carrier depletion have apparently been reached at about 400 nm.[4,7]

We have demonstrated that it is possible to define conducting channels in GaAs-AlGaAs 2DEG systems with widths as small as 75 nm. Magnetotransport measurements on these fine wires demonstrate that the electron mobility is not reduced and that the geometry of the conducting channels is well defined by the mask geometry. This ability to create such fine wires of arbitrary shape should scale to even smaller dimensions. It now opens up the possibility of physical measurements and exploratory device design on a size scale where the wave nature of the electron transport is dominant.

[1] H. G. Craighead, J. Appl. Phys. **55**, 4430 (1984).
[2] M. B. Stern, H. G. Craighead, P. F. Liao, and P. Mankewich, Appl. Phys. Lett. **45**, 410 (1984).
[3] K. K. Choi, D. C. Tsui, and K. Alavi, Appl.Phys. Lett. **50**, 110 (1987).
[4] H. van Houten, B. J. van Wees, M. G. J. Heijman, and J. P. Andre, Appl. Phys. Lett. **49**, 1781 (1986).
[5] A. Scherer and H. G. Craighead, J. Vac. Sci. Technol. B **5**, 374, (1987)
[6] G. A. Lincoln, M. W. Geis, S. W. Pang, and N. N. Efremow, J. Vac. Sci. Technol. B **1**, 1043 (1983).
[7] G. Timp, A. M. Chang, J. E. Cunningham, T. Y. Chang, P. Mankewich, R. Behringer, and R. E. Howard, Phys. Rev. Lett. **58**, 2814 (1987).
[8] S. K. Ghandi, P. Kwan, K. N. Bhat, and J. M. Borrego, IEEE Electron Device Lett. EDL-3, 48 (1982).
[9] S. W. Pang, G. A. Lincoln, P. W. McClelland, P. D. DeGraff, M. W. Geis, and W. J. Piacontini, J. Vac. Sci. Technol. **B** 3, 398 (1985).
[10] R. A. Webb, S. Washburn, C. Umbach, and R. A. Laibowitz, Phys. Rev. Lett. **54**, 2995 (1985).
[11] H. Sakaki, Jpn. J. Appl. Phys. **19**, L735 (1980).
[12] M. L. Roukes, A. Scherer, S. J. Allen, H. G. Craighead, R. M. Ruthen, E. D. Beebe, and J. P. Harbison (unpublished).
[13] E. Dobisz, H. G. Craighead, P. S. D. Lin, K. Kash, L. M. Schiavone, A. Scherer, J. P. Harbison, and B. Tell, Proc. SPIE (to be published).
[14] E. Yablonovich, C. J. Sandroff, R. Bhat, and T. Gmitter, Appl. Phys. Lett. **51**, 439 (1987); C. J. Sandroff, R. N. Nottenburg, J. C. Bischoff, and R. Bhat, Appl. Phys. Lett. **51**, 33 (1987).