Narrow conducting channels defined by helium ion beam damage

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We have developed a new technique for patterning narrow conducting channels in GaAs-AlGaAs two-dimensional electron gas (2DEG) materials. A low-energy He ion beam successfully patterned narrow wires with little or no etching of the thin GaAs cap. The damage propagation of the He ion even at low energies was sufficient to decrease the mobility of the 2DEG located deep within the structure. The damage can be removed by a low-temperature anneal but remains stable at room temperature. Conducting channels as narrow as 300 nm have been fabricated and measured using low-temperature magnetoresistance.

Narrow conducting channels fabricated from high-mobility GaAs-AlGaAs heterostructure two-dimensional electron gas(2DEG) materials are of interest for studying quantum transport phenomenon and devices. When the wire width is comparable to the Fermi wavelength, quantum confinement effects influence the transport characteristics.[1] Narrow conducting channels can be defined using techniques such as a deep mesa etch,[2] electrostatic confinement,[3] a shallow etch,[4] and selective damage depletion.[5] However, all of these techniques, with the exception of electrostatic confinement, require exposure of the donor layer to some extent. Exposure of the donor layer limits patterning of very small (<250 nm) conducting channels because of carrier depletion caused by surface states and sidewall damage.

In this letter, we report a new technique which uses He ion beam exposure for patterning small wires. This technique does not expose the donor layer because He ion degradation of the 2DEG in unmasked regions can be done with short exposure times and therefore almost no material etching. The damage created by the He ion beam can be removed by annealing at temperatures above 300 °C.

This study was initially conducted to investigate new methods of fabricating small wires using an ion beam. The experiments consisted of exposing 20 μm Hall bars to He, Ar, and Xe ion beams. The results were compared with Ar + Cl_2 chemically assisted ion-etched Hall bars, a process previously used for patterning small wires.[5] The Hall bars were fabricated from molecular beam epitaxially grown GaAs-AlGaAs 2DEG with the geometry shown in Fig. 1. The AlGaAs layer was doped with Si to 2×10^{18} cm^{-3}. The carrier density and mobility at 4 K were 3.3×10^{11} cm^{-2} and 6.4×10^{5} cm^2/V s, respectively. The ion beam parameters were 150 eV ion energy, an ion dose ranging from 10^{15} to 10^{17} ions/cm^2, approximately 3×10^{-4} Torr gas pressure and 15 A/cm^2 current density. The etch depth was monitored for each experiment with a patterned sample that was exposed to the ion beam along with the Hall bar.

The carrier density and mobility of ion-exposed samples were obtained using 4 K magnetoresistance measurements. The carrier density was obtained from the Shubnikov–de-Haas (SdH) oscillations and the mobility from the longitudinal resistance (R_{xx}) at zero magnetic field. The samples were etched and measured until the sheet resistance reached gigaohms/square at room temperature.

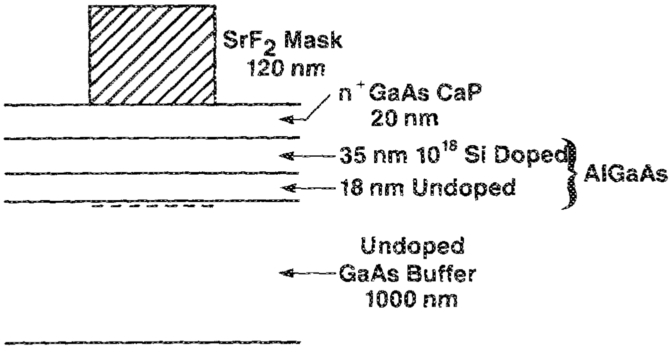

FIG. 1. Schematic drawing of the GaAs-AlGaAs 2DEG material structure with a SrF_2 ion mask for wire patterning.

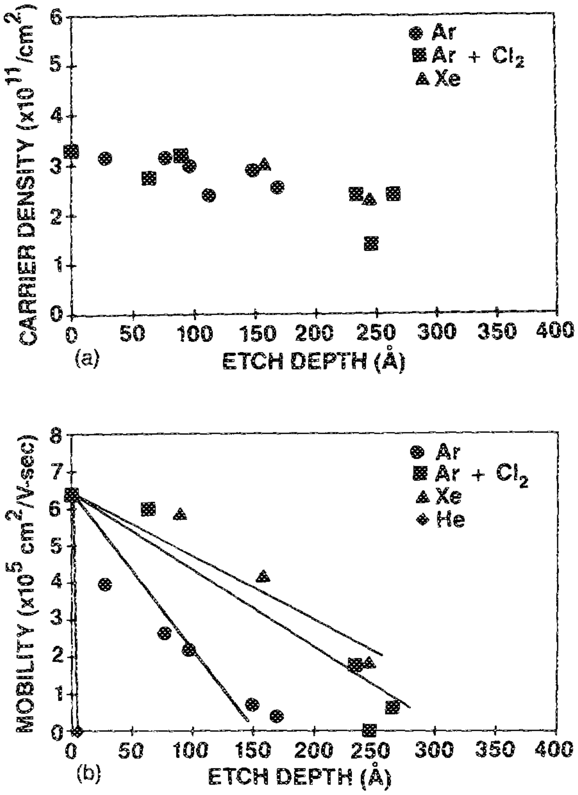

FIG. 2. Etch depth vs (a) carrier density and (b) mobility of GaAs-AlGaAs 2DEG using He, Ar, and Xe ion beam etching and Ar + Cl_2 ion beam assisted etching.

Figure 2 shows the carrier density and mobility versus etch depth into the material. Figure 2(a) shows that virtually no change in the carrier density occurred for Ar, Ar + Cl_2, or Xe ion exposure. However, Fig. 2(b) shows that the mobility was reduced by an order of magnitude after ion exposure. The mobility decrease was dependent on the ion mass, namely the smaller the ion mass the faster the mobility decreased. Samples exposed to Ar + Cl_2 and Xe ions showed a similar decline in mobility. Argon ion exposure resulted in a faster decline in mobility than Xe and Ar + Cl_2, and He ion exposure was the most efficient in reducing the mobility. Figure 2(b) also shows that 25 nm of material was removed by Ar + Cl_2 and Xe before the mobility degraded by an order of magnitude, while 15 nm was removed by Ar to produce the same mobility change. Surprisingly, the mobility decreased to shut-off conditions after 6 s of He exposure with no measurable (< 5 nm) etch depth. Subsequent experiments performed at lower ion energies showed that the mobility not the carrier density was affected by He ion exposure. These results show that after Ar + Cl_2, Ar, and Xe ion exposure, either the GaAs cap or part of the donor layer was removed before conduction was shut off. With He ion exposure, no material removal was required to produce the significant reduction in mobility.

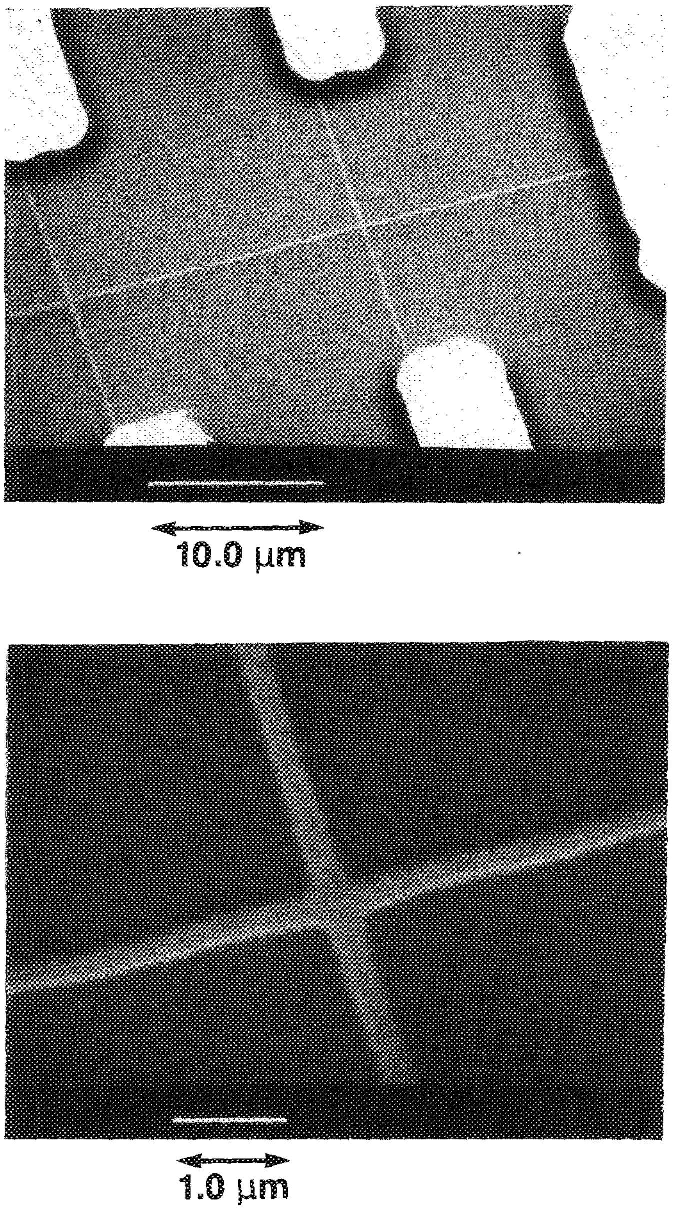

FIG. 3. Scanning electron micrographs of electron beam written 300 nm wire structure with (a) Au contact patterns to wire and (b) higher magnification of wire cross region.

Rapid thermal annealing of the He-, Ar-, and Xe-exposed samples at 500 °C for 20 s showed that conduction could be recovered in the He-exposed sample but could not be recovered for Ar- or Xe-exposed samples. The He damage was also removed at 300 °C if longer annealing times were used. At lower annealing temperatures, no recovery was observed. The 4 K measurements before He exposure, after He exposure, and after annealing showed that the mobility could be restored very close to its initial value.

The mobility reduction as a result of He ion exposure is related to ion penetration into the material. It is important to note that the 2DEG channel is located 70 nm away from the surface exposed to He ions and that the ion range of a 150 eV He ion calculated using TRIM[6] is 4 nm. These results imply that the He ion range exceeds the theoretical range. The results of the annealing study suggest that a different damage mechanism may be operative for He ion exposure compared to Ar and Xe because the damage could be removed after He ion exposure but not after Ar or Xe ion exposure. The mobility decline may be due to scattering centers introduced in or near the 2DEG channel by He atoms.

Narrow wires have been successfully fabricated using He ion beam exposure and the patterning technique employed by Scherer *et al.*[5] By selectively damaging the un-

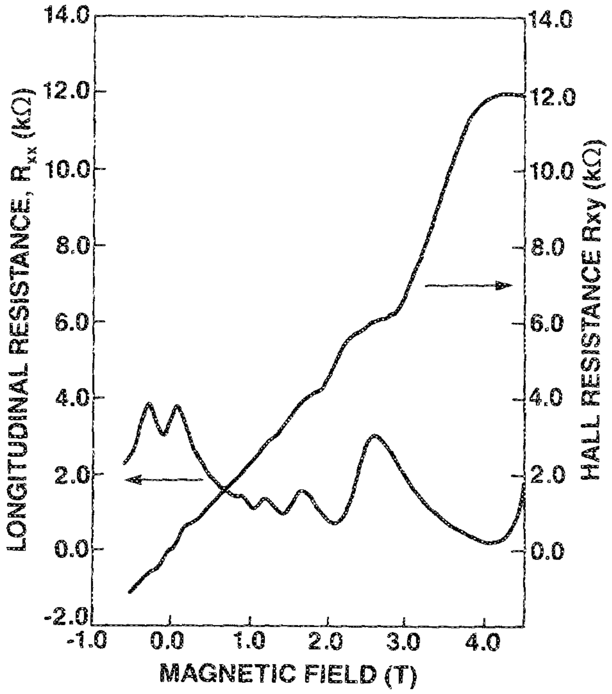

FIG. 4. Longitudinal and transverse magnetoresistance of a 300 nm wire measured at 4 K in the dark.

masked regions with He ions, a conducting channel under the masked regions was created. Figure 3 shows a scanning electron micrograph of a 300 nm wire with the gold Hall voltage probes and also an expanded view of the same wire. The electrical wire width measured at 4 K was comparable to the structural width of the wire obtained by using a scanning electron microscope. Figure 4 shows the measured magnetoresistance data taken from a 300-nm-wide wire. The zero-field features of the longitudinal resistance were similar to previous measurements on $Ar + Cl_2$ defined wire.[5] The details of the quantum transport phenomenon will be presented in a subsequent publication.

In summary, we have fabricated and performed 4 K magnetotransport measurements on small wires patterned with a He ion beam. By utilizing the damage propagation of the He ion, conduction of the 2DEG in the unmasked regions can be shut off with little or no material removal. The advantage of this technique is that the problems of depletion by surface states and sidewall damage are eliminated. Also the damage created by He ion exposure can be removed by a low-temperature anneal. Therefore, patterning of still smaller wires using this technique has great potential.

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