Electrical damage induced by ion beam etching of GaAs

A. Scherer, H. G. Craighead, M. L. Roukes, and J. P. Harbison
Bell Communications Research, Red Bank, New Jersey 07701

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We have examined the electrical damage induced in GaAs by ion milling and ion beam assisted etching, relevant to the fabrication of small conducting structures. The depth of the damage was measured by Schottky barrier measurements with *in situ* deposited gold contacts and by resistance and mobility measurements of etched two-dimensional electron gas structures. The effect of exposed etched sidewalls on the conductivity of narrow wires was examined for GaAs/AlGaAs structures. We find that it is possible to create wires narrower than surface depletion lengths by defining the structures through ion beam induced damage without exposing the sidewalls. In particular, narrow conducting wires can be defined solely by etching the thin-undoped-GaAs cap layer atop the modulation doped material.

Ion processing of GaAs has recently gained importance for the production of optoelectronic integrated circuits, lasers, and high-speed GaAs devices.[1,2] The fabrication of sub-100-nm structures in these high electron mobility and long-carrier mean free path semiconductors is becoming increasingly important for the study of microstructures. This has been in part a result of the development of new ion etching techniques, which provide smooth sidewalls and etched surfaces, and allow anisotropic etching of very small structures in these III–V semiconductor compounds.[3] The deterioration of the electrical and optical properties of the semiconductor material close to the etched surface caused by ion etching, and the increase in the surface to volume ratios in the resulting microstructures have to be taken into account, however, if useful submicrometer structures are to be made in GaAs.[4]

The electrical damage on ion milled surfaces has previously been studied using capacitance–voltage and current–voltage characteristics of Schottky barriers.[5–9] This damage was found to be reduced by decreasing the ion energy or increasing the atomic number of the ion species used during milling.[9] Electrical deterioration has been reported up to 100 nm deep in GaAs,[7] whereas structural disruption of the lattice 5–10 nm in depth has been identified by cross-sectional transmission electron microscopy (TEM) analysis and by Auger electron spectroscopy.[1,9] The damage depth has also been found to be reduced by the addition of reactive or inert gases during the etch, which are thought to adsorb to the etched surface and decrease the penetration depth of the sputtering ions.[8–10]

Often, as in the case of optical waveguides, laser mirrors, or narrow wires, the most important surfaces exposed during the etch are the sidewalls of the etched structures,[11] which are predominantly exposed to lower energy secondary ions impinging at glancing incidence (Fig. 1). The quality of these sidewalls becomes more important as smaller structures are patterned, since the surface to volume ratio increases with decreasing feature size.[12] In this study, the effects of generation of additional surface area by structuring small features into high-mobility GaAs two-dimensional electron gas (2DEG) by ion etching are described. We use *I–V* characteristics of *in situ* deposited Schottky contacts and the low-temperature transport properties of 2DEG conduction channels to characterize the electrical effect of the surface damage and the creation of new surface area. We believe the use of contacts deposited in vacuum directly after milling allows the analysis of true etch damage, since surface oxidation is thereby avoided.

Surfaces and sidewalls etched using ion beam assisted etching (IBAE), with conditions previously optimized for vertical sidewall etching, were compared to ion milled structures. GaAs 2DEG samples were etched with a 500-eV-Ar ion beam using a specimen current density of 150 μA/cm^2 and a 5-sccm-argon flow rate. A jet of 2 sccm chlorine was directed at the sample as reactive gas, yielding a total pressure of 6×10^{-4} Torr in the etching chamber. Unlike most previously described IBAE systems, the chlorine was not cold trapped.

Schottky barriers were generated on n^+-substrates with a carrier concentration of 2×10^{18} cm^{-3} by evaporation of

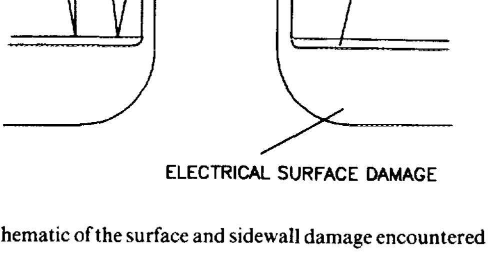

FIG. 1. Schematic of the surface and sidewall damage encountered in microstructures.

TABLE I. Metal–insulator–semiconductor fitted results of I–V data showing the effect of gas, voltage, and time on the damage depth on n^+ substrate. The etch time was 2 min and the sample current was 150 μA/cm^2 in all cases.

Sputtering gas	Ion energy (eV)	MIS damage depth (nm)
Neon	500	49
Argon	500	30
Argon	1500	58
Ar/Cl$_2$	500	26
Ar/Cl$_2$	1500	43

200-nm-gold layers immediately after ion beam assisted etching in the same chamber without exposure of the surfaces to atmosphere. The effective thickness of the insulating layer formed during the etching step d was extracted from the Schottky I–V measurement by using a metal–insulator–semiconductor model according to the following equation[13]:

$$I = AT^2 \exp\{-[e(\varphi_B - \sqrt{eV/4\pi d\epsilon_i})]/kT\}, \qquad (1)$$

where A is the effective Richardson constant, T is the temperature, φ_B is the barrier height, and d and ϵ_i are the thickness and insulator permittivity, respectively. Since we are primarily interested in relative comparison of the etch processes we have taken ϵ_i to be that of free space.

Damage depths calculated for several milling and etching conditions relevant to small feature etching are compiled in Table I. It is evident that neon ion milling generates the thickest damaged layers, whereas ion beam assisted etching with chlorine reduces the damaged thickness substantially. The damage depths calculated from the Schottky I–V behavior show a relative difference among the etching conditions. Since the depths indicate an effective insulating layer thickness, this does not represent the absolute depth of electrical damage. One would intuitively expect the real extent of induced damage to be greater than the number calculated from this MIS model. We believe this is a more straightforward comparison than considering only ideality factors and the elimination of oxide layers by *in situ* contact evaporation should give a more meaningful damage depth indication. The effect of ion etching on the carrier density of GaAs/AlGaAs 2DEG layers was measured by low-temperature magnetoresistance measurements of samples etched to different depths. We find that if the GaAs cap layer of the 2DEG structure (shown schematically in Fig. 2) is removed by chemical etching, no change in the mobility or carrier density can be observed in the conducting channel. However, if the cap layer is removed by ion etching, the 2DEG 80 nm below is completely depleted.

The effect of exposing sidewalls by ion etching was observed by measuring the conductance of submicrometer wide wires. Room temperature and 77 K resistivities of the two-dimensional gas after patterning small channels were recorded as functions of the etching depth and the wire widths (Fig. 3). This is in contrast to the damage discussed above that results from the directly exposed surface.

The electronic quality of a high-mobility 2DEG is very sensitive to both damage-induced imperfections in the GaAs and to surface depletion. Conducting paths in these materials are especially useful in the analysis of ion-etching effects. The 2DEG can be patterned into wires by etching conven-

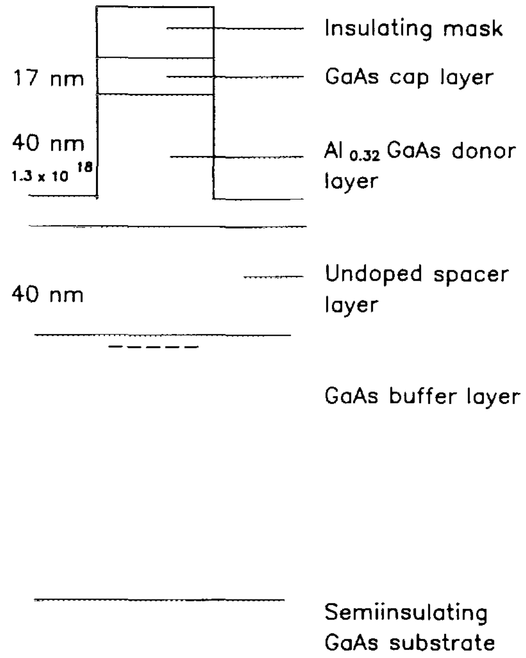

FIG. 2. Schematic of two-dimensional electron gas structure in GaAs/AlGaAs

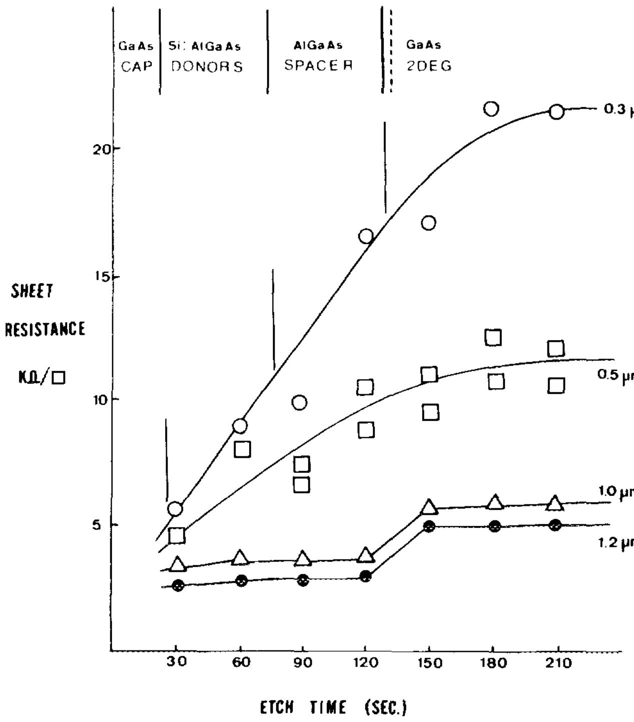

FIG. 3. Effects of etching depth and channel width on the room temperature resistivities of patterned GaAs/AlGaAs 2DEG.

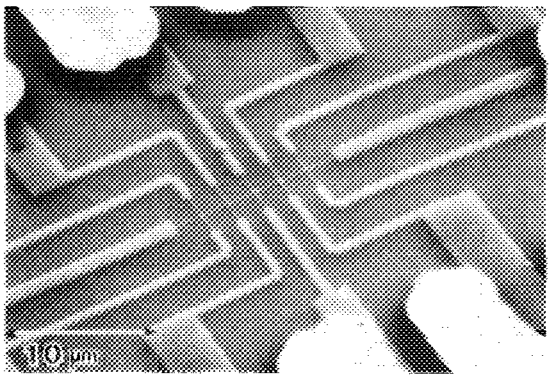

FIG. 4. Scanning electron micrograph of a 100-nm-wide wire with voltage probes defined by the etching only through the GaAs cap layer to a depth of 17 nm.

tional mesa structures through the 2DEG, by removing only the doped AlGaAs donor layer,[14] or through the selective introduction of damage that neutralizes the Si-donor impurities in the doped layer.[15] If sufficiently thick ion etch masks are chosen, the samples may repeatedly be etched. This permits the 2DEG sheet resistivities to be compared as functions of the etch depth and wire size, providing a characterization of the surface quality.

Both the effects of etching depth and wire widths on the sheet resistance are compiled in Fig. 3, which shows a steady increase in the resistivity of small wires with etch depth as the donor and spacer layers are etched through. Larger channels do not show any discernible increase in the sheet resistivity until the 2DEG is exposed, whereupon the resistivity abruptly increases. This increase can be explained by surface depletion of these wide wires. After the 2DEG interface is etched through, however, the resistivities of all of the measured wires stabilize, indicating only negligible sidewall damage by secondary ion bombardment. If only the cap layer is ion etched and the underlying donor layer is damaged, low-resistance channels result. By applying this technique, conducting paths of 100 nm in width have been fabricated in 2DEG (Fig. 4). The low-temperature magnetoresistance of these wires show clearly defined quantum Hall plateaus and Schubnikov–de Haas oscillations indicative of a well-defined geometry of the conducting path.[15] Low-temperature magnetoresistance measurements of wires with variable dimensions indicate that the electrical width is roughly the same as the mask width.[16] This suggests that our gentle patterning technique avoids the serious depletion effects seen in more deeply etched structures.

Table II lists the resistivities of 1.3-μm-wide conducting channels as a function of etch depth into the 2DEG structure shown in Fig. 2. If a 1500-eV-argon beam is used a considerable increase in the resistivity of the wire is observed after the 2DEG is exposed. The resulting high sheet resistivities can be compared to typical results obtained after ion beam assisted etching, which employs only 5% of the ion dose for an equivalent etch depth, and therefore generates wires with less sidewall damage. At low temperatures, the resistivities of both of these wires decrease, but more so in the etched than in the milled wire.

TABLE II. Resistivities of 1.3-μm-wide wires, patterned from the structure shown in Fig. 2 as a function of etch depth for different ion etching conditions.

Etch depth (nm)	Gas mixture	Ion energy (eV)	77 K (kΩ/square)	298 K (kΩ/square)
0		0	···	2.5
80	Ar	1500	···	3.6
160	Ar	1500	···	4.1
275	Ar	1500	1.24	6.5
20	Ar/Cl_2	500	···	3.5
70	Ar/Cl_2	500	···	3.6
359	Ar/Cl_2	500	···	4.1
385	Ar/Cl_2	1500	0.25	3.8

Patterning microstructures by ion processing deteriorates the electrical properties of GaAs. Sidewall damage and surface depletion can result in large decreases in the conductivity of small 2DEG wires. The ultimate resistivity obtained in patterned GaAs "quantum well wires" was found to be very sensitive to the ion etching depth and channel width. By adjusting the etching parameters and by limiting disruption of the 2DEG, sub-100-nm electrically conducting channels could be fabricated. Understanding the damage created by etching of small structures is important for optimization of their electrical properties. Such studies allow the re-evaluation of etching conditions which in the past reproducibly yielded high aspect ratios and high etch rates.

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