Inert gas reactive ion etching damage to GaAs using inverted heterojunctions

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Selectively doped inverted heterojunctions containing a two-dimensional electron gas were used as a sensitive vehicle for monitoring dry processing damage. We found that the electron sheet concentration, strongly dependent on the total number of carriers in the GaAs cap layer, and the mobilities were significantly depressed even for very short exposures to low-voltage helium plasmas. Argon, which caused less degradation than helium, was found to increase the sheet carrier concentration and hence the mobility after prolonged exposure. The damage mechanism responsible for the carrier loss in both cases is most likely the production of traps. The subsequent carrier increase seen for the argon case is probably attributable to the creation of a very thin donorlike damage layer on the surface of the GaAs cap layer.

GaAs/AlGaAs heterostructure devices are susceptible to electrical damage caused by dry etching.[1] The damage becomes more evident as the epitaxial layers are reduced in thickness. The tunneling hot-electron transfer amplifier (THETA) device,[2] whose base dimensions have decreased by 80% since first fabricated, experiences carrier depletion after reactive ion etching (RIE) at low dc self-bias voltages. Previous work[3] related the carrier depletion in the base layer of the device to overetching at an etch stop layer. That study, however, did not explore the role of the inert buffer gas in causing damage. While other work[4,5] did study the effect of inert gas ion damage on GaAs, this communication examines the particular effect of low-voltage inert gas plasmas on the sheet carrier concentration and electron mobility in heterostructures.

The selectively doped inverted heterojunction (SDIH)[6] samples used for this study were grown by molecular-beam epitaxy (MBE). An undoped GaAs buffer layer, grown on a semi-insulating GaAs (100) substrate, is followed by a thick (85.6 nm) $Al_{0.2}Ga_{0.8}As$ spacer layer. This spacer prevents the formation of a two-dimensional electron gas (2DEG) in the GaAs buffer layer. A 10-nm-thick layer of n^+-type ($1\times10^{18}/cm^3$) Si-doped $Al_{0.2}Ga_{0.8}As$ followed by a 6-nm, undoped $Al_{0.2}Ga_{0.8}As$ spacer layer comes next. The structure is completed with a 100-nm, undoped GaAs layer and a 32-nm n^+-type ($1\times10^{18}/cm^3$) GaAs cap layer. This GaAs/AlGaAs heterostructure, which serves as the diagnostic tool in this study, has a single 2DEG located in the GaAs on top of the AlGaAs layer. In this type of structure, the 2DEG concentration at the GaAs/AlGaAs interface is critically dependent on the number of carriers in the GaAs cap layer.

Square ($100\times100\ \mu m^2$) van der Pauw[7] patterns, lithographically defined and mesa etched on the heterostructure, had ohmic contacts [AuGe(120 nm)/Ni(20 nm)/Au (200 nm)] alloyed at 450 °C to the edges of the squares. After chemical or inert gas ion etch processing, van der Pauw squares were mounted on headers and bonded at a temperature of 160 °C. The Hall mobility, measured on as-grown samples at 77 K in the dark, was 34 400 cm^2/V s with a sheet carrier concentration of $6.7\times10^{11}/cm^2$. The solid dots in Fig. 1 represent these results.

The samples used as a baseline for the experiment had their cap layers etched in a 3:1:50 phosphoric acid etch (phosphoric acid: hydrogen peroxide: water) maintained at 0 °C. This etch removes 30 nm of GaAs per minute. Etch times ranged from 5 to 30 s. The 5-s etch samples displayed a decrease in the number of 2DEG carriers and a slight increase in the mobility. This suggests some parallel conduction in the as-grown heterostructure. The other chemically etched samples showed reduced sheet carrier concentrations as well as decreased mobility as more of the cap layer was removed. The solid triangles in Fig. 1, with the etch times listed next to each point, represent these data.

The decrease in sheet carrier concentration with the reduction in cap layer thickness is attributable to the systematic removal of carriers from this layer which caused an increase in the depletion layer width at the surface. Simple modeling results, using a heterostructure simulator which solves the one-dimensional (1D) Poisson's equation for the potential and uses Fermi–Dirac statistics to determine the charge, show a reduction in carrier concentration with a decrease in cap layer thickness. Plotted as a line in Fig. 2(a) is

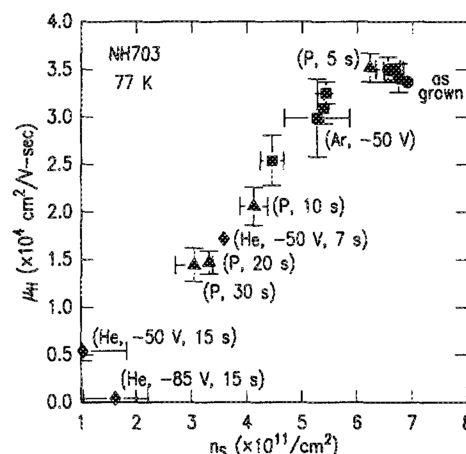

FIG. 1. Hall mobility plotted vs carrier concentration for the as-grown samples: (●), the phosphoric acid etched, baseline samples (▲), the helium exposed samples (◆), and the argon exposed samples (■). Note that the experimental points tend to lie on a line running diagonally through the figure.

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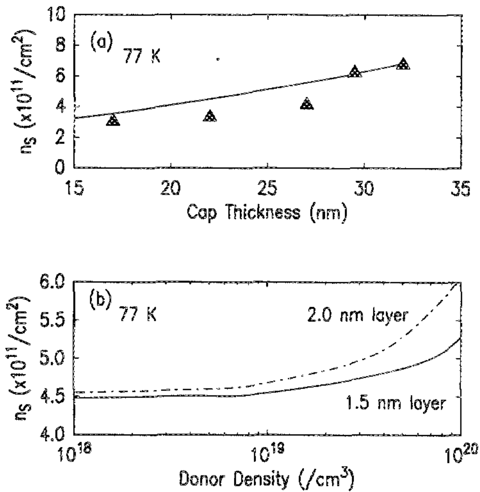

FIG. 2. Simulation results for a SDIH structure at 77 K. (a) The sheet carrier concentration as a function of the GaAs cap layer thickness is plotted as a line. The solid triangles are the experimental data points derived from the phosphoric acid etch results. (b) Plot of the increase in the sheet carrier concentration as the density of donorlike traps is increased within a thin (1.5 and 2.0 nm) surface layer of the GaAs cap.

the data derived from this simulation which qualitatively agree with the phosphoric acid etch data plotted as solid triangles. The decrease in mobility is directly related to the decrease in sheet carrier concentration because of the screening effect produced by the electron gas. A density reduction in this electron gas results in increased scattering and a subsequent mobility decrease.

The SDIH van der Pauw squares, subjected to helium and argon plasmas under RIE-like conditions, helped to quantify the electrical damage caused by the inert gases. The reactive ion etching system is a conventional, parallel plate reactor described elsewhere.[3,8] The van der Pauw samples were first exposed to a helium plasma under conditions similar to those used to etch the THETA devices. These conditions include a flow rate of 6 sccm, a pressure of 15 mTorr, a dc self-bias voltage of -85 V, a power density of 0.03 W/cm^2, and an exposure time of 15 s. Although no measurable etching of the heterostructure surfaces took place, these samples showed extensive reductions in sheet carrier concentration and mobility. A dc self-bias voltage of -50 V, at a pressure of 15 mTorr, a power density of 0.01 W/cm^2, and plasma exposure times of 7 and 15 s were the next set of helium parameters. The sheet carrier concentration and mobility were low but not to the extent of the -85 V case. The results for these samples, plotted as solid diamonds in Fig. 1, lie approximately on a line with the results for the chemically etched samples.

The van der Pauw surfaces exposed to an argon plasma at a flow rate of 6 sccm, a pressure of 15 mTorr, a dc self-bias of -50 V, and a power density of 0.01 W/cm^2 for times ranging from 10 to 40 s displayed less degradation. Figure 1 shows the argon data, plotted as solid squares, clustering between and approximately on a line with the 5- and 10-s phosphoric acid etch results. The sheet carrier concentrations and mobilities are slightly less than the as-grown samples, however these quantities both increase as the plasma exposure time increases.

The experimental data points, for the most part, lie along a line that runs diagonally through Fig. 1. This suggests that the mechanism for the sheet carrier concentration and mobility decrease in the ion exposed samples is similar to that in the chemically etched baseline samples. This mechanism is carrier loss in the cap layer. In the chemically etched samples, carriers are systematically removed from the cap layer. The generation of traps by ions and photons[9] that compensate the dopant in the GaAs cap layer appears to be responsible for the carrier loss in the plasma exposed samples. Trap generation induced in GaAs has been observed and characterized for various dry etching techniques.[10]

The experimental results indicate that the low-voltage helium and argon plasmas affect the heterostructure samples differently. The helium damage (-50 V and 7 s) is equivalent to the removal of carriers from the cap layer and reduces the number of carriers in the 2DEG by about 3×10^{11}/cm^2. A 15-s exposure results in a loss of about 5×10^{11}/cm^2 carriers. Argon, after an initial loss of about 2×10^{11}/cm^2 carriers, shows an increase in carrier concentration and mobility with increased exposure times. Figure 3 shows an expanded view of the argon data from Fig. 1. Listed beside each point is the plasma exposure time. A probable explanation for the carrier increase in the 2DEG is the creation of a high density of donorlike traps at the surface of the GaAs cap layer by the prolonged argon bombardment.[11,12] Modeling results given in Fig. 2(b) show an increase in carrier concentration as the density of these donorlike traps is increased within a thin layer at the GaAs cap surface. The results from the argon experiments represent a balance between the carrier loss in the cap layer and the creation of the donorlike damage layer. In Fig. 3, the 10-s argon exposure resulted in a loss of about 2×10^{11}/cm^2 carriers in the 2DEG. Shorter argon exposure times might have shown greater depletion. Longer times show the effect of the surface

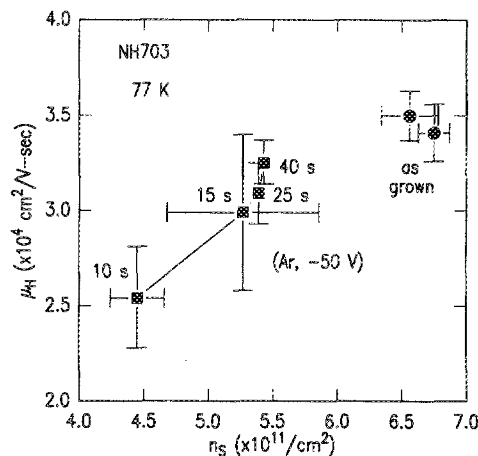

FIG. 3. The Hall mobility for the samples exposed to an argon plasma are plotted vs carrier concentration. The various exposure times are listed next to the experimental points. For these samples the effect of longer bombardment times increases the effective carrier concentration and the mobility. The as-grown values (⊗) are plotted as a guide.

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modification with an apparent limit to the carrier increase. The mobility, however, continues to increase and approaches the value of the as-grown samples plotted as solid dots in Fig. 3. It has been suggested[12] that arsenic depletion at the GaAs surface, with the arsenic vacancies having a donor character, is responsible for the donorlike damage layer.

The sheet carrier concentration and hence the mobility of the 2DEG in heterostructure devices is critically dependent on the integrity of surface epitaxial layers.[1] It is important to understand, therefore, that even low-voltage plasmas can drastically alter the conduction of a 2DEG. Also, for some device structures, thermal processing for damage removal is not feasible, so care is recommended when employing inert gases for cleaning and buffering.

In conclusion, we have examined the damage caused by low-voltage helium and argon plasmas on an inverted heterostructure. Helium severely degraded the sheet carrier concentration and the mobility of the 2DEG at a dc self-bias voltage of only -85 V for 15 s. Argon damage was limited, with extended bombardment causing an increase in the carrier concentration and the mobility. This increase is most probably due to the creation of a thin, donorlike damage layer at the surface of the GaAs cap layer. Future studies will examine the effects of other inert gases on heterostructures containing a 2DEG.

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Transport in reversibly laser-modified $YBa_2Cu_3O_{7-x}$ superconducting thin films

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A focused argon ion laser beam in a controlled ambient is used to modify the transport properties of superconducting $YBa_2Cu_3O_{7-x}$ thin films. The laser-modified region shows a sharp transition temperature ($T_c \approx 76$ K) that is reduced from the unmodified regions of the film ($T_c \approx 87$ K). *In situ* monitoring of the room-temperature electrical resistance is used to control the laser processing and prevent formation of the semiconducting phase. The original properties of the superconducting film can be recovered by plasma oxidation indicating that the laser-induced phase is oxygen deficient.

Electronics is a potentially important area for future applications of the high transition temperature (T_c) superconductors based on the La-Ba cuprates discovered by Bednorz and Muller,[1] and the Y-Ba cuprates discovered by Wu *et al.*[2] These potential applications will rely heavily on the ability to make and process thin films of these materials and control their local transport properties on a microscopic scale. In this communication, we report on the transport properties of superconducting $YBa_2Cu_3O_{7-x}$ films that have been locally modified by laser-induced heating in a controlled ambient. In contrast to previous work,[3-5] we demonstrate that the laser-modified film need not be driven to the insulating region of the phase diagram but may be controlled in such a way as to produce a superconducting phase with a reduced and well-defined transition temperature. This opens the possibility of controlling critical current and making weak links. Furthermore, by placing the laser-modified sample in an oxygen plasma, the original film properties can be recovered leading us to believe the laser-induced phase is oxygen deficient.

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