The influence of ion energy, ion flux, and etch temperature on the electrical and material quality of GaAs etched with an electron cyclotron resonance source

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The residual damage incurred to GaAs via etching with a Cl_2/Ar plasma generated by an electron cyclotron resonance (ECR) source was investigated as a function of variations in ion energy, ion flux, and etching temperature. The residual damage and electrical properties of GaAs were strongly influenced by changes in these etching parameters. Lattice damage was incurred in all processing situations in the form of small dislocation loops. GaAs etched at high ion energies with 200 W rf power, exhibited a defect density five times higher than GaAs etched at lower ion energies with 20 W rf power. This enhanced residual damage at the higher rf powers was paralleled by a degradation in the unannealed contact resistance. Higher etch rates, which accompany the higher rf power levels, caused the width of the disordered region to contract as the rf power was elevated. Therefore, the residual etch damage is influenced by both the generation and removal of defects. Increasing the microwave power or ion flux resulted in elevating the residual defect density, surface roughness, and unannealed contact resistance. GaAs etched at high temperatures, ~350 °C, resulted in a lower contact resistance than GaAs etched at 25 °C. The high temperature etching augmented the defect diffusion which in turn lowered the near surface defect density. This decrease in residual damage was deemed responsible for improving the electrical performance at 350 °C. The electrical measurements were found to be more sensitive to the density of defects than the vertical extent of disorder beneath the etched surface. Results of this investigation demonstrate that in order to minimize material damage and improve electrical performance, etching with an ECR source should be performed at low rf and microwave powers with a high substrate temperature. © *1995 American Institute of Physics.*

I. INTRODUCTION

The ability to design and develop ever smaller devices depends strongly on the capability to generate the desired device pattern. Physical dry etching (ion etching, ion beam etching, etc.) and chemical-physical dry etching [reactive ion etching (RIE), reactive ion beam etching, magnetron ion etching, etc.] are plasma based etching tools which are critical to the fabrication of submicron scale devices. These dry etching approaches are important because of their ability to provide fine line definition and highly directional etching.[1] Dry etching techniques are known to cause chemical and physical modifications to the material surface.[2] Such modifications include structural damage, heavy metal contamination from parts of the reactor, and deposition of involatile material. Numerous studies have reported that a modified surface will degrade the performance of devices (lower carrier mobility, reverse breakdown voltage, etc.) fabricated on that surface.[3,4] Plasma processing utilizing electron cyclotron resonance (ECR) discharge-rf electrode plasma reactor appears to be a promising technique which satisfies the increasingly stringent requirements of submicron device fabrication while relaxing the concerns of etched induced damage.[5] An important advantage of this etching technique is the independent control of the gas excitation and ion energy. Compared to conventional RIE methods, this configuration allows generation of a high density plasma at lower ion bombardment energies, resulting in high etch rates with low etch induced damage.[6] To date, little work has been formalized to detail and systematically characterize the surface defects induced by etching with an ECR source as a function of controllable etching parameters. Studies of this nature are necessary in order to optimize ECR source etching for device processing. In this study we evaluated the residual damage, surface morphology, and electronic properties of ECR source Cl_2/Ar dry etched GaAs as a function of variations in ion energy, ion flux, and etch temperature. Surface morphology and the distribution of near-surface disorder after etching was investigated via transmission electron microscopy (TEM). The effect of etch induced damage on surface electrical properties was determined by extracting the contact resistance from unannealed transmission lines.

II. EXPERIMENT

Dry etching was accomplished via a plasma system with an ECR source and an rf powered electrode. Details of the plasma system have been reported elsewhere.[7] The ECR source used is a multipolar plasma disk driven at 2.45 GHz and is surrounded by twelve permanent magnets. The ECR cavity is tunable with a sliding short and a microwave input probe. A rf power supply at 13.56 MHz is connected to the

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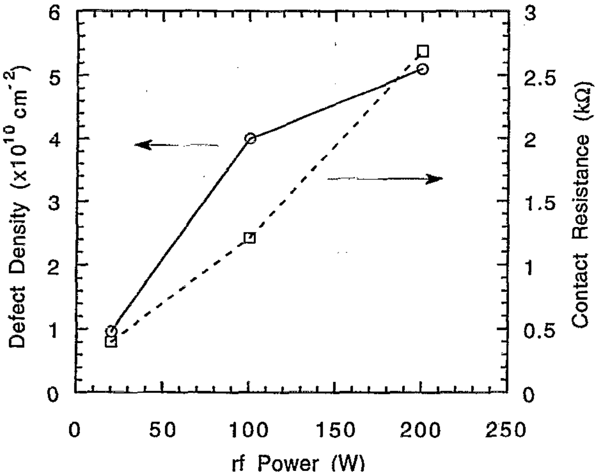

FIG. 1. The influence of ion energy on unannealed contact resistance and etch induced residual damage.

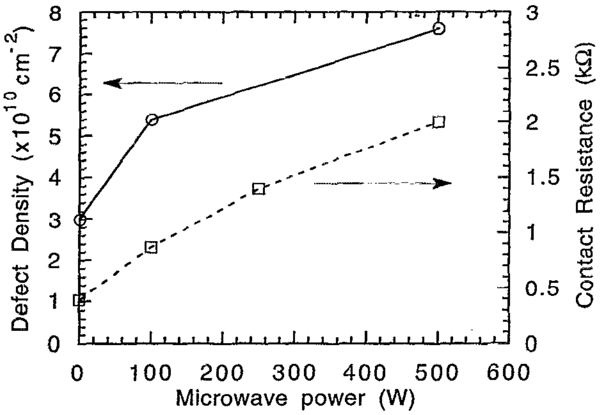

FIG. 2. The influence of ion flux on unannealed contact resistance and etch induced residual damage.

sample stage for independent control of the ion energy. The temperature of the stage is controllable between −130 and 380 °C using a combination of liquid N_2 cooling and resistive heating. Chlorine is introduced into the etch chamber through a gas ring situated 1 cm below the sample stage, while Ar is introduced radially through the base of the ECR source. Samples for the ion energy (rf power) dependence study were etched with 10% Cl_2 in a Cl_2/Ar plasma using 50 W microwave power at 0.5 mTorr. The ion flux (microwave power) dependence samples were etched under similar conditions with variable microwave power at a fixed self-induced dc bias voltage ($|V_{dc}|$) of 150 V. To maintain the $|V_{dc}|$ at 150 V the rf power was varied from 53 to 63 W as the microwave power was increased from 0 to 500 W. The samples for the temperature dependence study were etched with 20% Cl_2 in a Cl_2/Ar plasma using 50 W microwave power and 200 W rf power at 0.5 mTorr with stage temperatures ranging from −130 to 350 °C. The samples used for electrical characterization were etched at 15 cm below the ECR source and those used for TEM characterization were etched with a source to sample distance of 12 cm.

The electrical characterization was accomplished via transmission lines fabricated on a 1-μm-thick epitaxial layer of *n*-GaAs doped to 5.0×10^{18} cm^3 overlying a semi-insulating GaAs substrate. The etch depth for the transmission lines was 100 nm. Mesas for isolation were formed by wet etching. Ohmic contacts with spacings varying from 5 to 20 μm were defined using a liftoff process. The ohmic contacts consisted of Ni/Ge/Au/Ti/Au (25/33/65/10/150 nm) and were intentionally not annealed in order to maximize the sensitivity of the contact resistance to the effects of etching.

TEM samples were prepared in {110} cross sections. Samples were mechanically polished to 10 μm then thinned to electron transparency by ion milling with 4 keV Ar ions in a liquid N_2 cooled stage. Microscopy was performed using a JEOL 2010 TEM operated at 200 keV and a Philips 420 T STEM at 120 keV. Surface morphology and lattice damage evaluations were achieved via bright-field, centered weak beam dark-field ($g=220$), and crystal imaging techniques.

III. RESULTS AND DISCUSSION

The variations in process parameters were reflected in both the structural and electrical properties of the etched material. Figure 1 shows the effects of varying rf power levels (ion energy) on unannealed contact resistance and material surface disorder. It is clearly seen that the contact resistance increases as the rf power is elevated from 20 to 200 W. The increase in rf power level is accompanied by an increase in $|V_{dc}|$ from 83 to 370 V. The dc bias voltage indicates the maximum positive ion energy to which the sample was exposed during etching. A lower bias voltage implies a lower ion bombardment energy and therefore less etch induced lattice damage to the GaAs crystal.[4,8,9] Thus, the degradation in the electrical characteristics of the etched GaAs is due to higher damage levels generated at the higher rf power because of the higher ion bombardment energies (higher $|V_{dc}|$). The electrical evaluation, unannealed contact resistance, does not provide information related to the type, size, and distribution of defects generated as a result of etching. We have acquired this information via TEM. Lattice damage was present at all rf power levels in the form of small, 2.4 nm, dislocation loops. The lowest rf power level exhibited the lowest defect density, 9.6×10^9 cm^{-2}, while the highest defect density, 5.1×10^{10} cm^{-2}, was achieved at 200 W rf power. Figure 1 shows that this increase in defect density parallels the degraded electrical characteristics occurring at the elevated rf power levels. The depth of damage penetration into the GaAs decreases as the rf power increases, i.e., the depth of damage penetration is 133, 67, and 53 nm at 20, 100, and 200 W rf power, respectively. It is intuitively expected that increases in rf power are paralleled by increases in both defect density and width of the disordered residual damage region. Our results suggest that the higher rf power level results in a higher defect density, however, the faster etch rate (accompanying the higher power level) results in a trade-off between damage accumulation (depth of defect penetration) and damage removal. Specifically, even though there is more damage created in the GaAs at the higher power level (200 W), the GaAs is also being etched away at a faster rate, thus the width of the residual disordered region

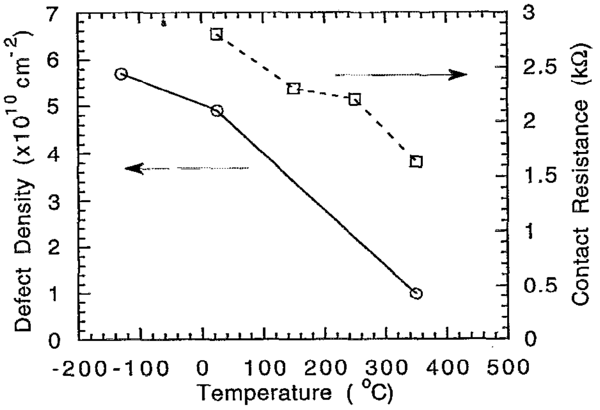

FIG. 3. The influence of etching temperature on unannealed contact resistance and etch induced residual damage.

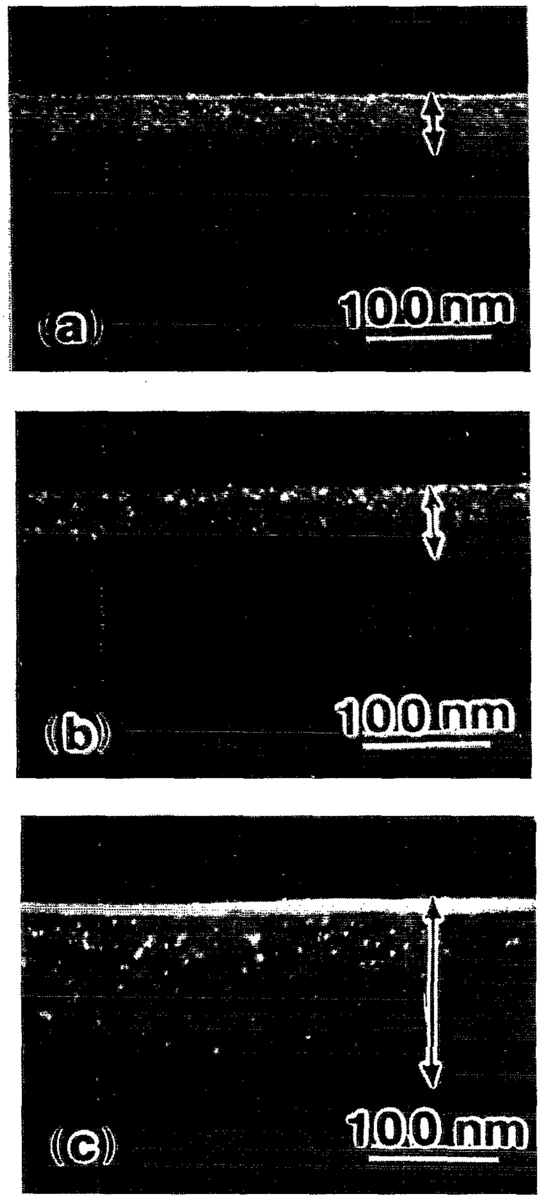

FIG. 4. TEM micrographs of GaAs etched with the ECR source at (a) −130, (b) 25, and (c) 350 °C. The double headed arrow indicates the extent of defect penetration.

after etching at 200 W is shallower than that etched at the lower rf power (20 W) with its lower etch rate. Similar results have been documented by others for RIE.[4,10] The surface morphology was smooth for the three rf power levels evaluated.

In order to study the effects of ion flux on residual material damage, the microwave power to the ECR source was varied, resulting in the variation of the density of reactive species. For these experiments the $|V_{dc}|$ was fixed at 150 V while the microwave power was varied from 50 to 500 W. The rf power was varied from 53 to 63 W in order to maintain $|V_{dc}|$ at 150 V. Figure 2 displays the effect of microwave power, ion flux, on unannealed contact resistance and etched induced defect density. The electrical characteristics degraded as the microwave power was elevated from 0 to 500 W. Figure 2 also shows that the defect density increases as the microwave power is elevated. Specifically, the defect density is 3.0×10^{10}, 5.4×10^{10}, and 7.6×10^{10} cm^{-2} at microwave powers of 0, 100, and 500 W, respectively. Thus, the defect density has nearly doubled as the microwave power increased from 0 to 500 W. Both the electrical and microstructural data suggest that more defects are generated in response to the higher ion flux. These results are not surprising, since an increase in microwave power causes the density of reactive species to increase, this in turn augments the residual damage level. The samples etched at 0 and 100 W microwave power exhibited extremely smooth surface morphologies while that of the 500 W sample was slightly rougher. Specifically, the peak to valley distances of the residual surface peaks were ~3 nm and the full width at half maximum (FWHM) was ~7 nm. It is well documented for reactive ion etched GaAs that a rough surface morphology manifests into poor electrical performance.[4,10,11] However, the surface morphology for these cases are on the order of 8–20 times rougher. Nonetheless, this small perturbation in surface morphology may indeed contribute to the elevated contact resistance associated with the GaAs etched at the 500 W microwave power.

It is noteworthy to mention that lowering rf power from 200 to 20 W, a decrease of only 180 W, caused the defect density to decrease by ~81% and the contact resistance to decrease by 85%. However, as the microwave power was decreased by 400 W, i.e., from 500 to 100 W, the defect density only decreased by ~29% and the contact resistance decreased by 56%. The data demonstrate that the electrical and damage level changes were significantly greater for a much smaller increment of change in rf power, compared to that of microwave power. Thus, for the parameters studied it is suggested that the electrical characteristics and residual damage are more sensitive to changes in ion energy than ion flux.

Figure 3 shows the influence of substrate temperature on both the electrical characteristics and material residual damage. The data demonstrate that higher etch temperatures improve the contact resistance and lower the defect density. At first glance the data are suggestive of two possible explanations: either less damage was induced at 350 °C or the damage has been reduced due to *in situ* dynamic annealing at the elevated substrate temperatures. Since the samples were etched under the same rf and microwave power conditions, and these two parameters have a strong influence on the etch induced damage, it is doubtful that less damage was introduced at the higher etching temperature. The TEM investigation gives a detailed account of the temperature effect on the etch induced damage. Figure 4 displays the TEM micrographs of the samples etched at these temperatures. It is visually realized, from the micrographs, that as the substrate temperature increases, the defect density decreases and the depth of damage penetration is augmented. Specifically, the depth of defect penetration ranges from 40 nm at -130 °C to 160 nm at 350 °C (an increase of 400%). This implies that the defect diffusion is enhanced at higher temperatures. As the defects diffuse away from the surface the density of the defects are lowered, thus the lower defect density at 350 °C is primarily due to defect diffusion. In addition, as the etching temperature was increased from 25 to 350 °C, the etch rate increased from 221 to 292 nm/min, thus, in the absence of diffusion one would expect a narrower disordered region based on the premise that the higher etch rate at 350 °C would result in a faster damage removal rate. Since this is not the case, this further supports the thesis of defect diffusion at elevated etching temperatures. At elevated temperatures, ~350 °C, *in situ* annealing cannot be ruled out entirely. Most likely, there is some *in situ* annealing associated with high etching temperatures but the fact that the defect depth has increased four fold implies that diffusion is a dominant mechanism, although *in situ* annealing probably operates in concert. The improvement of the electrical measurements at the 350 °C etching temperature suggests that under these etch conditions, the effect of the depth of damage penetration on the electrical behavior is secondary to that of defect density. In other words, the electrical measurements were found to be more sensitive to defect density than to the depth of damage penetration.

It should be noted that raising the etching temperature from -130 to 25 °C only decreased the damage density by 14%. However raising the temperature from 25 to 350 °C caused the defect density to decrease by 80% and the contact resistance to decrease by 39%. Therefore, changing the etching temperature, from 25 to 350 °C, caused a dramatic response in both residual damage and electrical performance.

IV. SUMMARY

The material and electrical quality of ECR etched GaAs in a Cl_2/Ar plasma has been evaluated as a function of ion energy, ion flux, and etching temperature. As ion energy was increased, i.e., rf power was raised from 20 to 200 W, the defect density was elevated, the width of the disordered region contracted and the electrical properties degraded. Etching at high microwave powers, high ion flux, increased the defect density, surface roughness, and unannealed contact resistance. Thus, the higher density of reactive species creates a rougher and more damaged surface which diminishes the electrical integrity of the etched GaAs. For the parameters investigated, the variations in ion energy had a much more profound effect on both residual etch induced damage and electrical integrity than that of ion flux. The unannealed contact resistance was lower for GaAs etched at 350 °C compared to that etched at 25 °C. TEM results revealed that etching at 350 °C caused the defects to diffuse deeper into the GaAs relative to etching at 25 °C, thereby lowering the density of dislocation loops at the surface by 80%. The lowering of defect density, via enhanced defect diffusion, is believed to be responsible for the superior electrical quality of the high-temperature etched GaAs. In summary, our work demonstrates that the controllable parameters of an ECR source-rf powered electrode plasma reactor need be tuned to minimize residual etch induced damage and optimize electrical performance. For the etch parameters used in this investigation, etching should be performed at low rf and microwave powers with a high substrate temperature.

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