PARAMETRIC STUDY OF COMPOUND SEMICONDUCTOR ETCHING UTILIZING INDUCTIVELY COUPLED PLASMA SOURCE

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ABSTRACT

Inductively Coupled Plasma (ICP) sources are extremely promising for large-area, high-ion density etching or deposition processes. In this review we compare results for GaAs and GaN etching with both ICP and Electron Cyclotron Resonance (ECR) sources on the same single-wafer platform. The ICP is shown to be capable of very high rates with excellent anisotropy for fabrication of GaAs vias or deep mesas in GaAs or GaN waveguide structures.

INTRODUCTION

Inductively coupled plasma (ICP) etching offers an attractive alternative dry etching technique.[1,2] The general belief is that ICP sources are easier to scale-up than ECR sources,[3] and are more economical in terms of cost and power requirements. ICP plasmas are formed in a dielectric vessel encircled by an inductive coil into which rf-power is applied.[4-8] A strong magnetic field is induced in the center of the chamber which generates a high-density plasma due to the circular region of the electric field that exists concentric to the coil. At low pressures (≤ 10 mTorr), the plasma diffuses from the generation region and drifts to the substrate at relatively low ion energy. Thus, ICP etching is expected to produce low damage while achieving high etch rates. Anisotropic profiles are obtained by superimposing a rf-bias on the sample to independently control ion energy.

In this paper we report the first etching results for GaAs and GaN in an ICP tool. It is found that ICP sources are capable of producing the extremely high rates needed for producing via holes on 4"Φ GaAs substrates, and have the high ion density needed to obtain high etch rates for strongly bonded material such as GaN, where the rate-limiting step is usually the initial bond breaking that must precede etch product formation. GaN has a bond energy of 8.92 eV/atom, compared to 6.52 eV/atom for GaAs,[9] and the low rates reported with reactive ion etching are due to the low rate of bond breaking in RIE discharges.

EXPERIMENTAL

A typical ICP system (Plasma Therm 790 series) is shown schematically in Figure 1. Power at 2MHz is inductively coupled into the plasma volume to create a high ion density ($\geq 10^{11}cm^{-3}$) discharge, while the sample sits on a He backside-cooled, rf (13.56MHz) powered chuck, which controls the ion energy. This is a prototypical single-wafer, high density system, in

which there is separate control of ion density (via the ICP power) and ion energy (via the rf biasing of the sample position). We directly compared the performance of the ICP and ECR sources, by placing them on a Plasma Therm SLR 770 platform that is designed for an ECR source.

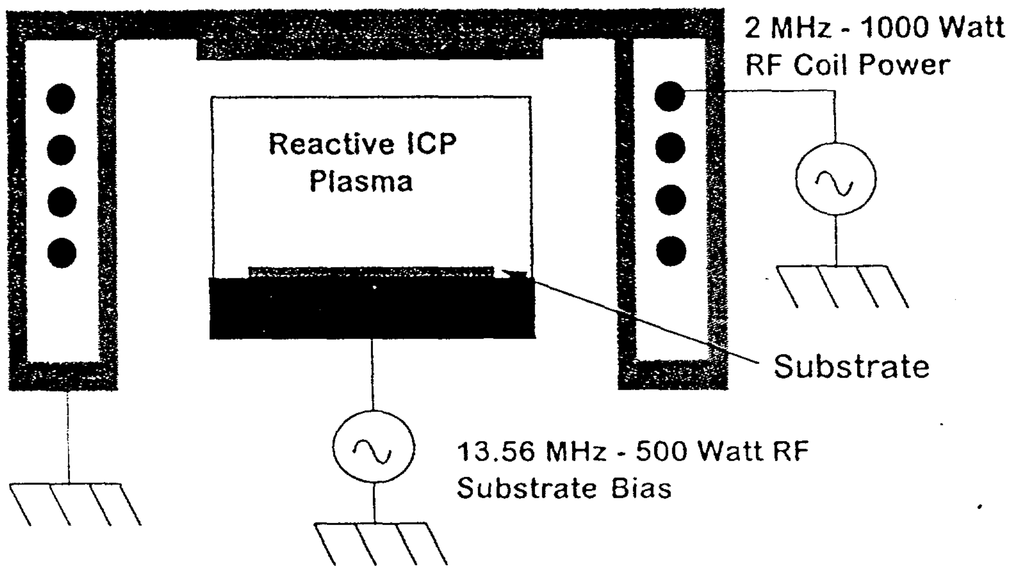

Figure 1. Schematic of ICP reactor.

The principle of the ICP source operation is shown schematically in Figure 2. The electric field produced by the coils in the horizontal plane induces an oscillating B field in the vertical plane, trapping electrons and producing high ionization and excitation efficiencies without leakage of the electrons to the chamber wall. Therefore, as in an ECR source, the ion density is high while the induced self-bias on the cathode is low.

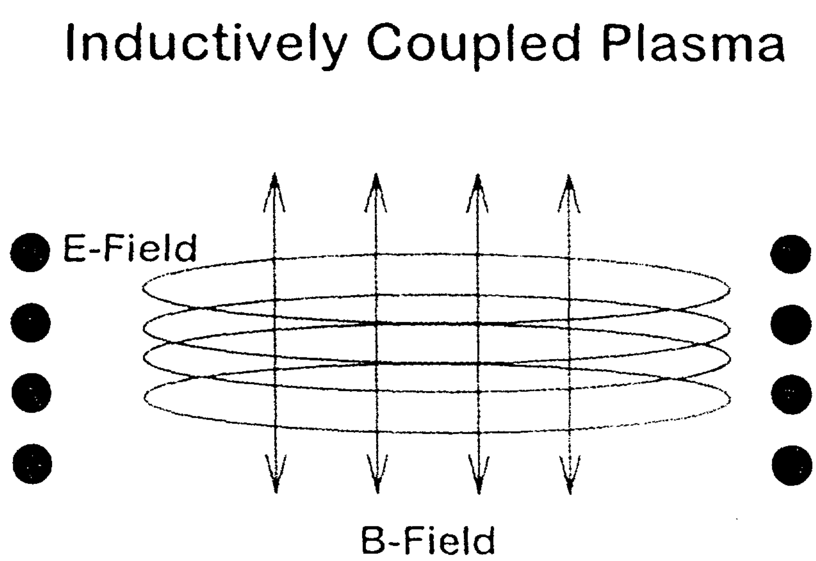

Figure 2. E- and B-field configurations in ICP.

RESULTS AND DISCUSSION

The self-bias developed on the sample chuck was measured as a function of applied rf power on the SLR 70 platform with the ICP or ECR (Astex 4400 low profile source) sources in place. Figure 3 shows that these self-biases are almost identical when the high density sources are not powered.

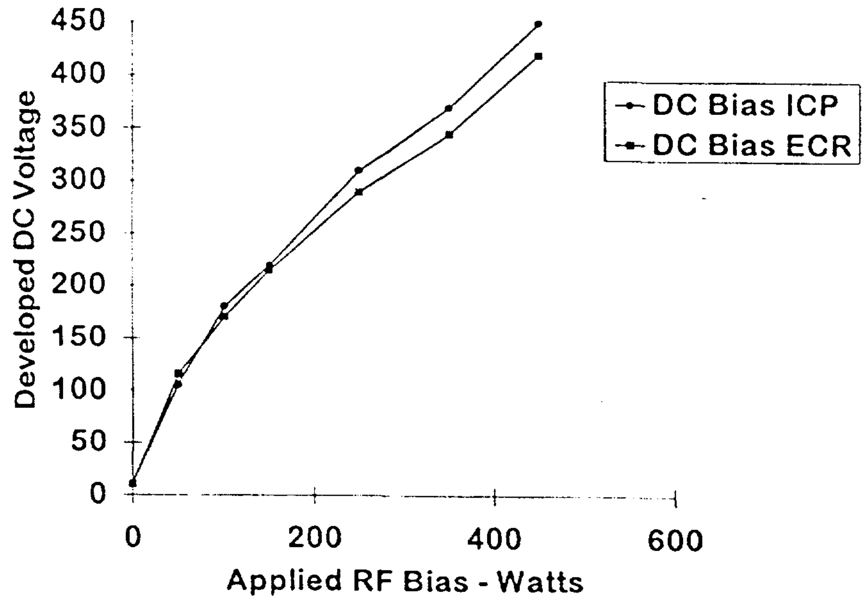

Figure 3. DC self-bias as a function of rf power in an ECR and ICP reactor.

As the ICP power is increased and hence the plasma density increases, there is a suppression of the cathode self-bias, as shown in Figure 4. Therefore it is possible to achieve very high ion densities while retaining low acceleration voltages. This is an important result when considering the etching of device structures where mask integrity or ion-induced damage can be an issue, such as in III-V semiconductor structures like heterojuction bipolar transistors or laser diodes.[10,11]

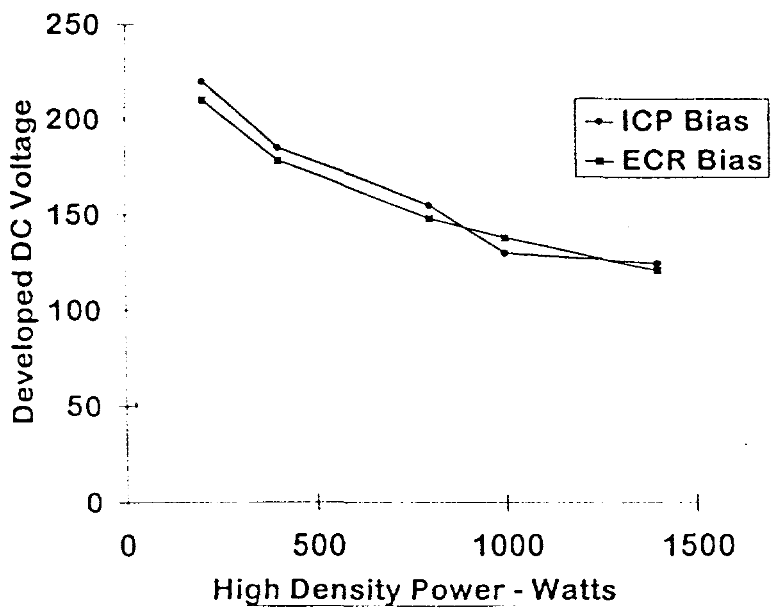

Figure 4. DC self-bias as a function of ECR or ICP power.

There was basically no dependence of self-bias on process pressure with either high density source, as shown in Figure 5. Thus both sources have a wide operating pressure, although the coupling efficiency of microwaves to the ECR plasma decreases above ~10 mTorr. It is expected that the ICP is capable of higher pressure operation and thus the cost of ownership should be lower because one can employ smaller pumps. This is a major consideration for manufacturing processes, where multiple reactors may be needed to produce a sufficiently throughput of wafers.

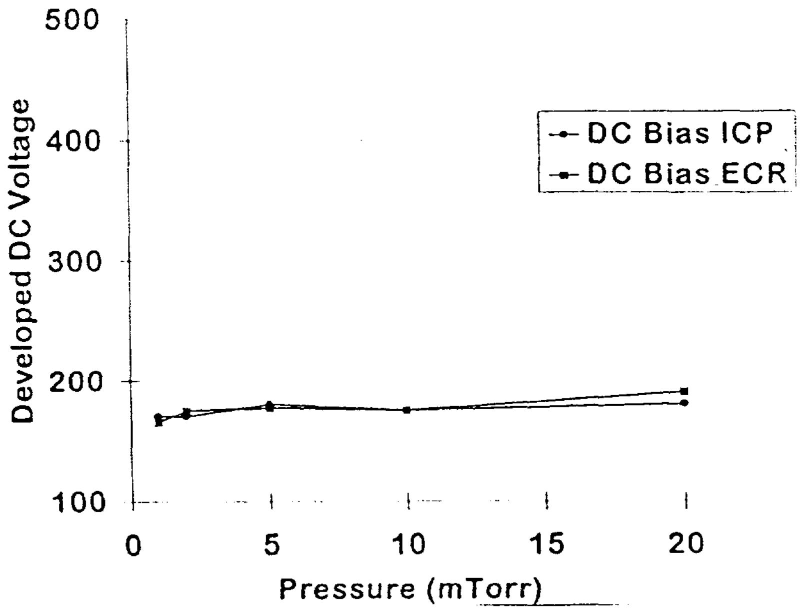

Figure 5. DC self-bias a function of pressure in an ICP tool.

For controlled rate etching of GaAs/AlGaAs for HBT mesas or laser diode waveguides, BCl_3 plasma chemistries are attractive since they are non-selective for GaAs over AlGaAs for BCl_3 or BCl_3/Ar. If a fluorinated gas such as SF_6 or SiF_4 is added to the chemistry , then it is possible to achieve high selectivities (>200:1) for GaAs over AlGaAs.[12,13] These etches are highly anisotropic even at moderate rf bias, in part because the BCl_x residues aid in sidewall protection. Figure 6 shows the GaAs etch rate and selectivity over photoresist at 750W or ICP power. The rate is controllable between 25-450 nm/min for fixed ICP power and rf powers between 50-350W. The selectivity over resist varies from 1-5.

The etch uniformity measured on 2"Φ GaAs wafers was strongly dependent on ICP power, as shown in Figure 7, which displays etch rate and uniformity percentage as a function of the ICP power. The rf chuck power up to 1000W (maximum rate ~500 nm/min) and decreases at 1500W , which may be due to one or both of the following factors: either sputter-enhanced removal of the chlorine neutrals before they can react with the GaAs surface, or a further decrease in self-bias at very high ICP powers. Note however that the uniformity degrades rapidly over 750W of ICP power. This effect is still under investigation, and it is not clear if this is due to non-uniform suppression of the self-bias or non-uniformities developing in the discharge itself.

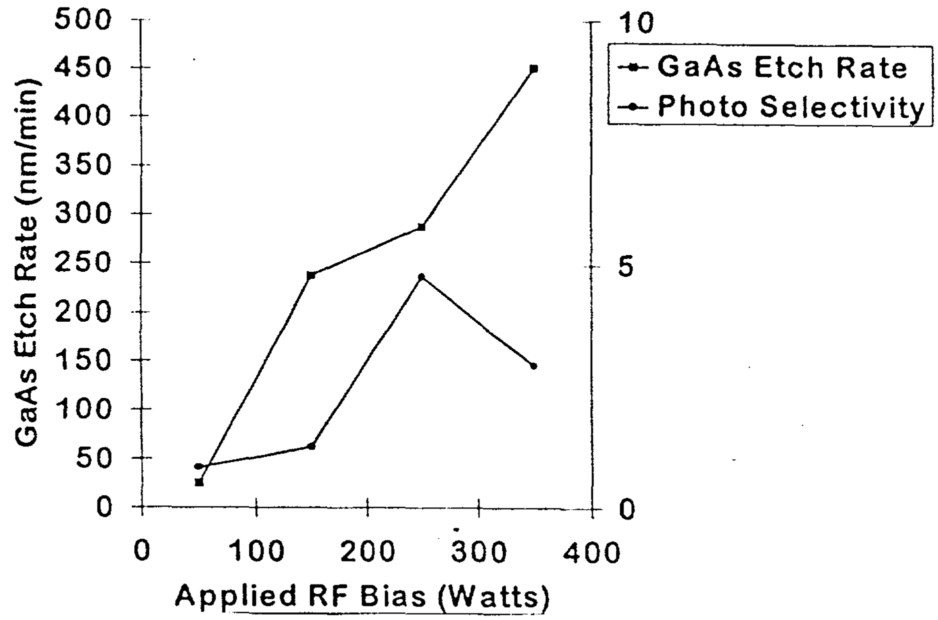

Figure 6. GaAs etch rate and selectivity over resist in a BCl_3 ICP discharge with 750W ICP power, as a function of rf chuck power.

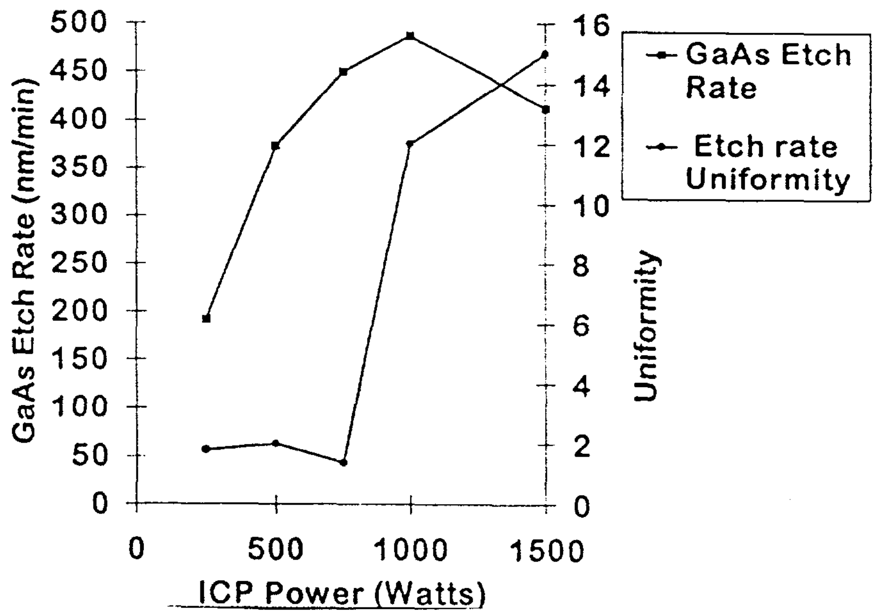

Figure 7. GaAs etch rate and uniformity in a BCl_3 discharge with 150W rf chuck power, as a function of ICP power.

If necessary the etch rate can be increased by addition of Cl_2. Figure 8 shows the dependence of etch rate on discharge composition at 1000W ICP power and 350W rf power. The etch rate of GaAs stays above ~2.3 μm/min for BCl_3 percentages ≤ 25%. The uniformity of etching is better than 5% for BCl_3 percentages above 50%. This may be due to the well-known efficiency of BCl_3 for removing the native oxide on III-V materials. For Cl_2-rich discharges the breakthrough of this oxide may be non-uniform, and with such a high etch rate, the overall etch rate uniformity suffers.

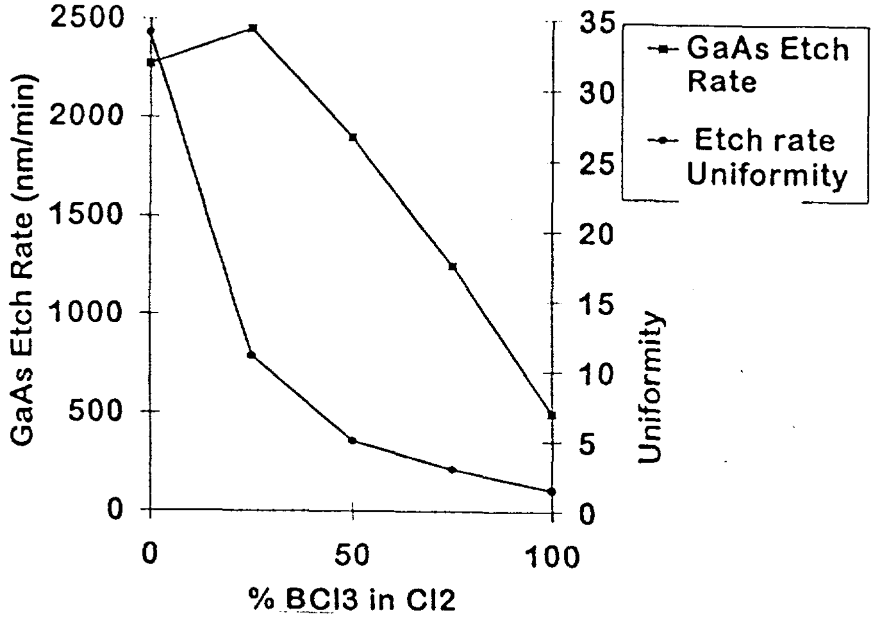

Figure 8. GaAs etch rate and uniformity in BCl_3/Cl_2 discharges with 1000W ICP power and 350W rf power, as a function of plasma composition.

Figure 9 shows the pressure dependence of GaAs etch rate and selectivity over photoresist for pure BCl_3 discharges (1000W ICP power, 350W rf power). The selectivity is between 3-6 over the pressure range 1-20 mTorr. The maximum in etch rate around 2-3 mTorr is also typical of ECR processes[14] and is related to an absence of ion collisions and recombination at low pressures.

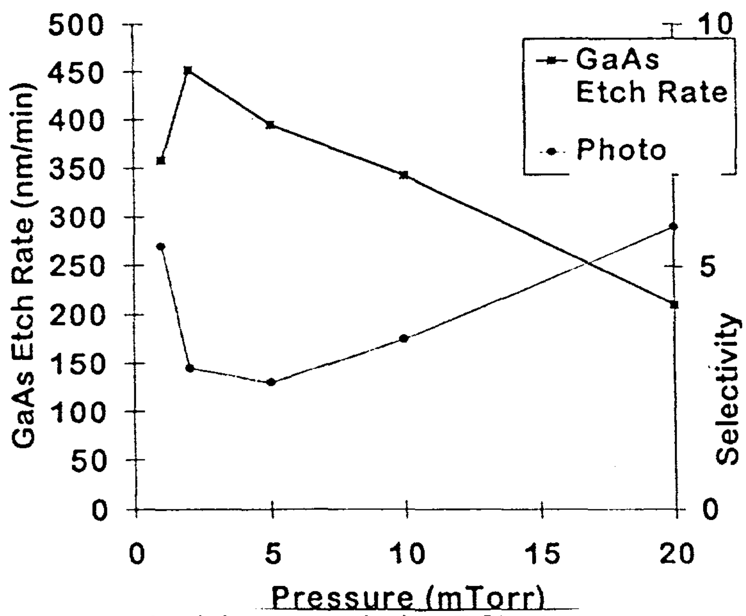

Figure 9. GaAs etch rate and selectivity over resist in a BCl_3 discharge with 1000W ICP power and 350W rf power, as a function of pressure.

A scanning electron micrograph (SEM) of features etched into GaAs with 750W ICP power, 100W rf power, 2 mTorr BCl_3 discharge (40 sccm of gas) is shown in Figure 10. The photoresist mask has been removed. The etch rate under these condition is 230 nm/min, and the surfaces are smooth with anisotropic sidewalls. The resist mask generally showed facetting at its edge, but the GaAs sidewalls were very smooth and straight. This is a critical requirement for laser mesas or waveguides where any sidewall roughness will lead to scattering of light as it traverses the stripe, and hence to a decreased optical output.[15,16]

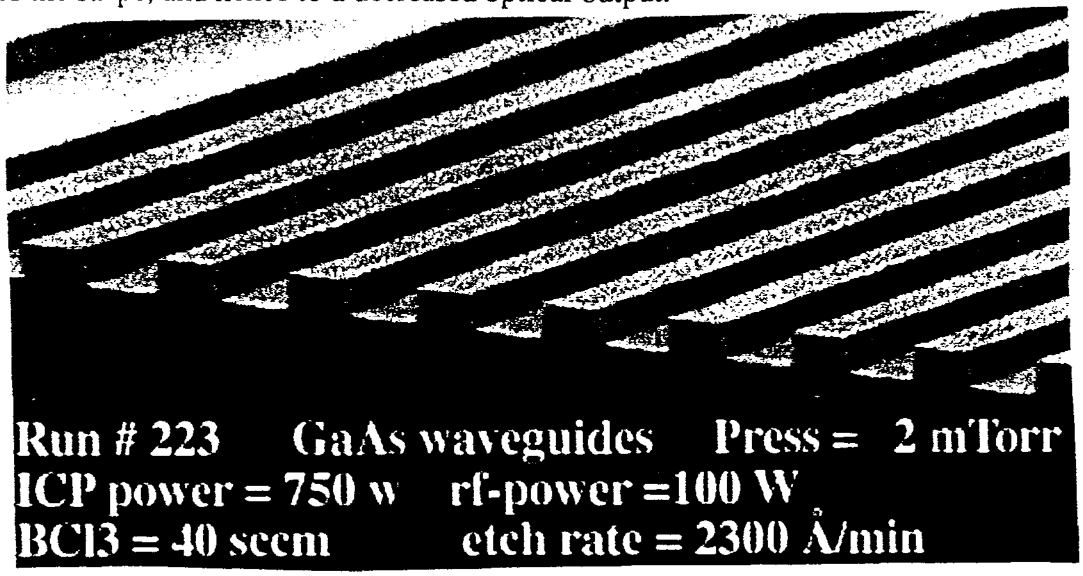

Figure 10. SEM micrograph of features etched into GaAs with a 750W ICP BCl_3 discharge.

As mentioned earlier, addition of Cl_2 to BCl_3 can produce high rates for GaAs and related alloys. A benchmark for backside via-hole processes is to achieve an etch-rate of greater or equal to 4 μm/min for 4"Φ GaAs wafers. For this process one will require both high ICP and rf power, and active wafer cooling (i.e. clamping to the He backside cooled chuck. the sidewalls must be relatively anisotropic and smooth because they will be plated with metal to complete the through-wafer via.[17,18]

Figure 11 shows the pressure dependence of GaAs etch rate and photoresist selectivity in 25%Cl_2:75%BCl_3 discharges at 750W ICP power as a function of rf power (5 mTorr pressure). There is little dependence on rf bias, since the etching is not strongly desorption-limited under these conditions, but the rate does increase from ~1 μm/min at 50W rf to 1.7μm/min at 350W, and the selectivity decrease from ~3.8 to ~2.

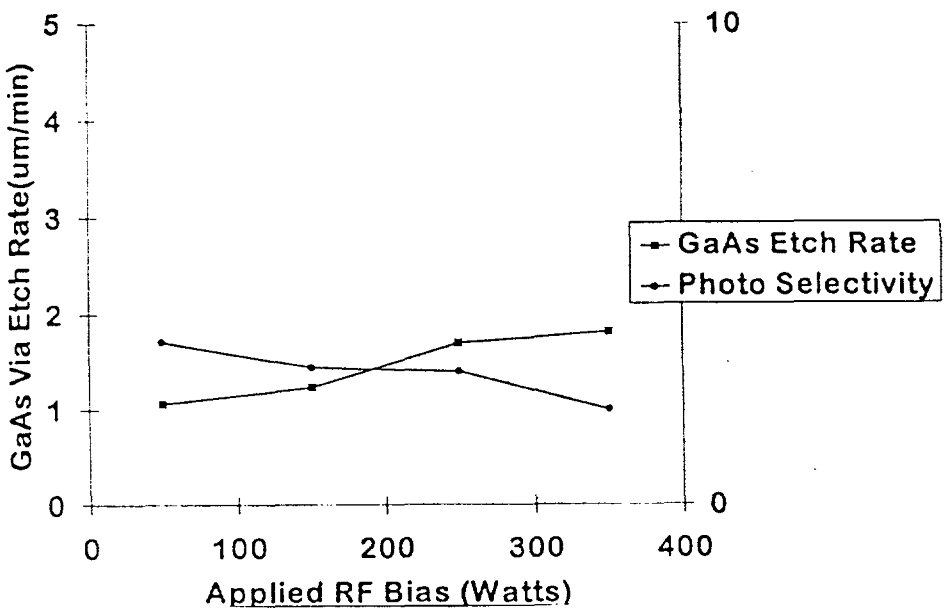

Figure 11. GaAs etch rate and selectivity over resist in a 1:3 Cl_2:BCl_3 discharge with 750W ICP power as a function of rf chuck power.

The GaAs etch rate and selectivity over photoresist is shown in Figure 12 as a function of ICP power. Once again the etch rate increases over the range 250–1000W from ~0.8 μm/min to ~1.3 μm/min as the ion and neutral density both increase at higher power. The selectivity over photoresist is in the range 2-3 over this set of conditions.

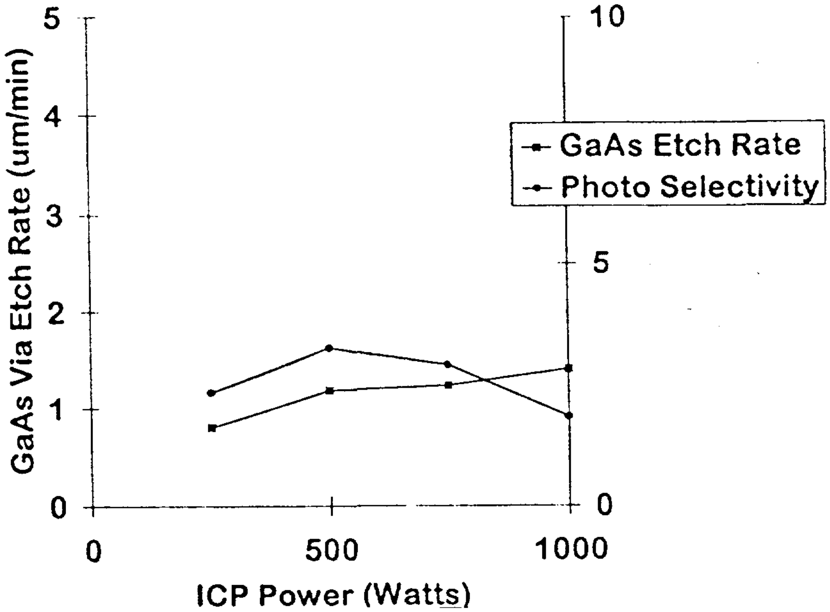

Figure 12. GaAs etch rate and selectivity over resist in a Cl_2/BCl_3 discharge as a function of ICP power.

As etch rate of slightly higher than 4 μm/min was achieved and 10 mTorr pressure, as shown in Figure 13. The selectivity is still only 3-5, which is barely sufficient for a typical 75μm etch depth with 12–16μm of resist. In these applications a Ni mask has proven effective.

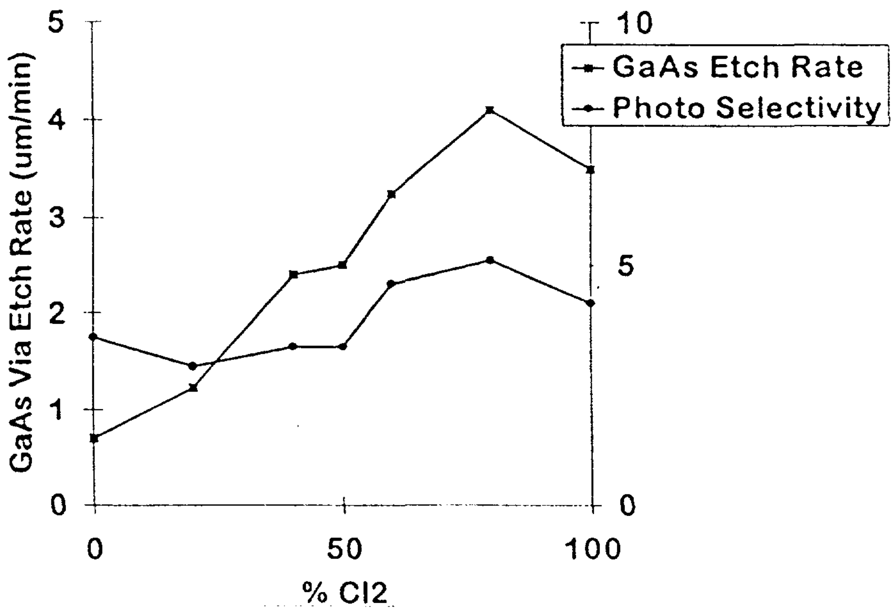

Figure 13. GaAs etch rate and selectivity over photoresist as a function of Cl_2 composition in a 750W ICP, 250W rf BCl_3/Cl_2 discharge.

As expected, the etch rate depends strongly on process pressure since the chemical component is enhanced at higher pressure. The neutral density is $3x10^{14}$ cm^{-3} at 10 mTorr, and with a gas such as Cl_2 a higher pressure should increase the etch rate. This is confirmed by the data in Figure 14, where the GaAs etch rate is seen to increase from 0.8 μm/min at 2 mTorr to 2.3 μm/min at 20 mTorr. An extremely anisotropic GaAs via-type feature is shown in the SEM micrograph of Figure 15. This was produced with a 80%Cl_2:20%BCl_3, 10mTorr, 750W ICP, 250W rf discharge. Note the excellent sidewall morphology, even in the absence of a photoresist mask.

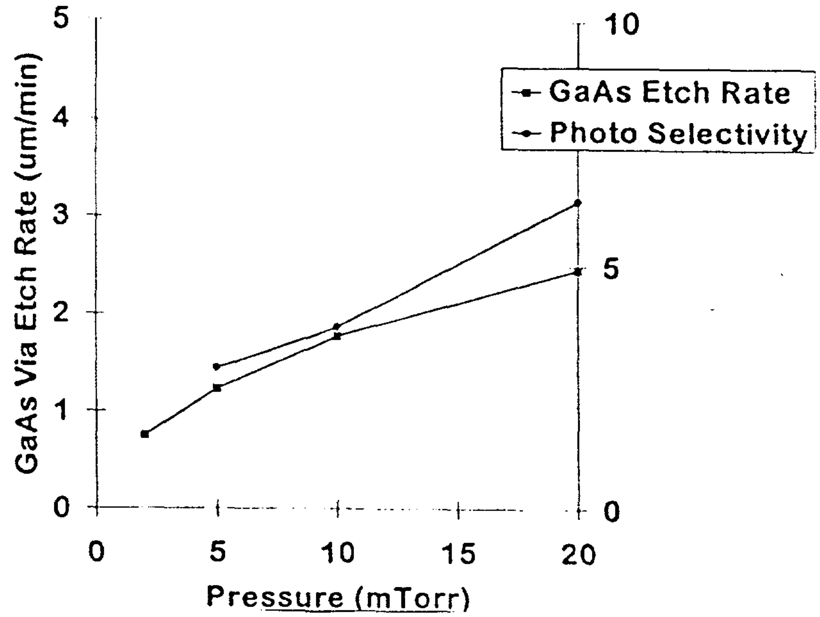

Figure 14. GaAs etch rate and selectivity over resist as a function of pressure in BCl_3/Cl_2 ICP discharges.

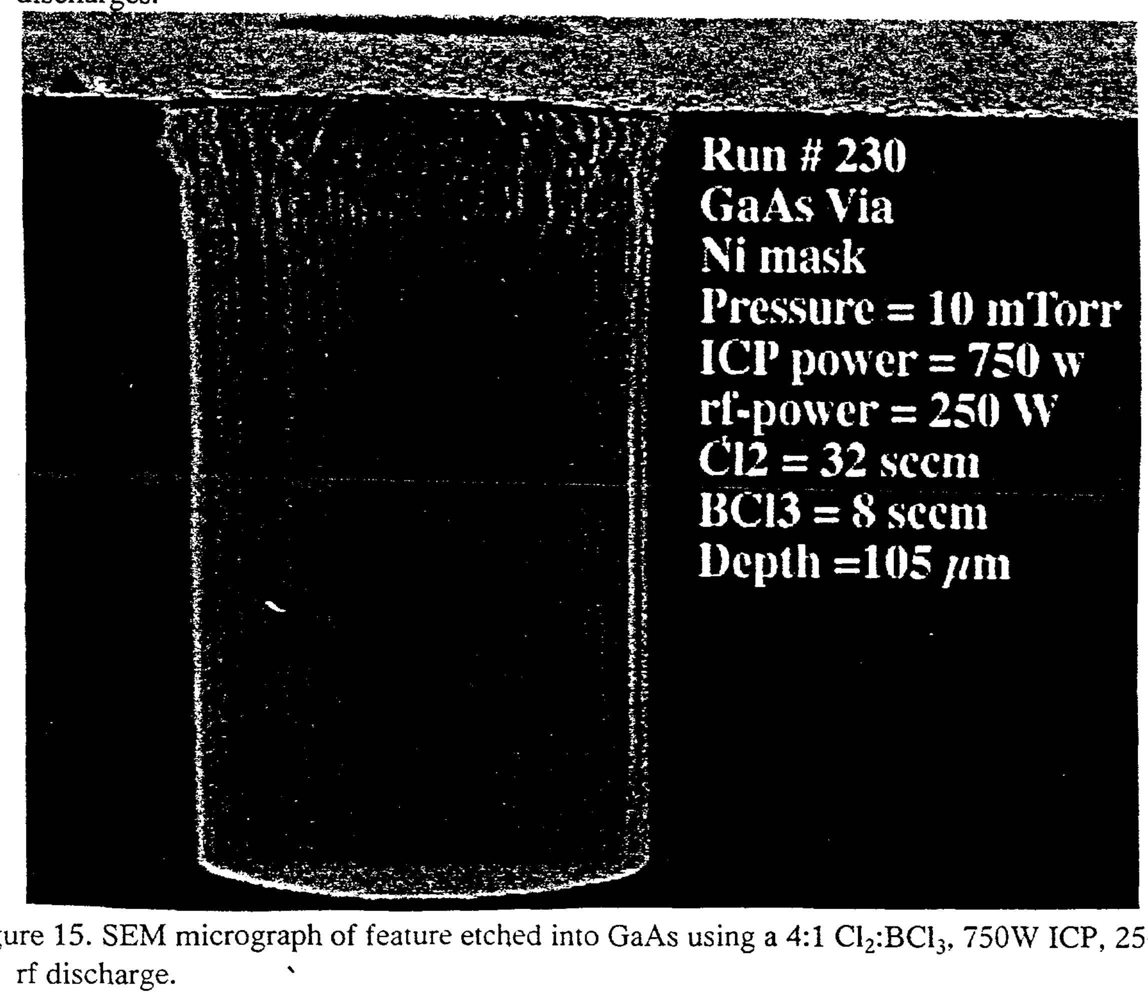

Figure 15. SEM micrograph of feature etched into GaAs using a 4:1 Cl_2:BCl_3, 750W ICP, 250W rf discharge.

RIE-lag is relatively minor in this low pressure tool, as shown in the SEM micrograph of Figure 16, which has closely-spaced via-type features (diameter of 20 or 60 μm) that were etched under the same conditions as the previous figure. There is a 10–15% lower effective etch rate in the smaller features due to the difficulty in getting reactants into, and etch products out of, these vias. This type of difference is typical of that reported previously for ECR-etched vias.[18] The anisotropy and smoothness of the sidewalls can be controlled by careful control of pressure, rf power and Cl_2:BCl_3 ratio.

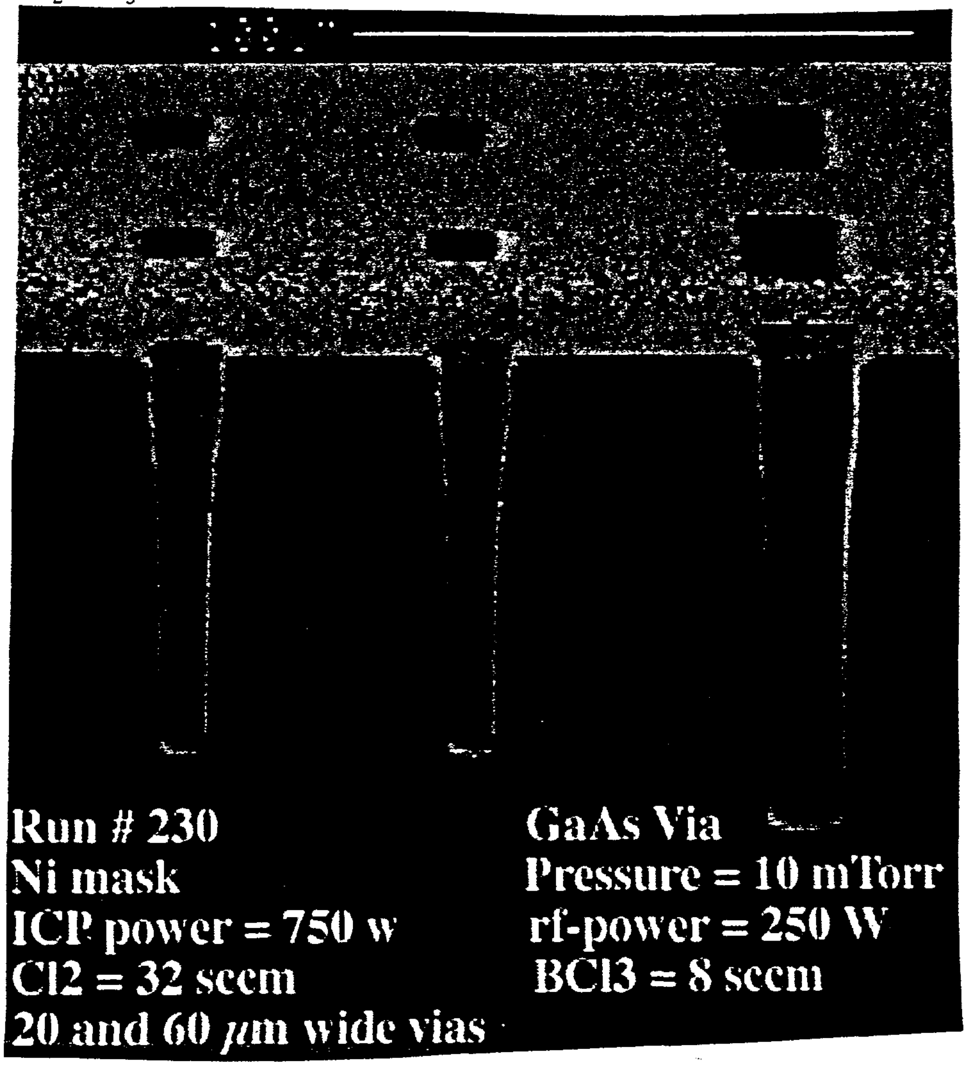

Figure 16. SEM micrograph of feature etched into GaAs using 4:1 Cl_2:BCl_3, 740W ICP, 250W rf discharge.

As mentioned previously the difficulty in finding practical wet etch solutions for GaN has placed a strong emphasis on developing dry etching methods. ECR etch rates up to an order of magnitude faster than for RIE are typical.[19-22] We have employed 22.5 sccm Cl_2, 2.5 sccm H_2, 5 sccm Ar, 1 mTorr pressure, 500W ICP power, 150W rf power (dc bias of −190V) discharges for etching of MOCVD grown GaN. Figure 17 shown the rf power dependence of GaN etch rate. The increase at higher powers can be attributed to enhanced sputter desorption of the etch products. The root-mean-square roughness as measured by atomic force microscopy remained fairly constant at ~2 nm (10x10μm^2 analysis area).

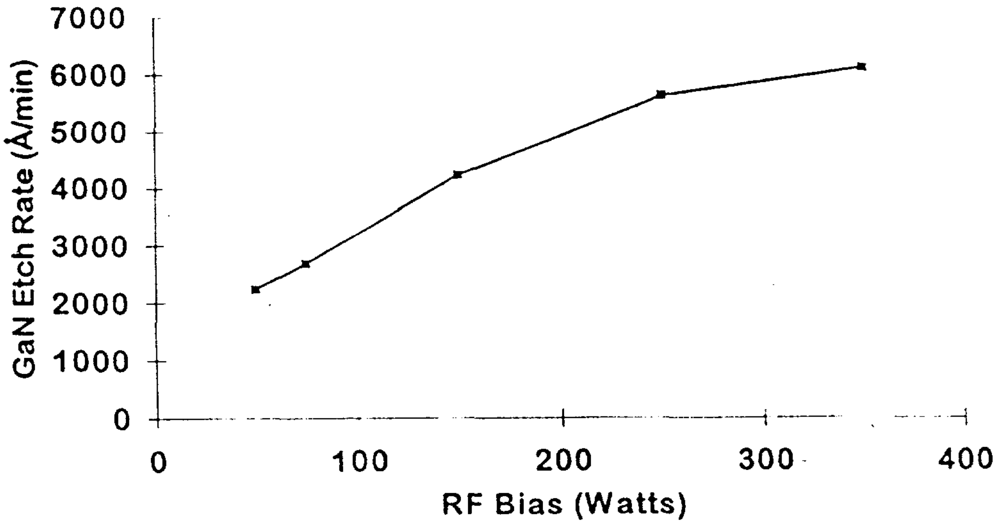

Figure 17. GaN etch rate as a function of rf power in a 00W ICP $Cl_2/H_2/Ar$ discharge.

The dependence of GaN etch rate on ICP power is shown in Figure 18. Since the rf power was held constant at 150W, the self-bias decreased at higher ICP powers. The etch rate initially increased due to a higher density of reactive species, but beyond ~500W, the rate falls off somewhat due either to lower ion energies or sputter desorption of the reactants at the surface prior to reaction. Etch rates as a function of pressure are shown in Figure 19. During these runs the rf power was again held constant at 150W, resulting in an increase in self-bias at higher pressure. The GaN etch rate increased up to ~5 mTorr due to an increased reactant supply, and remained constant beyond that, as expected. Once again the RMS surface roughness remained essentially constant over the entire pressure range investigated.

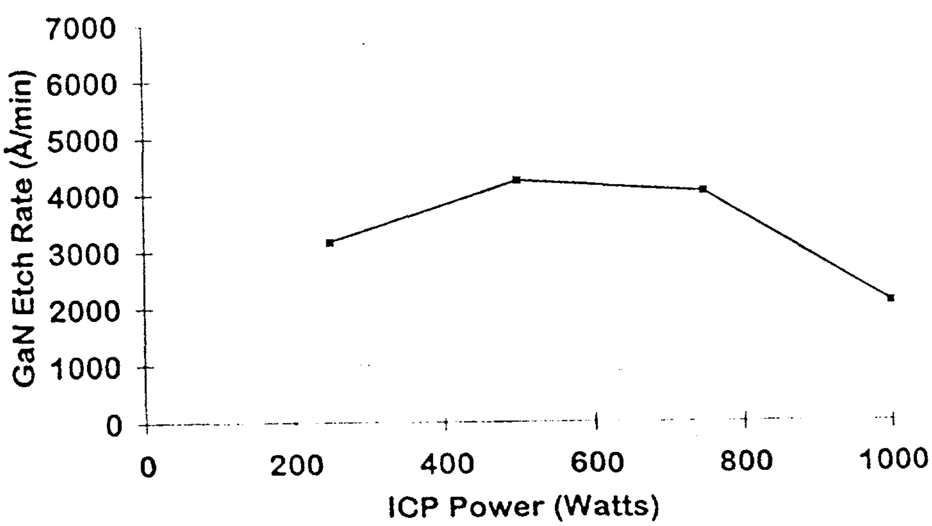

Figure 18. GaN etch rate as a function of ICP power in a 150W rf $Cl_2/H_2/Ar$ discharge.

A comparison of ICP and ECR etch rates as a function of percentage Cl_2 in $Cl_2/H_2/Ar$ is shown in Figure 20. The rates increase in both cases as the Cl_2:H_2 ratio increases, due to the higher reactive chlorine density. The ICP rates are slightly higher for the ICP source at the same source power, rf power and pressure. indicating a slightly higher plasma density for the former. An SEM micrograph of a GaN sidewall produced by ICP etching with a 5 mTorr, 500W ICP, 150W rf, $Cl_2/H_2/Ar$ discharge at room temperature is shown in Figure 21. The etch rate was ~6900 Å/min under these conditions. and produced smooth, vertical sidewalls.

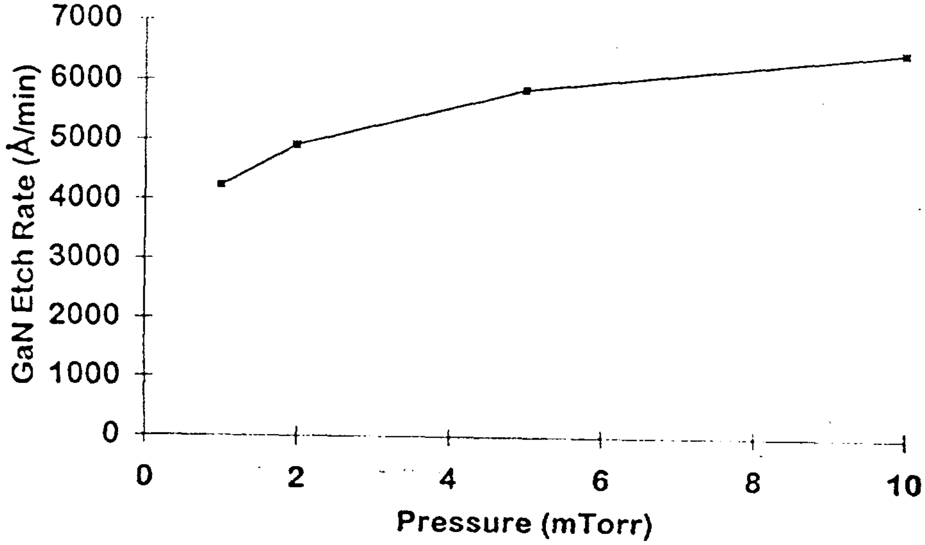

Figure 19. GaN etch rate as a function of pressure in a 500W ICP, 150W $Cl_2/H_2/Ar$ discharge.

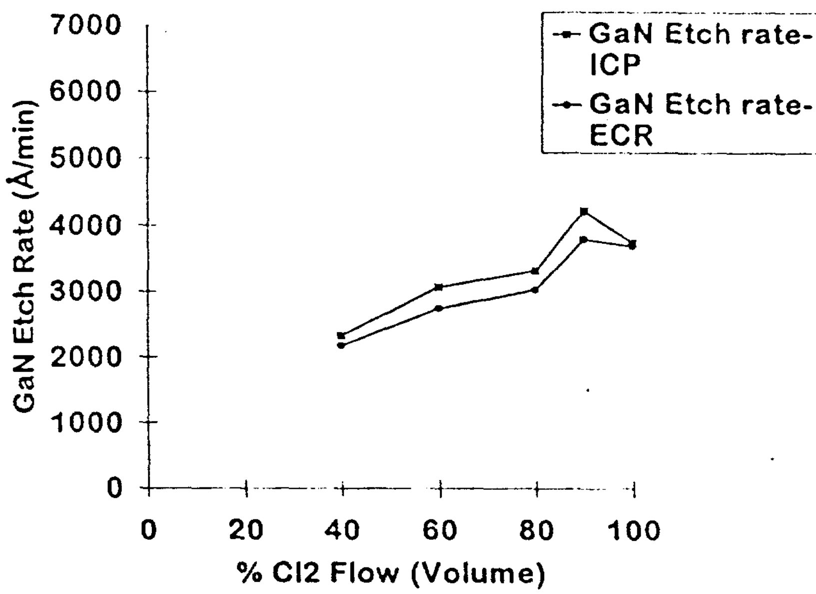

Figure 20. Composition of GaN etch rates in ICP or ECR $Cl_2/H_2/Ar$ discharges under the same conditions, as a function of Cl_2-to-H_2 percentage.

SUMMARY AND CONCLUSIONS

An ICP source has proven to be as effective tool for high ion density etching of GaAs, GaN and related materials in applications ranging from waveguide mesa formation to via holes. In basically all respects the ICP appears to perform as well as an ECR source under the same conditions, and has lower cost of ownership and should be scaleable to larger diameter while retaining excellent uniformity.

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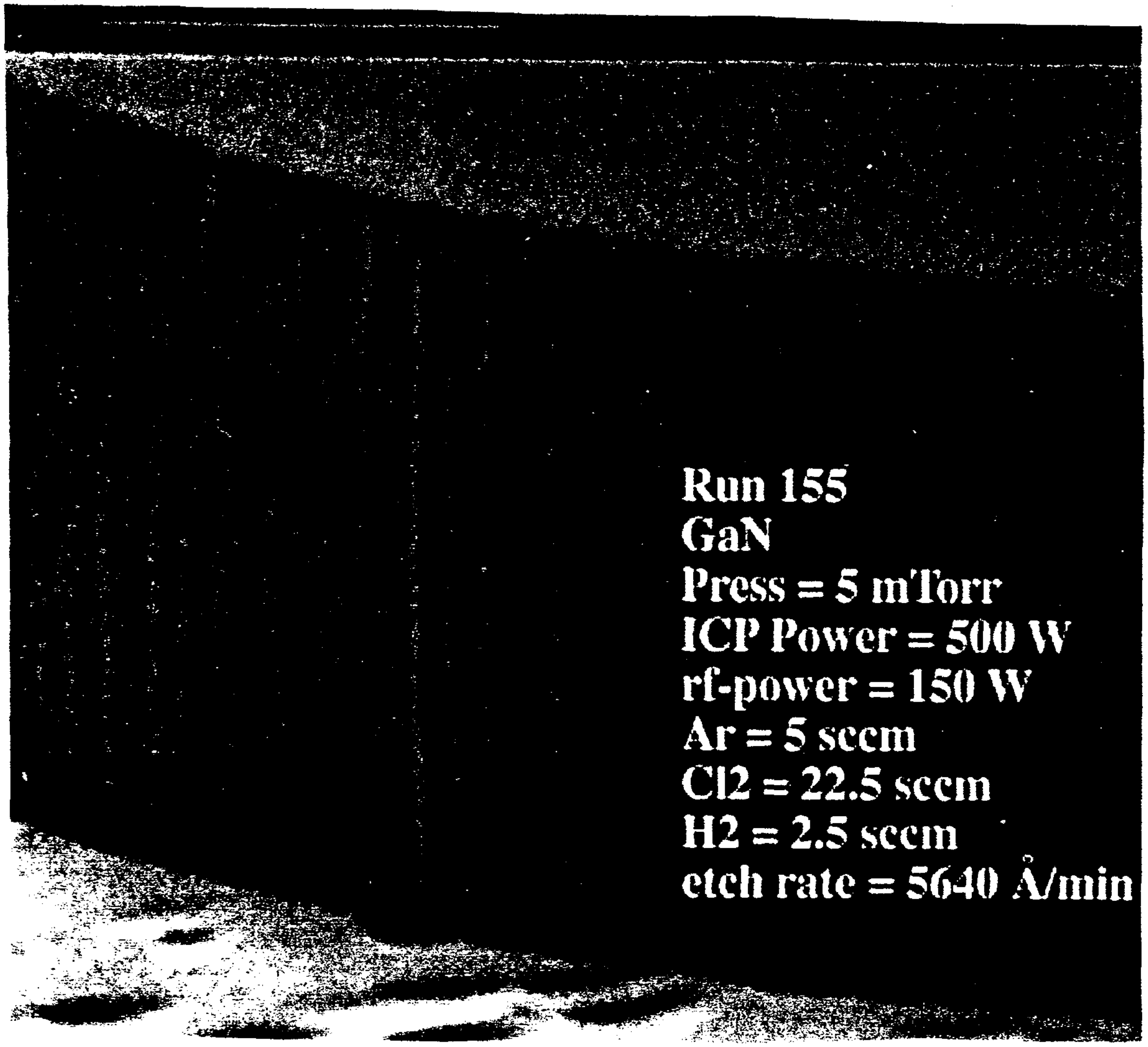

Figure 21. SEM micrograph of feature etched into GaN using a 5 mTorr, 500W ICP, 150W rf $Cl_2/H_2/Ar$ discharge.

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