SAND--97-2168C
SAND97-2168C

ICP DRY ETCHING OF III-V NITRIDES

C.B. Vartuli, J.W. Lee, J.D. MacKenzie, S.M. Donovan, C.R. Abernathy, S.J. Pearton, University of Florida, Dept MS&E, Gainesville Fl; R.J. Shul, Sandia National Laboratories, Albuquerque NM; C. Constantine, C. Barratt, PlasmaTherm IP, St. Petersburg Fl; A. Katz, EPRI, Palo Alto, CA; A.Y.Poyakov, M.Shin, M. Skowronski, Carnegie Mellon University, Dept of MS&E, Pittsburgh. PA.

CONF-970302--

ABSTRACT

Inductively coupled plasma etching of GaN, AlN, InN, InGaN and InAlN was investigated in $CH_4/H_2/Ar$ plasmas as a function of dc bias, and ICP power. The etch rates were generally quite low, as is common for III-nitrides in CH_4 based chemistries. The etch rates increased with increasing dc bias. At low rf power (150W), the etch rates increased with increasing ICP power, while at 350W rf power, a peak was found between 500 and 750 W ICP power. The etched surfaces were found to be smooth, while selectivities of etch were ≤ 6 for InN over GaN, AlN, InGaN and InAlN under all conditions.

INTRODUCTION

GaN and related compounds are high temperature materials with strong bond strengths and excellent chemical stability. This had made it difficult to develop etch processes for these materials that have high etch rates and selectivities and still produce smooth surfaces and anisotropic features.[1] A number of investigations of dry etching of GaN and related compounds in various chemistries have been done in both reactive ion etching, (RIE),[2-5] and electron cyclotron resonance (ECR) plasma modes.[6-9] ECR plasma etching, with its higher plasma density, has proven much more efficient than RIE etching for the nitrides.[10,11] Inductively coupled plasma (ICP) sources are an alternative method for achieving high density plasmas. The plasma is contained inside the dielectric shield which is surrounded by an inductive coil powered with a 2 MHz rf source.[12] An alternating magnetic field is induced inside the chamber by the oscillating electric field, and this helps to produce a high-density plasma due to confinement of electrons. The plasma diffuses out of the generation region and drifts to the sample position with accompanying low ion energies. The ICP source is generally believed to be easier to scale-up than the ECR, and to have advantages in terms of cost of ownership and availability of truly automatic matching networks for tuning of the discharge. Shul et al. have reported ICP etching of GaN in $Cl_2/H_2/Ar$ plasmas with etch rates to ~ 7000 Å/min.[13,14] We report the results of ICP etching of GaN, AlN, InN, InGaN and InAlN in $CH_4/H_2/Ar$ plasmas as a function of dc bias and ICP power. This chemistry avoids the use of corrosive gases and thus simplifies the process considerably.

EXPERIMENTAL

The GaN, AlN, InN, $In_{0.36}Al_{0.64}N$ and $In_{0.2}Ga_{0.8}N$ samples were grown using Metal Organic Molecular Beam Epitaxy (MO-MBE) on semi-insulating, (100) GaAs and Si substrates in an Intevac Gen II system as described previously.[15,16] The group-III sources were triethylgallium, trimethylamine alane and trimethylindium, respectively, and the atomic nitrogen was derived from an Wavemat ECR source operating at 200 W forward power. The layers were single crystal with a high density of stacking faults and microtwins.

The samples were patterned with a carbon-based mask and were etched in a Plasma-Therm ICP 790 reactor. The temperature of the He back-side cooled chuck was held at 23 °C, and the process pressure at 2 mTorr. The rf power (13.56 MHz) was varied between between 150 and 450 W (dc self biases between 0 and -645V) and the ICP power between 0 and 1500 W. Step heights were obtained from Dektak stylus profilometry measurements after the removal of the mask, and used to calculate the etch rates. The error in these measurements is approximately ± 5 %. The surface morphology of selected GaN samples were examined with Atomic Force

DISCLAIMER

DISCLAIMER

Microscope (AFM) using a Si tip in tapping mode. The selectivity of etch was calculated for InN over GaN, AlN, InGaN and InAlN.

RESULTS AND DISCUSSION

Figure 1 shows the etch rate for GaN, AlN, InN, InGaN and InAlN as a function of dc bias at 500 W ICP power (top) and 1000 W ICP plasmas. The dc bias was higher at lower ICP

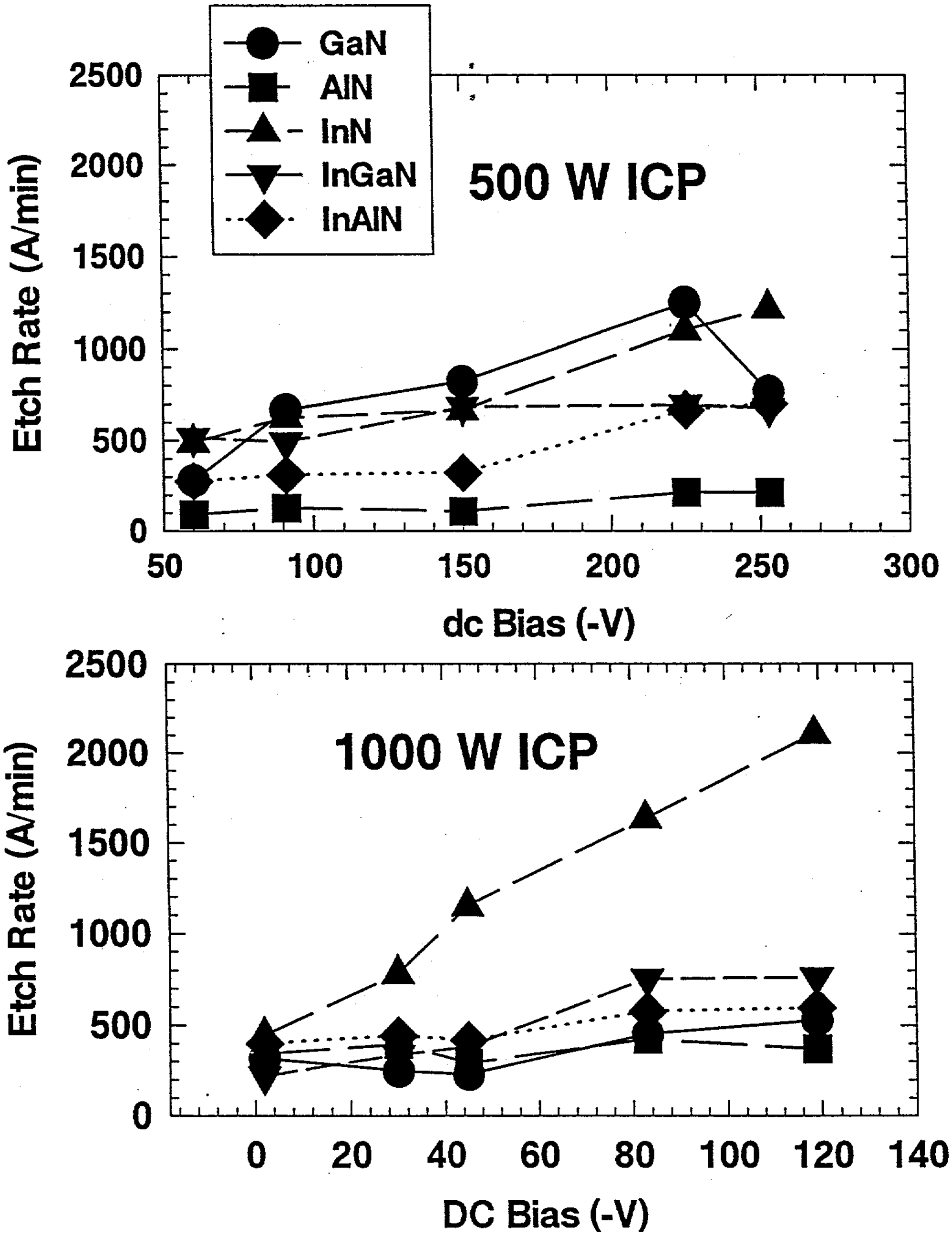

Figure 1. Etch rates for GaN, AlN, InN, InGaN and InAlN as a function of dc bias at 500 W ICP power (top) and 1000 W ICP power (bottom).

powers for the same applied rf power. This is due to the higher plasma density which suppresses the cathode dc self-bias at higher ICP powers. The etch rates were generally quite low (≤ 2000Å/min) for all materials in this chemistry. This is not expected from a consideration of the volatilities of the etch products, (the boiling point of $(CH_3)_3Ga$ is 55.7 °C, $(CH_3)_3In$ is 134 °C, and $(CH_3)_3Al$ is 126 °C),[17] but other factors such as film deposition or formation on the plasma-exposed surface which may reduce the effects of the impinging ions appear to dominate the final etch rate. There was a general upward trend in the etch rates as the dc bias increased. At similar dc biases, the etch rate was in general higher at 1000 W compared to 500 W ICP power, with InN removal approximately twice as fast at 1000 W ICP power.

In Fig. 2, etch rates for GaN, AlN, InN, InGaN and InAlN are shown as a function of ICP power at 150 W rf power (top) and 350 W rf power (bottom) in $CH_4/H_2/Ar$ plasmas at 2 mTorr. The dc bias at each source power is also shown. At 150 W rf power (dc bias ranged from -405V at 0W ICP to -29V at 1500W ICP), the etch rate increased with increasing ICP power. This indicates that the etch was reaction limited under these powers (bottom), with the etch rate increasing with increasing plasma density, irrespective of the decreasing ion energy. At 350 W rf chuck power, the etch rates initially increased rapidly as the ICP power was increased from 0 W to 500 W. The dc bias was higher under these conditions, ranging from -645V at 0W ICP to -58V at 1500W ICP power. At 500 W ICP power the etch rates were up to four times faster at the higher rf power (350 W). The GaN etch rate fell sharply above 500W ICP power, while the etch rates of the In containing materials increased to 750 W ICP power and then fell off. The etch would appear to no longer be reaction-limited above the particular powers at which the etch rates are a maximum. Rather, bond breaking or removal of the reacted products may be limiting the etch, or perhaps the reactive neutrals were being sputter removed before reaction could occur on the semiconductor surface.

Figure 3 shows the RMS roughness as a function of ICP power for GaN at 150 W rf power. The etched surfaces were all smoother than the as-grown sample. This may be due to the fact that sharp features tend to be etched faster due to the angular dependence on ion milling, and as long as there is no preferential loss of nitrogen from the surface, the RMS roughness may decrease. The smoothest surface was found at 500 W ICP power. The low roughness would indicate that there was little preferential loss of the group V species from the surface, though this needs to be verified by Auger Electron Spectroscopy.

Figure 4 shows the selectivities of etch for InN over GaN, AlN, InGaN and InAlN in $CH_4/H_2/Ar$ plasmas as a function of dc bias (top) and ICP power (bottom). As the dc bias increased, the selectivity for InN over AlN increased. The bond strength of InN is much less than that of AlN, (7.7 eV and 11.5 eV respectively),[17] which indicates that the ions were able to break the bonds in the InN material more efficiently as their energy increased, but did not have sufficient energy to efficiently break the bonds in AlN. The selectivity of InN over GaN also rose initially with increasing dc bias, for the same reason. Above -55V however the ions had enough energy to efficiently remove GaN (bond strength of 8.9 eV) as well, lowering the selectivity of etch. The selectivities of InN over InGaN and InAlN were less than 3 under all conditions. Both InN/GaN and InN/AlN showed a maxima in the plot at 1000 W ICP power (Fig. 9 bottom). The dc bias decreased with increasing ICP power. As the plasma density increased, the etch rates of AlN and GaN increased, while the accompanying decrease in ion energy leads to the etch rate of InN remaining approximately constant.

SUMMARY

Inductively coupled plasma etching of GaN, AlN, InN, InGaN and InAlN was examined in $CH_4/H_2/Ar$ plasmas as a function of dc bias and ICP power. The etch rates increased with increasing dc bias. At low rf power (150W), the etch rates increased with increasing ICP power, while at 350W rf power, a peak was found between 500 and 750 W ICP power. The dc bias was found to decrease with increasing ICP power. The selectivities of etch were generally low, ≤ 6 under all conditions for InN over GaN, AlN, InGaN and InAlN. The etched surfaces were found to be smooth under most conditions.

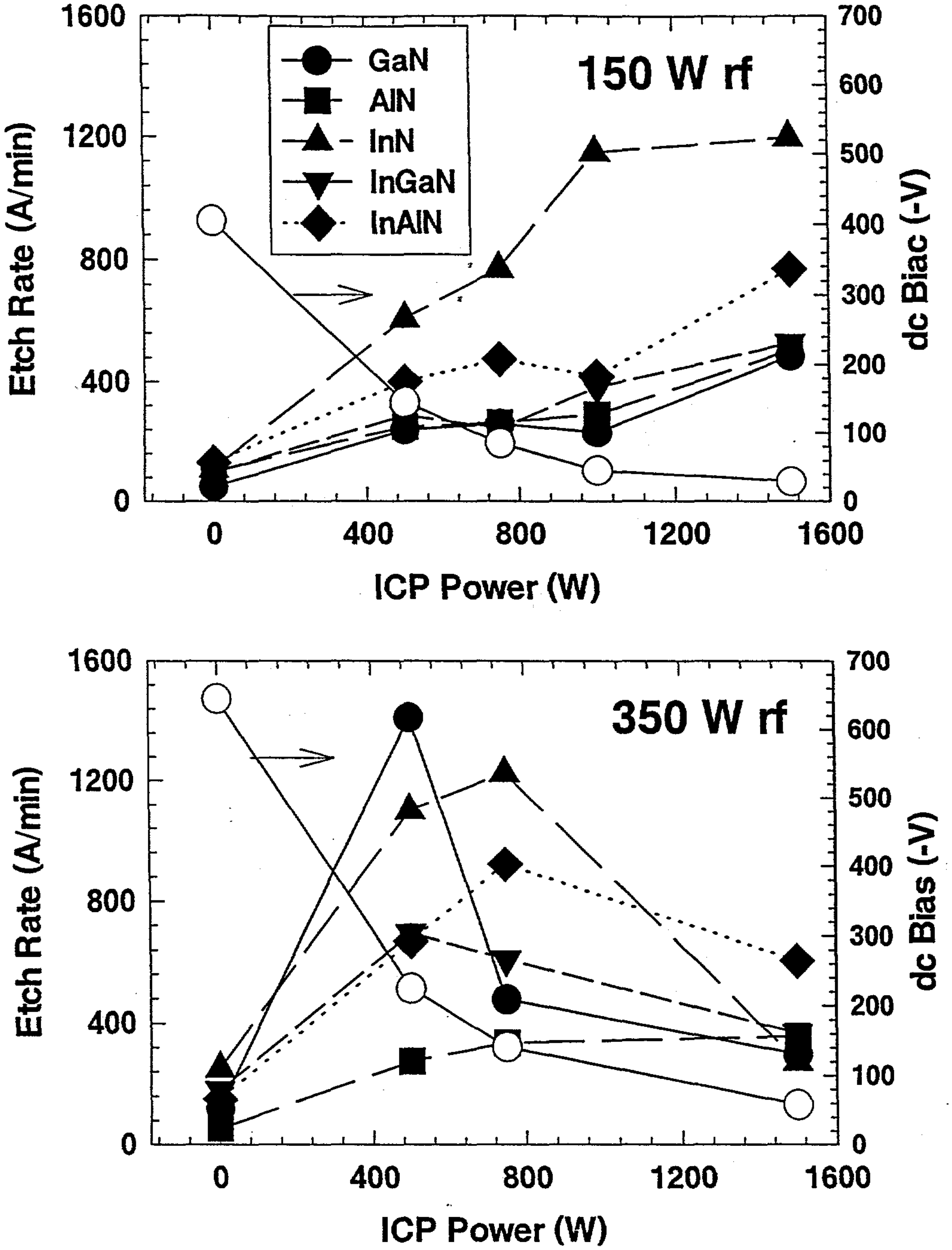

Figure 2. Etch rates for GaN, AlN, InN, InGaN and InAlN as a function of ICP power at 150 W rf power (top) and 350 W rf power (bottom).

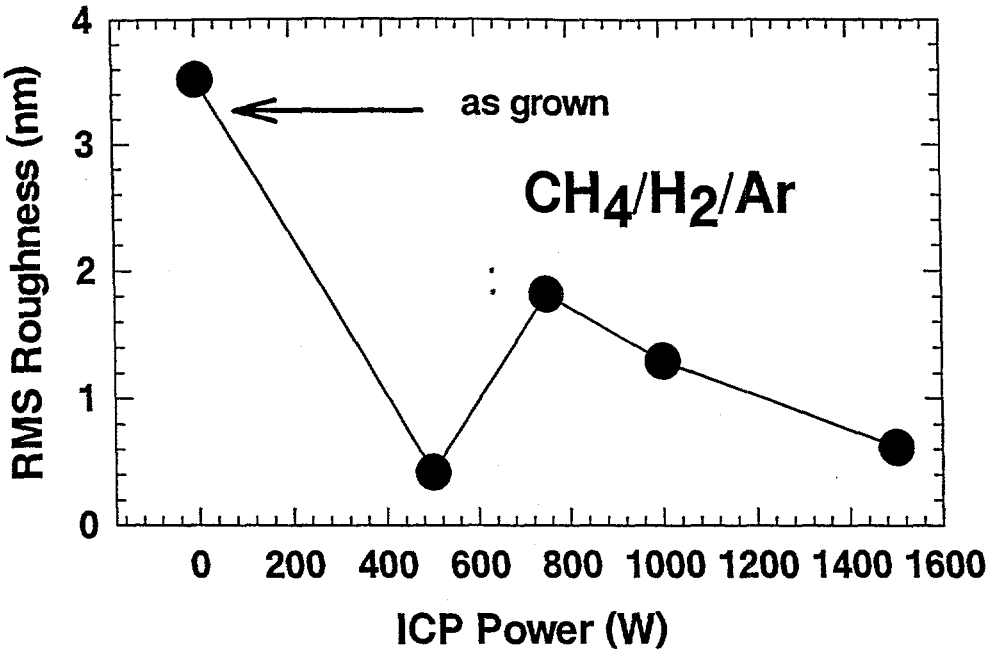

Figure 3. RMS roughness as a function of ICP power for GaN in $CH_4/H_2/Ar$ plasma at 2 mTorr and 150W rf power.

ACKNOWLEDGMENTS

The authors would like to thank the staff of the Microfabritech Facility for their help with this work. The work at the University of Florida, PTI and SNL is supported by DARPA (A. Husain) through AFOSR (G.L. Witt), an AASERT grant through ARO (Dr. J. M. Zavada), and a University Research Initiative grant #N00014-92-J-1895 administered by ONR. The work at SNL is supported by DOE under contract DEAC04-94AL85000. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed-Martin Company, for the US Department of Energy.

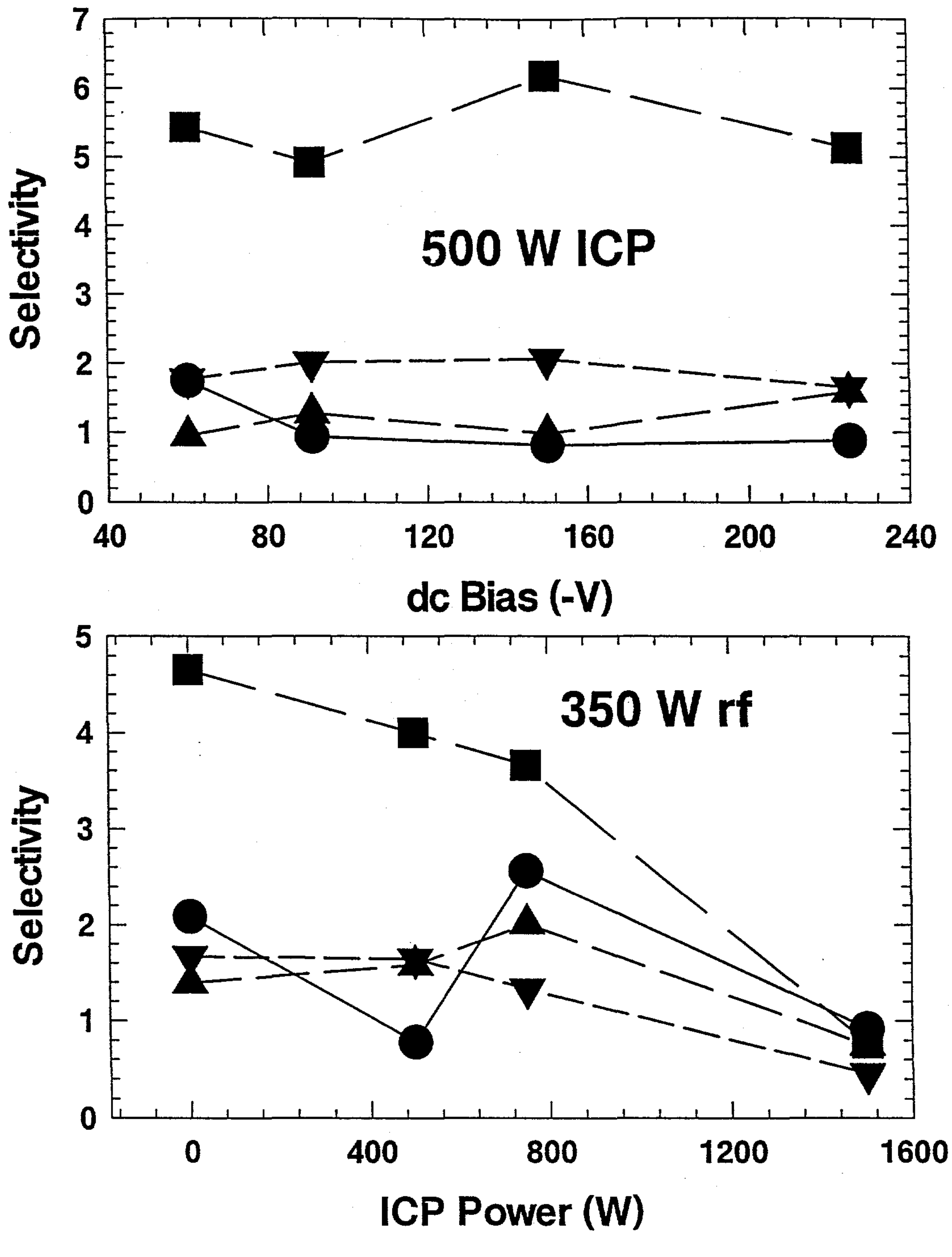

Figure 4. Selectivities of etch for InN over GaN, AlN, InGaN and InAlN in $CH_4/H_2/Ar$ plasmas as a function of dc bias (top) and ICP power (bottom).

REFERENCES

1. H.P. Gillis, D.A. Choutov and K.P. Martin, J.O.M. August 1996 pp 50-55.
2. I. Adesida, A. Mahajan, E. Andideh, M. Asif Khan, D.T. Olsen and J.N. Kuznia, Appl. Phys. Lett. **63** 2777 (1993).
3. M.E. Lin, Z.F. Zan, Z. Ma, L.H. Allen and H. Morkoc, Appl. Phys. Lett. **64** 887 (1994).
4. A.T. Ping, I Adesida, M. Asif Khan and J.N. Kuznia, Electron. Lett. **30** 1895 (1994).
5. H. Lee, D.B. Oberman and J.S. Harris, Jr., Appl. Phys. Lett. **67** 1754 (1995).
6. S.J. Pearton, C.R. Abernathy, F. Ren, J.R. Lothian, P.W. Wisk, A. Katz and C. Constantine, Semicond. Sci. Technol. **8** 310 (1993).
7. S.J. Pearton, C.R. Abernathy and F. Ren, Appl. Phys. Lett. **64** 2294 (1994).
8. L. Zhang, J. Ramer, J. Brown, K. Zheng, L.F. Lester and S.D. Hersee, Mat. Res. Soc. Symp. Proc. Vol **395** 763 (1996); Appl. Phys. Lett. **68** 367 (1996).
9. R.J. Shul, S.P. Kilcoyne, M. Hagerott Crawford, J.E. Parmeter, C.B. Vartuli, C.R. Abernathy and S.J. Pearton, Appl. Phys. Lett. **66** 1761 (1995).
10. R.J. Shul, presented at 189th ECS meeting, Los Angeles CA, May 1996; Electrochem. Soc. Proc. Vol **96-11** 159 (1996).
11. C.B. Vartuli, J.D. MacKenzie, J.W. Lee, C.R. Abernathy, S.J. Pearton and R.J. Shul, J. Appl. Phys. **80** 3264 (1996).
12. High Density Plasma Sources, ed. O.A. Pogov (Noyes Publications, Park Ridge NJ 1996).
13. R.J. Shul, G.B. McClellan, S.A. Casalnuovo, D.J. Rieger, S.J. Pearton, C. Constantine, C. Barratt, R.F. Karlicek, Jr., C. Tran and M. Schurman, Appl. Phys. Lett. **69** 1119 (1996).
14. R.J. Shul, G.B. McClellan, S.J. Pearton, C.R. Abernathy, C. Constantine and C. Barratt, Electon. Lett. **32** 1408 (1996).
15. C.R. Abernathy, J. Vac. Sci. Technol. A **11** 869 (1993).
16. C.R. Abernathy, Mat. Sci. Eng. Rep. **14**, 203 (1995).
17. CRC Handbook of Chemistry and Physics (CRC Press, Boca Raton, FL 1990).