plasma chem. plasma proc.
SAND98-2614 J

Inductively Coupled Plasma Etching in ICl- and IBr-Based Chemistries: Part I. GaAs, GaSb and AlGaAs

Y. B. Hahn(1)*, D. C. Hays (1), H. Cho(1), K. B. Jung (1), E. S. Lambers(1), C. R. Abernathy(1), S. J. Pearton(1), W. S. Hobson(2), and R. J. Shul(3)

(1) Department of Materials Science and Engineering, University of Florida, Gainesville, FL 32611.
(2) Bell Laboratories, Lucent Technologies, Murray Hill, NJ 07974
(3) Sandia National Laboratories, Albuquerque, NM 87185.

ABSTRACT

High density plasma etching of GaAs, GaSb and AlGaAs was performed in ICl/Ar and IBr/Ar chemistries using an Inductively Coupled Plasma (ICP) source. GaSb and AlGaAs showed maxima in their etch rates for both plasma chemistries as a function of interhalogen percentage, while GaAs showed increased etch rates with plasma composition in both chemistries. Etch rates of all materials increased substantially with increasing rf chuck power, but rapidly decreased with chamber pressure. Selectivities > 10 for GaAs and GaSb over AlGaAs were obtained in both chemistries. The etched surfaces of GaAs showed smooth morphology, which were somewhat better with ICl/Ar than with IBr/Ar discharge. Auger Electron Spectroscopy analysis revealed equi-rate of removal of group III and V components or the corresponding etch products, maintaining the stoichiometry of the etched surface.

---

* Present address: Department of Chemical Engineering and Technology, Chonbuk National University, Chonju 561-756, Korea.

INTRODUCTION

In the fabrication of high frequency transistors as well as optoelectronic devices, it is critically important to accurately control the pattern size, with minimal damage created during the patterning process. The III-V compounds such as GaAs, GaSb and AlGaAs are used for high electron mobility transistors (HEMTs), heterojunction bipolar transistors (HBTs), lasers and light-emitting diodes (LEDs).(1) The trend toward decreasing feature size has become an important issue and to this end various types of dry etching techniques have been under development. Reactive ion beam etching (RIBE) allows the ion energy and ion flux to be controlled independently,(2-5) but the ion energies are too high for electronic device fabrication.

High density plasma etching techniques have been reported to provide high etch rates for GaAs and related materials using Cl_2-based or BCl_3-based plasmas.(6-17) Most of the previous work has been focused on Electron Cyclotron Resonance (ECR) sources, in terms of etch rate and surface morphology or etch profiles, but little work has been reported on using Inductively Coupled Plasmas (ICP). The latter are the preferred embodiment of the high density plasma concept, with excellent uniformity and controllability.

Interhalogens such as ICl and IBr have been reported to be readily dissociated under ECR conditions, producing high concentrations of reactive species.(16,17) Etch rates of 1.2 μm/min for GaAs and 0.7 μm/min for GaSb were reported in ECR ICl/Ar plasmas.(16) However, no work has been done on the ICP etching of III-V compounds with ICl- and IBr-based plasma chemistries. These chemistries appear very attractive for high-rate etching of III-V compounds, for applications such as through-wafer vias.

In this work, the influence of interhalogen etch gases (ICl and IBr) in ICP etching of GaAs, GaSb and AlGaAs was carried out for various plasma parameters. The effects of plasma composition, rf chuck power, and ICP source on the etch rates, dc bias and ion fluxes, and morphology have been investigated. The ICP ICl/Ar and IBr/Ar discharges resulted in high etch rates for the typical III-V semiconductors, but there is no clear advantage in terms of etch rates and surface chemistry for either chemistry.

EXPERIMENTAL

The samples used for etching in this work are: semi-insulating undoped (100) GaAs and undoped (100) GaSb substrates grown by the Czochralski process, and nominally undoped ($p \sim 10^{16}$ cm^{-3}) $Al_{0.25}Ga_{0.75}As$ grown by either Metal Organic Molecular Beam Epitaxy (MOMBE)(18) or Metal Organic Chemical Vapor Deposition (MOCVD)(19) at 550 – 650 °C on semi-insulating GaAs substrates.

The samples were patterned with Apiezon wax and etched in a Plasma-Therm ICP 790 system. The system consists of etch gas feed lines, a 2 MHz ICP source (1500W), and a He backside-cooled rf (13.56 MHz) powered sample chuck. The rf chuck power was varied between 50 and 350 W, and ICP source between 300 and 1000 W. The chamber pressure was varied from 5 to 20 mTorr, while the total flow rate of the gas mixture was 15 sccm. Etch rates were calculated from stylus profilometry measurements of the etched samples with measuring error of approximately ± 5%. The morphology and near-surface chemistries of the eched samples were examined by atomic force microscopy (AFM) operating in tapping mode with Si tip, and Auger Electron Spectroscopy (AES), respectively.

RESULTS AND DISCUSSION

Figure 1 shows the effect of plasma composition on etch rates of GaAs, GaSb, and AlGaAs in IBr/Ar and ICl/Ar discharges at 5 mTorr, 750 W source power and 250 W rf chuck power. The etch rate of GaSb increased up to 33.3 % of interhalogen gas by flow in both ICl/Ar (Fig. 1, top) and IBr/Ar (middle) discharges and decreased thereafter. AlGaAs showed maximum etch rates at 33.3 % ICl and 66.7 % IBr, respectively. The attainable maximum etch rates were similar in both chemistries: 1.75 μm/min for GaSb and 400 min for AlGaSb. The etch rate of GaAs increased with increasing interhalogen content in both discharges. This result indicates that etching of GaAs in either chemistry is more attributed to chemical etching by increased concentrations of reactive neutrals than by ion-assisted sputtering, which is the mechanism for GaSb and AlGaAs.

The dc self-bias voltage increased with increasing etch gas concentrations, resulting in a decrease in ion flux entering the sheath layer (Fig.1, bottom). The ion flux at the sheath edge was calculated using a global self-consistent model developed for the ICP etching system.(20) The increase in dc biases or decrease in ion flux is attributed to additional collisional energy losses due to the presence of interhalogens.(21)

Figure 2 shows the effect of ICP source power on etch rates, dc bias voltages, and ion fluxes at the sheath edge for ICl/Ar (top) and IBr/Ar discharges (middle). Flow rates of etch gases were held constant at 2 sccm IBr or ICl and 13 sccm Ar. During these runs the chamber pressure and the rf chuck power were held constant at 5 mTorr and 250 W, respectively. Up to 500 W all materials showed gradual increases in etch rates. However, at higher source powers (> 500 W) the etch rates of GaAs and GaSb increased substantially: this leads to etch selectivities of > 10 for both GaAs and GaSb over AlGaAs, which is etched slowly in both mixtures due to the low volatility of the AlI_x and $AlBr_x$ products. The increase in etch rate with increasing the source power is due to the higher concentration of reactive species in the plasma, suggesting a reactant-limited regime, and to higher ion flux to the substrate surface. Lower dc biases were attributed mainly to increased ion density at higher ICP powers (Fig. 2, bottom).

The effect of rf chuck power on the etch rates, dc bias, and ion flux at the sheath edge is shown in Fig. 3. Etch rates for all materials increased in both ICl (top) and IBr (middle) discharges as the rf power or the ion-bombarding energy increased. The increase in etch rate with the chuck power can be attributed to enhanced sputter desorption of etch products. The dc bias voltage increased monotonically with increasing rf chuck power from 50 to 350 W, but the ion flux at the sheath edge increased slightly (Fig.3, bottom). This is because the main role of the chuck power is to increase the ion-bombarding energy. The effect of the rf power on etch rate (or etch yield) and ion flux at the sheath edge in the ICP system is described in detail elsewhere.(20)

Figure 4 shows the effect of reactor pressure on etch rate, etch yield (defined as number of atoms etched per incident ion), dc bias and ion flux in ICl/Ar plasmas. During these experiments the source and chuck powers were held constant at 750 W and 250 W, respectively. The etch rates of all materials decreased with increasing pressure. This is attributed to either lower ion flux to the substrate surface or to redeposition of etch products. Etch yield data are shown in the lower part of the figure. The higher dc voltages or lower ion fluxes at higher pressures were attributed to increased collisional recombination which decreased the plasma ion density.

Etched surface morphology was examined using AFM for GaAs samples etched at 750 W ICP power, 250 W rf chuck power and 5 mTorr in 2 sccm ICl/13 sccm Ar and 2 sccm IBr/13 sccm Ar discharges, respectively. The AFM results are shown in Fig. 5 with the rms roughness. It is seen that ICl/Ar chemistry (top) shows somewhat better morphology than ICl/Ar (top), but both surfaces are fairly similar to unetched controls, which show rms values of 0.7 - 1.1 nm..

In addition to the surface smoothness, equi-rate removal of group III and V components or their corresponding etch products are very important to guarantee the stoichiometry of the etched surface. Figure 6 and 7 show the AES surface scans and depth profiles of GaAs etched in, respectively, ICl/Ar and IBr/Ar plasmas at 750 W ICP power, 250 W chuck power and 5 mTorr. There is oxygen present that grows on the samples in the course of transfer from the ICP chamber to the AES system and also carbon contamination due to the exposurre to surrounding air. As shown in the depth profiles of Figs. 6 and 7, the etched surfaces with both interhalogen discharges are chemically quite clean. It is also seen from the AES scans that the etched surfaces remain stoichiometric, indicating equirate of removal of group III and V components in both plasma chemistries.

SUMMARY AND DISCUSSION

A parametric study of etching GaAs, GaSb and AlGaAs has been carried out with ICl/Ar and IBr/Ar chemistries in an Inductively Coupled Plasma discharge. The effects of plasma composition, ICP source power, rf chuck power and chamber pressure on etch rate, etch yield, dc-bias voltage and ion flux at the sheath edge were examined. GaSb and AlGaAs showed maximum etch rates depending on plasma chemistry and interhalogen percentage, while GaAs etch rates were proportional to the interhalogen content in both chemistries. Etch rates of all materials in the ICl- and IBr-based discharges decreased with reactor pressure, but increased substantially with increasing rf chuck power, indicating that higher bombardment energies are more efficient in enhancing sputter desorption of etch products. ICl/Ar plasma showed somewhat better morphology of etched GaAs than IBr/Ar discharge. AES analysis revealed equi-rate of removal of group III and V components and maintenance of stoichiometry on etched surfaces.

ACKNOWLEDGEMENTS

The work at UF is partially supported by a DOD/MURI monitored by AFOSR (H. C. DeLong), contract no. F49620-1-96-0026. Y. B. Hahn gratefully acknowledges the support of the Korea Research Foundation for Faculty Research Abroad and KOSEF through the Automation Research Center. Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed-Martin company, for the US Department of Energy under contract DEAC-94AL-85000.

REFERENCES

1. GaAs: Materials Devices and Circuits, ed. M. Howes and D. V. Morgan (Wiley & Sons, N. Y. 1985).
2. K. Asakawa and S. Sugata, J. Vac. Sci. Technol. B, **3**, 402 (1985).
3. G. A. Vawter and C. I. H. Ashby, J. Vac. Sci. Technol. B, **12**, 3374 (1994).
4. G. A. Vawter and J. R. Wendt, Appl. Phys. Lett., **58**, 289 (1991).
5. Y. B. Hahn, J. W. Lee, G. A. Vawter, R. J. Shul, C. R. Abernathy, D. C. Hays, E. S. Lambers, and S. J. Pearton, submitted, J. Vac. Sci. Technol. B (1998).
6. V. J. Law, M. Tewordt, S. G. Ingram, and G. A. C. Jones, J. Vac. Sci. Technol. B9, 1449 (1991).
7. M. E. Lin, Z. F. Fan, Z. Ma, L. H. Allen, and H. Morkoc, Appl. Phys. Lett., 64, 887 (1994).
8. R. J. Shul, S. D. Kilcoyne, M. H. Crawford, J. E. Parmeter, C. B. Vartuli, C. R. Abernathy, and S. J. Pearton, Appl. Phys. Lett., 66, 1761 (1995).
9. C. Constantine, D. Johnson, C. Barratt, R. J. Shul, G. B. McClellan, R. D. Briggs, D. J. Rieger, R. F. Karlicek, Jr., J. W. Lee, and S. J. Pearton, Mat. Res. Soc. Symp. Proc., 42, 431 (1996).
10. R. J. Shul, A. J. Howard, C. B. Vartuli, P. A. Barnes, and S. Weng, J. Vac. Sci. Technol. A14, 1102 (1996).
11. H. P. Gillis, D. A. Choutov, and K. P. Martin, JOM, 48, 50 (1996).
12. A. T. Ping, A. C. Schmitz, I. Adesida, M. A. Khan, Q. Chen, and J. W. Yang, J. Electon. Mater., 26, 266 (1997)

13. R. J. Shul, G. B. McClellan, S. A. Casalnuovo, D. J. Roeger, S. J. Pearton, C. Constantine, C. Barratt, R. F. Karlicek, Jr., C. Tran, and M. Schurmann, Appl. Phys. Lett., 69, 1119 (1996).

14. S. A. Smith, C. A. Wolden, M. D. Bremser, A. D. Hanser, R. F. Davis, and W. V. Lampert, Appl. Phys. Lett., 71, 3631 (1997).

15. C. R. Eddy, O. J. Glembocki, D. Leonhardt, V. A. Shmamian, R. T. Holm, B. D. Thoms, J. E. Butler, and S. W. Pang, J. Electron. Mater., 26, 1320 (1997).

16. J. W. Lee, J. Hong, E. S. Lambers, and S. J. Pearton, J. Vac. Sci. Technol. B15, 652 (1997).

17. C. B. Vartuli, S. J. Pearton, J. W. Lee, J. D. Mackenzie, C. R. Aabernathy, and R. J. Shul, J. Vac. Sci. Technol. B15, 98 (1997).

18. C. R. Abernathy, J. Vac. Sci. Technol. A11, 869 (1993).

19. W. S. Hobson, Mat. Res. Soc. Symp. Proc., 300, 75 (1993).

20. Y. B. Hahn and S. J. Pearton, submittted, Plasma Sources Sci. & Technol. (1998).

21. M. A. Lieberman and A. J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, John Wiley & Sons Inc., N. Y. (1994).

Figure Captions

Figure 1. Effect of plasma composition on etch rates in ICl/Ar (top) and IBr/Ar (middle) plasma chemistries, and dc bias and ion flux at the sheath (bottom).

Figure 2. Effect of ICP source power on etch rates in ICl/Ar (top) and IBr/Ar (middle) plasma chemistries, and dc bias and ion flux at the sheath (bottom).

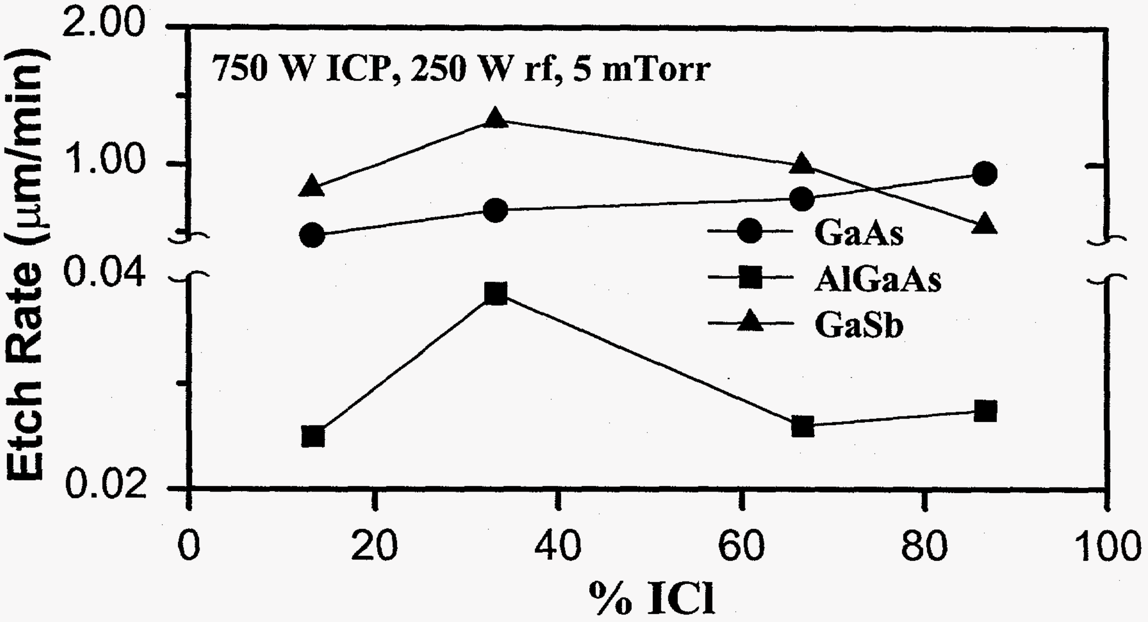
Figure 3. Effect of rf chuck power on etch rates in ICl/Ar (top) and IBr/Ar (middle) plasma chemistries, and dc bias and ion flux at the sheath (bottom).

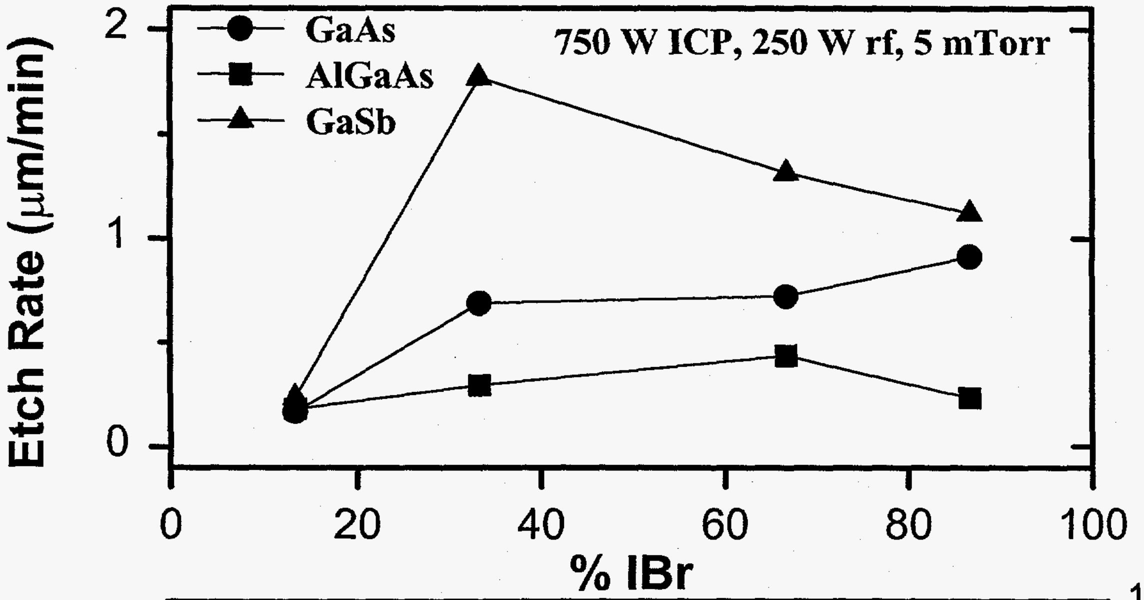
Figure 4. Effect of process pressure on etch rates in ICl/Ar (top) plasma chemistry, and dc bias and ion flux at the sheath (bottom).

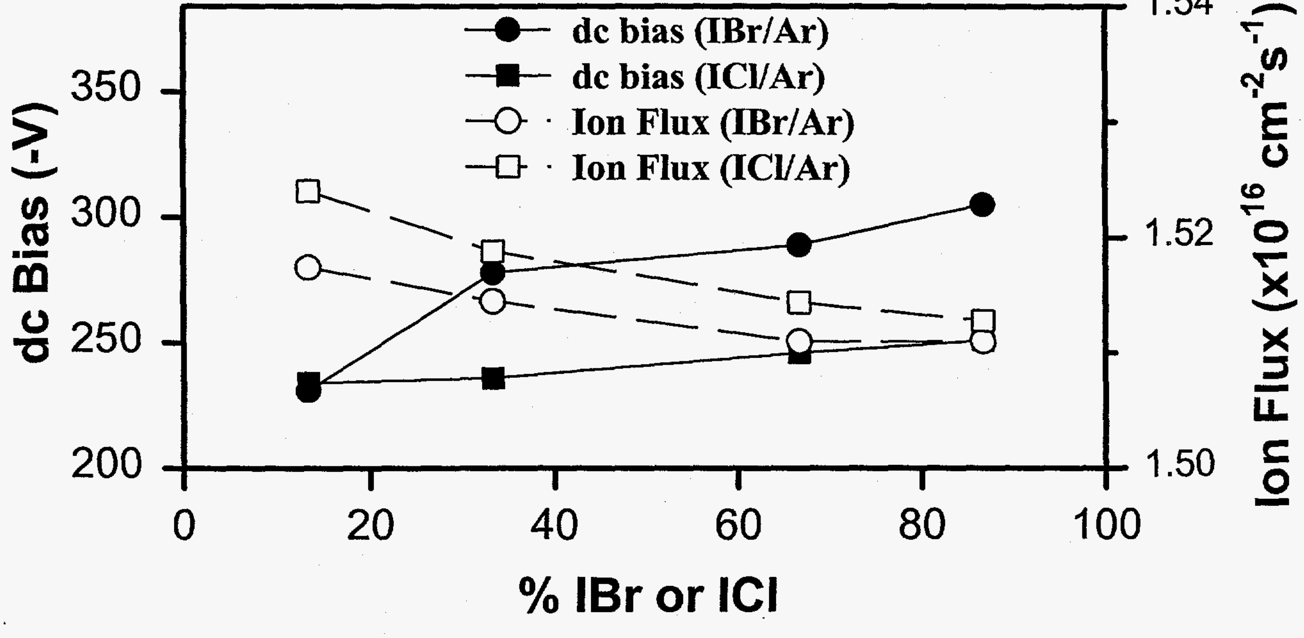
Figure 5. AFM scans for GaAs etched in ICl/Ar (top) and IBr/Ar (bottom) plasmas.

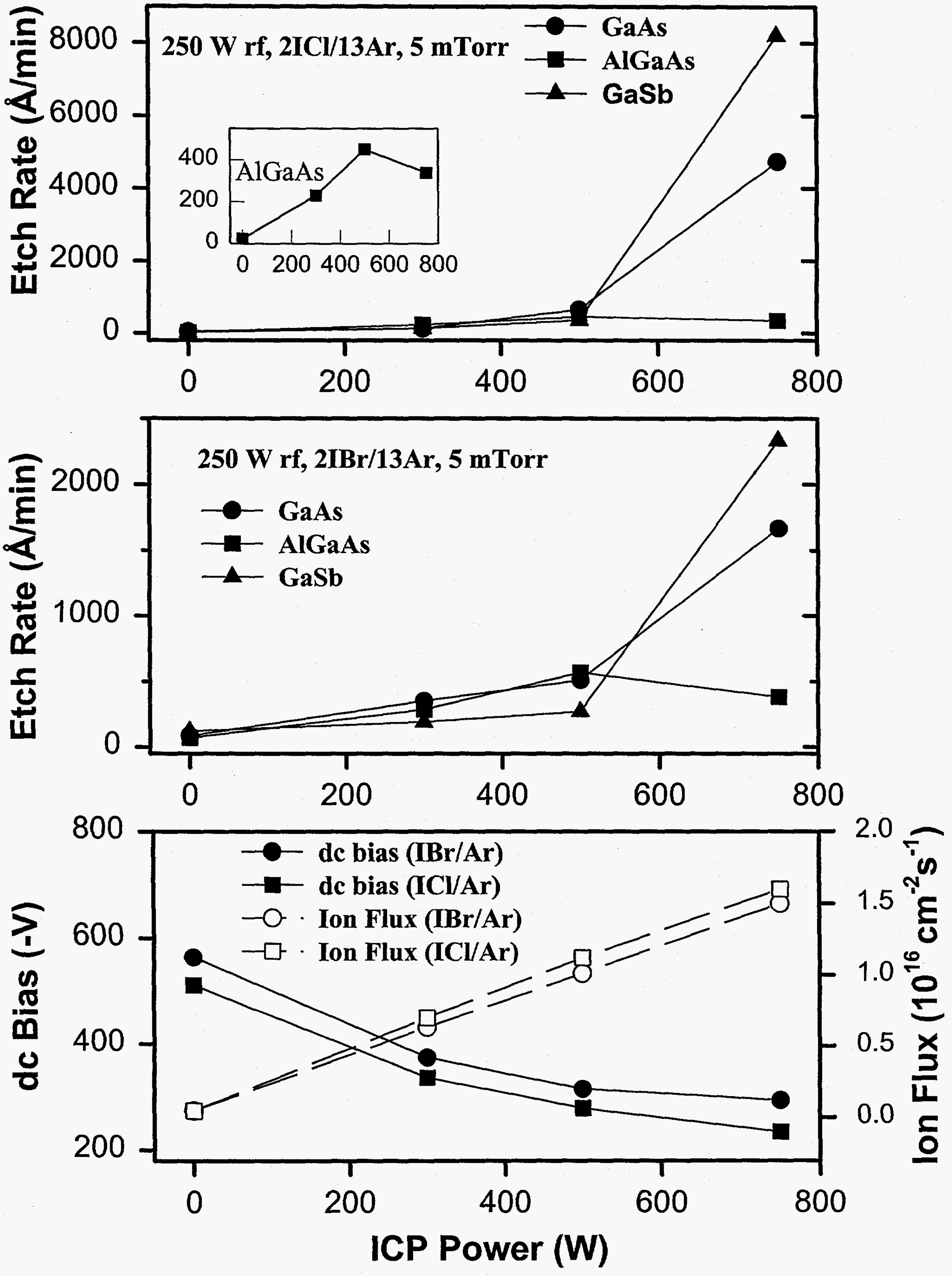
Figure 6. AES surface scan (top) and depth profile (bottom) of GaAs etched in 2ICl/13Ar plasma at 750 W source power, 250 W rf chuck power and 5 mTorr.

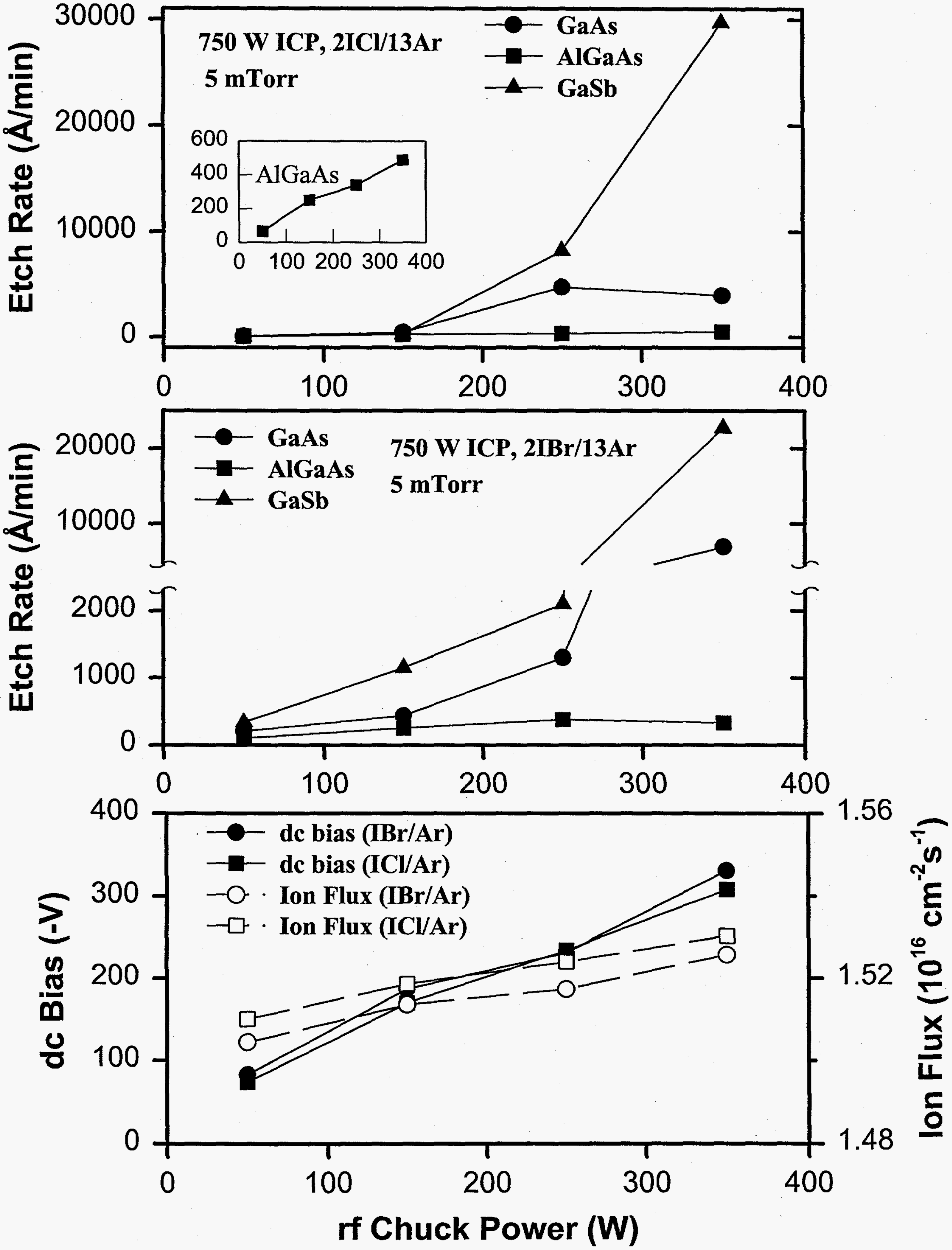
Figure 7. AES surface scan (top) and depth profile (bottom) of GaAs etched in 2IBr/13Ar plasma at 750 W source power, 250 W rf chuck power and 5 mTorr.

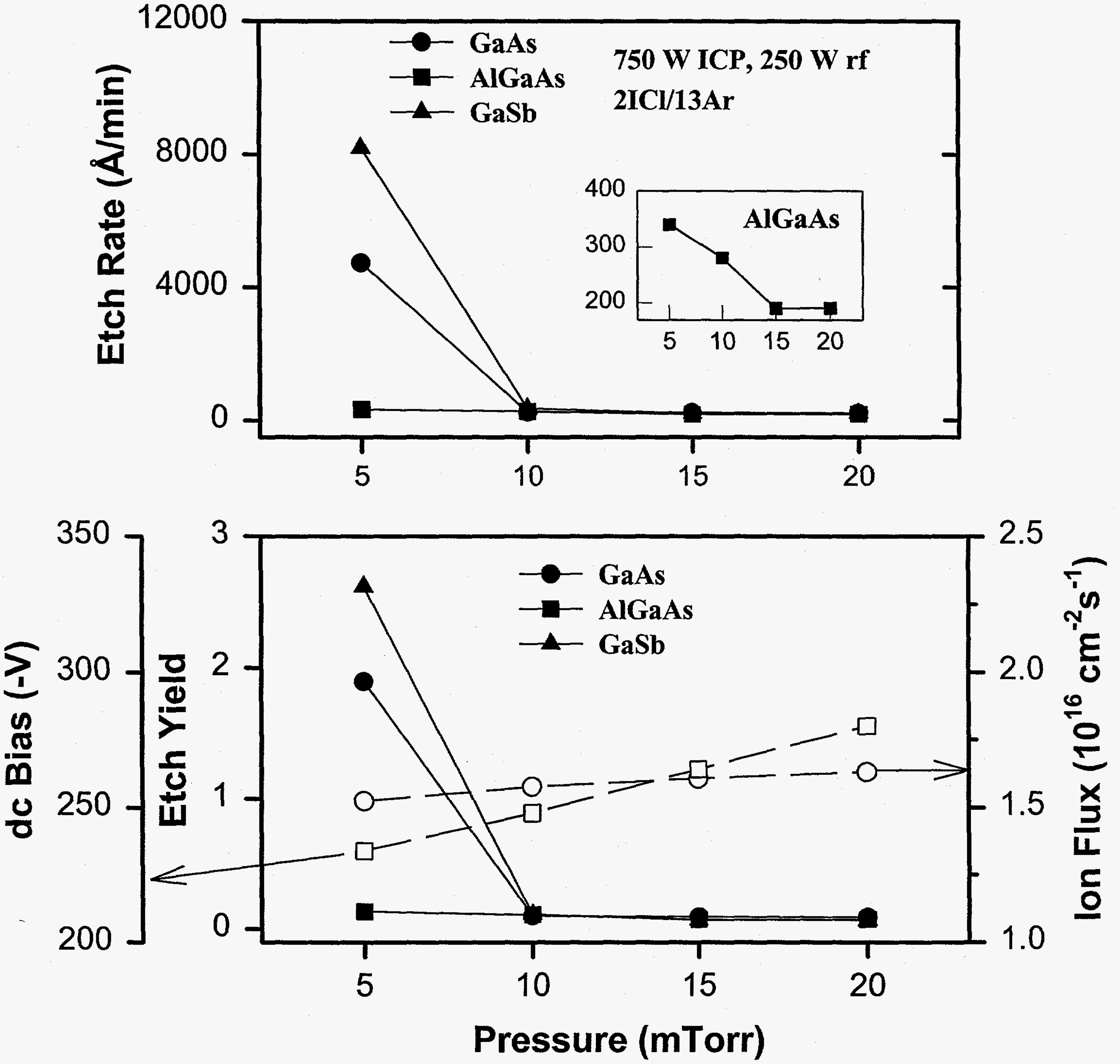

750 W ICP, 250 W rf, 5 mTorr
Etch Rate (μm/min)
2.00
1.00
0.04
0.02
GaAs
AlGaAs
GaSb
0
20
40
60
80
100
% ICl

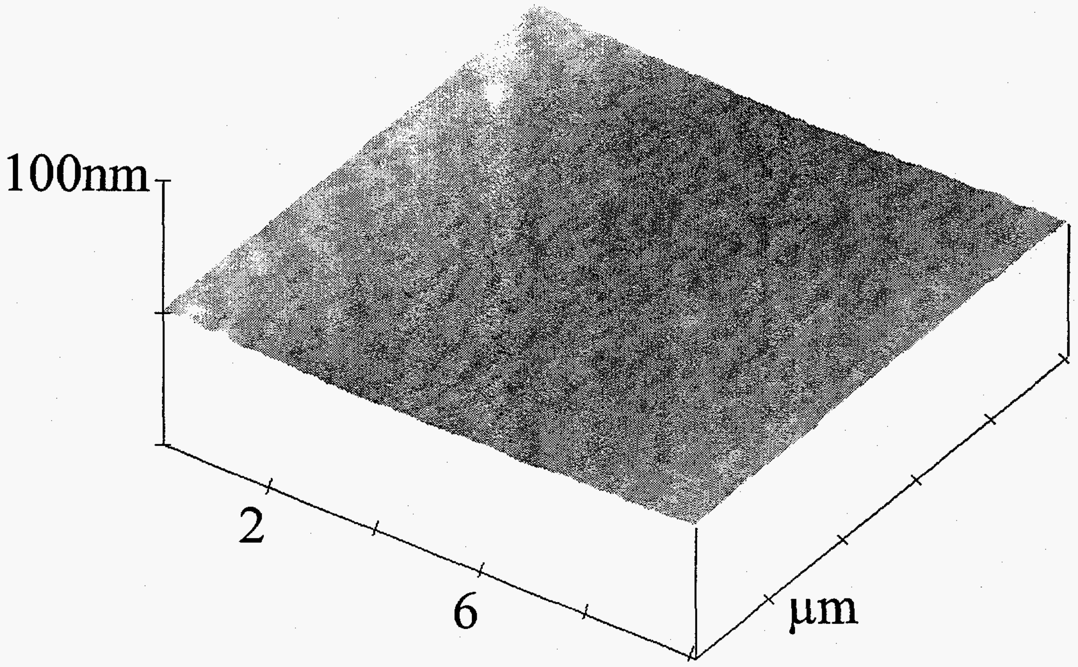

GaAs
AlGaAs
GaSb
750 W ICP, 250 W rf, 5 mTorr
Etch Rate (μm/min)
2
1
0
0
20
40
60
80
100
% IBr


dc bias (IBr/Ar)
dc bias (ICl/Ar)
Ion Flux (IBr/Ar)
Ion Flux (ICl/Ar)
dc Bias (-V)
350
300
250
200
Ion Flux (x10^16 cm^-2s^-1)
1.54
1.52
1.50
0
20
40
60
80
100
% IBr or ICl

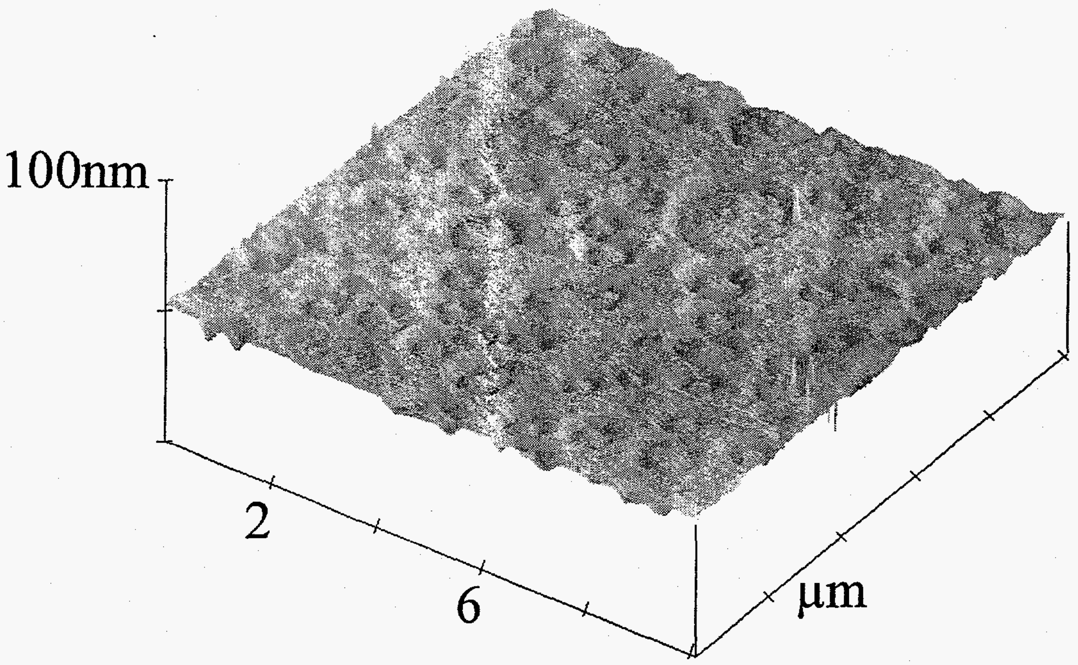

250 W rf, 2ICl/13Ar, 5 mTorr
GaAs
AlGaAs
GaSb
Etch Rate (Å/min)
8000
6000
4000
2000
0
AlGaAs
400
200
0
0
200
400
600
800
0
200
400
600
800
250 W rf, 2IBr/13Ar, 5 mTorr
GaAs
AlGaAs
GaSb
Etch Rate (Å/min)
2000
1000
0
0
200
400
600
800
dc bias (IBr/Ar)
dc bias (ICl/Ar)
Ion Flux (IBr/Ar)
Ion Flux (ICl/Ar)
dc Bias (-V)
800
600
400
200
Ion Flux (10^{16} cm^{-2}s^{-1})
2.0
1.5
1.0
0.5
0.0
0
200
400
600
800
ICP Power (W)


30000
20000
10000
0
Etch Rate (Å/min)
750 W ICP, 2ICl/13Ar
5 mTorr
GaAs
AlGaAs
GaSb
600
400
200
0
AlGaAs
0 100 200 300 400
0
100
200
300
400
20000
10000
2000
1000
0
Etch Rate (Å/min)
GaAs
AlGaAs
GaSb
750 W ICP, 2IBr/13Ar
5 mTorr
0
100
200
300
400
400
300
200
100
0
dc Bias (-V)
dc bias (IBr/Ar)
dc bias (ICl/Ar)
Ion Flux (IBr/Ar)
Ion Flux (ICl/Ar)
1.56
1.52
1.48
Ion Flux (10^{16} cm^{-2}s^{-1})
0
100
200
300
400
rf Chuck Power (W)

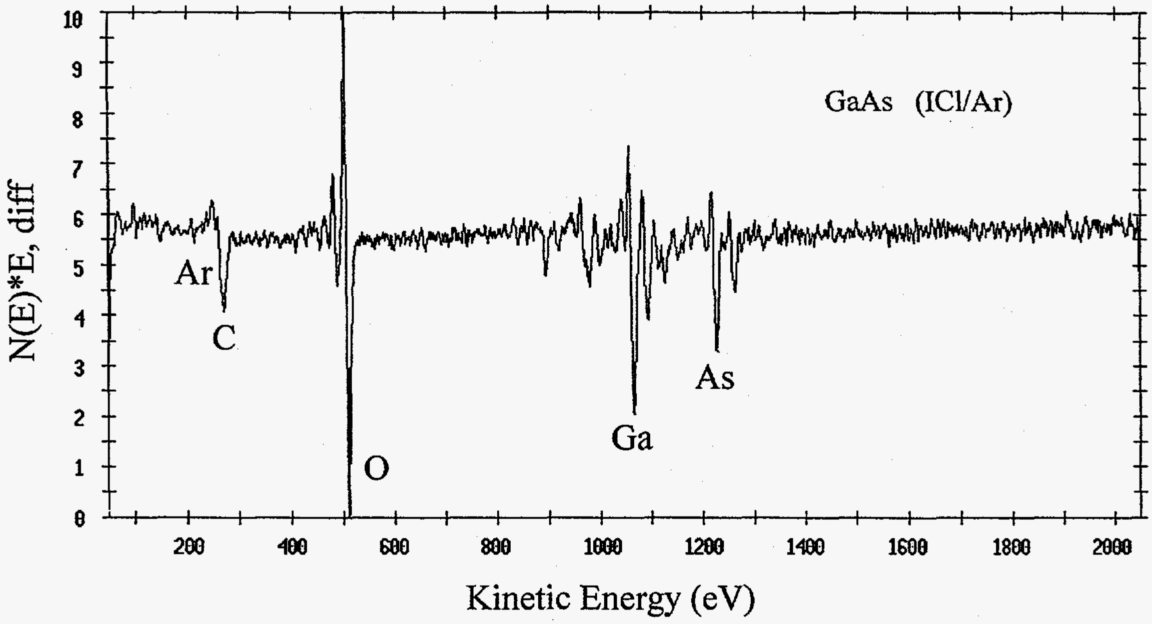

Etch Rate (Å/min)
12000
8000
4000
0
GaAs
AlGaAs
GaSb
750 W ICP, 250 W rf
2ICl/13Ar
400
300
200
AlGaAs
5
10
15
20
5
10
15
20
dc Bias (-V)
350
300
250
200
Etch Yield
3
2
1
0
GaAs
AlGaAs
GaSb
Ion Flux (10^{16} cm^{-2}s^{-1})
2.5
2.0
1.5
1.0
5
10
15
20
Pressure (mTorr)

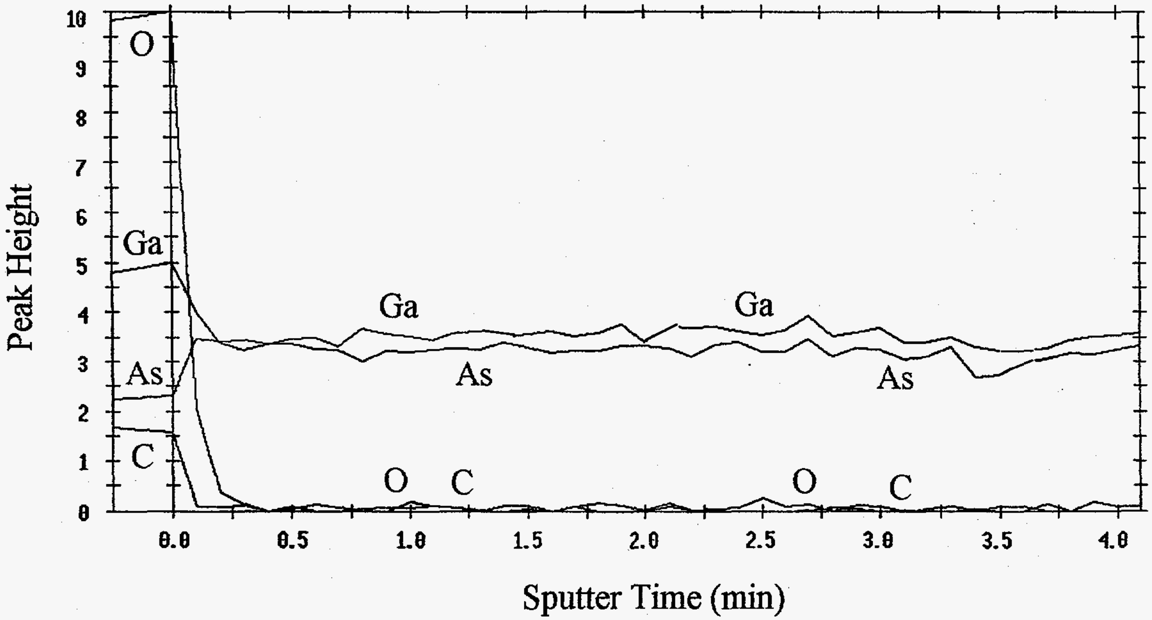


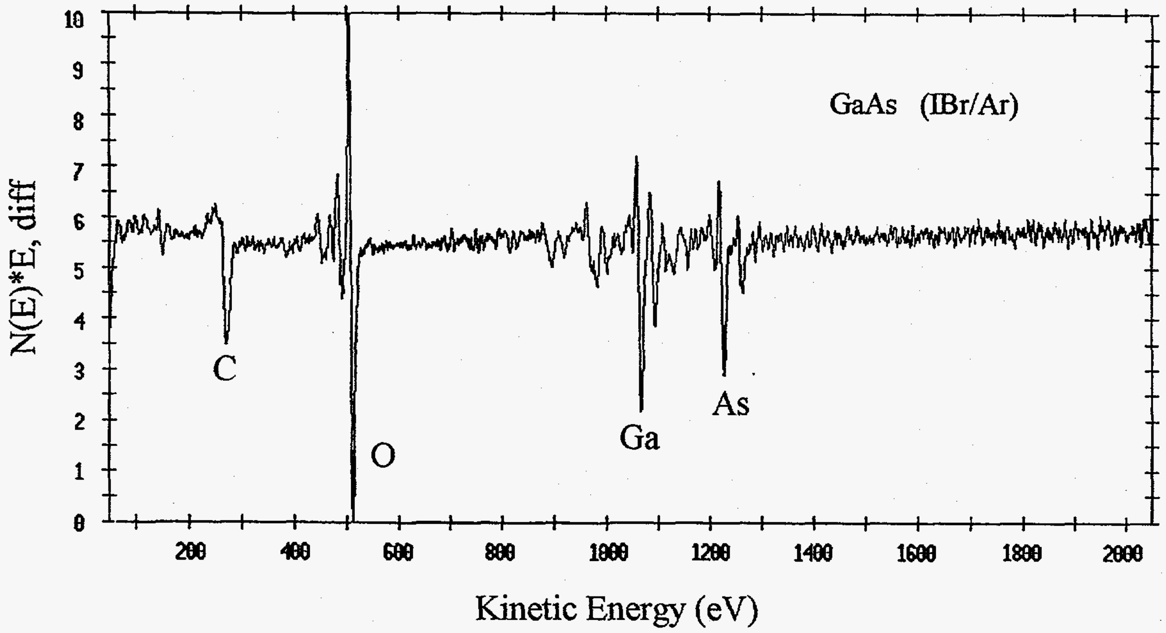
2ICl/13Ar
RMS Roughness = 0.9nm

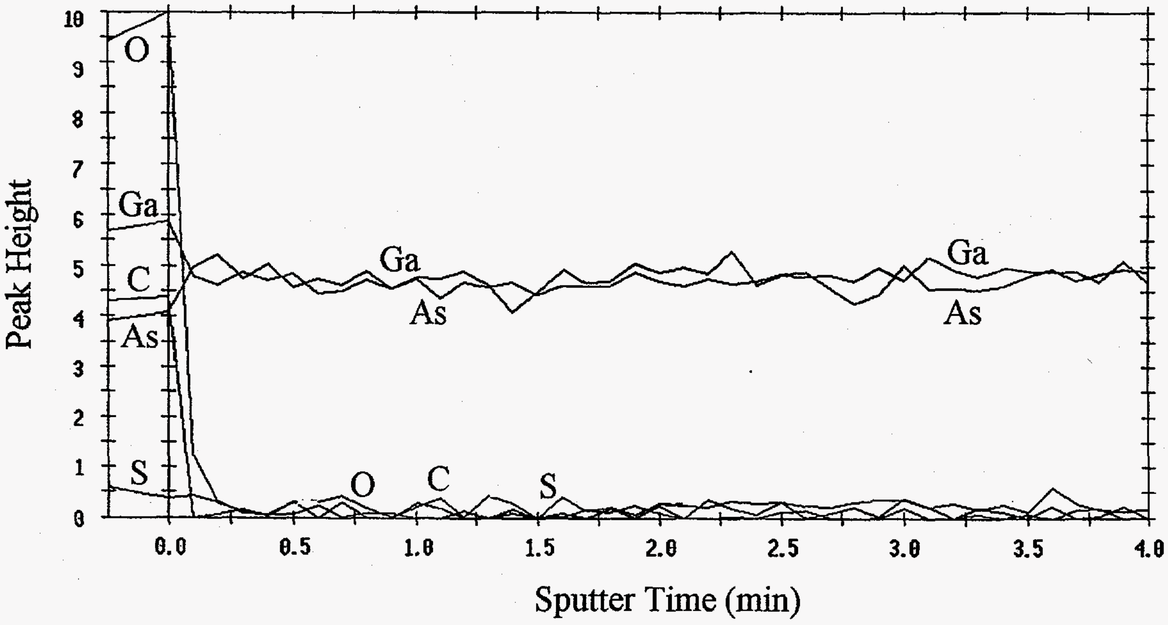


2IBr/13Ar
RMS Roughness = 1.6nm


GaAs (ICl/Ar)
N(E)*E, diff
0
1
2
3
4
5
6
7
8
9
10
Ar
C
O
Ga
As
200
400
600
800
1000
1200
1400
1600
1800
2000
Kinetic Energy (eV)


Peak Height
0
1
2
3
4
5
6
7
8
9
10
O
Ga
As
C
Ga
As
O
C
Ga
As
O
C
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Sputter Time (min)


GaAs (IBr/Ar)
N(E)*E, diff
0
1
2
3
4
5
6
7
8
9
10
200
400
600
800
1000
1200
1400
1600
1800
2000
Kinetic Energy (eV)
C
O
Ga
As


Peak Height
0
1
2
3
4
5
6
7
8
9
10
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Sputter Time (min)
O
Ga
C
As
S
Ga
As
O
C
S
Ga
As