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PLASMA CHEMISTRIES FOR HIGH DENSITY PLASMA ETCHING OF SiC

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ABSTRACT

A variety of different plasma chemistries, including SF_6, Cl_2, ICl and IBr, have been examined for dry etching of 6H-SiC in high ion density plasma tools (Inductively Coupled Plasma and Electron Cyclotron Resonance). Rates up to 4,500Å·min^{-1} were obtained for SF_6 plasmas, while much lower rates (≤800Å·min^{-1}) were achieved with Cl_2, ICl and IBr. The F_2-based chemistries have poor selectivity for SiC over photoresist masks (typically 0.4-0.5), but Ni masks are more robust, and allow etch depths ≥10μm in the SiC. A micromachining process (sequential etch/deposition steps) designed for Si produces relatively low etch rates (<2,000Å·min^{-1}) for SiC.

DISCLAIMER

INTRODUCTION

The rapid advances in high power/high temperature SiC electronics for use in high voltage switches, power conditioning, electric drive trains and utility power management has renewed interest in the development of improved processing techniques for the material.[1-15] The chemical inertness of SiC in conventional acid and base solutions has focussed attention on dry etching methods, typically involving F_2-based plasmas, There has been some success with photochemical etching of SiC that operate by enhancing oxidation of the surface, followed by oxide dissolution.[16,17] Most of the plasma etching methods developed for SiC have utilized conventional reactive ion etching (RIE) with high ion energies to efficiently break the bonds in the material.[18-25] The fluorinated etch products (SiF_x and CF_x species) are relatively volatile, and their removal from the surface is generally not the rate-limiting step.

Much less information is available on the dry etching characteristics of SiC in high density plasma reactors. A few reports have appeared on the use of Inductively Coupled Plasma (ICP)[26,27] and Electron Cyclotron Resonance (ECR)[28-34] sources for SiC etching, in which higher rates were obtained than with RIE. The lower operating pressure and lower average ion energies in these sources is offset by the much higher ion flux. While F_2-based plasma chemistries have produced the highest etch rates, there is little information on alternatives such as iodine or bromine.

In this paper we compare use of SF_6 (with O_2 or Ar addition), Cl_2, ICl and IBr plasma chemistries in ECR and ICP tools for dry etching of 6H-SiC substrates. Rates around $0.45\mu m \cdot min^{-1}$ were obtained with SF_6, while rates with the other chemistries were only a few hundred angstroms per minute.

EXPERIMENTAL

Bulk 6H-SiC substrates (Al doped; p = $6x10^{18}$ cm^{-3}), with (0001) orientation (Si-face) were employed for the experiments. The samples were masked with either AZ4330 photoresists or electro-plated Ni, and etch depths were obtained from stylus profilometry measurements. Two different reactors were employed. The first was a Plasma-Therm 790, in which the sample is thermally bonded to a He backside cooled chuck biased with 13.56 MHz rf power, which controls the incident ion energy. The high density ICP Source is a 2 MHz 1500W 3-turn coil geometry. Electronic grade gases are injected directly into this source through mass flow controllers at typical rates of 10-30 standard cubic centimeters per minute (sccm). The second system is a Plasma-Therm SLR 770 which has similar characteristics except that the source is a Wavemat 440 ECR, operating at 2.45 GHz and powers up to 1000W.

RESULTS AND DISCUSSION

(a) ECR

Figure 1 shows the influence of rf chuck power and pressure on SiC etch rates in $20SF_6/10$ Ar discharges with 750 W of ECR source power. The rate increases rapidly with chuck power, in good correlation with the induced dc bias at the sample position. To check that the etch rate depends strongly on ion energy, we also included SiO_2 samples (whose etch products should be as volatile as those of SiC, but whose bond strength is higher). Note that the behavior of the SiO_2 mimics that of the SiC, but at a lower overall etch rate. A similar conclusion is drawn from the pressure data in the lower part of the figure. In the latter case the etch rates fall-off at higher pressure even though self-bias is increasing, due to increased recombination in the plasma. The selectivity for etching SiC over photoresist is very poor (<1), as expected.

Figure 2 shows the influence of microwave source power on both SiC etch rate and selectivity with respect to photoresist for fixed rf chuck power, pressure and plasma gas composition. The behavior of SiC again is mimicked by that of SiO_2, and the selectivity to photoresist is ~0.5 over the entire range of source powers investigated.

The effect of gas additive (Ar or O_2) is shown in Figure 3. The rates are slightly higher for Ar, partially due to the slightly higher self-biases. The highest etch rates are similar for the two mixtures, and the selectivity with respect to photoresist is poor. By contrast, the erosion rate of Ni was in the range 200-400 Å·min^{-1} under these conditions, i.e. a selectivity for SiC over Ni of up to 20.

Representative scanning electron micrographs of features etched into SiC using either Ni masks (top and bottom left) or photoresist (top and bottom right) are shown in Figure 4. With a 4,000 Å thick Ni mask, we can etch up to ~12 μm deep without mask erosion affecting the feature profile. This process is of potential interest for forming through wafer vias in SiC for power device application. In that case, a minimum etch depth would be ~50 μm, requiring a comparatively thicker mask. Flemish et al.[33] reported previously that indium-tin-oxide performed well as a mask under ECR condition, and we reported selectivities as high as 70 for SiC over ITO under ICP conditions.[35]

In the ECR tool we obtained much lower etch rates with Cl_2, ICl and IBr plasma chemistries, which appears to be due to the lower volatility etch products formed with these mixtures.

(b) ICP

A common process for micromachining of Si is the use of a sequential etch/deposition technique to prevent sidewall undercutting. We employed this process with higher dc self-bias

during the etch step in order to overcome the higher bond strength of the SiC. Figure 5 shows the effect of both pressure and dc bias on the etch rates of SiC, Si and SiO_2. In both cases the deposition step was performed at ~23 mTorr, whereas the etch step occurred at 2-10 mTorr. The two strongly-bonded materials (SiC and SiO_2) show little influence of bias or pressure under our conditions and the selectivity over photoresist is again poor.

The true value of the micromachining process for Si is seen in Figure 6, which displays etch rates as a function of self-bias for two different pressures. The etch rates for Si are in the range 4-5 $\mu m \cdot min^{-1}$, roughly two orders of magnitude higher than those of SiC and SiO_2 at the 23 mTorr condition. However, the process does not produce any advantage for SiC etching, where the main limitation is simply etch rate and not the prevention of sidewall undercutting.

We have previously reported that F_2-based plasma chemistries work well under ICP conditions[27,35], producing rates up to ~3,500 $Å \cdot min^{-1}$, but that Cl_2 plasmas were much less effective. In an effort to determine if the inert gas additive was important, we studied the influence of He, Ar and Xe addition to ICP Cl_2 discharges. Figure 7 shows the effect of both chlorine percentage and ICP source power on SiC etch rate in Cl_2/He, Cl_2/Ar and Cl_2/Xe. In both cases the Xe addition produces the highest rates, but they are a factor of ~20 lower than obtained with F_2-based plasma chemistries. Increasing the chuck self-bias did not improve the rates, as shown in Figure 8. Indeed, the rates may actually decrease at higher biases, probably due to ion-assisted desorption of the chlorine radicals on the SiC surface before they can react to form etch products.

No better success in obtaining high rates for SiC was found with ICl on IBr plasma chemistries. Figure 9 shows the effect of halide gas percentage in ICl/Ar and IBr/Ar discharges at fixed pressure, rf chuck power and ICP source power. The rates for IBr reach ~800 $Å \cdot min^{-1}$,

well above those obtained with ICl. These results suggest that $SiBr_x$ and CBr_x species are more volatile than their chlorine and iodine counterparts. Increasing either source power (Figure 10) or rf chuck power (Figure 11) did not produce acceptable SiC rates.

Only F_2-based plasma chemistries are found to produce acceptable SiC etch rates under high density plasma conditions. The SiF_x and CF_x etch products are volatile, and readily leave the surface once they are formed. By contrast their chlorine, bromide and iodide counterparts are much less volatile, leading to substantially lower etch rates. A sequential etch/deposition process developed for micromachining of Si is much less effective in SiC, even with increased ion energy and lower pressure, and produces etch rates less than half those obtained with straightforward SF_6/Ar etching. We assume this is a result of the polymer formation during the deposition step shielding the SiC during the subsequent etch step, reducing the effectiveness of bond-breaking by incident ions.

ACKNOWLEDGMENTS

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Figure Captions

Figure 1. Etch rates of SiC and selectivity over photoresist in $20SF_6/10Ar$, 750 W source power discharges, as a function of either rf chuck power (top) or pressure (bottom).

Figure 2. Etch rates of SiC and selectivity over photoresist in $20SF_6/10Ar$, 250 W chuck power, 2 mTorr discharges, as a function of source power.

Figure 3. Etch rates of SiC and selectivity over photoresist in SF_6/Ar on $SF_6/O_2/Ar$ discharges (250 W chuck power, 750 W source power, 2 mTorr).

Figure 4. SEM micrographs of features etched into SiC using Ni masks (left, top and bottom) or photoresist masks (right, top and bottom) in $20SF_6/10Ar$, 2 mTorr, 750 W source power, 375 W chuck power discharges.

Figure 5. Etch rates of SiC and selectivity over photoresist in an SF_6-based micromachining process (etch/deposition), as a function of self-bias (top) and pressure (bottom).

Figure 6. Etch rates of SiC and selectivity over photoresist in an SF_6-based micromachining process (etch/deposition), as a function of self-bias at two different pressures.

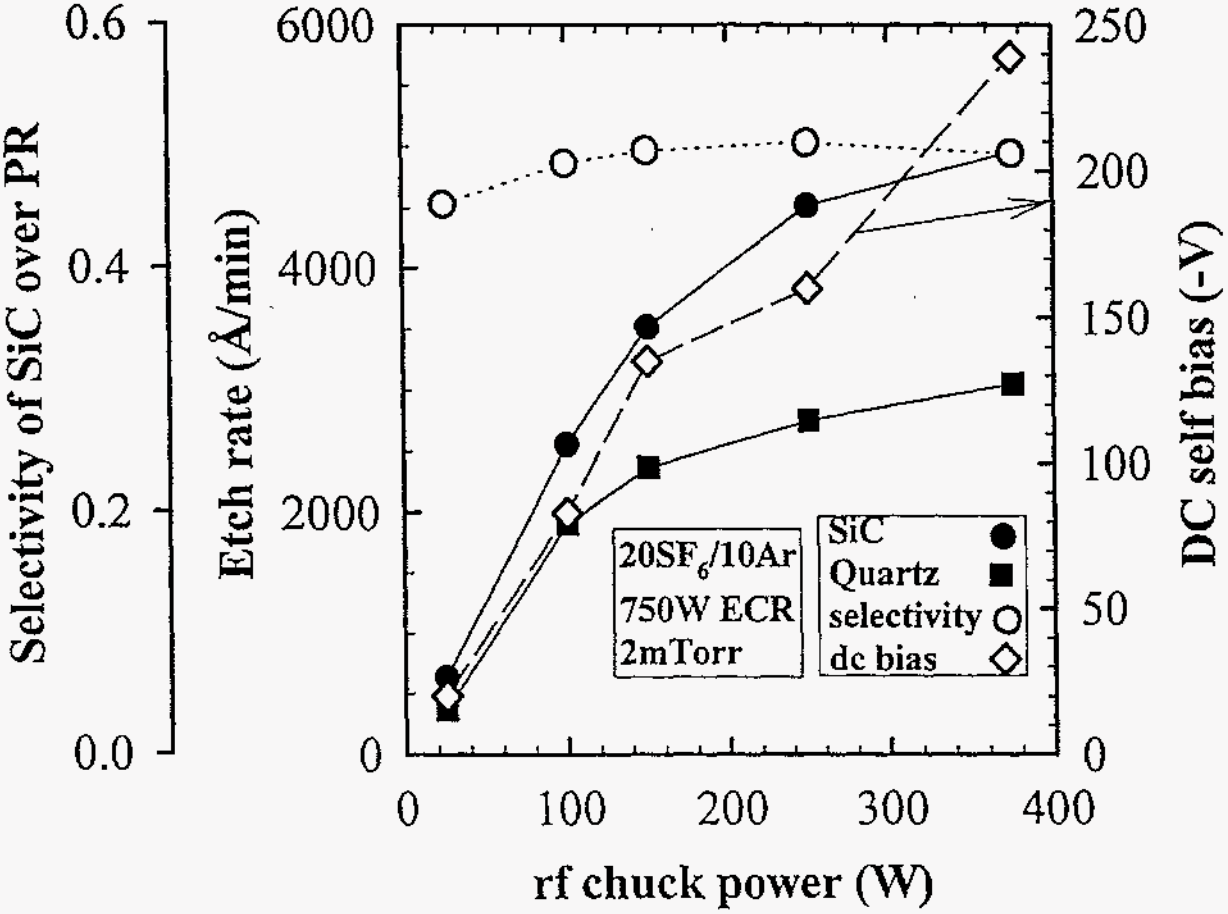
Figure 7. Etch rates of SiC in Cl_2/He, Cl_2/Ar and Cl_2/Xe discharges as a function of both percentage Cl_2 (top) or ICP source power (bottom).

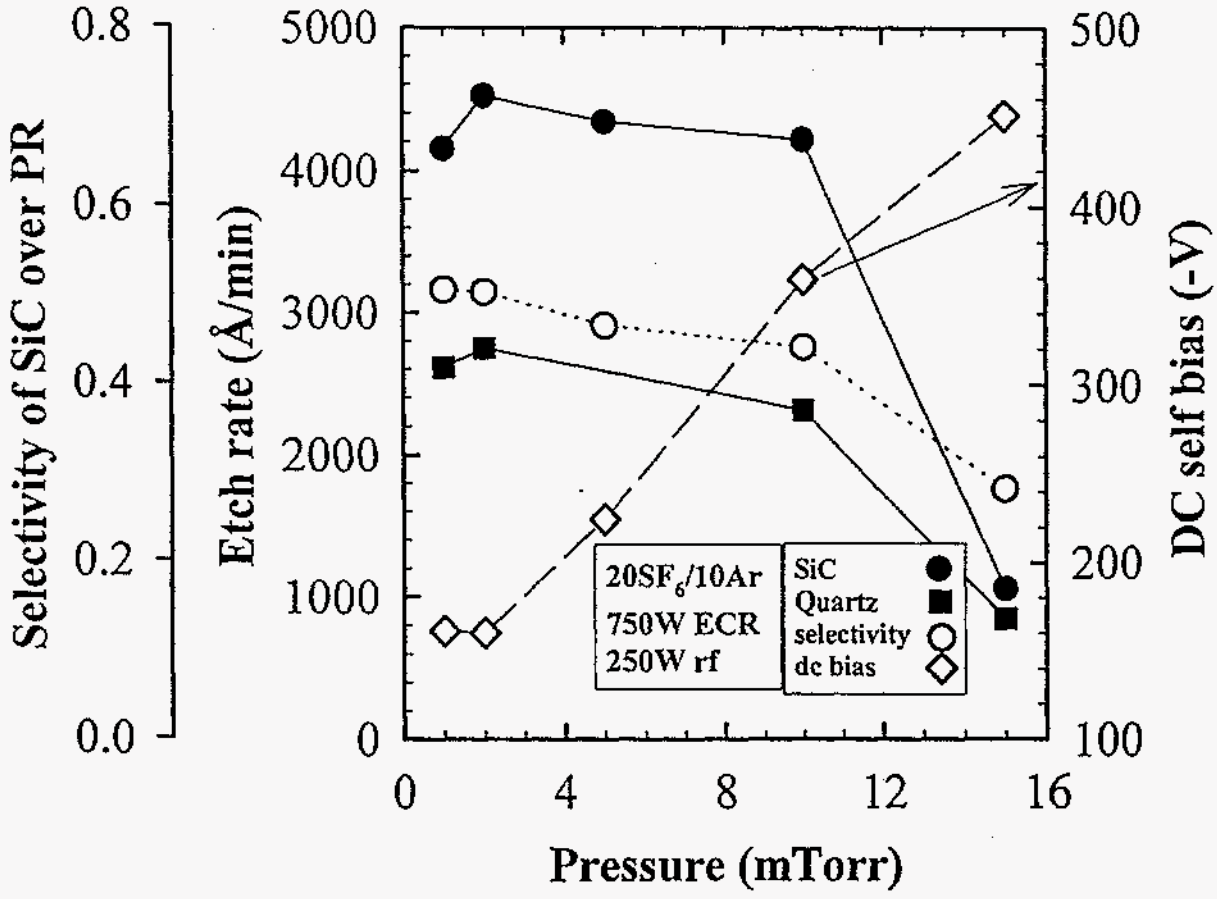
Figure 8. Etch rates of SiC (top) and dc chuck self-bias (bottom) as a function of rf chuck power in Cl_2/He, Cl_2/Ar and Cl_2/Xe discharges (5 mTorr, 750 W source power).

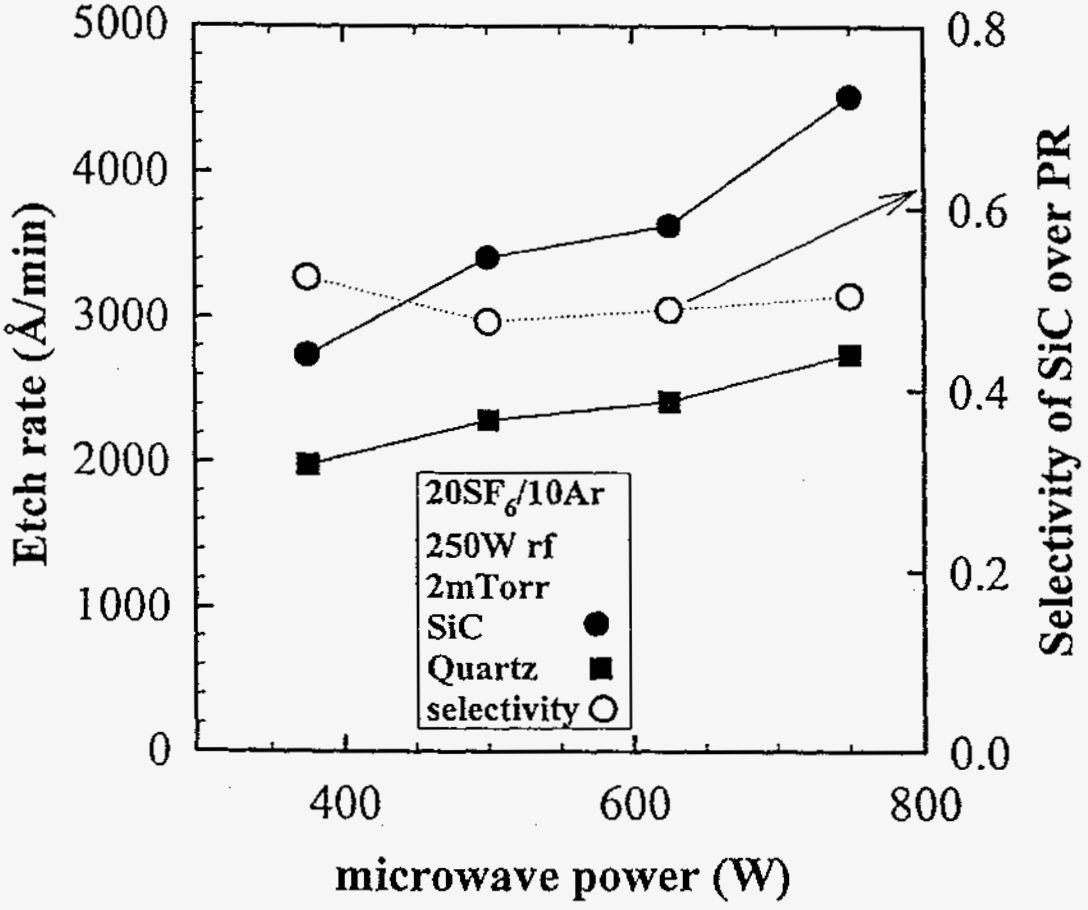
Figure 9. Etch rates of SiC and dc chuck self-bias in IBr/Ar and ICl/Ar discharges (750 W source power, 250 W chuck power, 5 mTorr) as a function of halide percentage.

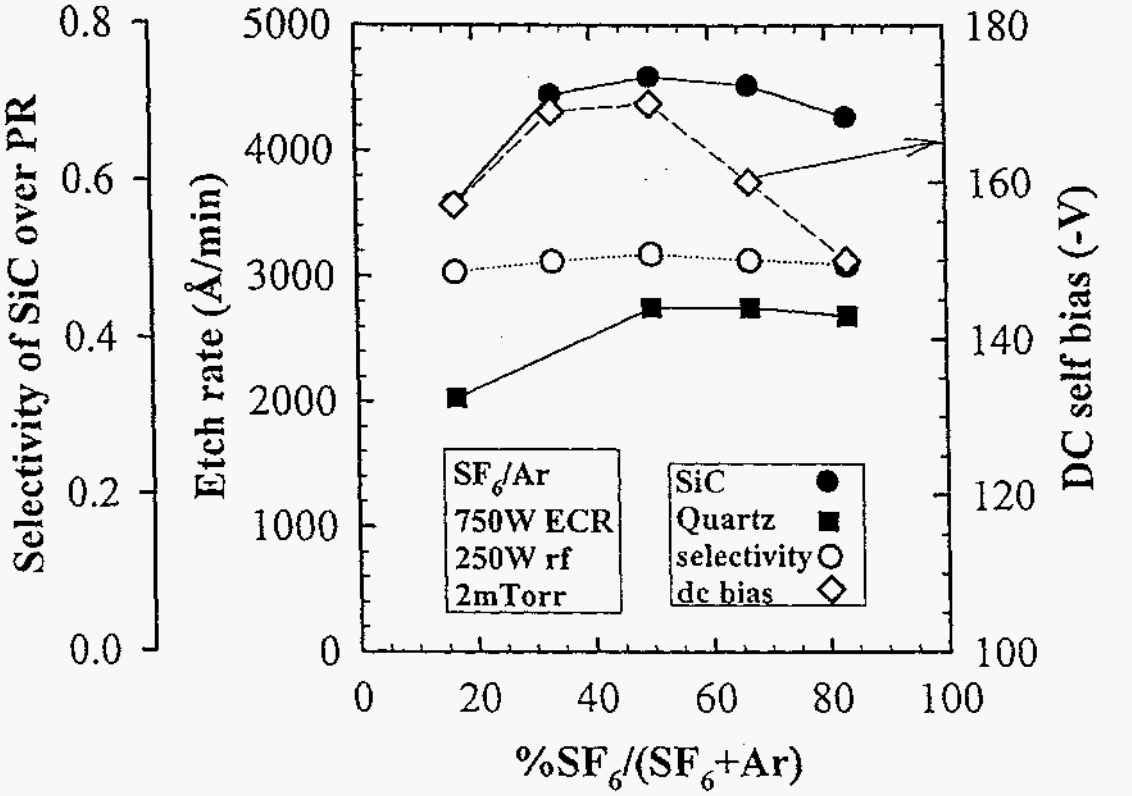
Figure 10. Etch rates of SiC and dc chuck self-bias in 2ICl/13Ar and 2IBr/13Ar discharges (750 W source power, 5 mTorr), as a function of rf chuck power.

Figure 11. Etch rates of SiC and dc chuck self-bias in 2ICl/13Ar and 2IBr/13Ar discharges (250 W chuck power, 5 mTorr), as a function of source power.

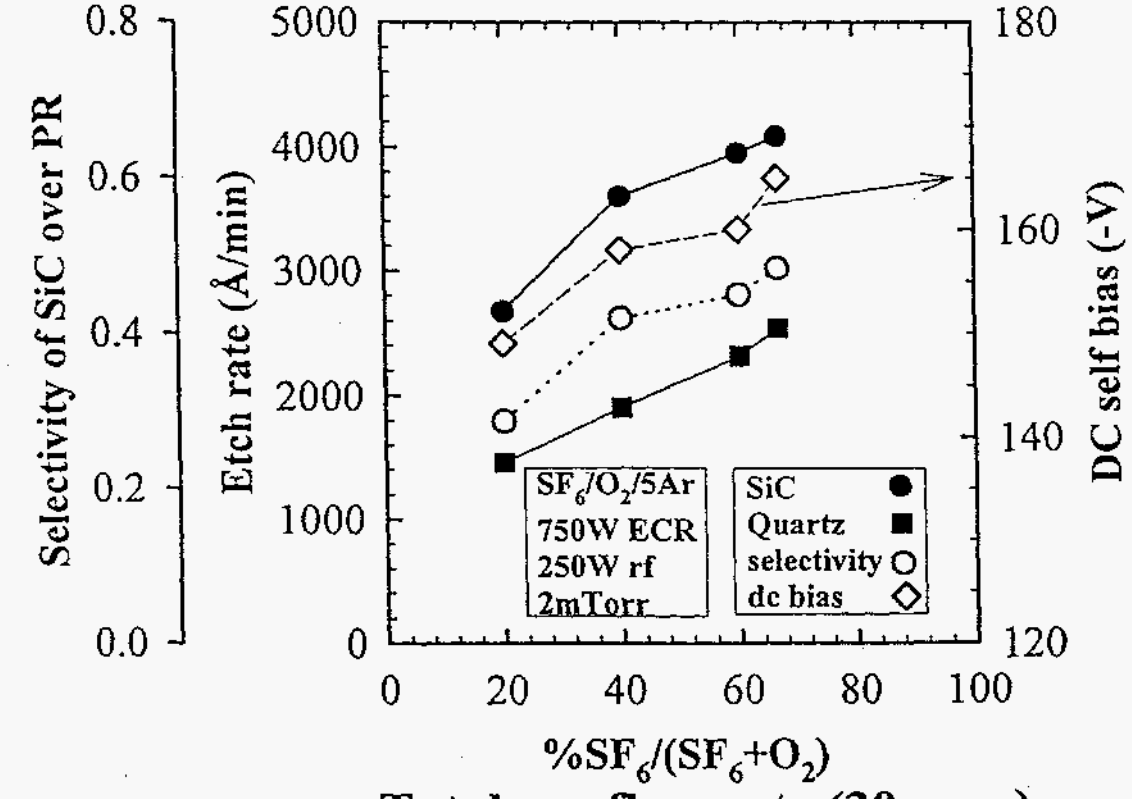

Selectivity of SiC over PR
Etch rate (Å/min)
DC self bias (-V)
rf chuck power (W)
20SF6/10Ar
750W ECR
2mTorr
SiC
Quartz
selectivity
dc bias


Selectivity of SiC over PR
Etch rate (Å/min)
DC self bias (-V)
Pressure (mTorr)
20SF6/10Ar
750W ECR
250W rf
SiC
Quartz
selectivity
dc bias

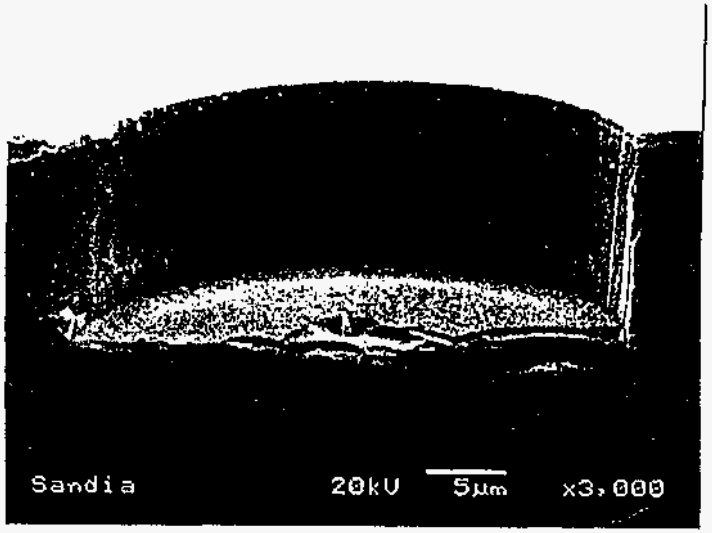

5000
4000
3000
2000
1000
0
0.8
0.6
0.4
0.2
0.0
400
600
800
Etch rate (Å/min)
Selectivity of SiC over PR
microwave power (W)
20SF6/10Ar
250W rf
2mTorr
SiC
Quartz
selectivity

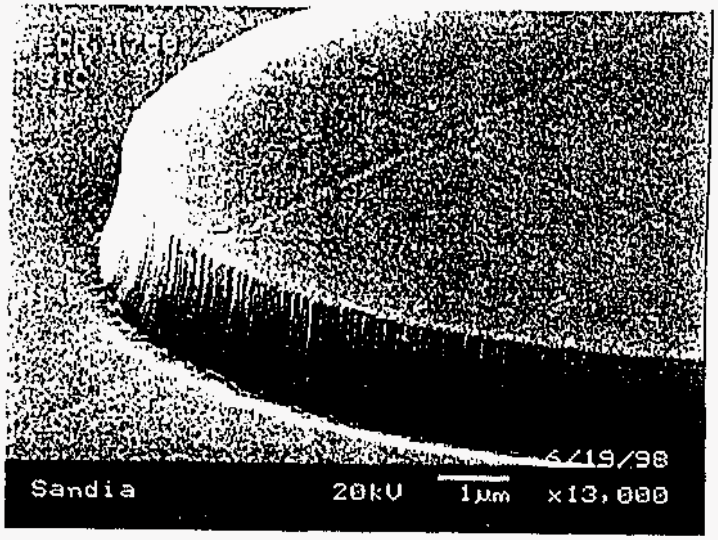


Total gas flow rate (30sccm)



Total gas flow rate (30sccm)


Sandia 20kU 5µm x3,000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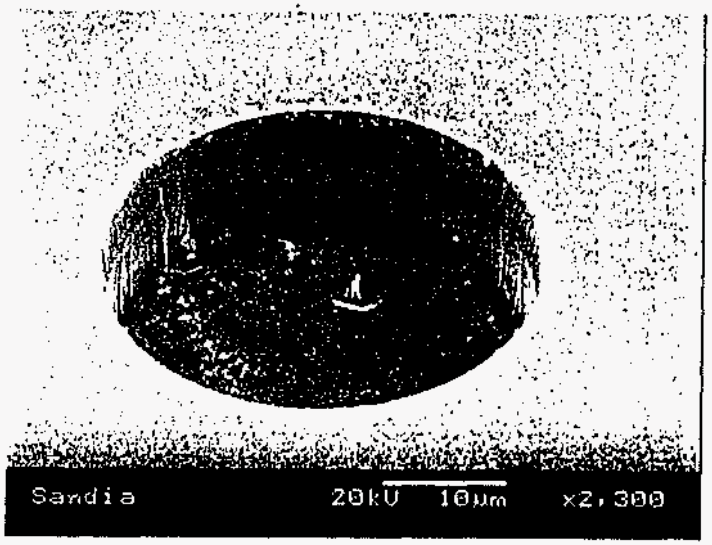
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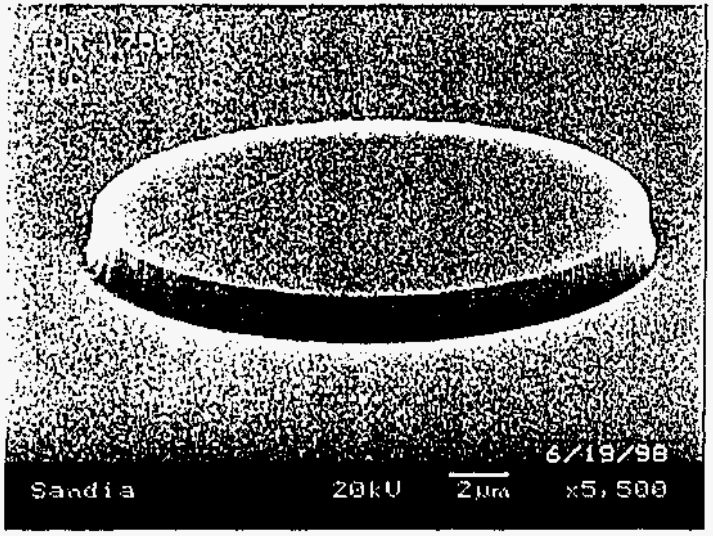
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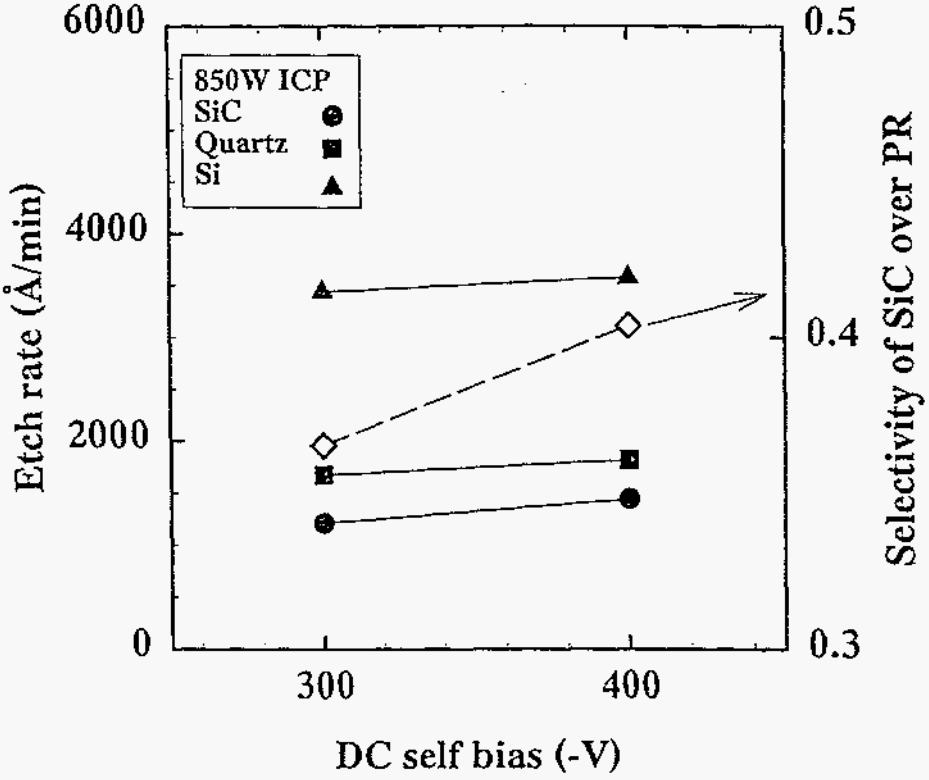
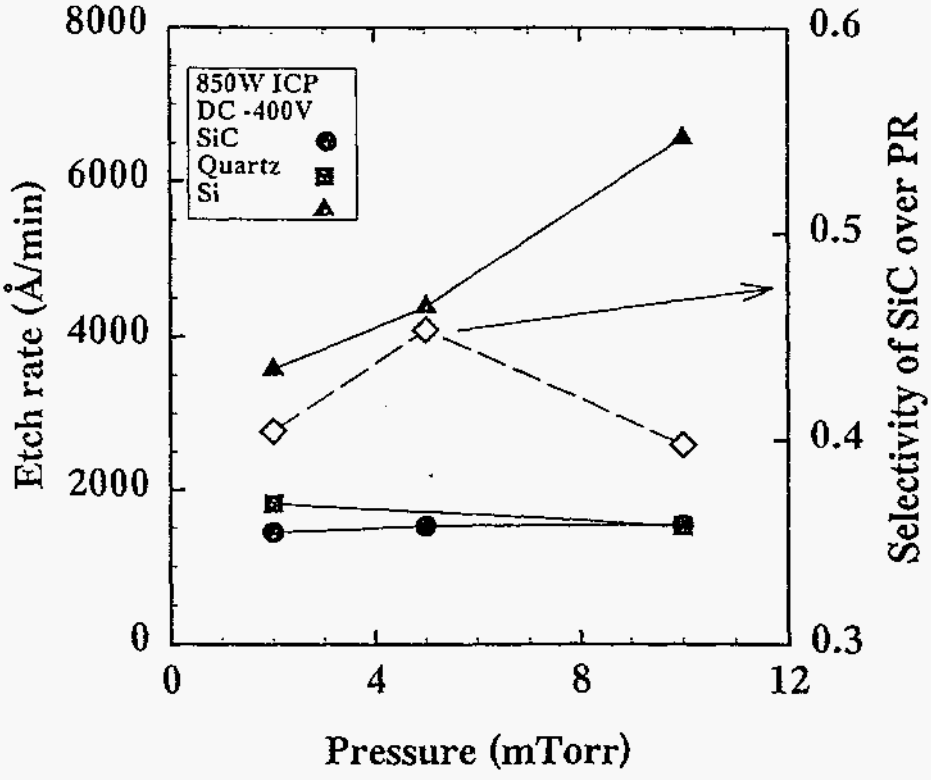
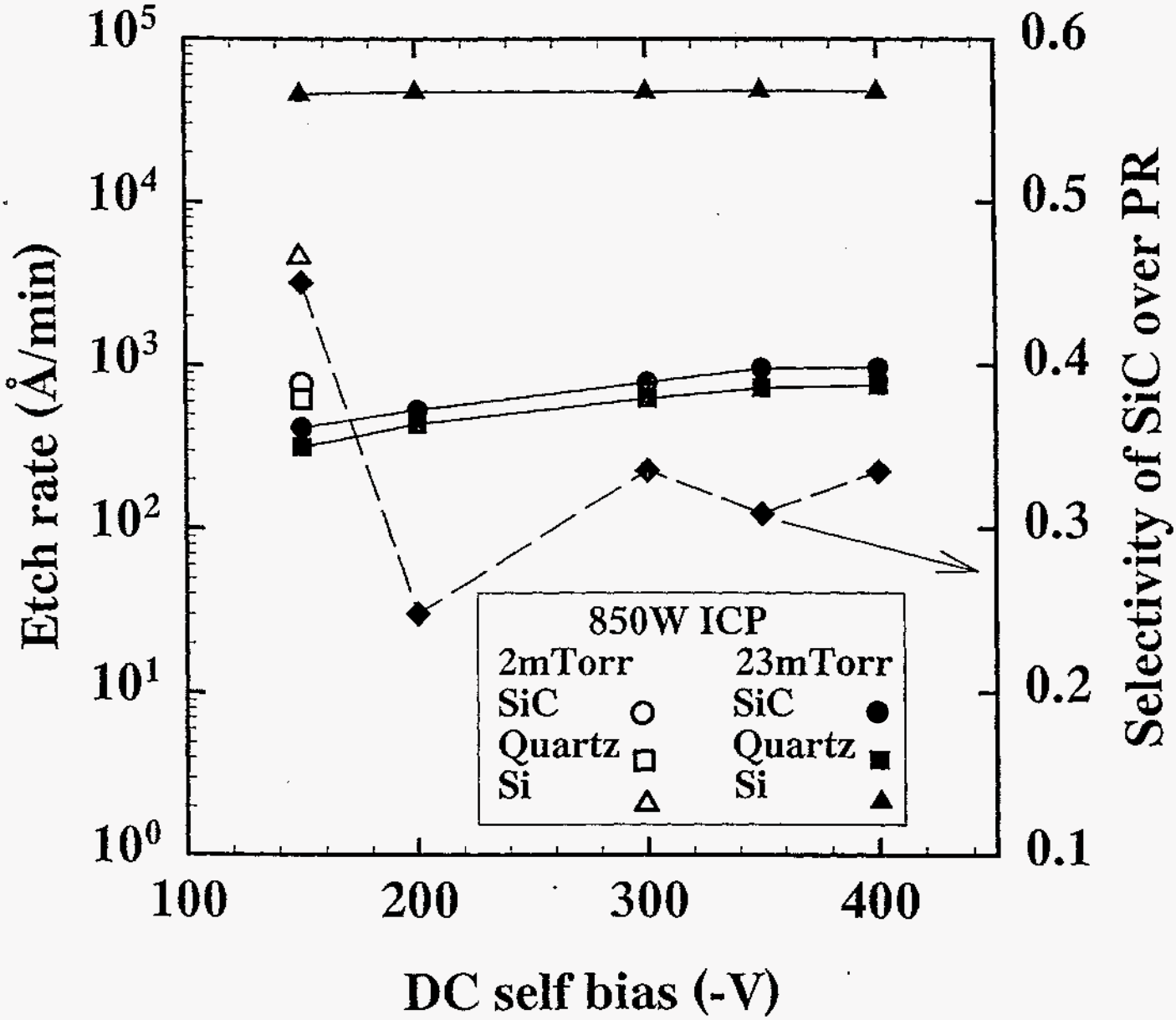
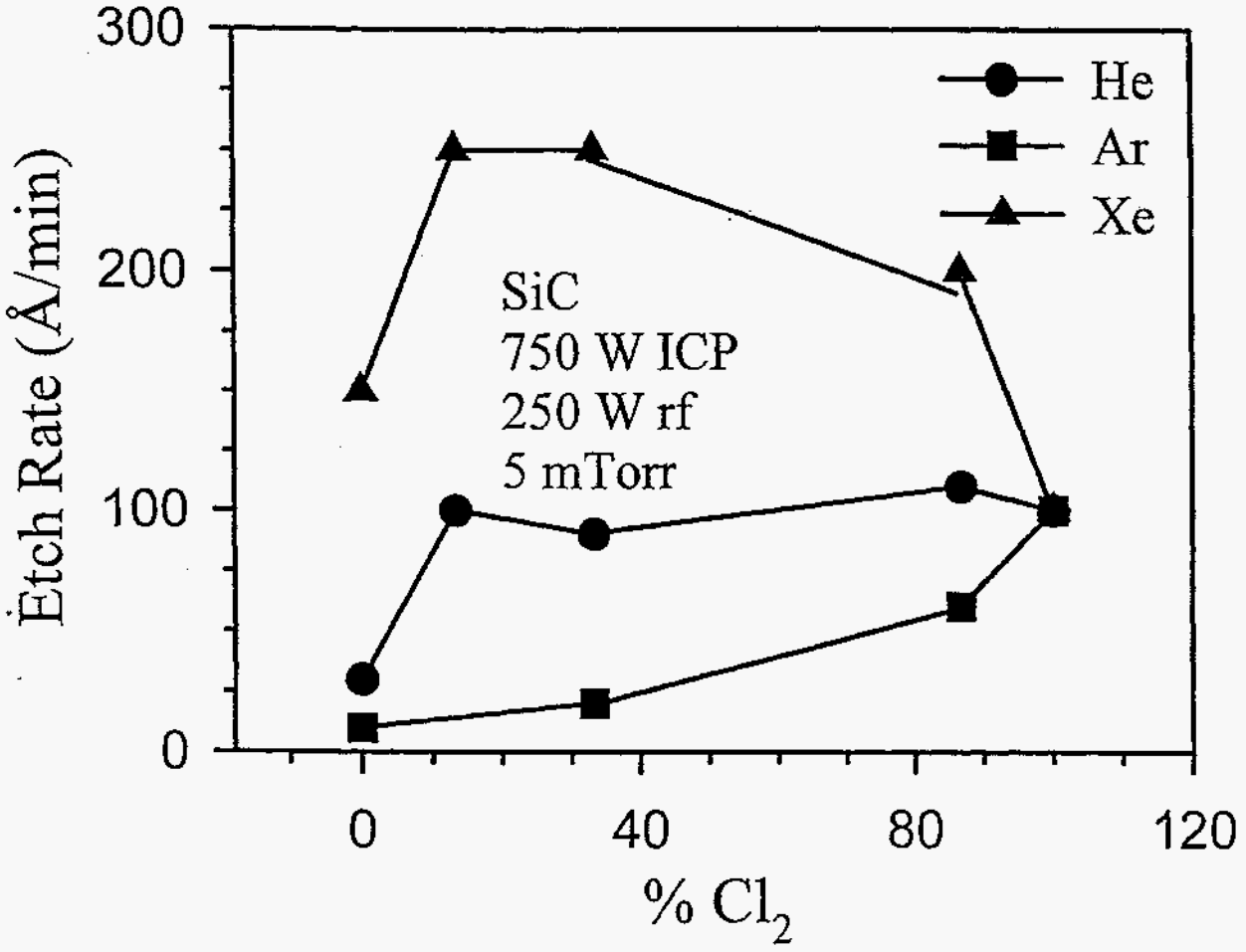
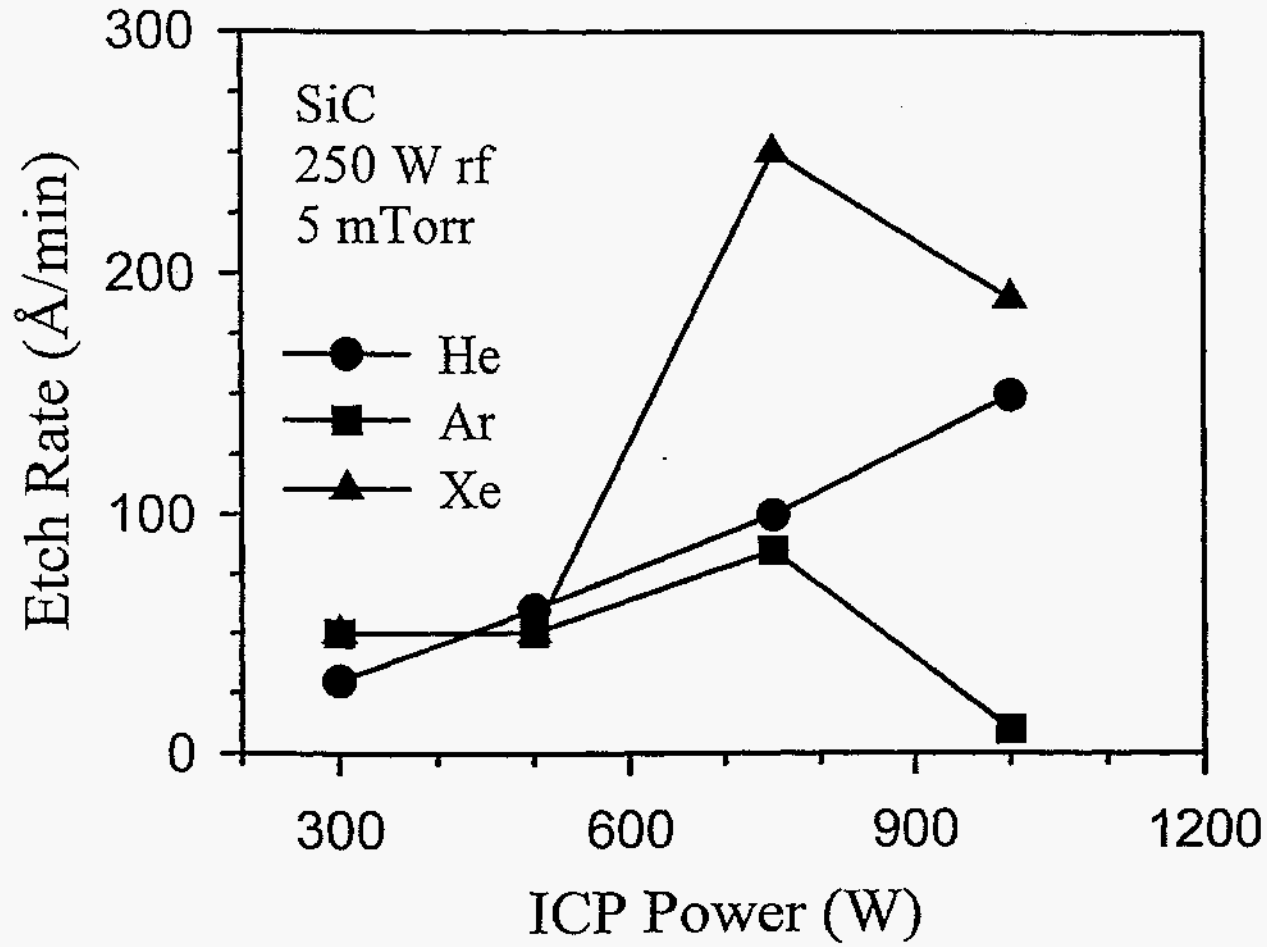
Sandia 20kU 2µm x5,500

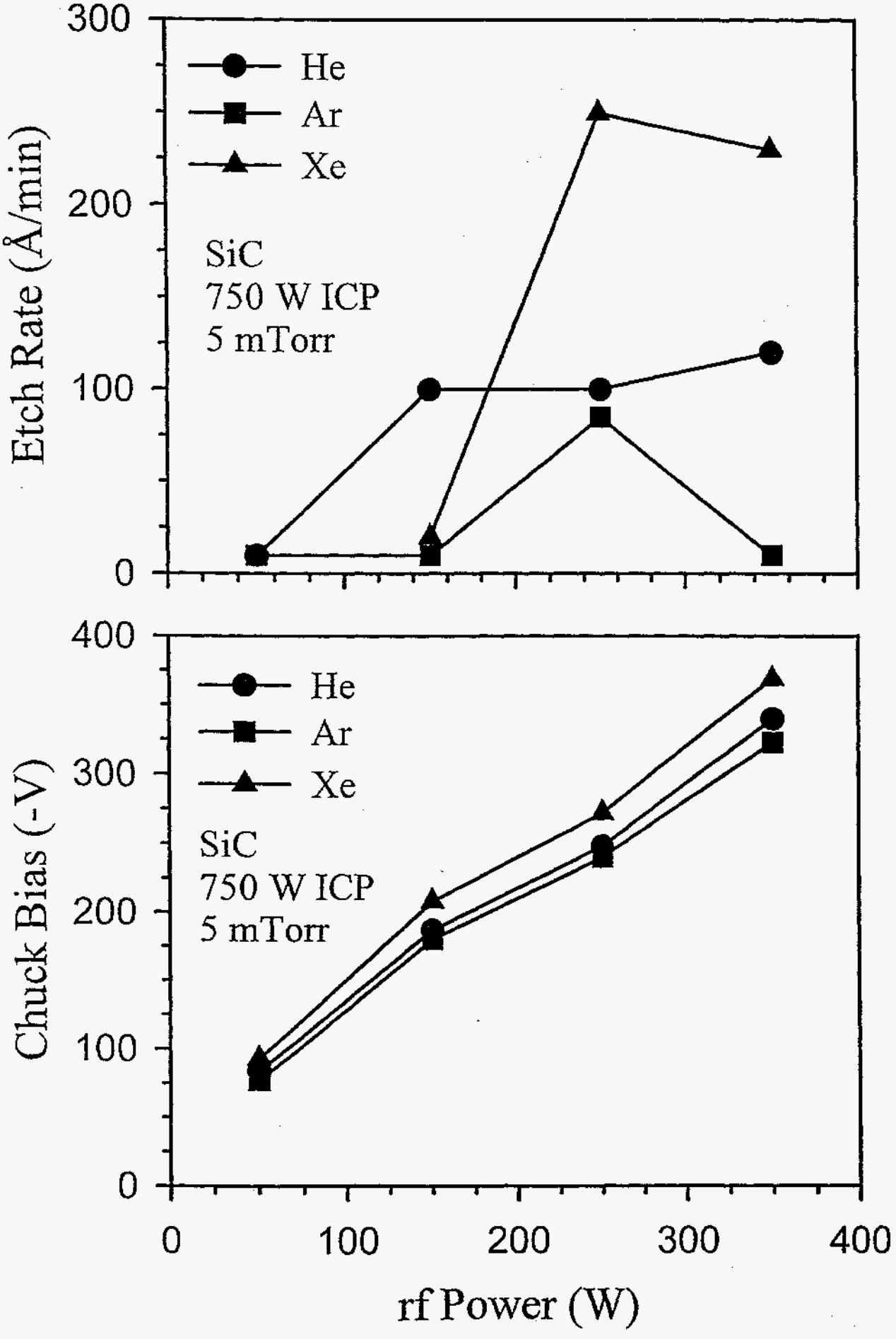

850W ICP
SiC
Quartz
Si
6000
4000
2000
0
0.5
0.4
0.3
300
400
Etch rate (Å/min)
Selectivity of SiC over PR
DC self bias (-V)

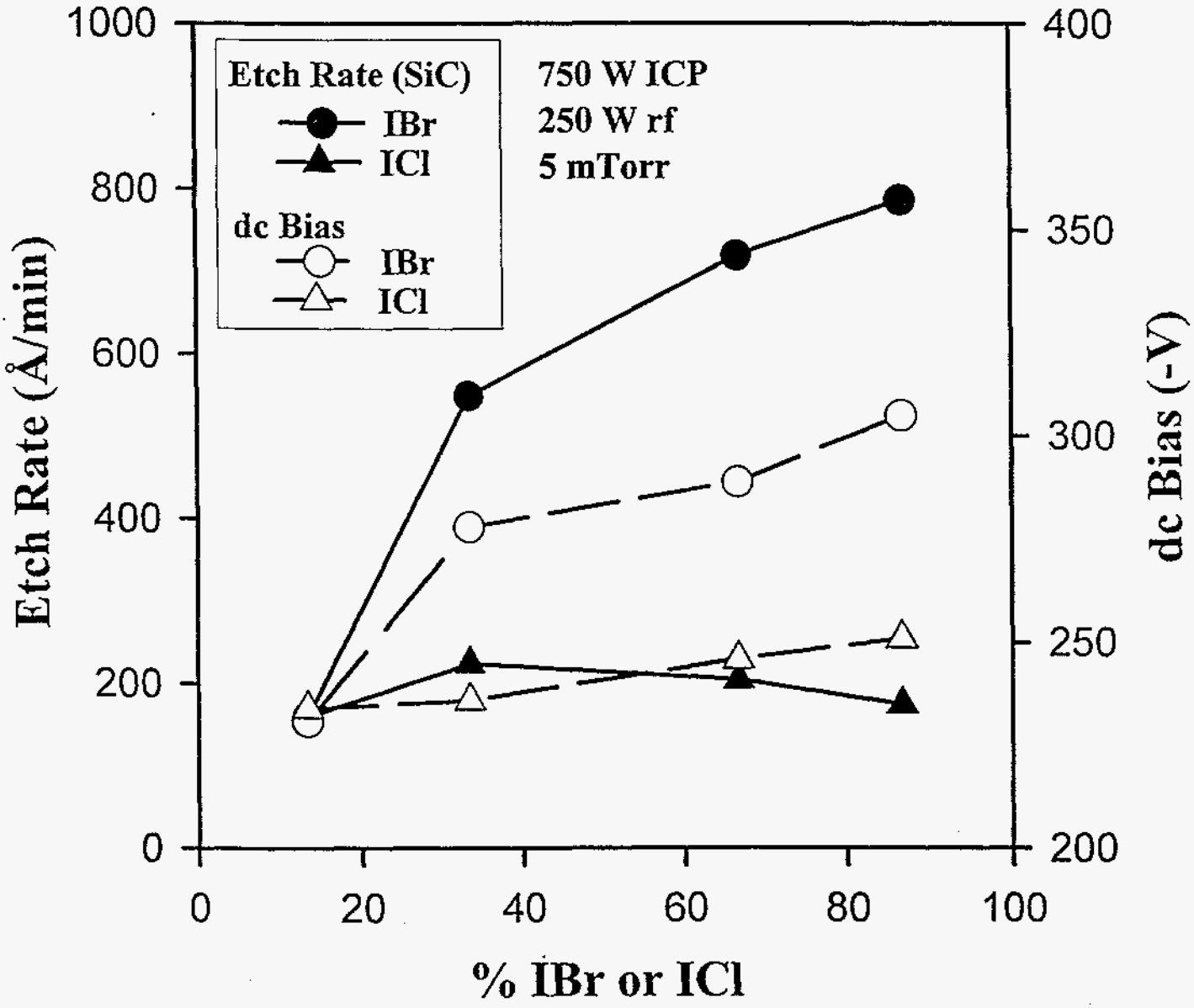

850W ICP
DC -400V
SiC
Quartz
Si
8000
6000
4000
2000
0
0.6
0.5
0.4
0.3
0
4
8
12
Etch rate (Å/min)
Selectivity of SiC over PR
Pressure (mTorr)

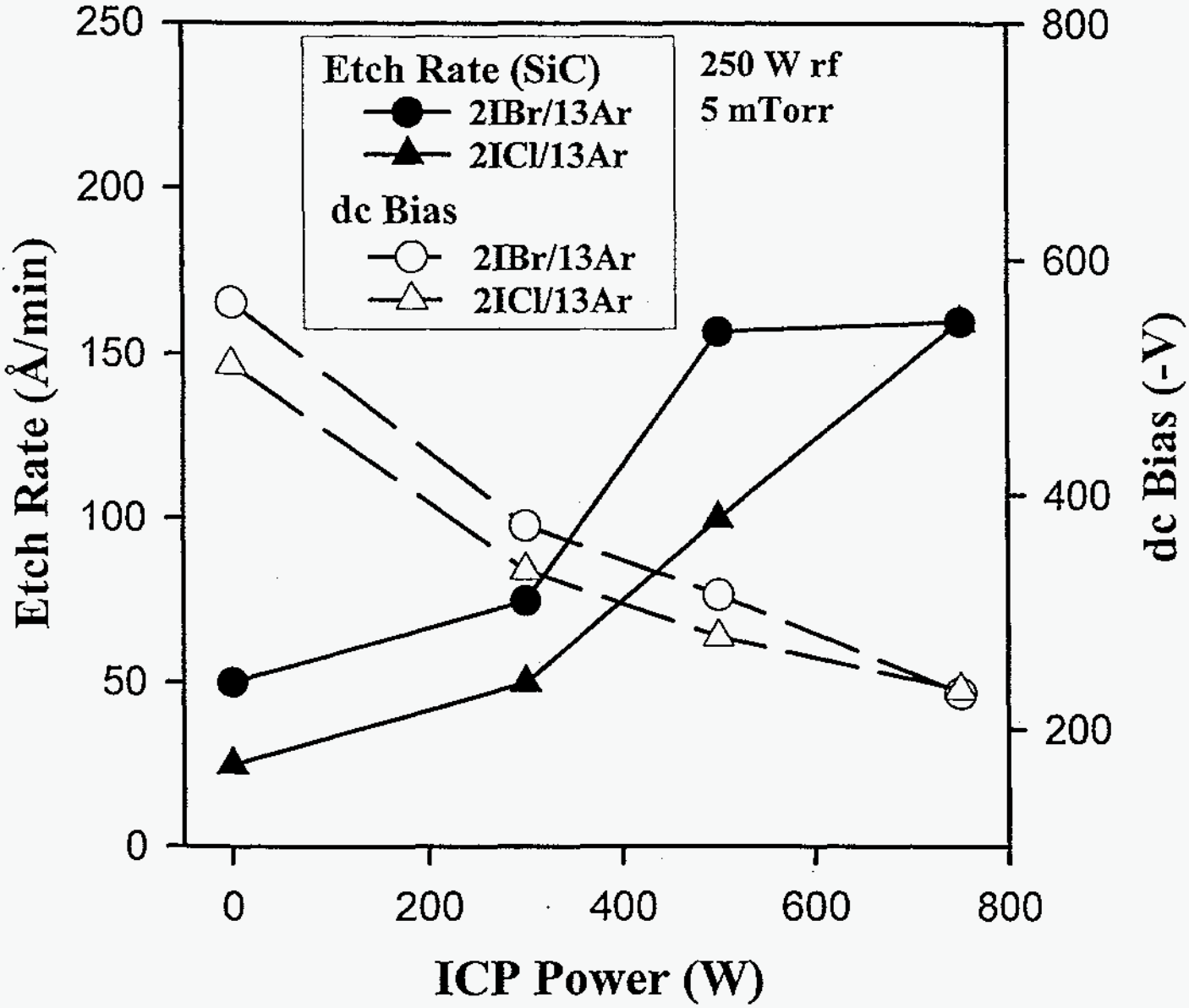

Etch rate (Å/min)
Selectivity of SiC over PR
DC self bias (-V)
10^5
10^4
10^3
10^2
10^1
10^0
0.6
0.5
0.4
0.3
0.2
0.1
100
200
300
400
850W ICP
2mTorr
SiC
Quartz
Si
23mTorr
SiC
Quartz
Si

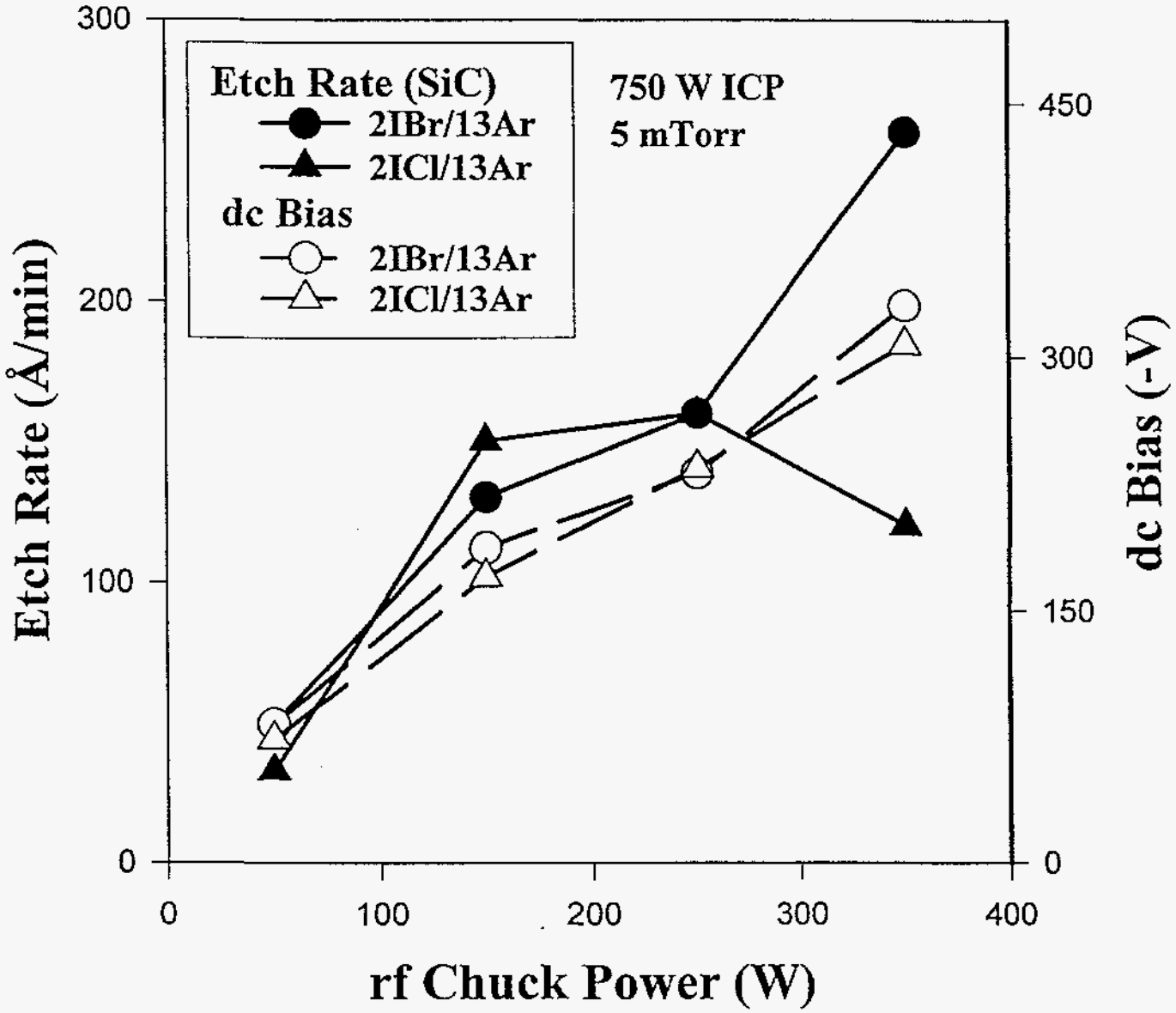

300
200
100
0
Etch Rate (Å/min)
He
Ar
Xe
SiC
750 W ICP
250 W rf
5 mTorr
0
40
80
120
% Cl_2


300
200
100
0
Etch Rate (Å/min)
SiC
250 W rf
5 mTorr
He
Ar
Xe
300
600
900
1200
ICP Power (W)


300
200
100
0
Etch Rate (Å/min)
He
Ar
Xe
SiC
750 W ICP
5 mTorr
400
300
200
100
0
Chuck Bias (-V)
He
Ar
Xe
SiC
750 W ICP
5 mTorr
0
100
200
300
400
rf Power (W)


Etch Rate (SiC)
IBr
ICl
dc Bias
IBr
ICl
750 W ICP
250 W rf
5 mTorr
Etch Rate (Å/min)
dc Bias (-V)
% IBr or ICl
0
200
400
600
800
1000
200
250
300
350
400
0
20
40
60
80
100


Etch Rate (SiC)
2IBr/13Ar
2ICl/13Ar
dc Bias
2IBr/13Ar
2ICl/13Ar
250 W rf
5 mTorr
Etch Rate (Å/min)
dc Bias (-V)
ICP Power (W)
0
50
100
150
200
250
200
400
600
800
0
200
400
600
800


Etch Rate (SiC)
2IBr/13Ar
2ICl/13Ar
dc Bias
2IBr/13Ar
2ICl/13Ar
750 W ICP
5 mTorr
Etch Rate (Å/min)
dc Bias (-V)
rf Chuck Power (W)
0
100
200
300
400
0
100
200
300
0
150
300
450