EXTREMELY HIGH SELECTIVITY ETCHING OF GaAs/AlGaAs IN INDUCTIVELY COUPLED PLASMAS

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ABSTRACT

$BCl_3/SF_6/N_2$/He ICP plasma chemistry has been developed for high selectivity etching of GaAs over $Al_{0.2}Ga_{0.8}As$. The best result showed selectivities of GaAs over AlGaAs of > 200:1, excellent sidewall verticality (> 87 °), smooth surfaces (RMS roughness is ~2 nm) and relatively high etch rate (1500 Å/min) of GaAs features. Addition of nitrogen into BCl_3/SF_6 plasma improved sidewall passivation of GaAs during etching. It was also noticed that addition of He increased the etch rate of GaAs and selectivity of GaAs over $Al_{0.2}Ga_{0.8}As$. In this paper, we report etch results as a function of the process parameters, ICP source power, rf chuck power, % nitrogen, chamber pressure and total gas flow with $BCl_3/SF_6/N_2$/He chemistry. The results show that a simple ICP recipe is an attractive candidate for advanced selective etching of GaAs-based devices, especially for deep feature etching and/or a large (≥ 100 mm) diameter wafer for production scale.

INTRODUCTION

The rapid growth of the opto-telecommunication market has accelerated development of advanced processing technologies for GaAs-based semiconductors. Selective etching of GaAs over AlGaAs has been a key process for fabrication of GaAs-based electronic devices, for example, heterojucntion bipolar transistors (HBTs) and high electron mobility transistors (HEMTs). Conventionally, use of reactive ion etching (RIE) with BCl_3/SF_6, $BCl_3/SF_6/N_2$ or $SiCl_4/SF_6/N_2$ has been a typical choice for the selective etch process.(2-8)

However, there are some difficulties with the process. The RIE technique requires relatively high pressure for etching due to the need for plasma stability at low ionization efficiency. Typical operating pressures are 10 - 30 mTorr. The etch uniformity of a wafer is somewhat related to the chamber pressure. Low pressure processing is attractive for obtaining better uniformity over the wafer. In addition, GaAs chip manufacturers recently scaled up the wafer size from 100 (4 inch) to 150 mm (6 inch). It will be a strong challenge for RIE processes to achieve good etch uniformity on such a large size wafer. However, the operating pressure in an inductively coupled high density plasma (ICP) is 2 to 10 mTorr. It is expected that uniformity will be improved with an ICP process.

Another issue is plasma damage to the semiconductor device during etching. The RIE process is based on capacitively coupled plasma and only one power source is employed. The applied rf chuck power induces a self dc bias on the chuck, which will accelerate ions. The physical impact of the ions on the wafer will accumulate damage in the device.(9-16) If high etch rate is desirable, high rf chuck power is necessary, which will accumulate more damage on the device at the significantly accelerated ion energy.(17-18)

In a high density ICP reactor,(19-24) there are two power inputs for the plasma. One is chuck power, which is similar to the power source for RIE and the other is ICP source power. The main role in generating the plasma is attributed to ICP source power not RIE chuck power. The result provides almost independent control of ion density and ion energy.(21) Ion density is controlled by ICP source power alone. Increasing ICP source power increases ion density. Meanwhile, ion energy is affected by both ICP source power and rf chuck power. It is noted that increasing ICP power decreases induced dc bias (i.e. ion energy) while increasing rf chuck power (i.e. RIE power) raised dc bias on the chuck. Therefore, the ICP source power increases ion density but decreases ion energy. The ICP reactor provides another process parameter to control ions, which is a more advanced process concept than the RIE-only approach because minimum damage (or damage-free) process is possible with an optimized ICP condition with a low rf chuck power and a high ICP source power. Some rf chuck power is still necessary in order to get a vertical sidewall.

One disadvantage of all high density plasma sources has been a low selectivity for etching GaAs over AlGaAs.(25) Realization of high selectivity (> 50:1) has been difficult in high density plasma sources due to too high an ion flux on the wafer, even though ion energy is minimal. Therefore high ion density sources have not been popular for a selective etching process. In this paper, we present an excellent pattern transfer process for selective etching of GaAs/AlGaAs in a high density ICP plasma source. The results show a relatively high etch rate (1500 - 3000 Å/min) of GaAs with extremely high selectivity (> 200:1). Compared to conventional RIE process, our simple ICP process provided more than 3 ~ 6 times faster GaAs etch rate without sacrificing selectivity of

GaAs over $Al_XGa_{1-X}As$, where $x < 0.3$. Therefore, this process has a strong advantage in terms of throughput as well as low damage to the devices, especially for devices which require deep feature etching. It will reduce cost-of-ownership significantly. It also eliminates some problems for device design by providing both high rate and selectivity for GaAs etching.

EXPERIMENTAL

A Plasma-Therm SLR 770 inductively coupled plasma etcher was utilized for selective etching of GaAs over $Al_{0.2}Ga_{0.8}As$. The etcher has He back-side cooling configuration and a mechanical ceramic clamp on the wafer. Bulk GaAs and 3000 Å thick AlGaAs epi-layers with 20 % Al composition were prepared on GaAs wafers. One micron thick photoresist on top of 400 Å SiNx was patterned as a mask for etching of both GaAs and AlGaAs. Each of the 4” GaAs and AlGaAs wafers was cleaved into a quarter and attached next to each other on a 4” bare GaAs carrier with a thermally conductive paste. A short breakthrough etching step was done before selective etching started in order to remove any native oxide on the materials. Gas flows of BCl_3, SF_6, He and N_2 were controlled by electronic mass flow controllers. Total gas flow rates and chamber pressure were varied from 10 to 40 standard cubic centimeter per minute (sccm) and 2.5 to 10 mTorr, respectively. A 2 MHz ICP source power and a 13.56 MHz rf chuck power were changed from 300 to 900 W and 5 W to 20 W, respectively. Self-induced dc bias on the electrode was measured to be about ~ - 45 V. Etch depth was measured by a profilometry. Sidewall and surface morphology was measured by a scanning electron microscope (SEM) and tapping mode atomic force microscopy (AFM), respectively. In order to have accurate calculation for selectivity with a simulation of extremely long over-etching time for the AlGaAs layer, all the characterization data was obtained after 15 min. etching, which produced GaAs etch depths of several micron. It is common to have short over-etching time (less than 10 %) in order to ensure complete removal of GaAs and full exposure of the AlGaAs surface. (2,4)

RESULTS AND DISCUSSION

Figure 1 shows the etch rates of GaAs and AlGaAs and selectivity of GaAs over AlGaAs in terms of % N_2 in total flow of N_2 and He at fixed BCl_3 and SF_6 flow rate. The result of 10 sccm of BCl_3/SF_6 ICP plasma without any addition of N_2 and He gave a rate of about 1700 Å/min of GaAs and selectivity of 70:1. In order to study their effects on etch rate, both He and N_2 gases were introduced separately at a fixed total flow. It is worthwhile to mention that large amounts of He may cause high reflectivity of ICP source power at low ICP power and make the plasma unstable due to the high ionization potential of He.(26) However, we found that a small amount of He addition to BCl_3/SF_6 ICP plasma dramatically increased the etch rate of GaAs and resultant selectivity of GaAs over AlGaAs without affecting the plasma stability. Etch rate of GaAs was raised to 3,700 Å/min in BCl_3/SF_6/He plasmas with 10 sccm He flow, while that of AlGaAs was very hard to measure (< 150 Å) after 15 min etching. It was not difficult to have greater than 200 selectivity for GaAs in BCl_3/SF_6/He plasmas, which was about 3 times higher compared to the value without He addition. Selectivity of GaAs to photoresist was also noticed to be very high (> 10:1). Accuracy of the selectivity data was actually limited by etching time and measurement, and selectivity could be virtually infinite.

Addition of N_2 into BCl_3/SF_6 plasmas decreased the GaAs etch rate slightly. For example, the etch rate of GaAs dropped from 1700 A/min to 1400 A/min with 10 sccm of N_2. It was noticed that N_2 addition enhanced sidewall passivation and produced very anisotropic pattern transfer into GaAs. This result is extremely important for deep etching (> 2 micron thick) of GaAs. By contrast to He, N_2 addition enhanced plasma stability. Optimization of N_2 flow in BCl_3/SF_6 (more strictly, BCl_3) is also very important to achieve residue-free surfaces as well as the sidewall passivation. $BCl_3/SF_6/N_2$ chemistries may create organic polymer in the plasma in the presence of resist and deposit it on the etched surface as well as sidewall of the feature. Residues on the etched surface might reduce yield of the devices because the cleanliness of the AlGaAs surface is very important for metal contact or re-growth after etching.

Figure 2 shows SEM micrographs after ICP etching. Figure 2 (top) shows a GaAs feature after etching with a pure BCl_3/SF_6 ICP plasma without any N_2 or He dilution. Notice that undercutting on the sidewall is significant. This implies passivation from the BCl_3 component alone is insufficient. However, increasing the BCl_3 flow will reduce selectivity of GaAs over AlGaAs. The basic mechanism of selective etching of GaAs over AlGaAs is formation of AlF_X on the AlGaAs layer.(4,5) The AlF_X has high bond strength and is non-volatile at room temperature. The AlF_X on the AlGaAs plays a role as a protecting layer, and prevents underlying hte AlGaAs from being etched. Addition of more BCl_3 means reduction of % SF_6 in the plasma composition. Also BCl_3 increases the physical component of the etch process. These effects increase ion bombardment on the thin ($\leq$ 200 Å) AlGaAs layer. This will reduce selectivity of GaAs over AlGaAs due to incomplete AlF_X coverage on AlGaAs. Another way to control sidewall passivation is to add N_2 into the BCl_3/SF_6 plasma, as we discussed earlier.

Addition of N_2 and He also significantly improved surface morphology. Figure 3 shows atomic force microscopy (AFM) data on the GaAs control (top), GaAs etched in BCl_3/SF_6 (middle) and $BCl_3/SF_6/N_2$/He plasmas (bottom). Etched depths were more than 2 micron for both samples. RMS roughness of GaAs control from the scan size of 10 x 10 μm^2 was 0.5 nm. For GaAs etched in BCl_3/SF_6 plasma the RMS value was 86 nm. However, the RMS roughness dramatically dropped to 2.0 nm for GaAs etched in a $BCl_3/SF_6/N_2$/He plasma. This shows that GaAs surfaces processed in a $BCl_3/SF_6/N_2$/He ICP plasma remain very smooth after even a few microns of etching. Figure 4 shows RMS roughness of GaAs etched in $BCl_3/SF_6/N_2$/He plasmas as a function of % N_2. Again, when N_2 and He were added to BCl_3/SF_6 plasma, GaAs had very smooth surfaces as shown on Figure 4. According to Figure 3 and 4, addition of N_2 and/or He to BCl_3/SF_6 is essential in order to obtain a smooth surface. We believe that ion assistance from N_2 and He plasma improved balanced removal of group III and V by-products during etching even though ion energy was significantly reduced compared to a conventional RIE process.

Figure 5 shows etch rate of GaAs and AlGaAs and selectivity as a function of ICP source power. In overall range from 300 to 900 W ICP power, etch rate of GaAs and AlGaAs was not changed significantly. Etch rate of GaAs was about 1400 Å/min and that of AlGaAs was < 10 Å/min. Selectivity was over 200 :1. The advantage of lower source power is improved selectivity over resist.

Etch rate of GaAs and AlGaAs was a strong function of rf (or RIE) chuck power (Figure 6). Once rf chuck power increased from 5 to 20 W, etch rate of GaAs and AlGaAs increased from 1100 to 1800 Å/min and 3 to 45 Å/min, respectively. Therefore, selectivity decreased dramatically from 380 to 38. According to Figure 5 and 6, etch rate of the two materials, especially $Al_{0.2}Ga_{0.8}As$ in ICP $BCl_3/SF_6/N_2/He$ is ion energy-limited, once gas flows are fixed. Keep it mind that it is necessary to apply some rf chuck power in order to get a vertical sidewall. The data indicates that optimization of the rf chuck power (i.e. dc bias or ion energy) is very important for obtaining both high selectivity and anisotropy.

Chamber pressure and total flow also changed selectivity (Figure 7 and 8). High pressure and high total flow increased selectivity by reduction of ion energy with more collisions in short mean free path of ions. Both chamber pressure and total flow have to be optimized because both of them affect uniformity, selectivity and sidewall passivation during etching. For an example, in order to obtain better uniformity it is preferred to use low chamber pressure. However, too low pressure may degrade selectivity over both AkGaAs and photoresist due to physical bombardment of highly accelerated ions.

SUMMARY AND CONCLUSIONS

Combined addition of N_2 and He into BCl_3/SF_6 plasmas made it possible to have a new process window for high selective etching of GaAs over $Al_{0.2}Ga_{0.8}As$ with clean surfaces and excellent anisotropy. Plasma etching with the $BCl_3/SF_6/N_2/He$ ICP chemistry made it possible to have extremely high selectivity (> 200:1), clean surface (RMS is ~ 2 nm) and reasonably fast etch rate (1500 Å/min). Sidewall angle of the etched

GaAs was measured as ≥ 87°, which indicated excellent control on critical dimension. Selectivity of GaAs to a photoresist was also noticed to be very high (> 10:1). It is found that etching of GaAs and AlGaAs in the $BCl_3/SF_6/N_2/He$ ICP plasma at fixed gas flow is ion energy-limited. This process is also applicable for selective etching of GaAs over InGaP. In summary, the ICP selective etching recipe can be a strong candidate as an advanced process for GaAs-based devices, especially for deep feature etching and/or a large size (≥ 100 mm) wafers.

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FIGURE CAPTIONS

Figure 1. Etch rate and selectivity of GaAs and AlGaAs as a function of % N_2 in N_2 + He with fixed BCl_3/SF_6 flow in ICP $BCl_3/SF_6/N_2$/He etching .

Figure 2. SEM micrographs of GaAs after etching with BCl_3/SF_6 (top) and $BCl_3/SF_6/N_2$/He. Photoresist is still in place (top and middle) and has been removed (bottom).

Figure 3. Atomic force microscopy scans on GaAs etched in BCl_3/SF_6(top) and $BCl_3/SF_6/N_2$/He (bottom) plasma at 300 W ICP, 10 W rf and 5 mTorr.

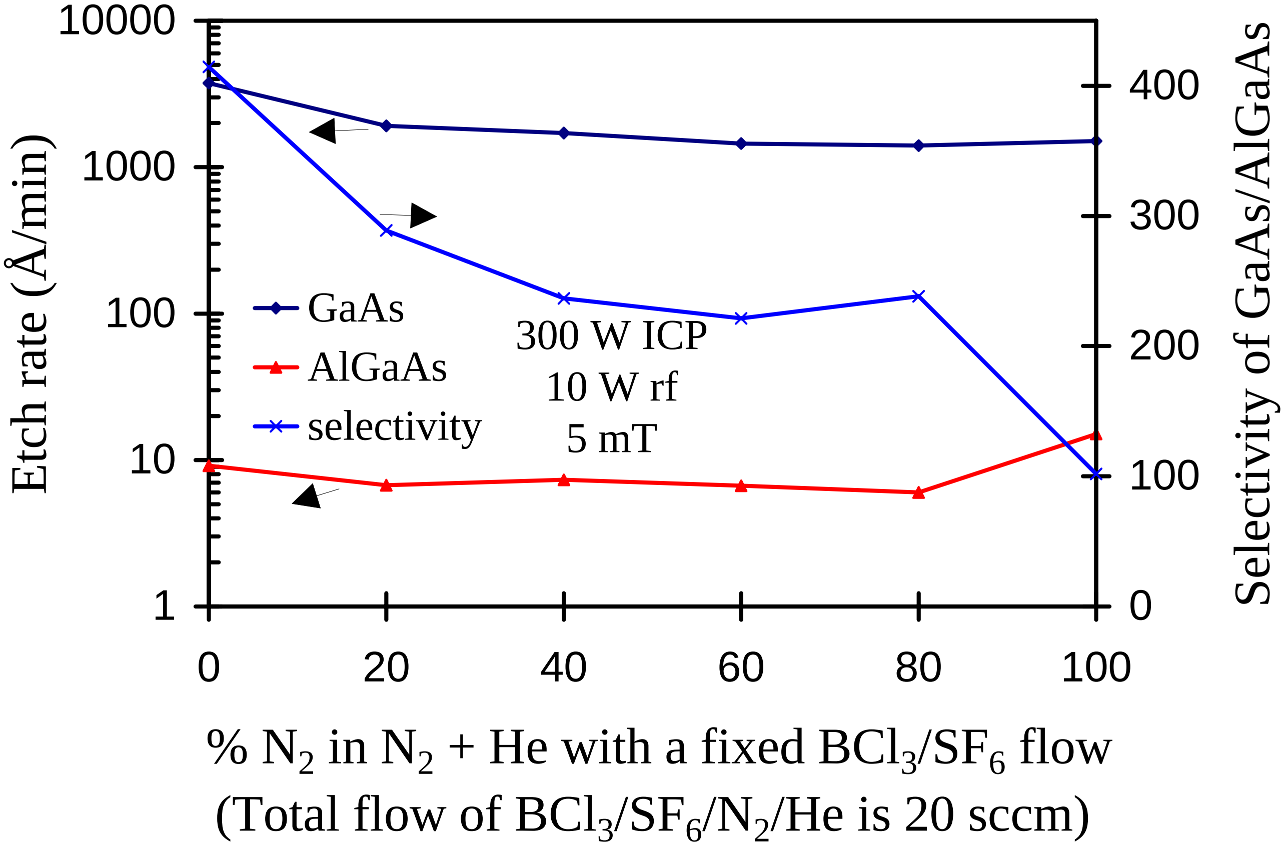
Figure 4. RMS roughness of GaAs etched in $BCl_3/SF_6/N_2$/He plasmas as a function of % N_2 in the mixture of N_2 + He at a fixed BCl_3 and SF_6 flow.

Figure 5. Etch rate of GaAs and AlGaAs, and selectivity as a function of ICP source power.

Figure 6. Etch rate of GaAs and AlGaAs, and selectivity as a function of rf (or RIE) chuck power.

Figure 7. Etch rate of GaAs and AlGaAs, and selectivity as a function of chamber pressure..

Figure 8. Etch rate of GaAs and AlGaAs, and selectivity as a function of total gas flow.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100
10
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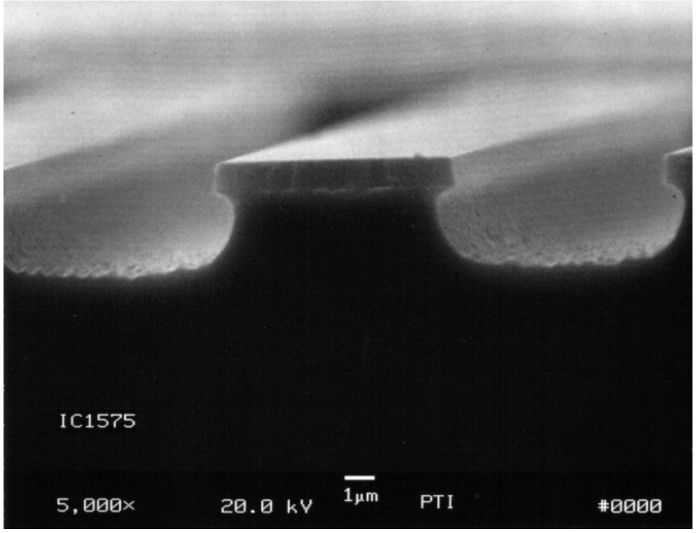
Etch rate (Å/min)
400
300
200
100
0
Selectivity of GaAs/AlGaAs
GaAs
AlGaAs
selectivity
300 W ICP
10 W rf
5 mT
0
20
40
60
80
100
% N_2 in N_2 + He with a fixed BCl_3/SF_6 flow
(Total flow of $BCl_3/SF_6/N_2$/He is 20 sccm)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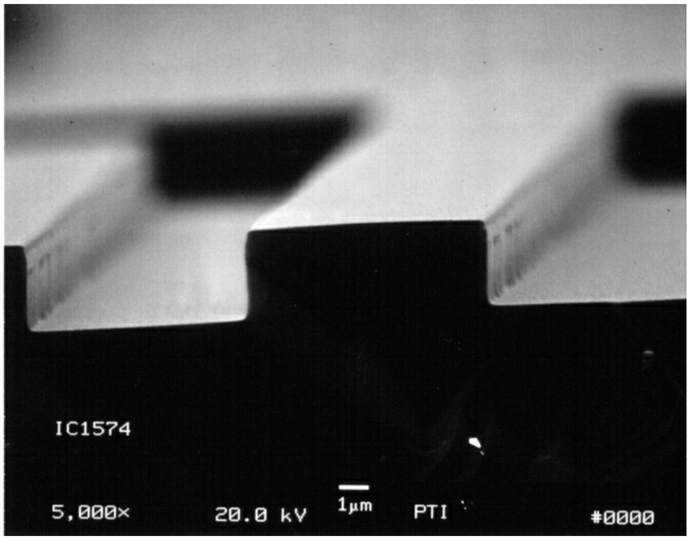
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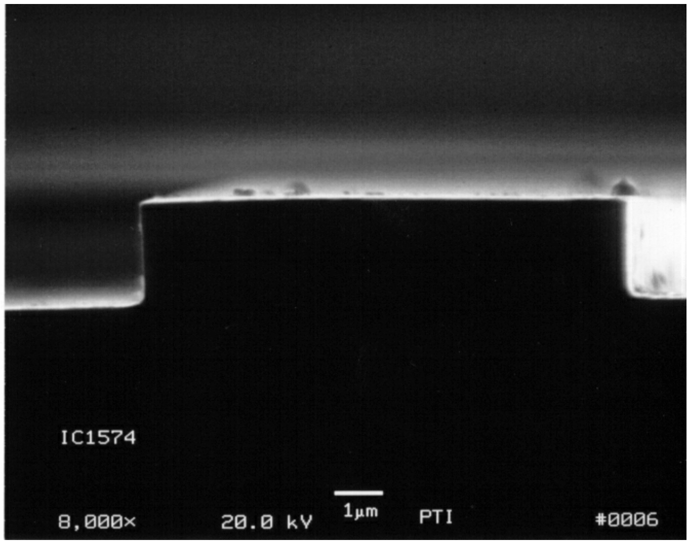
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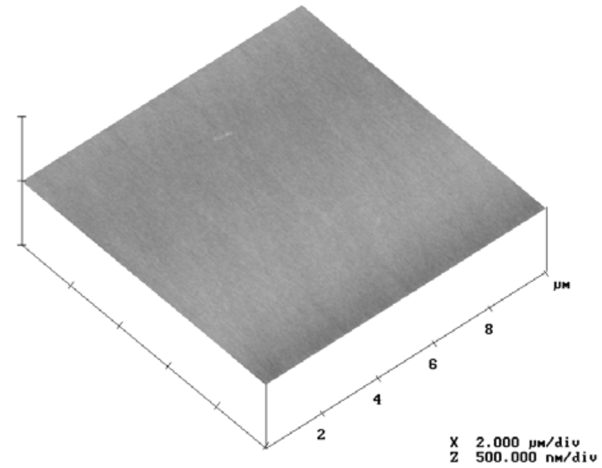
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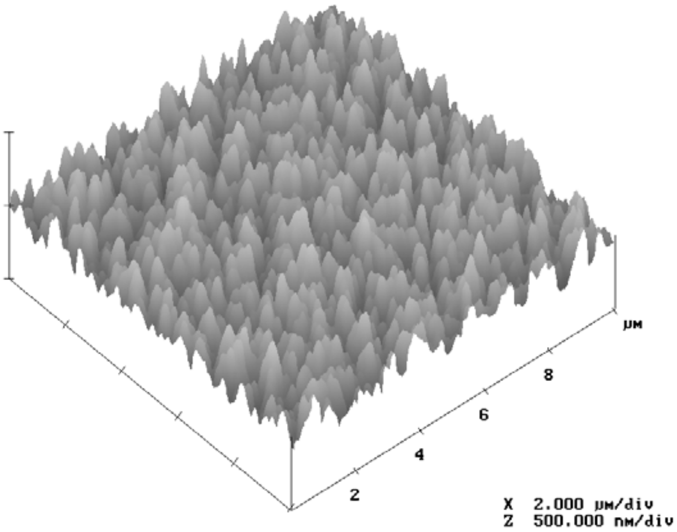
8
6
4
2
X 2.000 μm/div
Z 500.000 nm/div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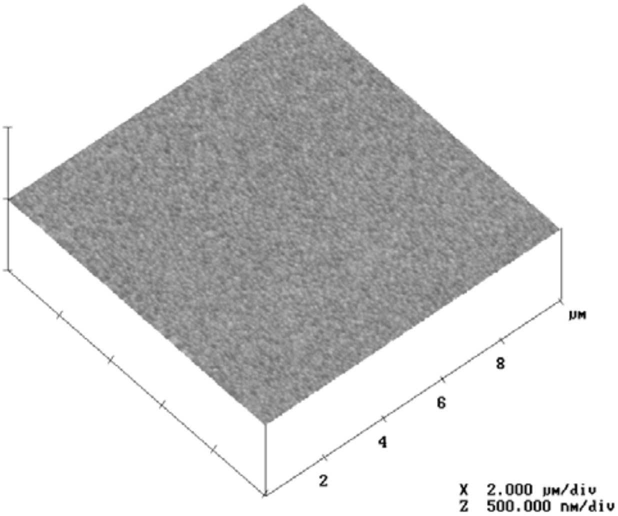
6
4
2
X 2.000 μm/div
Z 500.000 nm/div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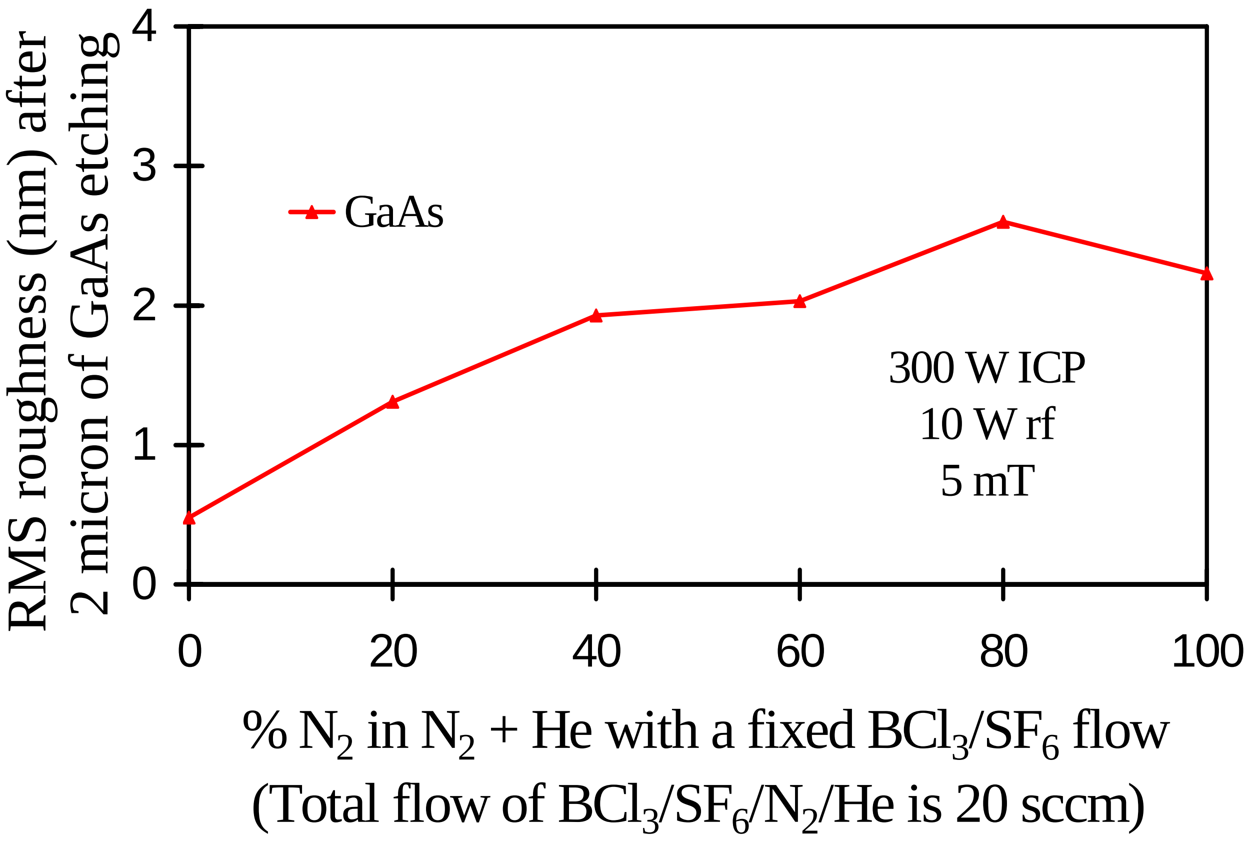
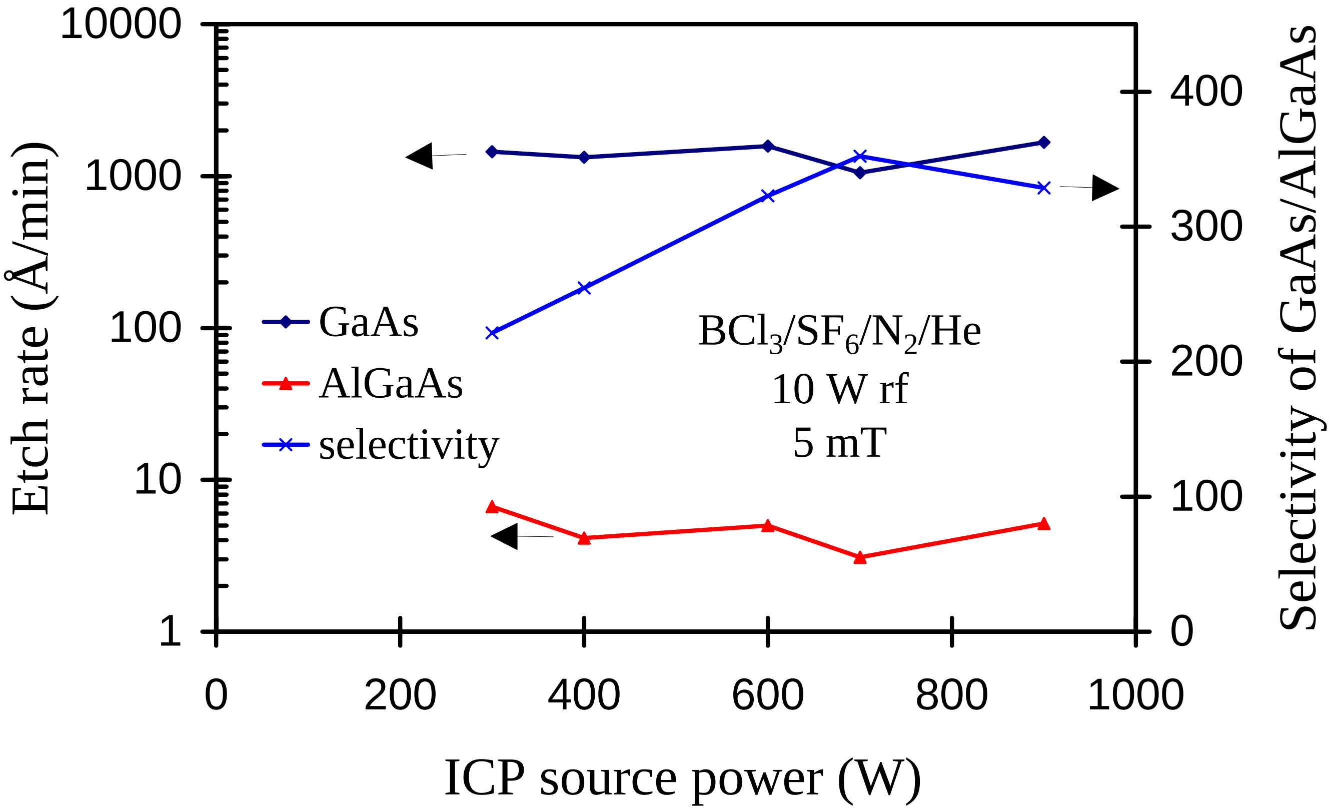
2
X 2.000 μm/div
Z 500.000 nm/div


RMS roughness (nm) after
2 micron of GaAs etching
0
1
2
3
4
GaAs
300 W ICP
10 W rf
5 mT
0
20
40
60
80
100
% N_2 in N_2 + He with a fixed BCl_3/SF_6 flow
(Total flow of $BCl_3/SF_6/N_2/He$ is 20 sccm)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100
10
1
Etch rate (Å/min)
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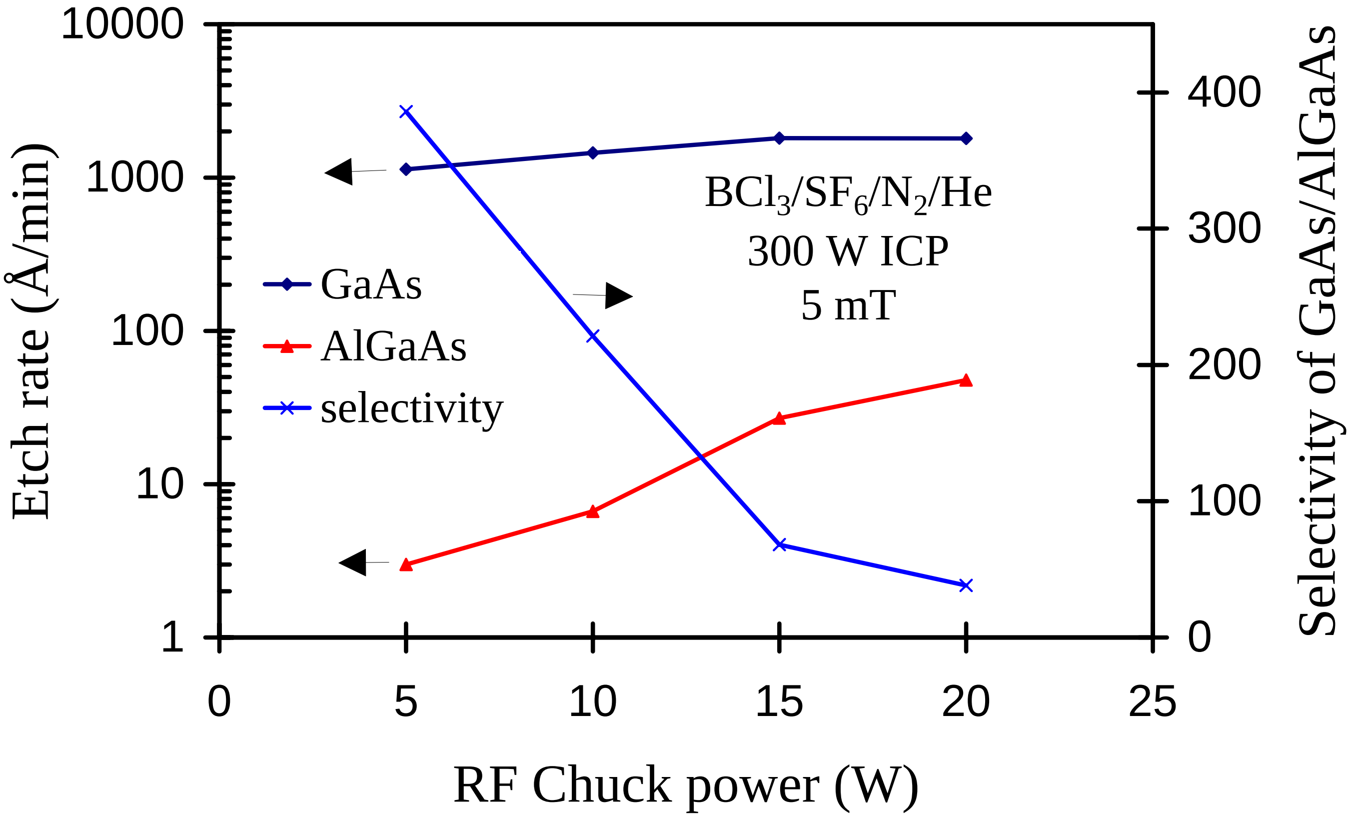
300
200
100
0
Selectivity of GaAs/AlGaAs
0
200
400
600
800
1000
ICP source power (W)
GaAs
AlGaAs
selectivity
BCl$_3$/SF$_6$/N$_2$/He
10 W rf
5 mT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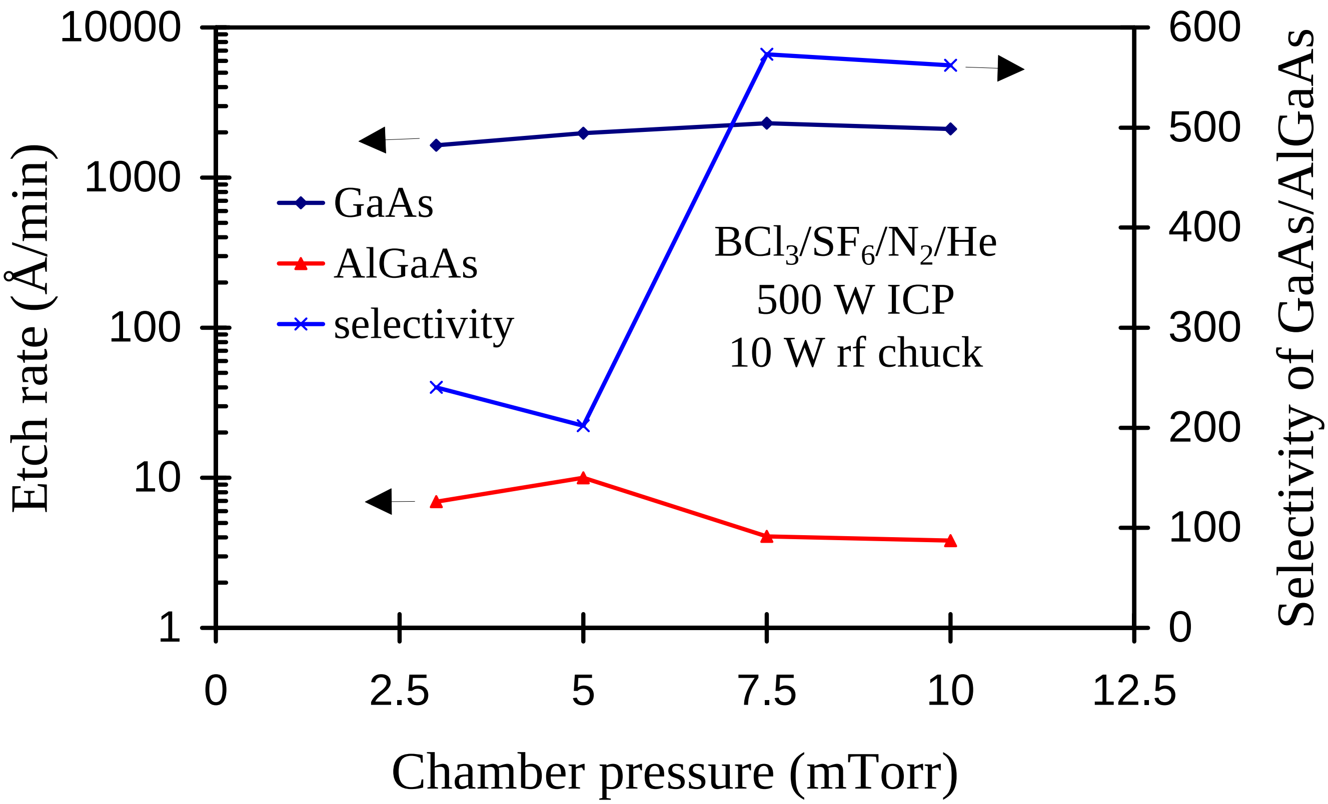
1000
100
10
1
Etch rate (Å/min)
400
300
200
100
0
Selectivity of GaAs/AlGaAs
0
5
10
15
20
25
RF Chuck power (W)
GaAs
AlGaAs
selectivity
$BCl_3/SF_6/N_2/He$
300 W ICP
5 mT


Etch rate (Å/min)
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1000
100
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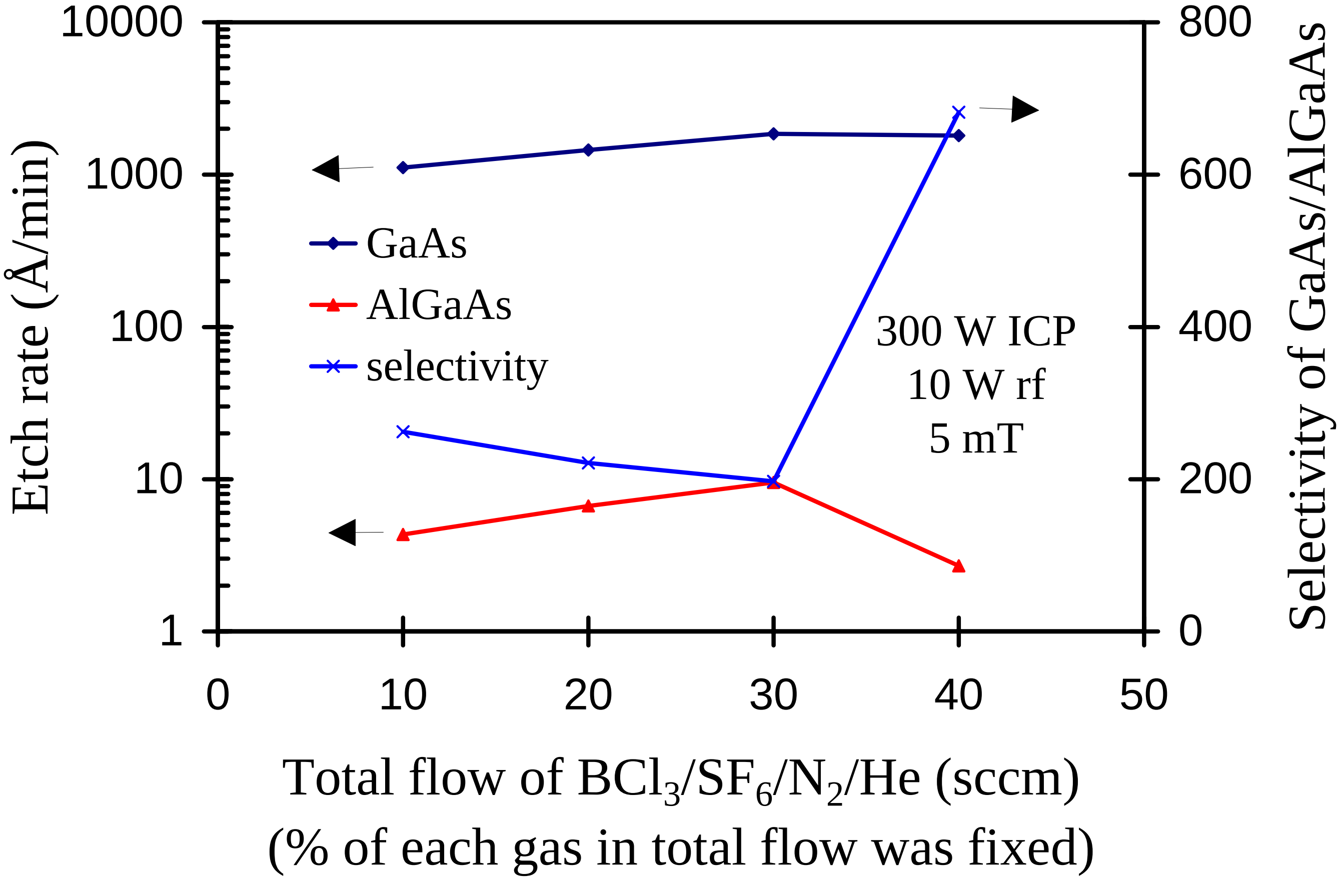
Selectivity of GaAs/AlGaAs
600
500
400
300
200
100
0
GaAs
AlGaAs
selectivity
$BCl_3/SF_6/N_2/He$
500 W ICP
10 W rf chuck
0
2.5
5
7.5
10
12.5
Chamber pressure (mTorr)


10000
1000
100
10
1
Etch rate (Å/min)
800
600
400
200
0
Selectivity of GaAs/AlGaAs
GaAs
AlGaAs
selectivity
300 W ICP
10 W rf
5 mT
0
10
20
30
40
50
Total flow of BCl3/SF6/N2/He (sccm)
(% of each gas in total flow was fixed)