

Influence of surface material on the BCl density
in inductively coupled discharges

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Abstract

The relative density of BCl radicals has been measured in a modified Applied Materials DPS metal etch chamber using laser-induced fluorescence. In plasmas containing mixtures of BCl₃ with Cl₂, Ar and /or N₂, the relative BCl density was measured as a function of source and bias power, pressure, flow rate, BCl₃ / Cl₂ ratio and argon addition. To determine the influence of surface materials on the bulk plasma properties, the relative BCl density was measured using four different substrate types; aluminum, alumina, photoresist, and photoresist-patterned aluminum. In most cases, the relative BCl density was highest above photoresist-coated wafers and lowest above blanket aluminum wafers. The BCl density increased with increasing source power and the ratio of BCl₃ to Cl₂, while the addition of N₂ to a BCl₃ / Cl₂ plasma resulted in a decrease in BCl density. The BCl density was relatively insensitive to changes in the other plasma parameters.

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I. Introduction

Plasmas containing gas mixtures of boron trichloride (BCl_3) and chlorine (Cl_2) are used for a number of microelectronics applications including metal interconnect definition and III-V material processing. In such plasmas, the gas phase atomic and molecular radical densities are fundamental plasma parameters that are influenced by a number of gas and surface reactions. For example, BCl is a major dissociation product of BCl_3 . BCl can be produced by a number of mechanisms that are sensitive to the electron density and energy, surface conditions, and tool parameters. Thus the BCl density is an important plasma parameter that should be measured as an aid to improved fundamental understanding of discharges used in microelectronic device fabrication and to benchmarking of numerical models.

Recently, we reported measurements of the relative BCl density in a Gaseous Electronics Conference (GEC) rf reference cell that had been modified with an inductive plasma source.¹ That investigation used laser induced fluorescence (LIF) to measure the relative BCl density in an inductively coupled plasma (ICP) containing BCl_3 in combination with Cl_2 , Ar, and / or N_2 . The plasma induced emission (PIE) was also recorded to compare the scaling of the excited state emission with the ground state BCl density. However, the BCl density and PIE intensity did not always exhibit the same dependence on reactor parameters, further confirming that PIE alone is not a reliable indicator of relative BCl density in ICP discharges. No evidence of significant interactions between BCl_3 and either Ar or Cl_2 were evident. The BCl density was suppressed by addition of N_2 to the discharge, which was attributed to changes in the electron energy distribution function caused by the nitrogen addition, or dissociation of BCl by excited N_2 .

Measurements of the spatial variation of the BCl density showed uniform BCl density from the center of the plasma to the edge of the glow region, and only a slight decrease in BCl density near the upper electrode. Finally, after running a discharge in $\text{BCl}_3 / \text{N}_2$ mixtures, a persistent BCl signal was observed when only Cl_2 was flowing, indicating that a BN film was formed which could be etched by chlorine. This showed that chamber cleaning is important after $\text{BCl}_3 / \text{N}_2$ mixtures are used. For the experiments in the GEC chamber, the influence of surface material on the BCl density was not investigated; the wafer surface was bare silicon.

This work extends our previous measurements of the BCl density to a commercial etch tool, the Applied Materials DPS metal etch system. To examine directly the influence of surface material on the BCl density, four different substrates were used; aluminum, alumina, photoresist and photoresist-patterned aluminum. In addition to measuring fundamental plasma parameters in the DPS chamber, a comparison of the measurements obtained in the two very different discharge geometries (GEC and DPS) provides insight into the influence of reactor material, geometry, surface coverage, and operating conditions. An example of such a comparison is our recent measurements of the electron and negative ion densities in both the DPS and GEC plasma chambers.²⁻⁴ That work demonstrated the importance of surface condition on the electron and negative ion density for realistic surface materials. Finally, these measurements provided data essential to effective benchmarking of computer models and to the demonstration of a validated, geometry-independent set of chemical mechanisms to model aluminum etching by radicals containing chlorine.⁵

II. Experimental configuration

The experiments were performed in an Applied Materials DPS metal etch chamber that had been modified for enhanced diagnostic access. The modification, provided by Applied Materials, consisted of a number of additional diagnostic access ports that were machined into the standard upper chamber assembly. As shown in Fig. 1, provision was made for seven 1.7 and 2.2 inch diameter windows at a number of points around the chamber. When diagnostic access to the plasma region above the 200 mm diameter wafer was not required, the windows were replaced with anodized aluminum inserts which were flush with the inside of the etch chamber wall. The chamber walls were anodized aluminum and the chamber dome was alumina. The balance of the process chamber, platform, gas handling and rf system were standard commercial products. Extensive measurements of the metal etching parameters of the tool with and without the window plugs indicated that the windows did not perturb the etch rate or the uniformity.

The relative BCl density in the plasma was measured using LIF. A frequency quadrupled Nd:YAG laser was used to excite the (0,1) vibrational levels of the $A^1\Pi-X^1\Sigma^+$ electronic manifold at 266 nm. The energy was attenuated to less than one mJ per pulse. For these experiments, the Nd:YAG cavity injection seed laser was turned off. While the unseeded laser linewidth was not measured, this linewidth would be expected to be on the order of a few tenths of a wavenumber, enough to excite 3 to 4 different BCl rotational transitions.⁶⁻⁸ This supposition is supported by the observation that the LIF with the laser unseeded was approximately four times larger than with the laser seeded (and presumably exciting only one rotational transition), despite only a 20 percent increase in the laser energy when operated unseeded.

LIF was observed from both the (1,1) transition at 272 nm and the (1,0) transition at 266 nm of the $A^1\Pi-X^1\Sigma^+$ manifold. The LIF at both wavelengths became zero when either an argon plasma was operated in the chamber or the plasma was turned off, indicating that scattering of the 266 nm probe beam was not significant, and that the argon plasma does not sputter significant amounts of BCl-containing species from the coating that develops on the chamber surfaces after extended operation. For all of the data presented in the work below, the LIF was detected at 272 nm. LIF was imaged at right angles to the pump beam using a combination of UV enhanced mirrors and a 200 mm focal length lens. A 0.5-m monochromator and photomultiplier tube were used to detect the LIF. The monochromator slit width was 150 μm with a slit height of 8 mm. Output from the photomultiplier tube was recorded using a transient digitizer. The background plasma induced emission (PIE) signal was also recorded. In most cases, the LIF signal was a factor of 3 to 8 higher than the PIE signal. The BCl density reported here was obtained by fitting the time dependent fluorescence decay, averaged over 128 shots, to a single exponential, and normalizing to the pump laser intensity. This procedure compensated for possible changes in the collisional quenching rate of the BCl excited state as the reactor parameters were changed, and also compensated for variations in the laser energy. Over the parameter space investigated during these experiments, the fluorescence lifetime did not vary.¹ The measurement volume, as determined by back illuminating the monochromator, was approximately 8 mm high, 6 mm deep and 0.2 mm wide and located approximately 35 mm above the center of the wafer ($r = 0$ cm).

In order to observe the influence of surface material, four different surfaces, representative of typical processing surfaces were used. Surfaces included aluminum,

alumina, blanket photoresist (Shipley Apex Deep UV) and patterned aluminum. The patterned aluminum wafers consisted of a 1 μm thick aluminum layer deposited over a silicon oxide layer. The aluminum layer was then patterned using photoresist into approximately 0.5 inch squares with a 50 percent open area. During measurements above the patterned aluminum wafers, optical endpoint (Al atomic emission at 396 nm) was used to insure the measurements were obtained during metal etching, and before all of the aluminum layer was removed. The blanket photoresist wafers were examined before and after the measurements to insure the photoresist was not removed or reticulated during the measurement time. The Al and Al_2O_3 wafers were pure, solid materials that had been machined to wafer dimensions. Alumina was included in the material set since it is a common reactor material (e.g. the dome and some interior surfaces) and it is thought to be relatively unreactive.

Measurements were obtained for a minimum of 18 standard tool settings covering a wide range of source power, pressure, bias, flow rate, Cl_2 to BCl_3 ratio, and argon addition. Tool parameters were varied about a nominal center operating point of 1100 W source power, 200 W bias power, 10 mTorr pressure, Cl_2 flow rate of 100 sccm and a BCl_3 flow rate of 40 sccm. Typically, measurements were obtained after allowing the plasma to stabilize for 10 seconds and required approximately 7 seconds to complete. Depending on the plasma conditions, typical aluminum etch times were on the order of 40 to 65 seconds. To insure that the tool condition had not significantly shifted during the measurements, several tool settings and surfaces were repeated multiple times. In general, the measurements were reproducible to within 15 percent from day to day.

III. Results and Discussion

As the inductive source power was increased from 600 to 1100 W, the relative BCl density increased between 20 and 40 percent (Fig. 2). When the power was increased above 1100 W, the BCl density was approximately constant. While the BCl density depended on the surface material, the general functional trends did not; the BCl density increased for lower rf source power but appears to saturate at higher powers. Over this same parameter space, previous measurements showed that the electron density increased linearly with rf source power.² As a result, for the lower rf powers, the BCl production by electron driven dissociation of BCl_2 and BCl_3 appears to be important. However, for source powers above 1100 W, the BCl dissociation fraction was approximately constant, despite an increase in the electron density. Thus there appears to be a balance between the electron driven BCl production processes, presumably dissociation of BCl_2 and BCl_3 , and loss processes such as electron dissociation of BCl to form B and Cl. In previous work in the GEC rf reference cell, the BCl density was constant, irrespective of the inductive source power in gas mixtures containing BCl_3 and Cl_2 or Ar.¹ The observations in the GEC chamber are consistent with these measurements in the DPS chamber since the power per unit volume of plasma in the GEC chamber was a factor of approximately 2 to 4 higher than in the DPS chamber.

The influence of the different surface materials is evident in these measurements. In previous work in the DPS chamber, the electron density above aluminum wafers was approximately a factor of two higher than above photoresist coated surfaces.² However, the trends in the negative ion density were reversed; the negative ion density was a factor of two higher above photoresist surfaces compared with aluminum surfaces. Previously, it

was argued that these differences were likely due to material dependent differences in the surface recombination rates for the formation of Cl_2 from Cl , and the subsequent gas phase formation of Cl^- by dissociative attachment of Cl_2 .² In addition to changes in the surface recombination rate, other possible mechanisms included the unknown influence of the sputtered photoresist and / or photoresist etch products (C_xCl_y) on the gas phase chemistry and ionization rate. Whatever the exact mechanism, it was clear that the presence of any photoresist had a dominant influence on the electron and negative ion density formation.

While there are a couple of exceptions, a general observation in all of the BCl data obtained in this investigation was that the BCl density was highest above the photoresist surface, and lowest above the aluminum surface. The BCl density measured above patterned aluminum and alumina was generally between the values obtained for the photoresist and aluminum surfaces. Surprisingly, the BCl density was highest above the blanket photoresist surface, despite the fact that the electron density was a factor of two smaller than the value measured with an aluminum surface. This observation is similar to the trends in the negative ion density.² In light of these observations, it may be possible that a surface related process is influencing the gas phase BCl density or one of its precursors. If the BCl were produced only by gas phase, electron-driven dissociation mechanisms, the BCl density would be highest above the aluminum substrate due to the higher electron density. However, since the BCl density does depend on the surface, and furthermore, since the BCl density was highest above the surface with the lowest electron density, it seems likely that surface production mechanisms of BCl and / or production of a precursor molecule, e.g. BCl_2 which is subsequently dissociated in the plasma, contribute

in some way to the measured BCl density. However, the relative difference in the BCl density above the four different surface materials is significantly smaller than the differences that were previously reported in the electron and negative ion density for these same discharge conditions.² As a result, the contributions of surface reactions to the gas phase BCl density were probably not as important as they were to the negative ion density.

A comparison of the BCl density above the aluminum and alumina surfaces shows that the flow of etch products off the aluminum surface into the gas phase did not significantly influence the BCl density. Alumina was added to the study to provide a nominally unreactive surface compared with the aluminum, and to examine the influence of the etch products on the gas phase species density. For example, for a patterned aluminum wafer and a typical aluminum etch rate of 1.2 $\mu\text{m} / \text{min}$, the calculated gas flux of aluminum etch products (mostly AlCl_3 from mass spectroscopy measurements) off the surface and into the gas phase is approximately 40 sccm.⁹ By comparison, a typical flow rate from the mass flow controllers was 140 sccm. However, this large flow of etch product from the surface did not significantly alter the BCl density when compared with a nominally unreactive alumina surface. In our previous measurements of the electron and negative ion density, it was reported that the electron density in the presence of aluminum and alumina was also insensitive to the flow of etch products from the wafer surface back into the gas phase.²

As the rf bias power was increased from 0 to 300 W, the relative BCl density above each substrate material was constant (Fig. 3). It was proposed above that surface reactions may play a small role in determining the gas phase BCl density. With no bias power applied to the wafer chuck, the ion bombardment energy at the surface is

significantly smaller than when an rf bias is applied. With no rf bias, the energies of the ions that strike the surface are approximately the plasma potential (10 - 20 V), while with rf bias, the ion energy striking the surface can increase to hundreds of volts. However, over the range of bias power investigated, the BCl density was independent of the wafer bias conditions. If ion driven surface desorption mechanisms are important in determining the BCl density, then the threshold energy for the sputter process is less than the plasma potential, and the yield is roughly independent of ion energy. Alternatively, the important desorption mechanism (if present at all) may not be ion driven.

As shown in Fig. 4, increasing the total chamber pressure from 5 to 30 mTorr resulted in a factor of two increase in the BCl density above an aluminum substrate. However, the BCl density above the photoresist containing surfaces and the alumina surface were independent of chamber pressure. In our previous measurements of the BCl density in the GEC discharge chamber, the BCl density increased proportionally with pressure while the electron density was approximately constant.^{1,3,4} As a result, it was proposed that the dissociation fraction of the precursor gas was constant. Unlike the GEC discharge data, the electron density in the DPS chamber decreased as the pressure was increased; the electron density above the aluminum substrate decreased 40 percent while the electron density above the photoresist surface decreased 60 percent.² If the BCl formation is dominated by gas phase electron dissociation mechanisms, an increasing BCl₃ density and a decreasing electron density would result in the a sublinear increase, or constant BCl fraction with increased chamber pressure. Looking at the details of the data, this trend is observed. For example, the electron density above the photoresist coated surface decreased the most with increased pressure, and the trend in the BCl density with

pressure was the flattest. Conversely, the electron density above the aluminum surface decreased the least of any of the surfaces and the change in the BCl density with pressure was increasing but less than proportional to pressure. Thus the major features of the BCl density scaling with pressure can be explained with a gas phase mechanism. This may suggest that, if present, the surface desorption mechanisms that produce the BCl or its gas phase precursor are independent of pressure.

As the Cl_2 to BCl_3 ratio was changed from pure Cl_2 to pure BCl_3 , the BCl density increased linearly from zero (Fig. 5). For these measurements, the total flow rate was held constant at 140 sccm and the $\text{Cl}_2 / \text{BCl}_3$ ratio was changed. Over this same parameter space, the electron density was constant above the photoresist surfaces and slightly decreasing above the alumina and aluminum substrates.² The linear relationship indicates that the Cl_2 mostly acts as a simple diluent, reducing the BCl density by lowering the density of BCl_3 input gas. In addition, the linear relationship between BCl density and BCl_3 fraction in the input gas indicates that for a constant power and pressure, the BCl_3 dissociation fraction to BCl is constant with added Cl_2 concentration. Therefore, there is minimal chemical interaction between the Cl_2 and BCl_3 or their dissociation products. This measurement is in good agreement with our previous measurements in the GEC discharge chamber.¹ In that measurement, the BCl density also increased linearly when the BCl_3 to Cl_2 , or BCl_3 to Ar ratio was varied between 0 and 1. In addition, the electron density was constant with BCl_3 to Cl_2 , or BCl_3 to Ar ratio.

As shown in Fig. 6, decreasing the total flow rate from 140 sccm to 35 sccm, had a minimal change in the BCl density. Over this same parameter space, the electron and negative ion density were also approximately constant. However, as the total flow rate

was decreased, the surface reaction rates and the amount of etch product that was recycled back into the plasma and dissociated could be expected to change since the etch rate was a function of total gas flow. Since the gas phase BCl density was independent of total flow rate, the flow of etch products from the surface into the plasma had minimal influence on the mechanisms that produced the gas phase BCl. This is further supported by the BCl density being the same above an etching surface (the blanket aluminum) and the nominally unreactive alumina surface.

The influence of argon addition on $\text{Cl}_2 / \text{BCl}_3$ metal etch mixtures, typical of overetch recipes, is shown in Fig. 7. For this set of measurements, the tool settings were changed to 900 W source power, 185 W bias power, Cl_2 flow rate of 60 sccm and a BCl_3 flow rate of 30 sccm. Argon flow rate was 0, 25 and 50 sccm and pressure was maintained at 7 mTorr for all conditions. As argon was added to the plasma, the BCl density did not change. In addition, previous work showed that the electron and negative ion density were also constant with argon addition for these experimental conditions.² The constant BCl density with argon addition is consistent with our previous measurements in the GEC chamber that showed argon addition had a minimal impact on the bulk plasma species densities.⁴ The only exception to this observation was when the Ar / Cl_2 ratio was greater than one.^{4, 10}

In some cases, nitrogen is added to $\text{BCl}_3 / \text{Cl}_2$ containing plasmas to reduce residue formation and post-etch corrosion. The influence of nitrogen addition on the BCl density was investigated above aluminum and alumina surfaces. Nitrogen was added to the baseline chamber operating conditions of 1100 W source power, 200 W bias power, Cl_2 flow rate of 100 sccm and a BCl_3 flow rate of 40 sccm. The discharge was operated in

both a constant pressure (10 mTorr) mode where the downstream throttle valve control was active, and a constant partial pressure mode, where the chamber pressure was allowed to increase with nitrogen addition and the throttle valve was fixed. As shown in Fig. 8, in all cases the addition of nitrogen to the gas mixture resulted in a decrease in the BCl density. The fractional decrease in the BCl density was the same when the discharge was operated with constant Nitrogen partial pressure or a constant total pressure. However, the fractional decrease with nitrogen addition did depend on the surface material. Unfortunately, we did not perform electron or negative ion density measurements for these discharge conditions. The decrease in BCl density with nitrogen addition is consistent with our previous measurements in the GEC discharge chamber.¹ It is noted that all the measurements in the GEC discharge chamber were performed above a bare silicon wafer.

As noted above, the thin aluminum layer on the patterned wafers was deposited over a layer of silicon oxide. To examine the influence of the silicon oxide on the BCl density, LIF was recorded during the entire etch process. Figure 9 shows the BCl LIF signal as the aluminum was removed from the surface. The times marked on the figure were determined by the optical endpoint monitor. The "begin clearing" tick is placed at the time when the atomic Al emission line at 396 nm had fallen to approximately 95 percent of its peak value while the "end clearing" tick is placed at the time when the 396 nm emission had dropped to approximately 5 percent of the peak value. For this measurement, the uncertainty in the BCl density is larger than the rest of the data in the paper due to the decreased number of averaged points. To within the uncertainty in the data, the BCl density after aluminum removal may be slightly higher than the value before

removal. However, the increase in the BCl density during the transition period is somewhat surprising. Since the surfaces present during the aluminum clearing is a combination of aluminum, silicon oxide, and photoresist, one might expect a monotonic change between the two surface extremes of aluminum-photoresist to silicon oxide-photoresist. However, during this transition, our previous measurements showed changes in the electron density as well as the automatic rf matching system (as determined by observation of the forward and reflected power), probably due to changes in the plasma when the aluminum is completely removed.² Thus the slight increase in the BCl density during clearing of the aluminum is likely due to changes in the tool setting affecting the electron density or temperature.

IV. Summary

The relative density of BCl radicals has been measured in a modified Applied Materials DPS metal etch chamber using laser-induced fluorescence. To determine the influence of surface material on the bulk plasma properties, the relative BCl density was measured using four different substrate types; aluminum, alumina, photoresist and patterned aluminum. While the major trends in the data could be explained by using electron driven production and loss arguments, the magnitude of the BCl density above each surface material suggests that surface processes may also contribute to the observed gas phase BCl density. For example, in most cases, the BCl density was highest above photoresist coated wafers and lowest above blanket aluminum wafers despite the electron density being higher above the aluminum surface. However, the relative change in the BCl density due to surface material was significantly smaller than our previously measured,

factor-of-two, changes in the electron and negative ion density. Thus surface processes appear to play a minor role compared with gas phase, electron driven dissociation processes in determining the BCl density. Finally, the surface reactions appear to be insensitive to the range of ion bombardment energies used in this experiment and insensitive to the chamber pressure.

The gas phase BCl density decreased linearly as the BCl_3 was replaced by Cl_2 . As a result, there appears to be a minimal interaction between BCl_3 , Cl_2 and their dissociation products. This would be expected if the major pathway for BCl formation was electron driven dissociation of BCl_2 and BCl_3 . The BCl density is also independent of argon addition or the flow of aluminum etch products from the wafer surface back into the plasma. However, the addition of N_2 to the $\text{BCl}_3 / \text{Cl}_2$ plasma resulted in a significant decrease in the BCl density. The decrease is attributed to N_2^* driven dissociation of BCl.

In general, the trends observed in the DPS chamber and our previous measurements in the GEC were in reasonable agreement. The minor discrepancies can be reasonably attributed to the larger discharge volume and larger surface to volume ratio in the DPS chamber, and small differences in the input power per unit volume.

V. Acknowledgments

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Figure Captions

- Fig. 1 Top and side views of the DPS chamber showing the location of the seven access ports in the modified upper etch chamber. The drawing is not to scale.
- Fig. 2 Relative BCl density as a function of source power for several wafer surface materials. The aluminum surface is denoted by Al (●). The alumina surface is denoted by AlO (◆). The photoresist patterned surface is denoted by Al / PR(▼). The blanket photoresist surface is denoted by PR (■). The bias power was 200 W, pressure was 10 mTorr, Cl₂ flow rate was 100 sccm and the BCl₃ flow rate was 40 sccm.
- Fig. 3 Relative BCl density as a function of wafer bias power for several wafer surface materials. The aluminum surface is denoted by Al (●). The alumina surface is denoted by AlO (◆). The photoresist patterned surface is denoted by Al / PR(▼). The blanket photoresist surface is denoted by PR (■). The source power was 1100 W, pressure was 10 mTorr, Cl₂ flow rate was 100 sccm and the BCl₃ flow rate was 40 sccm.
- Fig. 4 Relative BCl density as a function of chamber pressure for several wafer surface materials. The aluminum surface is denoted by Al (●). The alumina surface is denoted by AlO (◆). The photoresist patterned surface is denoted by Al / PR(▼). The blanket photoresist surface is denoted by PR (■). The source power was 1100 W, bias power was 200 W, Cl₂ flow rate was 100 sccm and the BCl₃ flow rate was 40 sccm.
- Fig. 5 Relative BCl density as a function of Cl₂ / BCl₃ ratio for several wafer surface materials. The aluminum surface is denoted by Al (●). The alumina surface is

denoted by AlO (◆). The photoresist patterned surface is denoted by Al / PR(▼). The blanket photoresist surface is denoted by PR (■). The source power was 1100 W, bias power was 200 W, pressure was 10 mTorr, total flow rate was 140 sccm.

Fig. 6 Relative BCl density as a function of total flow rate for several wafer surface materials. The aluminum surface is denoted by Al (●). The alumina surface is denoted by AlO (◆). The photoresist patterned surface is denoted by Al / PR(▼). The blanket photoresist surface is denoted by PR (■). The source power was 1100 W, bias power was 200 W, pressure was 10 mTorr, and the Cl₂ / BCl₃ ratio was 100 / 40.

Fig. 7 Relative BCl density as a function of additional argon flow rate for several wafer surface materials. The aluminum surface is denoted by Al (●). The alumina surface is denoted by AlO (◆). The photoresist patterned surface is denoted by Al / PR(▼). The blanket photoresist surface is denoted by PR (■). The source power was 900 W, bias power was 185 W, pressure was 7 mTorr, Cl₂ flow rate was 60 sccm and the BCl₃ flow rate was 30 sccm.

Fig. 8 Relative BCl density as a function of additional nitrogen flow above alumina and aluminum surfaces. The source power was 1100 W, bias power was 200 W, and the Cl₂ and BCl₃ flow rates were 100 and 40 sccm, respectively. For the constant total pressure case (●), the pressure was 10 mTorr. For the constant partial pressure case (▼), the chamber pressure (◇) was allowed to increase as the nitrogen flow rate increased.

Fig. 9 Relative BCl density as a function of time during etching of a 50 / 50, aluminum / photoresist patterned wafer. The source power was 1100 W, bias power was 200 W, pressure was 10 mTorr, Cl₂ flow rate was 100 sccm and the BCl₃ flow rate was 40 sccm. The begin clearing tick was when the 396 nm plasma induced aluminum emission had fallen to approximately 95 percent of its peak value while the end clearing tick was when the optical emission had dropped to approximately 5 percent of the peak value.

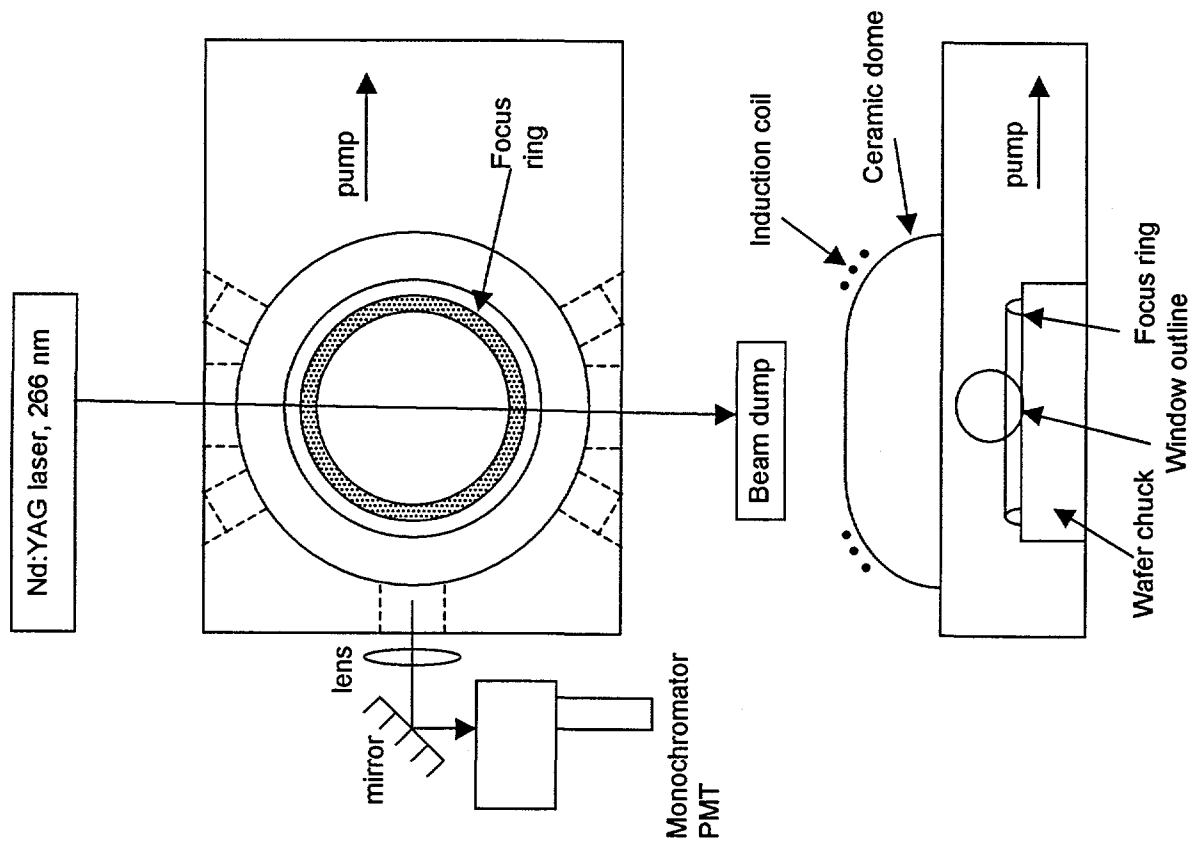


Fig.1
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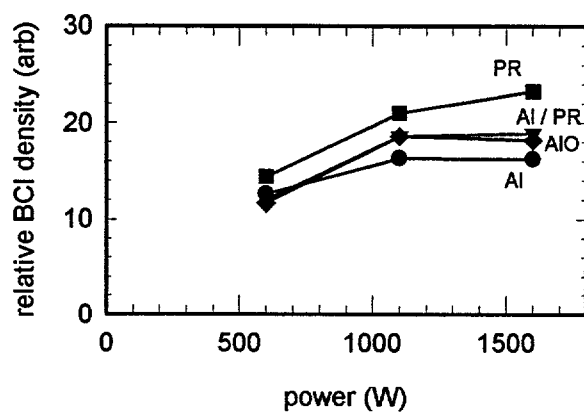


Fig. 2
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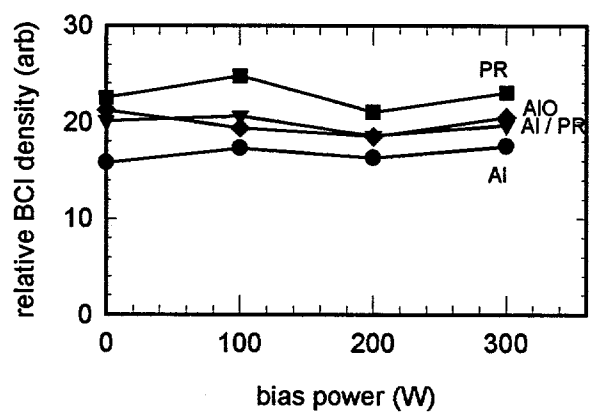


Fig. 3
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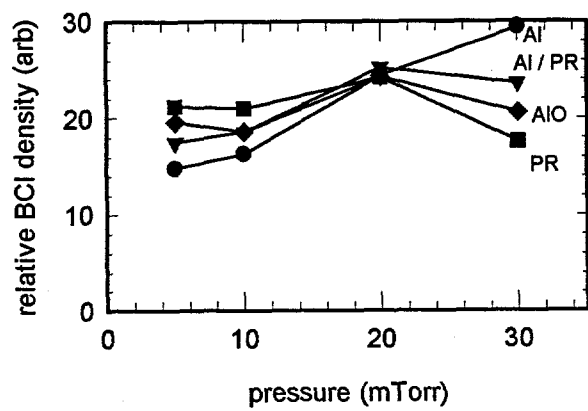


Fig. 4
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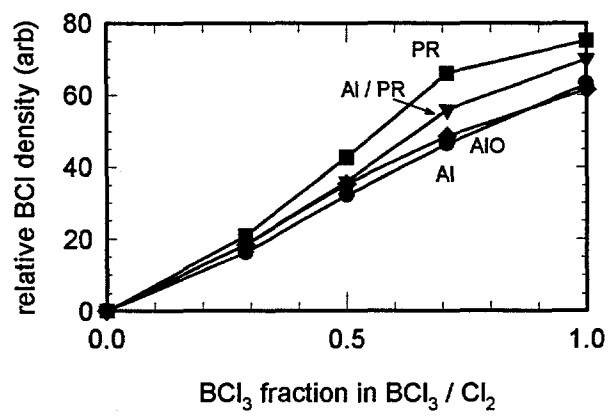


Fig. 5
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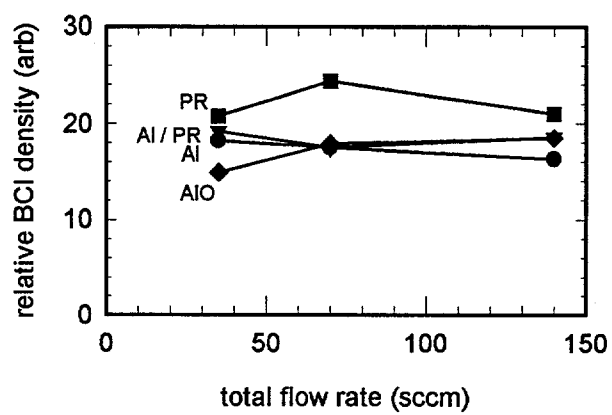


Fig. 6
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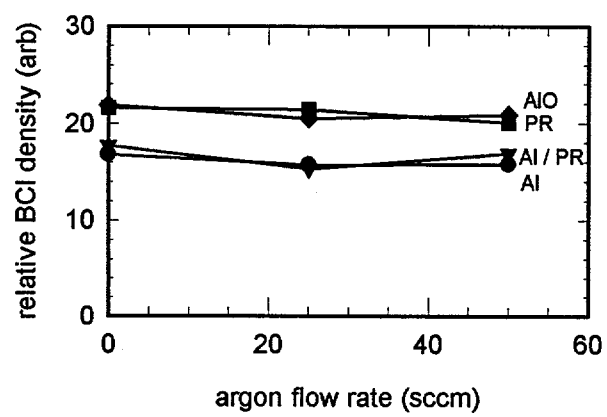


Fig. 7
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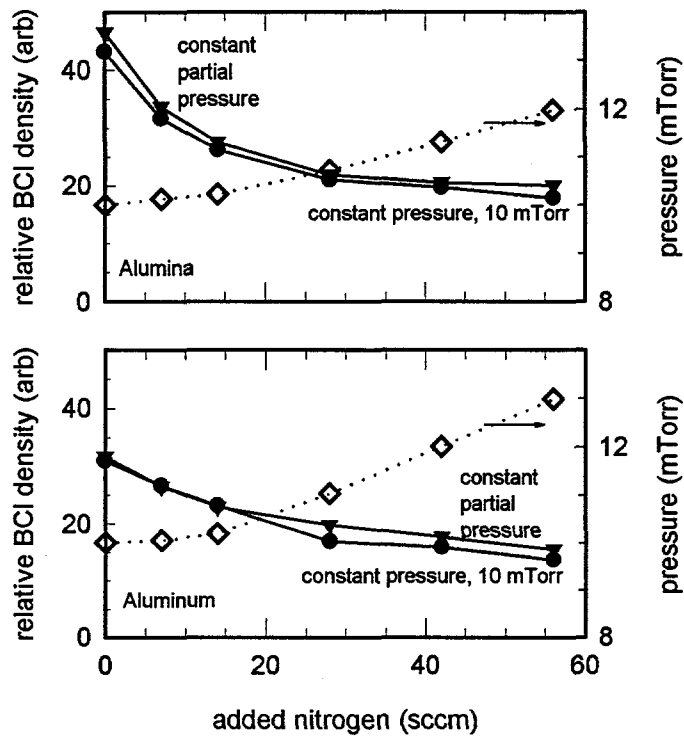


Fig. 8
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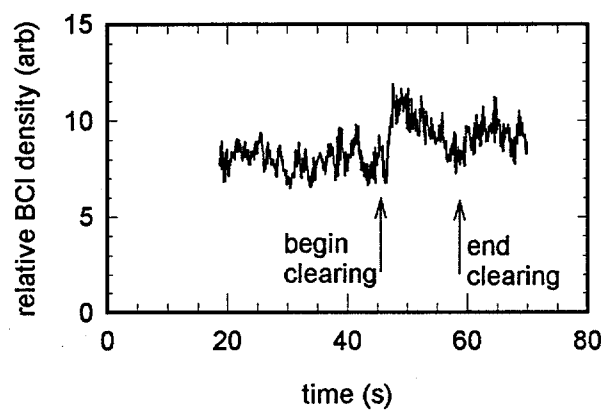


Fig. 9
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