Spatial Characterization of Emission Intensities and Temperatures of a High Power Nitrogen Microwave-induced Plasma

MASAKI OHATA AND NAOKI FURUTA*
Faculty of Science and Engineering, Department of Applied Chemistry, Chuo University, 1–13–27, Kasuga, Bunkyou-ku, Tokyo 112, Japan

The spatial characterization of a high power nitrogen microwave-induced plasma (N\textsubscript{2}-MIP), using an Okamoto cavity, was undertaken. The plasma operating conditions were fixed during all the experiments at a microwave frequency of 2.45 GHz, an incident power of 1.3 kW, a plasma gas flow rate of 11.0 l min\(^{-1}\), a carrier gas flow rate of 1.0 l min\(^{-1}\) and a sample uptake rate of 1.6 ml min\(^{-1}\). A Ca solution was used to measure the emission intensity distribution for both Ca atom and ion lines in the N\textsubscript{2}-MIP, and an Fe solution was used to determine the excitation temperature distribution of the N\textsubscript{2}-MIP, which was obtained by using a Boltzmann plot under the assumption of LTE. In addition, rotational temperature measurements were carried out using the N\textsubscript{2} (0–0) B\textsubscript{2}Σ\textsubscript{g} – X\textsubscript{2}Σ\textsubscript{g} \(^{-}\) band. Because the H\textsubscript{2} line (486.13 nm) could not be excited in the N\textsubscript{2}-MIP, measurement of the electron number density was carried out by a method involving the Saha equation using both the emission intensity ratio (Ca II: Ca I) and the excitation temperature of the N\textsubscript{2}-MIP. The degree of ionization of various elements in the N\textsubscript{2}-MIP was also calculated. The spatial characteristics of the N\textsubscript{2}-MIP were compared with those of the Ar-ICP.

Keywords: high power nitrogen microwave-induced plasma; spatial characterization; temperature; electron number density; atomic emission spectrometry; mass spectrometry

Plasma sources have been widely used for trace element analysis using AES or MS. There are several plasma sources, but the most popular plasma source is the Ar-ICP. In general, both Ar-ICP-AES and Ar-ICP-MS have found widespread use in various fields, because they give high sensitivity and good precision in trace element analysis. However, K\textsuperscript{+}, Ca\textsuperscript{2+}, Fe\textsuperscript{3+} and Se\textsuperscript{4+} cannot be determined directly by Ar-ICP-MS, because these elements suffer interferences from Ar\textsuperscript{2+}, Ar\textsuperscript{+}, Ar\textsuperscript{3+}, Ar\textsuperscript{+}O\textsuperscript{2−}, and Ar\textsuperscript{+}O\textsuperscript{2−}, respectively, that are caused by the plasma sustained gas of the Ar-ICP. Therefore, other types of plasma sources such as MIPs have been explored and examined by many workers. Existing microwave plasma systems, including the Beenakker cavity,\textsuperscript{1} the surfatron\textsuperscript{7–12} and the microwave plasma torch (MPT),\textsuperscript{13–17} are subject to a number of serious limitations. Usually, the input microwave power of these MIPs is operated at 200–300 W (up to 500 W), and therefore they cannot provide sufficient plasma energy to desolvate and ionize elements from a directly nebulized sample solution. More recently, the kilowatt-plus helium microwave-induced plasma system (KiP-MIP) was developed and investigated by Carnahan’s group.\textsuperscript{20–24} Because the KiP-MIP is of high power (1600 W), the expected analytical performance is more effective than that of low power MIPs. Okamoto and co-workers\textsuperscript{25–28} have described an annular-shaped high power MIP at atmospheric pressure, that could be sustained by helium (He), nitrogen (N\textsubscript{2}), oxygen (O\textsubscript{2}) and air. The plasma produced by the Okamoto cavity was in a surface wave mode and could be operated at up to 1.5 kW. The background mass spectrum was dominated by NO\textsuperscript{+}, N\textsuperscript{2+} and O\textsuperscript{2+} using N\textsubscript{2} gas, and argon associated polyatomic ions were not observed. Therefore, high power N\textsubscript{2}-MIP-MS could determine the elements that could not be determined by Ar-ICP-MS.\textsuperscript{25–28} On the other hand, the high power N\textsubscript{2}-MIP is more robust than the Ar-ICP, for example, the plasma is not extinguished even if an air sample is injected into the plasma. Moreover, the gas running costs of the high power N\textsubscript{2}-MIP are lower than those of the Ar-ICP. It is considered that the high power N\textsubscript{2}-MIP will be used in many fields because of the advantages mentioned above. In this sense, an investigation of the spatial characteristics of the high power N\textsubscript{2}-MIP is important.

According to reports by Furuta and co-workers,\textsuperscript{29–31} the excitation temperature, electron temperature and electron number density of the Ar-ICP are 5000–7000 K, 7000–8000 K and 0.5 × 10\textsuperscript{15}–3.0 × 10\textsuperscript{16} cm\textsuperscript{−3}, respectively. Hook\textsuperscript{32} estimated that the typical ion temperature and electron number density in the analytical region of the Ar-ICP were 7500 K and 1.0 × 10\textsuperscript{16} cm\textsuperscript{−3}, respectively, based on other literature reports. As regards the rotational temperature of the Ar-ICP, values of 3000–4500 K have been reported by several workers.\textsuperscript{33–34} However, these plasma characteristics have not yet been reported for the high power N\textsubscript{2}-MIP. The purpose of this work was to investigate the spatial characteristics of the high power N\textsubscript{2}-MIP in detail and to compare them with those of the Ar-ICP.

EXPERIMENTAL

Instrumentation

The instrument used is shown in Fig. 1; the measurement system has been described in a previous paper.\textsuperscript{35} In this work, a high power N\textsubscript{2}-MIP source replaced the Ar-ICP source. An
Operating Conditions and Procedures

Okamoto cavity was used for the high power \( \text{N}_2 \text{-MIP} \), and is shown in Fig. 2. The details of this cavity are described in ref. 37. Iron emission spectra were measured with an ISPD (Intensified Self-scanning Photodiode array Detector, Model 1420B, Princeton Applied Research, Princeton, NJ, USA), and both the Ca line and \( \text{N}_2 \) (0–0) \( \text{B}^2\Sigma_u^+ \rightarrow \text{X}^2\Sigma_g^+ \) band emissions were measured with a PMT (Model R919, Hamamatsu Photonics, Hamamatsu, Japan).

Reagents

De-ionized water was further purified with a Milli-Q system (Milli-Q SP Low TOC, Millipore, Bedford, MA, USA). High-purity grade \( 68\% \text{HNO}_3 \) (Kanto Chemical Co., Tokyo, Japan) was used. Standard solutions \((1000 \text{mg} \text{l}^{-1})\) of Ca and Fe were purchased from Kanto Chemical Co. (Tokyo, Japan). Sample solutions of \( 50 \text{ mg} \text{l}^{-1} \) Ca, \( 1 \text{ mg} \text{l}^{-1} \) Ca and \( 500 \text{ mg} \text{l}^{-1} \) Fe were prepared by diluting the standard solutions with \( 0.1 \text{ m} \text{HNO}_3 \). A blank solution of \( 0.1 \text{ m} \text{HNO}_3 \) was prepared by diluting HNO\(_3\) with Milli-Q water.

Operating Conditions and Procedures

The operating conditions of the \( \text{N}_2 \text{-MIP} \) and measurement parameters are listed in Table 1. The width and height of the entrance and exit slits of the monochromator were both fixed at 50 \( \mu \text{m} \) and 2 mm, respectively, during all experiments. A wavelength of 422.7 nm was selected for the atom line (Ca I) and 393.4 nm for the ion line (Ca II). These Ca lines were selected so as to avoid correction for chromatic aberration. Since the wavelengths of the Ca atom and ion lines are very close to each other, they can be measured without changing any of the measurement conditions. The concentration of Ca was \( 50 \mu \text{g ml}^{-1} \) for \( \text{Ca} \) I measurement and \( 1 \mu \text{g ml}^{-1} \) for \( \text{Ca} \) II measurement. The extra high tension of the PMT was fixed at \( -550 \text{ V} \) for both measurements. The optical lens position was optimized for the \( \text{Ca} \) II emission line, and was not changed while the \( \text{Ca} \) emission lines were measured. In order to measure the excitation temperatures of the \( \text{N}_2 \text{-MIP} \), the emission lines of Fe (from 368 to 378 nm) were monitored by the ISPD. Since accurate \( g_A \) and \( g_J \) values of Fe have been reported in the literature,\(^{34–36} \) Fe was chosen as the thermometric species. An Fe concentration of \( 500 \mu \text{g ml}^{-1} \) was used and the non-uniform response of the ISPD channels \((1024 \text{ channels})\) was corrected for by using the continuum emission of a tungsten lamp.

**RESULTS AND DISCUSSION**

**Spatial Profiles of Calcium Atom and Ion Emission Intensities and the Emission Intensity Ratios**

The emission profiles for both Ca I and Ca II are shown in Fig. 3(a) and (b), respectively. These profiles were obtained from the lateral emission intensities of the plasma, and no Abel inversion was performed. In Fig. 3, the \( x \) and \( y \) coordinates are the distances from the centre of the plasma and the height above the choke, respectively. The values designated in Fig. 3 represent the obtained voltage \((\text{V})\). The behaviour of the elements in the \( \text{N}_2 \text{-MIP} \) can clearly be seen. It is evident from Fig. 3(a) that the most intense emission of Ca I is observed at 2 mm above the choke and at the centre of the plasma. The observed voltage at this point is about 8 V. It can also be seen that a sharp emission is observed from 2 to 8 mm above the choke along the central channel of the plasma, however, the emission intensities become smaller with an increase in the height above the choke along the central channel of the plasma. The most intense emission of Ca II is also observed at 2 mm above the choke and at the centre of the plasma [Fig. 3(b)]. At this point, the observed voltage is about 7.5 V. It is clear that the \( \text{N}_2 \text{-MIP} \) is a doughnut-shaped plasma, \( \theta \), of the Ar-ICP.

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Table 1 \( \text{N}_2 \text{-MIP-AES operating conditions and measurement parameters} \)

<table>
<thead>
<tr>
<th>Source parameters</th>
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<tr>
<td>Microware frequency</td>
<td>2.45 GHz</td>
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<tr>
<td>Microwave power</td>
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<tr>
<td>( \text{N}_2 ) plasma gas flow rate</td>
<td>10.0 l min(^{-1})</td>
</tr>
<tr>
<td>Carrier gas flow rate</td>
<td>1.0 l min(^{-1})</td>
</tr>
<tr>
<td>Uptake rate</td>
<td>1.6 ml min(^{-1})</td>
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</table>

<table>
<thead>
<tr>
<th>Monochromator:</th>
<th></th>
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<tbody>
<tr>
<td>Focal length</td>
<td>1 m</td>
</tr>
<tr>
<td>Slit-width (both entrance and exit)</td>
<td>50 ( \mu \text{m} )</td>
</tr>
<tr>
<td>Slit-height (both entrance and exit)</td>
<td>2 mm</td>
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<tr>
<td>Grating</td>
<td>2400 grooves ( \text{mm}^{-1} )</td>
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<tr>
<td>Reciprocal linear dispersion</td>
<td>0.4 nm ( \text{mm}^{-1} )</td>
</tr>
<tr>
<td>PMT:</td>
<td></td>
</tr>
<tr>
<td>High voltage power supply</td>
<td>(-550 \text{ V})</td>
</tr>
<tr>
<td>Wavelength of Ca I</td>
<td>422.7 nm (50 ( \mu \text{g ml}^{-1}))</td>
</tr>
<tr>
<td>Wavelength of Ca II</td>
<td>393.4 nm (1 ( \mu \text{g ml}^{-1}))</td>
</tr>
<tr>
<td>ISPD:</td>
<td></td>
</tr>
<tr>
<td>Wavelength range</td>
<td>368–378 nm</td>
</tr>
<tr>
<td>Selected wavelength</td>
<td>1. 372.0 nm; 2. 373.5 nm; 3. 373.7 nm; 4. 374.6 nm; 5. 374.9 nm; 6. 375.8 nm; 7. 376.6 nm (500 ( \mu \text{g ml}^{-1}))</td>
</tr>
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and that the sample aerosol can be introduced into the centre of the plasma. In order to investigate the equilibrium between Ca atoms and ions in the N₂-MIP, the emission intensity ratios of Ca II to Ca I were calculated from Fig. 3(a) and (b), and are depicted in Fig. 4. Both the x and y coordinates are the same as those of Fig. 3. As can be seen in Fig. 4, the observed value of the ratio is about 30 at 2 mm above the choke along the central channel of the plasma, and rather low ratio values (40–60) are observed along the central channel of the N₂-MIP. This is due to the strong emission of Ca I at the central channel of the plasma, i.e., ionization does not prevail in this region. The highest ratio value of 100 is observed at 2 mm above the choke and off-axis of the plasma. The ratio value becomes smaller as one goes further from the choke along the off-axis of the plasma. As compared with the reported value of 180 for the Ar-ICP, it is concluded that the degree of ionization of elements in the N₂-MIP is slightly lower than in the Ar-ICP.

Spatial Profiles of Iron Excitation Temperatures

The emission intensity of an atom line in an LTE plasma can be expressed by the following Boltzmann equation:

\begin{equation}
I_{\text{at}} = \frac{n_a e^2}{m c} \frac{g_p}{Z_a} \frac{l_a}{T_{\text{ex}}} \exp \left(-\frac{E_q}{k T_{\text{ex}}} \right)
\end{equation}

where \( n_a \) = number density of the atom, \( e \) = charge of an electron, \( m \) = mass of an electron, \( c \) = velocity of light, \( g_p \) = statistical weight of the lower level \( p \), \( f_{pq} \) = oscillator strength, \( Z_a \) = partition function of the atom, \( k \) = Planck's constant, \( l_a \) = wavelength of the atom line, \( T_{\text{ex}} \) = excitation temperature, \( E_q \) = excitation energy of the atom line, and \( k \) = Boltzmann's constant. Fig. 5 shows an example of Fe emission spectra measured by the ISPD at 2 mm above the choke and at the centre of the plasma. Background correction was carried out by sub-

Fig. 3 Contour map of (a) Ca I 422.7 nm line and (b) Ca II 393.4 nm line. Isopleth values are output voltage (V).

Fig. 4 Contour map of the emission intensity ratios of the Ca II/Ca I lines obtained from the profiles in Fig. 3(a) and (b).

was added to obtain the high excitation temperature. Moreover, an Fe line with high excitation energy (376.6 nm) was chosen for excitation temperature measurements. When the seven Fe lines were selected, the Fe lines with accurate $g_f$ values and high emission intensity were chosen. The corresponding Boltzmann plot is shown in Fig. 6. The numbers of the Fe I peaks (1–7) indicated in Fig. 5 correspond to those of Fig. 6. The excitation temperature can be calculated from the slope of the plot of $\log(I_{\lambda}/g_f)_{ex}$ against $E_{ex}$. The excitation temperature obtained from low energy level Fe I lines (line numbers 1–6) is referred to as the low excitation temperature ($T_{ex}[low]$). The Boltzmann plot obtained for both low and high energy level Fe I lines is a straight line. Therefore, the obtained $T_{ex}[low]$ and $T_{ex}[high]$ are very close to each other. This is one of the differences between the $N_2$-MIP and the Ar-ICP. For the Ar-ICP, the obtained $T_{ex}[low]$ and $T_{ex}[high]$ exhibit a large difference. A contour map of $T_{ex}[low]$ and $T_{ex}[high]$ is shown in Fig. 7. The $x$-axis is the lateral coordinate ($\pm 3$ mm) and the $y$-axis is the height above the choke (2–20 mm). The values indicated in Fig. 7 are in K. The highest excitation temperature of 5400 K is observed at 2 mm above the choke and at the centre of the $N_2$-MIP. The excitation temperature is in the range 4500–5400 K. Typical excitation temperatures of the Ar-ICP are 6500–7000 K, which were estimated by Houk based on other literature reports. Similar excitation temperatures of the Ar-ICP (5000–7000 K) have been reported by Furuta. Therefore, it can be concluded that the excitation temperature of the $N_2$-MIP is about 1500 K lower than that of the Ar-ICP.

**Comparison of Plasma Temperatures Between $N_2$-MIP and Ar-ICP**

The determined temperature of the Ar-ICP has different values according to the definition of temperature, e.g., electron temperature ($T_e$), ionization temperature ($T_\text{ion}$), excitation temperature ($T_{ex}$), temperature ($T$), gas temperature ($T_g$), Doppler temperature ($T_D$) and rotational temperature ($T_R$). In general, the temperature decreases in the order $T_g > T_D > T_\text{ion} > T_R > T_e > T$ in the Ar-ICP. If these temperatures are equal, it can be considered that the plasma is in LTE. Apart from the excitation temperature ($T_{ex}$), the rotational temperature ($T_R$) has been measured using the first negative of the nitrogen band $(\lambda 2537$ nm). The following equation was used to obtain the rotational temperature:

$$\log \left( \frac{I_{\lambda}}{a^2 K} \right) + \frac{B(K^2 - 1)}{b} \times \frac{h}{k} \times T_R$$

where $I_{\lambda}$ is the emission intensity of the $P$ branch of the $N_2^+(0–0)$: $\Pi\Sigma^+ \rightarrow \Sigma^+$ band, $a$ is the Alternating Intensity Factor, $v$ is wavenumber of the line, $K$ is the quantum number of the $P$ branch, $B$ is rotational constant, $b$ is constant, $T_R$ is the rotational temperature, and the other symbols have the same meaning as defined earlier. In this work, the resolution of the monochromator was better than 0.03 nm; therefore, $K > 25$ of the $P$ branches of the $N_2^+(0–0)$: $\Pi\Sigma^+ \rightarrow \Sigma^+$ band were used for the rotational temperature measurements. In Fig. 8, the rotational temperatures are plotted together with the low and high excitation temperatures. Temperatures are plotted as a function of the height above the choke along the central channel of the plasma. The highest excitation temperature of 5500 K is observed at 2 mm above the choke and the excitation temperature is in the range 5000–5500 K along the central channel of the plasma. On the other hand, the highest rotational temperature of 4500 K is observed at the same height above the choke, and the rotational temperature is in...
the range 3500–4500 K. These results are summarized in Table 2, together with those for a N$_2$-MIP sustained by a Bartenkée cavity$^{39,40}$ with a low power (<500 W) and a 27.12 MHz Ar-ICP. These plasmas were all operated at atmospheric pressure. Many temperature values have been reported for a 27.12 MHz Ar-ICP$^{4,39,41}$ and for a low power MIP sustained by using He and Ar$^{39,42}$ however, reports of the temperature values of an MIP sustained by N$_2$ are scarce, and only an excitation temperature of 5800 K was reported in ref. 19.

Calculation of Electron Number Density

Usually, the electron number density can be obtained by measuring the Stark broadening of the hydrogen line (H$_2$ 486.13 nm) without any assumption of LTE$^{43}$. An attempt was made to use the hydrogen line profile to measure the electron number density; however, as shown in Fig. 9, the H$_2$ line could not be observed in the N$_2$-MIP background. Therefore, the electron number density was calculated by the following Saha equation with an assumption of LTE$^{43}$

$$K_M = \frac{n_e}{n_i} = 4.83 \times 10^{16} \left( \frac{E_i}{T} \right)^{\frac{3}{2}} \times \exp \left( -\frac{E_i}{kT} \right),$$

(3)

where $K_M$ = equilibrium constant, $n_i$ = ion number density, $n_e$ = electron number density, $T$ = ionization temperature, $E_i$ = ionization energy, and other symbols have the same meaning as defined earlier. Here, the electron number density was calculated by using the excitation temperature, because the excitation temperature is equal to the ionization temperature if LTE is assumed. The electron number density was $5.0 \times 10^{13}$ cm$^{-3}$ at 2 mm above the choke and at the centre of the plasma where the most intense Ca emission and the highest excitation temperature were observed. The typical electron number density of the Ar-ICP is $1.0 \times 10^{13}$ cm$^{-3}$, which was estimated by Houk$^{43}$ based on other literature reports. Similar electron number densities of the Ar-ICP ($0.5-1.0 \times 10^{13}$ cm$^{-3}$) have been reported by Furuta et al.$^{39}$ It is estimated that the electron number density of the N$_2$-MIP is smaller than that of the Ar-ICP, because both the temperature and the ratio of Ca II/Ca I of the N$_2$-MIP are lower than those of the Ar-ICP.

Comparison of Degree of Ionization Between N$_2$-MIP and Ar-ICP

The degree of ionization of various elements in both the N$_2$-MIP and Ar-ICP was calculated by using the characteristic parameters listed in Table 3. The result is shown in Fig. 10. In Table 3, the temperature of the N$_2$-MIP was evaluated as the excitation temperature, which is equal to $T_{ex}$, if LTE is assumed. In the Ar-ICP, the ratio of Ca II/Ca I was taken from the paper by Furuta et al.$^{39}$ The temperature and the electron number density values were taken from those estimated by Houk$^{43}$ based on other literature reports. In Fig. 10, the y-axis is the ionization energy for various elements, and the x-axis is the degree of ionization (%). The degree of ionization was calculated by using the characteristic parameters listed in Table 3. The result is shown in Fig. 10. In Table 3, the temperature of the N$_2$-MIP was evaluated as the excitation temperature, which is equal to $T_{ex}$, if LTE is assumed. In the Ar-ICP, the ratio of Ca II/Ca I was taken from the paper by Furuta et al.$^{39}$ The temperature and the electron number density values were calculated by using the characteristic parameters listed in Table 3. The result is shown in Fig. 10. In Table 3, the temperature of the N$_2$-MIP was evaluated as the excitation temperature, which is equal to $T_{ex}$, if LTE is assumed. In the Ar-ICP, the ratio of Ca II/Ca I was taken from the paper by Furuta et al.$^{39}$ The temperature and the electron number density values were taken from those estimated by Houk$^{43}$ based on other literature reports.

CONCLUSIONS

The spatial characterization of a high power N$_2$-MIP was conducted in detail under fixed plasma operating conditions. The N$_2$-MIP could be evaluated as a doughnut-shaped plasma from the emission profiles of both atom and ion lines. The equilibrium of elements in the N$_2$-MIP could be estimated from the value of the Ca II/Ca I ratio. The result implies that the ionization equilibrium of elements in the N$_2$-MIP is more shifted towards atoms than in the Ar-ICP. Excitation temperature measurements of the N$_2$-MIP were undertaken by using atom lines of Fe. The highest temperature was observed at 2 mm above the choke and at the central axis of the plasma, where the most intense emission of Ca I and Ca II was observed. The typical spatial characterization of a high power N$_2$-MIP was conducted in detail under fixed plasma operating conditions. The N$_2$-MIP could be evaluated as a doughnut-shaped plasma from the emission profiles of both atom and ion lines. The equilibrium of elements in the N$_2$-MIP could be estimated from the value of the Ca II/Ca I ratio. The result implies that the ionization equilibrium of elements in the N$_2$-MIP is more shifted towards atoms than in the Ar-ICP. Excitation temperature measurements of the N$_2$-MIP were undertaken by using atom lines of Fe. The highest temperature was observed at 2 mm above the choke and at the central axis of the plasma, where the most intense emission of Ca I and Ca II was observed. The typical spatial characterization of a high power N$_2$-MIP was conducted in detail under fixed plasma operating conditions. The N$_2$-MIP could be evaluated as a doughnut-shaped plasma from the emission profiles of both atom and ion lines. The equilibrium of elements in the N$_2$-MIP could be estimated from the value of the Ca II/Ca I ratio. The result implies that the ionization equilibrium of elements in the N$_2$-MIP is more shifted towards atoms than in the Ar-ICP. Excitation temperature measurements of the N$_2$-MIP were undertaken by using atom lines of Fe. The highest temperature was observed at 2 mm above the choke and at the central axis of the plasma, where the most intense emission of Ca I and Ca II was observed. The typical spatial characterization of a high power N$_2$-MIP was conducted in detail under fixed plasma operating conditions. The N$_2$-MIP could be evaluated as a doughnut-shaped plasma from the emission profiles of both atom and ion lines. The equilibrium of elements in the N$_2$-MIP could be estimated from the value of the Ca II/Ca I ratio. The result implies that the ionization equilibrium of elements in the N$_2$-MIP is more shifted towards atoms than in the Ar-ICP. Excitation temperature measurements of the N$_2$-MIP were undertaken by using atom lines of Fe. The highest temperature was observed at 2 mm above the choke and at the central axis of the plasma, where the most intense emission of Ca I and Ca II was observed. The typical spatial characterization of a high power N$_2$-MIP was conducted in detail under fixed plasma operating conditions. The N$_2$-MIP could be evaluated as a doughnut-shaped plasma from the emission profiles of both atom and ion lines. The equilibrium of elements in the N$_2$-MIP could be estimated from the value of the Ca II/Ca I ratio. The result implies that the ionization equilibrium of elements in the N$_2$-MIP is more shifted towards atoms than in the Ar-ICP. Excitation temperature measurements of the N$_2$-MIP were undertaken by using atom lines of Fe. The highest temperature was observed at 2 mm above the choke and at the central axis of the plasma, where the most intense emission of Ca I and Ca II was observed. The typical spatial characterization of a high power N$_2$-MIP was conducted in detail under fixed plasma operating conditions. The N$_2$-MIP could be evaluated as a doughnut-shaped plasma from the emission profiles of both atom and ion lines. The equilibrium of elements in the N$_2$-MIP could be estimated from the value of the Ca II/Ca I ratio. The result implies that the ionization equilibrium of elements in the N$_2$-MIP is more shifted towards atoms than in the Ar-ICP.
addition, the calculated degrees of ionization are in good agreement with the experimental results obtained by \textit{N}_2-MIP-MS. An evaluation of the analytical performance of the high power \textit{N}_2-MIP source is currently underway in this laboratory using AES.

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Paper 6/093910
Received August 28, 1996
Accepted October 28, 1996