SPECTROSCOPY AND LANGMUIR PROBE DIAGNOSTICS OF MAGNETICALLY ENHANCED CAPACITIVE RF DISCHARGE IN ARGON

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Abstract

Determination of plasma parameters in the RF capacitive discharge enhanced by an external magnetic field using emission spectroscopy, double Langmuir probes and electro-technical methods has been performed. Discharge voltage and discharge current, sheath thickness, electron temperature, as well as charged particle densities as a function of discharge parameters are determined. The system operating parameters can be adjusted in the following ranges: gas pressure in the discharge chamber 0.1-10 Pa, discharge power 80-160 W, magnetic field strength 25-125 G. Argon was used as working gas. It is shown that the external magnetic field has significant influence on plasma parameters.

1. Introduction

Radio frequency (RF) capacitive discharges are actively used in microelectronics as a powerful tool for processing methods such as plasma enhanced chemical vapour deposition (PECVD), sputtering and etching [1-2]. These technologies have been developed to yield high-quality films in plasma CVD and finer patterning in etching. Taking advantage of electron magnetic confinement and low operating pressure, developed magnetron reactive ion etching (RIE) system has demonstrated high rate, uniform and anisotropic etching [3,4]. Yeom at al. has investigated effect of magnetic field strength on the processing parameters [5-7]. The presence of the magnetic field makes a magnetron system quite different from other conventional systems. In RF magnetron discharges it is possible to decrease energy of ions bombarded electrode surface and to decrease a level of defects in bombarded surface in comparison with processes in conventional RF discharges. Moreover magnetically enhanced RF discharges can be maintained at lower gas pressure that allows increase ratio of ions flow to chemical active radical flow at electrode surface. This system has opened up new possibilities for the use of low-energy plasma-surface interactions.

Plasma-chemical processes used magnetron RF discharges are determined by plasma parameters which depend on system operating parameters such as pressure, flow rate, gas chemistry, RF power input and magnetic field strength. For understanding and control of such complicated system, a thorough study of the relationship between the plasma properties and system operating parameters is essential.
2. Experimental details

The magnetically enhanced asymmetrical capacitive coupling RF reactor [8] has been used in the experiments. The reactor chamber consisted of the stainless steel cylindrical vessel with a diameter of 30 cm and height of 25 cm with ports to allow optical and contact diagnostics. The chamber walls were grounded. RF power (frequency 13.56 MHz) from a RF generator was applied to the stainless steel plane square electrode (10x10x1.6 cm$^3$) arranged in the middle of the chamber. The power supply was connected to the electrode through a special matching device. Two magnetic coils induced a homogeneous magnetic field with respect to the vertical symmetry axis in the chamber. The gas pressure could be adjusted in the range 0.1 - 10 Pa, discharge power between 80 and 160 W and the magnetic field in the range 25 - 125 G.

RF discharge currents were measured by toroidal coil slipped over the driven wire. RF discharge voltages were measured using a capacitive divider and RF voltmeter. A filter separated the dc self-bias voltages at the driven electrode with the low resonance frequency.

The optical system based on a high-resolution monochromator and photomultiplier was used to measure the spectral line intensities. Mechanically scanning system based on optical fibre and pinhole was used for the measurements of the discharge spatial characteristics. Such system has spatial resolution of ≈1 mm, and could move about 112 mm in the plane parallel to the driven electrode.

For the determination of electron density and the electron temperature a double Langmuir probe was employed. The probe was made from molybdenum wire of diameter 0.14 mm with a free tip length of 7 mm. The probe was immersed in the plasma region at the distances of 1 cm and 5 cm from the powered electrode. The perpendicular probe orientation with respect to the magnetic field was used in experiments.

3. Experimental results

3.1. Discharge currents and voltages

RF currents and RF voltages of the discharge as well as dc bias-voltages were measured as function of argon pressure, supplied power and magnetic field. Current-voltage characteristic of the magnetically enhanced capacitive RF discharge in argon is shown in figure 1 (a). The current-voltage characteristic has growing trend as for the conventional RF capacitive discharges at low pressure. So almost all voltage drops across sheaths at electrodes, which have increasing current-voltage characteristic [9]. As the RF discharge is asymmetric (ratio of electrode surfaces is ≈0.1), so most part of the voltage drops across the sheath at driven electrode.

Dependencies of RF voltage ($U_{RF}$), dc bias-voltage ($U_r$) and ratio of the dc bias-voltage to RF voltage ($U_r/U_{RF}$) on supplied power, magnetic field and argon pressure are shown in figure 1(b-d).

Difference in mobility of electrons and ions causes irreversible departure of electrons and formation of electrode sheaths. The dc negative self-bias voltage relative to the large area electrode formats at the electrode with least area by difference in electrode areas. One can see that the ratio of dc self-bias voltage to RF voltage was not constant for different discharge operating parameters. Maximal effect on the ratio $U_r/U_{RF}$ has magnetic field. The ratio $U_r/U_{RF}$ decreases with increasing of magnetic field. Decrease in pressure also causes decrease in the ratio $U_r/U_{RF}$. It should be noted that decrease in pressure under constant magnetic field causes
Figure 1. Current-voltage characteristic for the magnetically enhanced RF discharge in argon (a), discharge RF voltages ($U_{RF}$), dc self-bias voltages ($U_{dc}$) and ratios of dc self-bias voltage to RF voltage ($U_{dc}/U_{RF}$) as a function of (b) supplied power; (c) magnetic field strength and (d) argon pressure.

reduction in electron mobility, as in the case with increase in magnetic field under constant pressure. Increase in supplied power has weakest influence on the ratio $U_{dc}/U_{RF}$.

3.2. Optical measurements

The optical emission from the plasma of magnetically enhanced RF discharges is far from homogeneous along the discharge axis. The inhomogeneity of the optical emission is a clear indication of inhomogeneities in the local plasma conditions, which in turn determine the local plasma chemistry responsible for the etching or deposition processes. It is well recognized that there are boundary effects close to the electrodes analogous to the cathode and anode sheaths in dc glow discharges. The nature of these sheaths, however, specifically their size, the electric field distribution, as well as the distribution of ion and electron densities is still very much a subject of active research.

We have performed spectroscopic measurements to study the optical properties of the RF electrode region of the magnetically enhanced RF discharge. The time-averaged spatial distributions of spectral line intensities (Ar I 750.3 nm, Ar II 434.8 nm) in the area near the RF electrode (±64 mm) were investigated. The line intensity has a maximum at small distance from the driven electrode. The position of intensity maximum near electrodes can be used to evaluate the average thickness of sheath near electrodes [9]. Thus in this paper the sheath thickness was estimated as a distance from the driven electrode to the peak in the spatial

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distribution of spectral line intensity.

The sheath thickness as a function of magnetic field and argon pressure is shown in figure 2(a, b). The peak intensity in the spatial distribution of ionic line intensity was observed each time more close to the driven electrode than for the spatial distribution of atomic line intensity. So sheath thickness estimated by the spatial distribution of atomic line intensity had the larger value than it estimated by the spatial distribution of ionic line intensity. These differences, apparently, are caused by the difference in the excitation potentials for the atomic and ionic lines.

Figure 2 (c, d) shows intensities for both atomic and ionic lines as a function of magnetic field and argon pressure. Behaviour of spectral line intensities in RF discharges is caused by excitation conditions of atomic and ionic energy levels (electron temperature and density) and argon atom density. Drop in intensity of spectral lines of argon atoms with increase of argon pressure does not couple with quenching of the radiative or metastable states by collisions with argon atoms, it so far as this processes are negligible in conditions of our experiments [8].

3.3. Electron temperature and charged particle density

A double Langmuir probe was used to determine time-averaged electron temperature and charged particle density. Calculations of the electron temperature and charged particle density were made in accordance with a method described earlier [10].

Effects of power, magnetic field and argon pressure on the charged particle density are shown in figure 2(e, f). Electron temperature varies with discharge operating parameters less than electron density. Increase in power and magnetic field causes weak decrease in electron temperature. It was difficult to separate any dependencies of electron temperature on argon pressure. Measured values of electron temperatures are in range ~ 6-10 eV. The error in measurements of electron temperature by the double probe can be significant due to influence of magnetic field on slope of current-voltage characteristic of double probe at zero probe potential.

4. Discussion

Enhancing RF discharge with magnetic field causes electron drift in E×B direction, so electron mobility in radial direction decreases. The magnetic field can be expected to reduce wall losses and to promote volume electrons heating, excitation and ionisation in desirable regions adjacent to the electrodes. As shown in Figure 2 (e), electron density increases sharply with magnetic field. Increase is faster in regions adjacent to the driven electrode. This causes some decrease in electron temperature, so a high energy is not necessity for maintenance of the discharge.

Electron density grow for about factor of 4 at increase in magnetic field from 25 G to 100 G. At the same time the electron mobility in radial direction decreases significantly. Magnetic field reduces the electron mobility in the radial direction by a factor \(1 + (\omega_c / \nu)^2\)^{-1}, where \(\omega_c\) is the electron cyclotron angular frequency and \(\nu\) is the total electron collision frequency. For magnetic field range of 25-100 G \(\omega_c \approx (0.42-1.7) \times 10^9\) rad/s. The electron-atom collision frequency in argon at pressure range of 1-10 Pa is about \((4 \times 10^7 - 4 \times 10^8)\) s\(^{-1}\). Thus in the pressure range of 1-10 Pa, \((\omega_c / \nu) \approx 40-4\) for magnetic field 100 G. Therefore it can be expected that electron mobility in the radial direction to be reduced significantly. As a result the active resistance of plasma increases but discharge current decreases. At that phase shift
Figure 2. Effect of magnetic field strength and argon pressure on (a,b) the average sheath thickness, (c,d) emission line intensities and (e,f) charged particle densities.

between discharge current and voltage must decrease too. Also in pressure range of 1-10 Pa \( (\omega_c/\nu) \sim 10-1 \) for magnetic field 25 G so electron mobility to be reduced significantly only at low pressure of about \( \leq 1 \) Pa.

In the same time the ions as consequence of their larger mass less depends on the effect of magnetic field. Relative reduction in mobility of electrons in comparison with the ion
mobility decreases the need for dc bias-voltage at driven electrode. Ratio of the dc bias-voltage to RF voltage \((U/U_{RF})\) decreases too.

In the first approximation electron oscillation magnitude is \(A = \mu_e E_\phi / w\), where \(\mu_e\) is electron mobility, \(E_\phi\) is peak value of electric field strength and \(w\) is angular frequency of electric field oscillations. Decrease in electron mobility also causes reduce in electron oscillation magnitude in RF field and hence decrease in thickness of the electrode sheath (figure 2 (a)). Increase in electron density results in increase of excitation rate and hence the intensities of the argon atomic spectral lines increase.

These results are in agreement with the conclusions of other authors. In the paper [7] it was shown a decrease of dc self-bias voltage in RF magnetron discharge in \(\text{CF}_4\) and \(\text{CF}_4/\text{H}_2\) with magnetic field. Also increase in ion and \(F\) atom densities with increasing magnetic field up to 250 G was shown. In [5] it is shown that I-V characteristics of RF magnetron discharge have growing behavior, discharge voltages became lower and charged particles density increases with magnetic field. The authors of [6] have shown that the ratio of the dc bias-voltage to RF voltage \((U/U_{RF})\) and phase shift decrease with increasing of magnetic field.

Increase in argon pressure decreases influence of magnetic confinement of electrons, therefore variations in discharge parameters are due to namely this effect. However already at \(B = 25\) G the magnetic confinement of electrons becomes so weak, that pressure effects start to be play dominant role. At magnetic field 100 G the main effects with pressure variation are decrease of the magnetic confinement of electrons and increase of electron losses on walls, therefore the electron density decreases with the pressure. At magnetic field 25 G the main effect is increase of ionisation rate, as collision frequency increases, so the electron density grow with pressure.

Power, apparently, slightly couples with the magnetic electron confinement effect, therefore the properties of magnetically enhanced RF discharge vary with power as well as with properties of direct current discharges.

References