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Effect of Magnetic Mirror Plasma Confinement on Microwave Electron Cyclotron Resonance/D.C. Discharge for Low Pressure Sputtering†

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Abstract

The possibility of using magnetic mirror plasma confinement for microwave electron cyclotron resonance (ECR) plasma enhanced low pressure sputtering is studied. A hollow cylindrical cathode with a target is in the plane of symmetry of the magnetic mirror trap. Two features of the magnetic field axial distribution are important for good operation of the combined ECR/d.c. discharge with mirror confinement. The target current is maximum when the region of plasma generation, the ECR zone, is closer than 10 cm from the center of the cathode. The mirror ratio has to be higher than 2.5, otherwise the discharge is not self-sustained for simultaneously large microwave power and target voltage. The substrate holder at the chamber axis, when electrically floating or negatively biased, improves the plasma confinement. Plasma density of about 10^{11} cm^{-3}, *electron temperature 20 eV and plasma potential 50 V are measured by a plane Langmuir probe for microwave power 200 W, pressure* 5×10^{-3} *Pa and zero cathode voltage.*

KEY WORDS: (microwave plasma), (electron cyclotron resonance), (d.c. sputtering), (plasma confinement), (Langmuir probe).

1. Introduction

Microwave electron cyclotron resonance (ECR) plasma is widely used for plasma processing including etching, plasma enhanced chemical vapor deposition and, since 1984, also for sputtering deposition [1]. The reason for using ECR plasma for sputtering lies mainly in the possibility to use a low working gas pressure $p<10^{-2}$ Pa [2] and to achieve a high ionization ratio of about 10 %. High quality compound films were deposited by reactive sputtering using microwave ECR plasma [3,4], probably due to the efficient dissociation of molecular gas and moderate energy ion irradiation of the growing film.

The working gas pressure influences the transport of the sputtered metal atoms to the substrate, which has consequences for the deposition process.

At high pressures, the mean free path of sputtered atoms is short. Consequently, the sputtered atoms rapidly thermalize near the cathode and the transport mechanism to the substrate is diffusion of relatively slow (energy of the order 0.1 eV) atoms [5].

Under conditions of low pressure, the mean free path of sputtered metal atoms is comparable with, or larger than, the dimension of the plasma chamber and the distance from target to substrate. As a result, most of the sputtered atoms travel from the target to the substrate along straight lines at their original energy (the mean about 10 eV). From this, two features of the transport of sputtered material at low pressures follow: Sputtered atoms deliver higher energy to the growing film and they spend shorter times in the plasma than at higher working gas pressures. Dense microstructures, preferred crystal orientations (texture) and compressive stresses were observed in metal thin films deposited by energetic condensation [6,7].

As concerns the latter feature, shorter times spent in the plasma means that the probability of volume reaction with plasma activated species (e.g. oxygen radicals from the residual gas) is lower. This can be important, when highly reactive species such as Ti are to be deposited. It can help to avoid the necessity of using expensive ultra high vacuum equipment and long pump-down times. The effect of pressure on the transport of sputtered atoms depends on the type of working gas and target material involved. In spite of this, the largest change is generally observed, when the pressure is decreased from

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1 Pa down to 0.1 Pa [5,7].

The high ionization ratio, about 10 %, which is achieved in microwave ECR plasma, means that even at a low pressure of 5×10^{-3} Pa the plasma density is relatively high, about 10^{11} cm^{-3}. It results in a high ratio of ion to metal flux at the substrate at deposition rates of hundreds nm/min. Additional ion bombardment is another means of control of microstructure and crystal structure of deposited thin films. Recently, the trend is to use high ion fluxes with moderate energy [6]. Ions are accelerated in the sheath of space charge between substrate and plasma, where the plasma potential drops to the substrate potential. The difference between plasma and floating potential can be quite high (50 V or more) due to the high electron temperature in microwave ECR plasma at low pressure. Thus, even in the case of deposition of dielectric films, ion bombardment at low energy is possible. The potential difference is sustained by the electrons from the tail of the electron energy distribution function. Ions can also acquire additional energy by the mechanism of plasma acceleration in a decreasing magnetic field. This energy is transferred from electrons and the underlying physics is the conservation of electron magnetic moment. However, the unavoidable side effect is the decrease of ion flux at the substrate due to expansion of the plasma along lines of force of the diverging magnetic field.

The commonly used configuration of microwave ECR plasma enhanced d.c. sputtering includes a divergent magnetic field produced by a coil electromagnet and hollow cylindrical cathode. The extinction pressure (the lowest pressure of stable operation) of the 2.45 GHz microwave ECR discharge in argon for a cylindrical chamber of about 150 mm in inner diameter and in the divergent magnetic field, is about 10^{-2} Pa. When the cylindrical cathode is added and the magnetic field properly designed, the combined magnetic-electrostatic plasma confinement is achieved and the extinction pressure is about 5×10^{-3} Pa.

The linear magnetic mirror trap is another concept of plasma confinement. It can be easily realized by two electromagnetic coils. Although this is rather well known, the magnetic mirror plasma confinement has not yet been tried for the low pressure microwave ECR enhanced d.c. sputtering, maybe for the following reason. When the cylindrical cathode is in the plane of symmetry of the trap, where the highest plasma density is expected, the magnetic field is nearly parallel to the cathode surface. Then, the plasma transport to the cathode is across the magnetic field and there could be some doubts whether a target current, sufficiently high for efficient sputtering, would be achieved. Nevertheless, we have tried the magnetic mirror confinement for the microwave ECR enhanced low pressure sputtering. This paper reports on the discharge performance, expressed in terms of target current as a function of discharge parameters, and on the space distribution of plasma microparameters measured by Langmuir probe.

2. Experimental details

The schematic view of the deposition apparatus is presented in **Fig.1**. The stainless steel vacuum chamber was made of tube of 135 mm in inner diameter (i.d.). The cylindrical water cooled hollow cathode, equipped with a copper target, was 100 mm in length and 110 mm in i.d. The distance between the flange with waveguide and the cathode was approximately 200 mm.

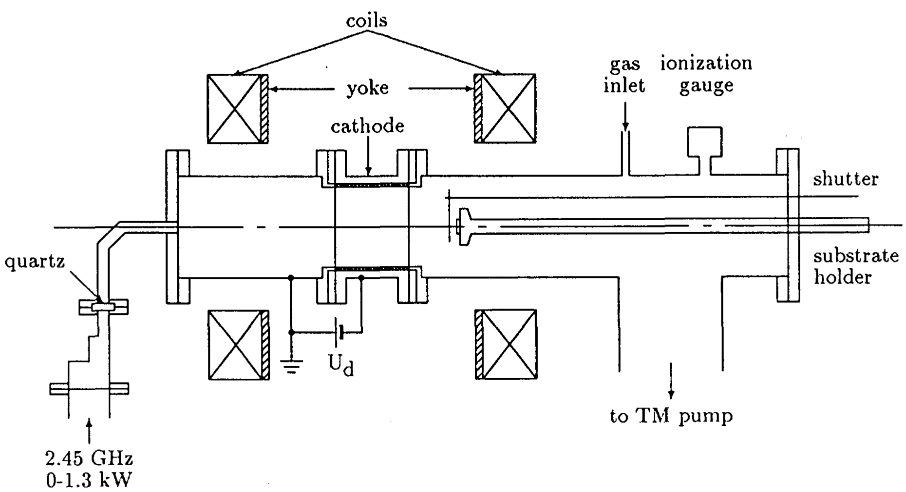

Fig.1 Arrangement of the experiment.

Microwaves of frequency 2.45 GHz and up to power 1.3 kW were launched into the plasma axially by direct coupling of a rectangular waveguide with the vacuum chamber. The microwave transmission line consisted of a magnetron, ferrite isolator with a dummy load, directional coupler, E-H tuner and E-corner with the vacuum sealing quartz window. Two widths of the waveguide E-corner were used, namely 54.6 mm and 13.1 mm. Decreased width and a bent (E-corner) of the vacuum part of the waveguide were used to prevent covering of the quartz window by sputtered particles a) from target due to the bias and b) from waveguide itself due to the sheath potential.

Two identical electromagnetic coils were used to produce the mirror magnetic field necessary for ECR discharge. Magnetic field profile was modified by the variation of the coils distance v and/or by the use of soft iron yoke, see Fig.1. The working gas was argon at pressures from 5×10^{-3} Pa to 2×10^{-2} Pa.

An axially and radially movable plane Langmuir probe was used to measure plasma microparameters. The probe consists of a tip of molybdenum wire 2 mm in diameter shielded by a ceramics tube. The probe was constructed in such a way that the problem of increasing probe surface during sputtering was eliminated.

3. Results and discussion

The extinction pressure of the discharge was about 4×10^{-3} Pa. Similar values were found in the case of combined magnetic/electrostatic confinement. Under certain circumstances (high microwave power, wide E-corner, magnetic field distribution with relatively small gradient at ECR zone), a discharge is observed even at lower pressures. However in these cases, the plasma emissivity seems to be concentrated around the axis and is much lower than for $p>4\times10^{-3}$ Pa, while the target current is just about 10 mA. This is not enough for efficient sputtering deposition and we have not studied systematically this plasma mode.

As a first step, we tried to study the effect of magnetic field distribution on target current I_d. The most important parameters of magnetic field axial distribution are the mirror ratio MR and the axial distance z_{ECR} of the ECR zone from the center of the cathode. MR is the ratio of minimum to maximum magnetic flux density in the magnetic trap. MR is varied by the coil distance v and by yoke. For fixed distances, z_{ECR} is varied by the coil current I_c.

I_d increases with I_c until $I_c=I_{cr}$ and then saturates, see **Fig.2**. I_{cr} depends on the coil distance v. The magnetic

Table 1 Various aspects of the magnetic field where the target current achieves its saturated value with increasing coil current I_c. $p=5\times10^{-3}$ Pa, P=200 W, U_d=200 V, wide waveguide, no substrate holder.

v [cm]	yoke	mirror ratio	I_c [A]	B_{min}[G]	B_{max}[G]	z_{ECR} [cm]	$dB/dz\,|_{ECR}$ [G/cm]
30	yes	2.3	420	600	1380	7	80
35	yes	2.9	400	390	1310	10	80
40	no	2.2	460	700	1190	11	50
45	no	2.7	490	540	1470	11	60
40	yes	3.6	-*	320-453	1150-1640	14-11	80

*For this coil configuration the higher current mode was not observed for coil current from 350 A to 500 A (maximum value of the source used in the experiment). The values in this row indicate the range of parameters for the above mentioned coil current range.

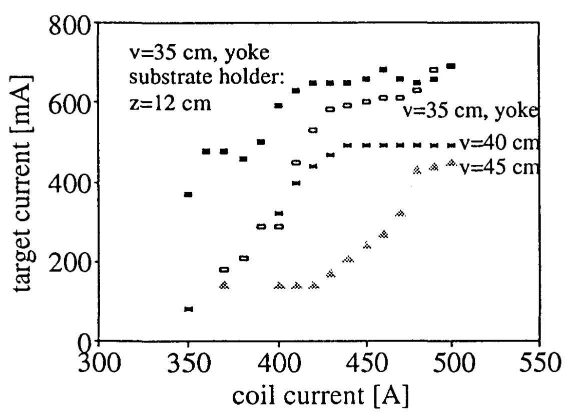

Fig.2 Target current as a function of coil current for different coil configurations. v is the distance of coils. $p=5\times10^{-3}$ Pa, P=200 W, U_d=300 V.

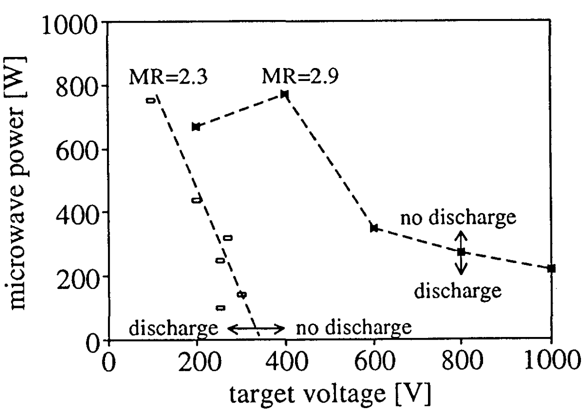

Fig.3 Maximum microwave power of stable discharge as a function of target voltage for MR=2.3 and 2.9. Without substrate holder, $p=5\times10^{-3}$ Pa, I_c=450 A.

field axial distribution for $I_c=I_{cr}$ is characterized in **Table 1** for various values of v, with or without yoke. The most important parameter seems to be z_{ECR}, which is nearly the same for different coil configurations (with one exception). From this, we have a condition for magnetic field distribution that the ECR zone should be close enough to the cathode (for our geometry less then 10 cm), for a high target current to be obtained. I_d is increased when an electrically floating substrate holder is inserted inside the magnetic trap at z=12 cm, see Fig.2. This is due to additional axial confinement of electrons. Electrons with energy smaller than $e(U_{pl}-U_{fl})$, where e is electron charge, U_{pl} is plasma potential and U_{fl} is floating potential, are confined. The most of electrons have energies in this range. When the substrate holder is biased positively with respect to U_{fl} by approximately $(U_{pl}-U_{fl})/3$, the discharge extinguishes.

The discharge extinguishes when the microwave power reaches some critical level. The critical level of microwave power decreases with increasing voltage and is higher for higher mirror ratios, see **Fig.3**. When the floating substrate is inserted into the magnetic trap, a limitation of microwave power is not observed up to the maximum output of our source. This result shows how important is axial confinement of electrons. The discharge is obtained at simultaneously large cathode bias and microwave power only when there is sufficient axial confinement of electrons. This can be achieved by magnetic profile with high mirror ratio MR>2.5 or by additional axial electrostatic confinement as in the case of insertion of the substrate holder.

Target current I_d as a function of target voltage U_d, microwave power P and pressure p was measured in the optimum magnetic field distribution and with the substrate holder at z_s=12 cm, see **Figs.4-6**. A saturation of I_d with increasing U_d and P is apparent. I_d varies only slightly with p in the given pressure range. The target current of about 1 A is quite high for the pressure 5×10^{-3} Pa. A deposition rate of about 100 mn/min can be estimated for I_d=1 A, U_d=1 kV, z_s=12 cm and a copper target.

The quartz window, through which microwaves enter the vacuum chamber, has to be placed out of the sight of the target. Otherwise, metal film, which reflects and absorbs microwaves, is deposited on the window. To solve this problem, we used a common type of E-corner (cross-section 109×54 mm^2) as a vacuum waveguide. However, the plasma potential is high, as much as 60 V or more, in the low pressure microwave ECR plasma. The positive ions after acceleration in the plasma sheath are capable of sputtering chamber walls, accidentally onto the quartz window. To avoid this, we

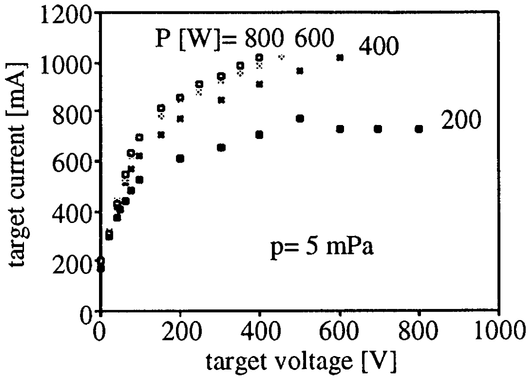

Fig.4 I-V characteristics of the cylindrical cathode. $p=5\times 10^{-3}$ Pa, P=200, 400, 600, 800 W, v=35 cm, yoke, I_c=430 A, narrow waveguide, sampler holder at z=12 cm.

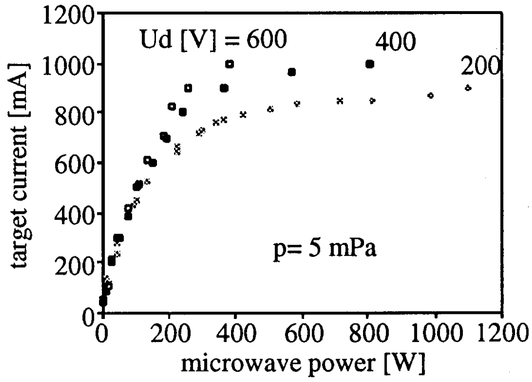

Fig.5 Target current as a function of the microwave power. $p=5\times 10^{-3}$ Pa, U_d=200, 400 and 600 V, v=35 cm, yoke, I_c=430 A, narrow waveguide, sampler holder at z=12 cm.

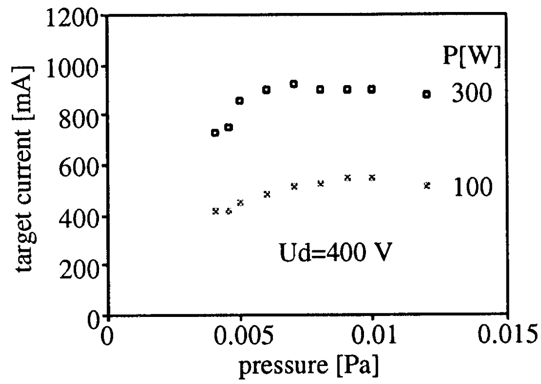

Fig.6 Target current as a function of the argon pressure. U_d=400 V, P=100 W and 300 W, v=35 cm, yoke, I_c=430 A, narrow waveguide, sampler holder at z=12 cm.

used an E-corner with decreased width (cross-section 109×13 mm^2) and a double bend. In this case, the quartz window was seen neither from the target nor from the place where plasma, escaping from the magnetic mirror trap along the axis, strikes the chamber wall. We have not found any problems with metal film deposition on the quartz window after the change to the narrow type of E-corner.

The axial and radial distributions of the plasma density, electron temperature, plasma and floating potentials were measured by a plane Langmuir probe. The axial distribution shows the confinement of the plasma between the ECR zones, see **Fig.7**. There is also seen another positive effect of the change of wide E-corner for narrow one. In the latter case, the plasma density is higher and electron temperature is lower.

The radial distribution of plasma microparameters was measured at z=12 cm for two pressures and with and without cathode bias, see **Fig.8**. At the higher pressure, the plasma density radial profile becomes more hollow with a minimum at the axis.

When bias, U_d=600 V, is applied to the cathode, sputtered atoms strongly influence the plasma. Electron temperature decreases. Plasma density radial distribution becomes flat inside the plasma column with a pronounced peak at the periphery at r=3.5 cm. It is interesting to note that the magnetic file line, which intersects the plane of probe measurement z=12 cm at the radius r=3.7 cm, tangentially touches the target surface at z=0. Both secondary electrons and sputtered atoms can contribute to the development of the density peak. Plasma potential is half, as compared to the case of zero bias.

The ratio R of the ion flux to the metal atom flux onto the substrate can be estimated from the target current and substrate current. This ratio can be varied, mainly by target voltage, pressure and substrate position. High values, about R=1, are available.

4. Conclusions

The microwave ECR/d.c. low pressure discharge with the mirror magnetic field distribution is comparable in target current and extinction pressure to one with the divergent magnetic field arrangement. However, more dense plasma near the substrate is available in the former case.

Both sputtering from the target and from the chamber walls are to be taken into account, when considering a microwave launcher for the microwave plasma enhanced low pressure sputtering discharge. There are no problems with the microwave reflection

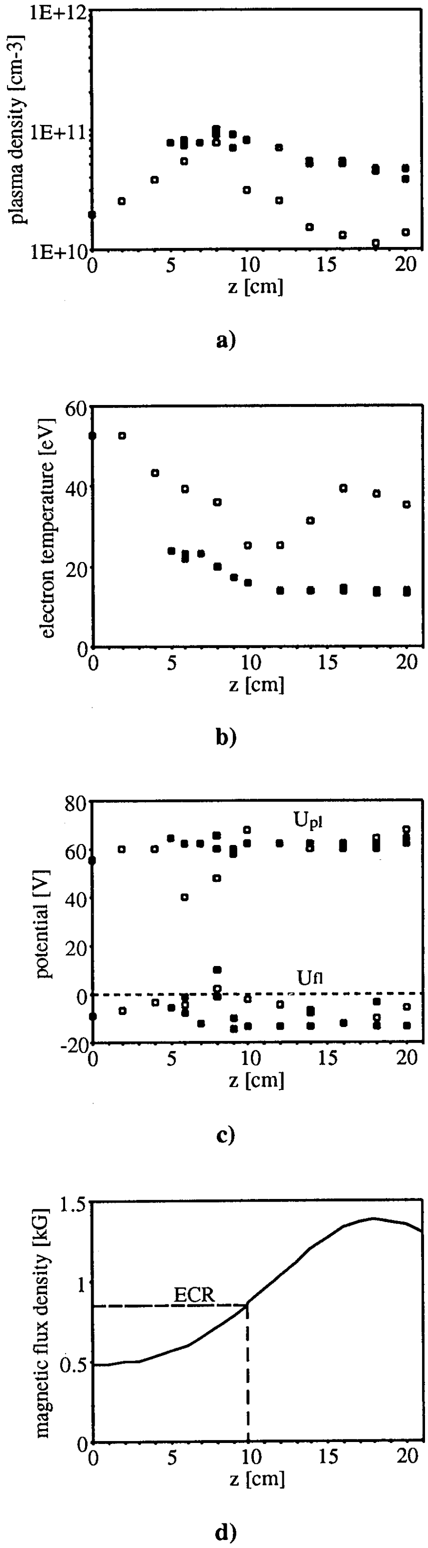

Fig.7 Plasma microparameters as a function of axial position z for wide (□) and narrow (■) E-corner: a) plasma density, b) electron temperature, c) floating and plasma potentials and d) magnetic flux density. v=35 cm, I_c=420 A, U_d=0 V, P=200 W, p=5×10^{-3} Pa.

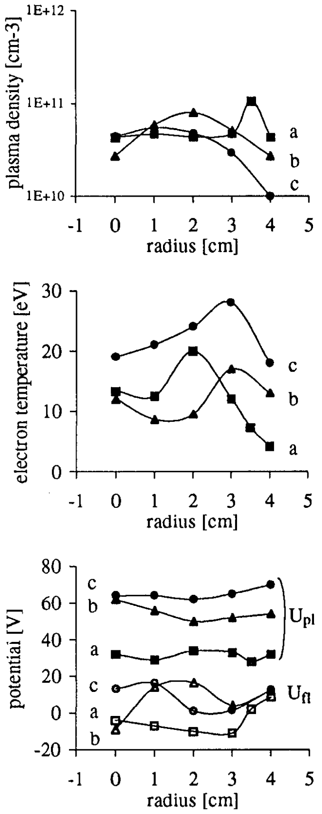

Fig.8 Plasma microparameters as a function of radius at z=12 cm. P=400 W, MR=2.9, z_{ECR}=10 cm.
a: (p=5$\times$10^{-3} Pa, U_d=600 V); b: (1.5$\times$10^{-2} Pa, 0 V); c: (5$\times$10^{-3} Pa, 0 V).

from the metal film at the quartz window, when E-corner with decreased width 13 mm and double bend is used for the vacuum waveguide. However, this solution is only applicable for low pressure discharges p<2$\times$10^{-2} Pa.

It was found that for present geometry the mirror ratio should be large, MR>2.5, and the ECR zone should be close to the target, z_{ECR}<10 cm, when high target current of about 1 A at low pressure, 5$\times$10^{-3} Pa, has to be achieved. When the confinement is not sufficient, the discharge is self-sustained only when one of microwave power or target voltage is small. The substrate holder, when electrically floating or negatively biased, further improves the plasma confinement.

The plasma density and electron temperature are peaked off the axis. The radial distribution of plasma microparameters is changed by the cathode voltage. Due to sputtered metal atoms, electron temperature decreases and plasma density increases in the vicinity of the target with increasing target voltage.

References

1) T.Ono, C.Takahashi and S.Matsuo, Jpn.J.Appl.Phys. 23 (1984) L534.
2) P.Kidd, J.Vac.Sci.Technol.A9 (1991) 466.
3) M.Kadota, T.Kasanammi and M.Minakata, Jpn.J.Appl.Phys. 31 Pt.1 (1992) 3013.
4) M.Matsuoka, K.Hoshino and K.Ono, Int. symp. on 3d transition-semi metal thin films, March 5-8, 1991, Sendai, Japan, Proceedings, p.29.
5) Y.Yamamura and M.Ishida, J.Vac.Sci.Technol.A13 (1995) 101.
6) J.S.Colligon, J.Vac.Sci.Technol. A 13 (1995) 1649.
7) D.W.Hoffman, J.Vac.Sci.Technol. A 12 (1994) 953.