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# Effects of RF pulsing and axial magnetic field on ionized magnetron sputtering

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**Abstract** – To enhance the ionization level of I-PVD and reduce the coil voltage two approaches were tried and as a diagnostic, optical emission spectroscopy and impedance analysis of the plasma was done with a range of Ar pressures and RF powers along with XRD analysis of deposited Ag films. RF sputtering power was pulsed with various on/off time scales to recover the ICP quenched by sputtered metals. This in average enhances the ionization of the sputtered atoms with 10 ms/10 ms and 100 ms/ 100 ms pulse on/off time duration and gives higher (200) preferred orientation over (111) in deposited Ag films. Secondly, Small axial B field about 8G remarkably reduced RF coil sputtering and showed scaled relationship between RF power and magnetic field strength for optimal process condition. From OES of $Ar^0$ and $Ar^+$, wave-like dispersion structure appeared and reduced the coil voltage about 20% at very weak field strength of 8G. This should be studied further to have any relation with low mode Helicon wave launching.

## I. Introduction

Magnetron sputter deposition is a commonly used at semiconductor processing, optical coating, even some hard coatings like TiN. Most of sputtered atoms don't have any charge, there has been no useful method to give directionality to those atoms but collimator, so called collimated sputtering. But in smaller feature sizes than 1 μm, only ions can fly into the trenches and holes with small negative bias of the substrate. So there should be a method to make more ions from sputtered atoms in-between a sputtering target and a substrate. Therefore, Inductively Coupled Plasma (ICP) has been used in post-ionization process by some authors [1,2] for this use. But metals have much lower ionization energy easily quench the Ar plasma generated by ICP coil and limit the ion flux toward substrates. For heating of quenched plasma, pulsing of sputtering power was tried. Namely, during the sputtering off time, ICP can accelerate electrons to recover ICP only state. Additional ICP RF power can also compensate partly this quenching, but coil sputtering can make problems worse. So, in order to solve these two problems of ionized PVD, pulsed sputtering and axial magnetic field application were tried.

## II. Experimental

In Fig. 1, I-PVD chamber with 400 mm diameter and 350 mm height was shown with water cooled internal RF ICP coil, optical emission spectrometer system, RFZ-60 impedance analyzer and RF, Pulse power supplies, where sputtering can be done with either DC power supply or low frequency RF generator (50 KHz, PEP-2500) with variable pulse on-off time from 1 ms to 500 ms. ICP was generated by 13.56 MHz generator through L-type matching network. Optical Emission Spectroscopy (OES) and impedance analyzer were used to measure the existing quantity of excited neutrals and ions in the plasma.

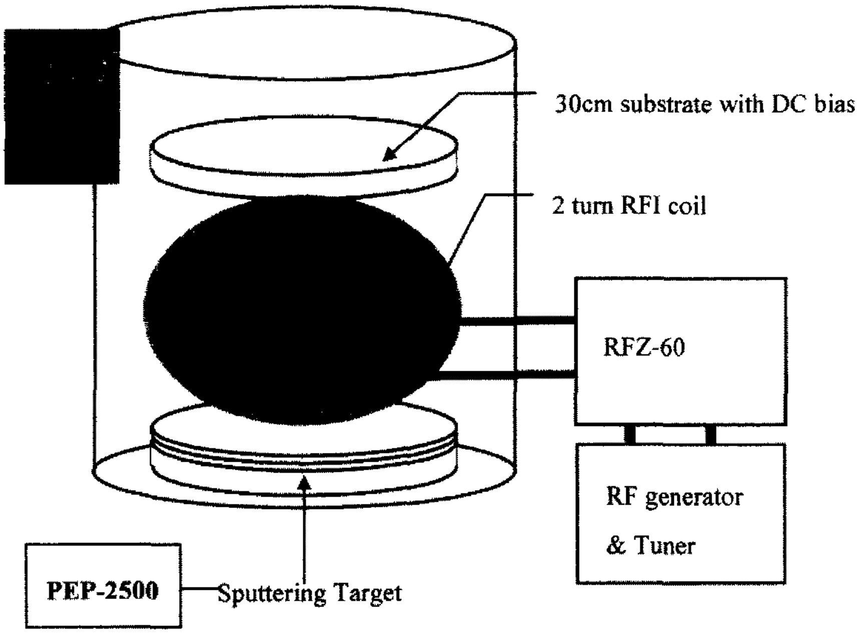

**Fig. 1.** Experimental system. Sputtering power source is either DC or low frequency (50 kHz) pulse power supply. 2 turn ICP coil is used with impedance analyser between RF feedthrough and RF tuner.

From the intensities of close emission lines, ion flux ratio was estimated. For direct investigation of the effects of pulsing on deposited films, Ag was deposited at room temperature and thickness measurement by stylus method, sheet resistance by 4 point probe and X-ray diffraction analysis were done. The detailed deposition conditions were shown in Table 1. In this study, sputtering target of 2 inch diameter was run with 500 W, so giving 25.4 W/cm$^2$ of power density as a whole and considering etch track area (11 cm$^2$) 45 W/cm$^2$. This is fairly high sputtering power density in engineering point of view.

## III. Results and Discussion

As shown in Table 1, we chose two time scales pulse on time 10 ms and 100 ms and varied pulse off time from 1 ms to 300 ms. During sputtering pulse on time, heavily sputtered metal atoms easily quench the Ar ICP. In Fig. 2, the emission intensity from Ag$^+$ and calculated ion flux ratio

**Table 1.** Experimental conditions and measured film properties

| Pulse Time | | ICP | PEP | Depo Time (min) | Current (mA) | $I_{(200)}/I_{(111)}$ | $\rho$ ($\mu\Omega$) |
|---|---|---|---|---|---|---|---|
| On (ms) | Off (ms) | | | | | | |
| 10 | 1 | 500 W | 435 W | 11 | 300 | 0.585 | 2.31 |
| 10 | 5 | | 328 | 15 | 300 | 0.892 | 2.81 |
| 10 | 10 | | 249 | 20 | 270 | 3.612 | 2.88 |
| 10 | 20 | | 169 | 30 | 250 | 1.206 | 2.25 |
| 10 | 30 | | 127 | 40 | 220 | 1.106 | 1.94 |
| 100 | 1 | | 494 | 10 | 300 | 1.263 | 3.61 |
| 100 | 5 | | 475 | 10 | 300 | 1.701 | 2.80 |
| 100 | 10 | | 453 | 11 | 290 | 2.267 | 7.47 |
| 100 | 50 | | 333 | 15 | 250 | 1.202 | 0.80 |
| 100 | 100 | | 248 | 20 | 230 | 2.730 | 10.4 |
| 100 | 200 | | 164 | 30 | 220 | 1.173 | 1.29 |

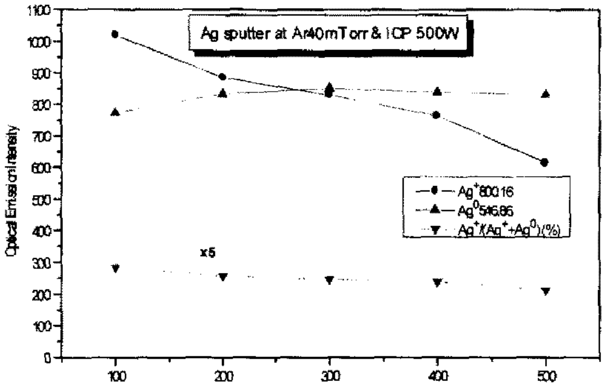

**Fig. 2.** Optical Emission data of Ag$^+$ shows quenching of ICP by heavily sputtered metal atoms.

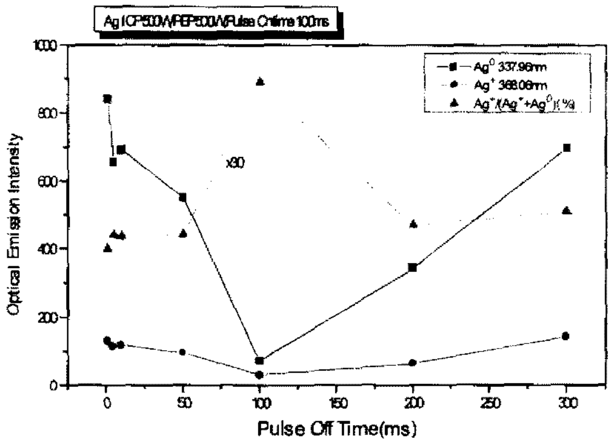

**Fig. 3.** Optical Emission Intensities of Ag$^+$, Ag$^0$ show change of relative ion flux ratio at pulse on/off time (100 ms/100 ms).

are decreased as sputtering power is increased. When sputtering pulse is off, only ICP is turned on and heating of ICP electron should occur and some etching of deposited films depending on the substrate bias, which is kept mostly less than $-20$ V far lower than severe sputtering threshold of deposited films. The determination of sputtering pulse off time is only related to recover the quenched ICP by sputtered metals. Ag was selected as our starting material, because Ag has very high sputter yield at even low ion energy (3.6 at 600 eV Ar$^+$ [3]), we could easily verify our idea. In estimating ion flux ratio, atomic emission lines of Ag$^0$ and Ag$^+$ from very close positions, if available, were chosen to reduce Electron Energy Distribution Function (EEDF) changing effect and used to check the pulsing effects. For most productive process, shorter pulse off time is better if it is enough to restore ICP's electron energy and giving more ionization. For pulse on time of 10 ms, there was little evidence of ICP restoration at 10 ms of pulse off-time based on Ag$^0$ emission. But for 100 ms of on-time, clearly there was a double enhancement of ionization flux ratio (Fig. 3). The decrease of averaged Ag$^0$ and Ag$^+$'s emission intensity is closely related with pulse's duty ration and out-diffusion toward a chamber wall. In shorter off-times like 1, 5, 10 ms, plasma's emission intensity does not change much. In approximation, the characteristic diffusion velocity is about 7.6 m/s. On this basis, the optimal pulsing condition should be dependent on chamber's geometry and gas diffusion velocity. At longer pulse off time, full restoration of quenched plasma back to pure ICP was occurred. But for Ar case, there is slight change less than 5% in ion flux ratio, i.e. Ar$^+$/(Ar$^+$+Ar$^0$). So during the off-time, more surface mobility can be obtained from low energy ion bombardment from ICP generated Ar$^+$. It can change the growing characteristics of Ag on the glass. In XRD results (Fig. 4), (200) plane dominates (111) plane also in 1 to 1 on-off time scale, i.e. 10 ms/10 ms and 100 ms/100 ms. For 10 ms case, higher than 3.5 times was obtained for preferred orientation and almost every crystalline orientation of Ag can be easily found, which means enough surface mobility was obtained from incoming ions (Fig. 5). The measured optical emission data for wide range of Ar gas pressure and ICP power are shown in Fig. 7 and Fig. 8. Ar$^0$ and Ar$^+$ show similar tendency of peak emission condition that is 30 mTorr of Ar gas pressure and 800 W of ICP power. As expected, the higher ICP power can generate more Ar$^+$ at same neutral gas pressure but creates more sputtered coil materials, in this experiment, Cu. If high power of ionization is required, there should be a remedy for coil sputtering. In this

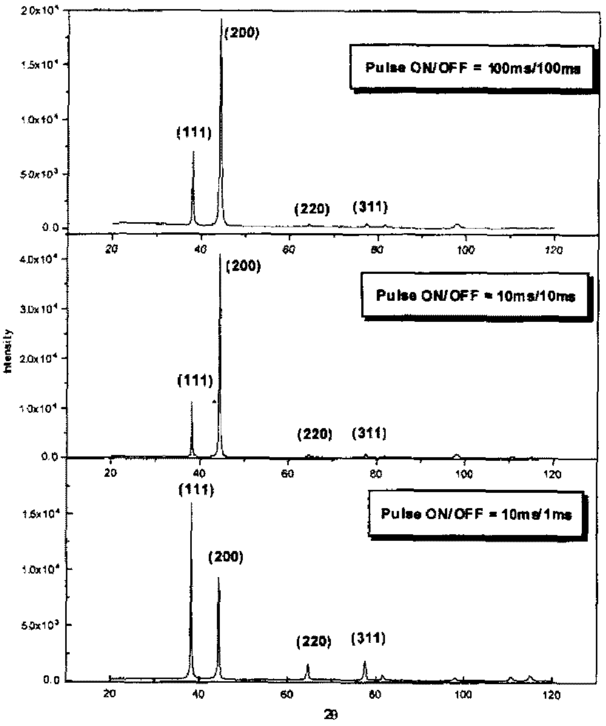

**Fig. 4.** X-ray diffraction pattern of deposited Ag film with three different pulse on/off ratio.

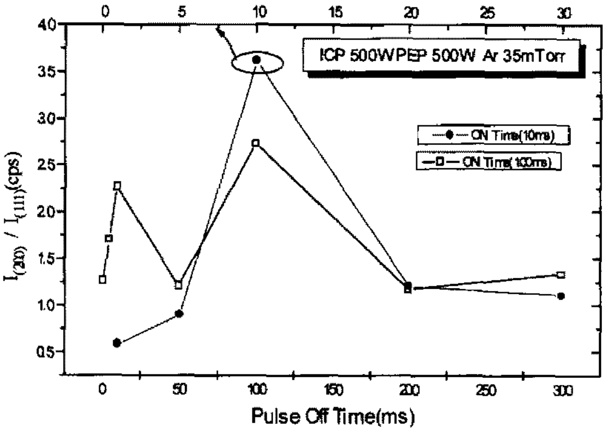

**Fig. 5.** Preferred orientation changes with sputtering pulse on/off ratio in two on time scales (10 ms, 100 ms) and shows highest (200) preferred orientation at equal on/off duty.

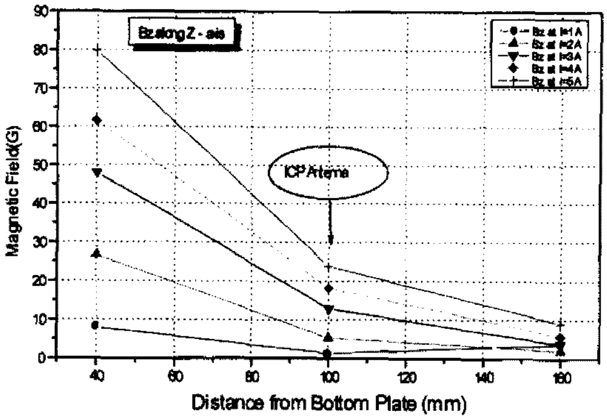

**Fig. 6.** Axial magnetic field as a function of bobbin currents. ICP antenna is located at 100 mm high from bottom plate.

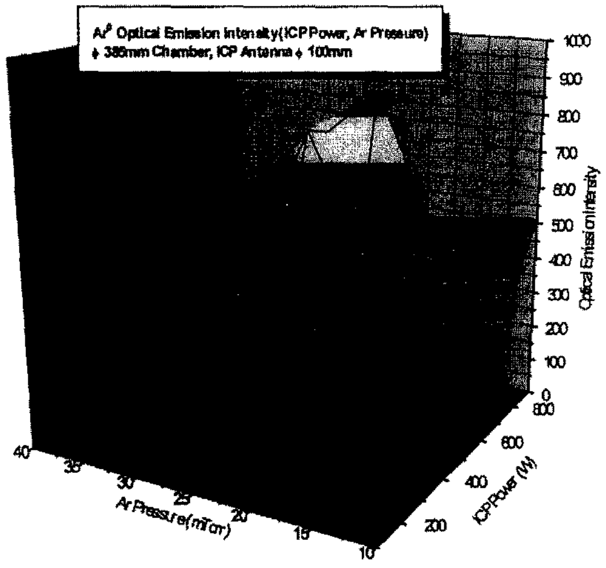

**Fig. 7.** Optical Emission Intensities of Ar° as a function of gas pressure and ICP power.

study, we tried axial magnetic field to solve this problem. Therefore, we applied axial magnetic field of strength up to 30G at ICP coil position shown in Fig. 6 which is very low field strength comparing to Helicon (200G~600G) or ECR (875G) case. From extended surveys of RF power, Ar gas pressure and axial B field, we could verify the effects of $B_z$ on ionization enhancement at scaling relation of B field and RF power in Helicon plasma. Theoretical modeling is undergoing based on the measured data to determine this is due to only ionizing electron confinement or some interaction between RF and axial magnetic field. From the emission of $Ar^0$ and $Ar^+$, the maximum emission of $Ar^0$ occurs at 1A axial current, which is corresponding to 3G at center and at increased RF powers like 300 W, 400 W, 500 W, the maximum point moves to higher axial current. This means in higher RF powers, higher $B_z$ is necessary to confine the electrons and to gets some coherent magnetic

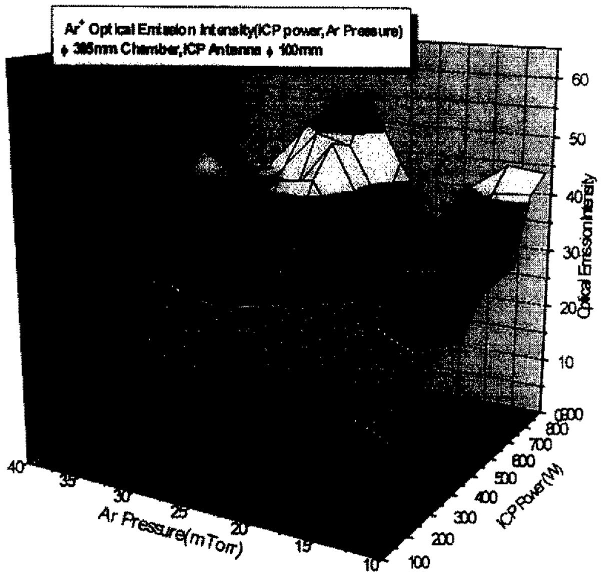

Fig. 8. Optical Emission Intensities of $Ar^+$ as a function of gas pressure and ICP power.

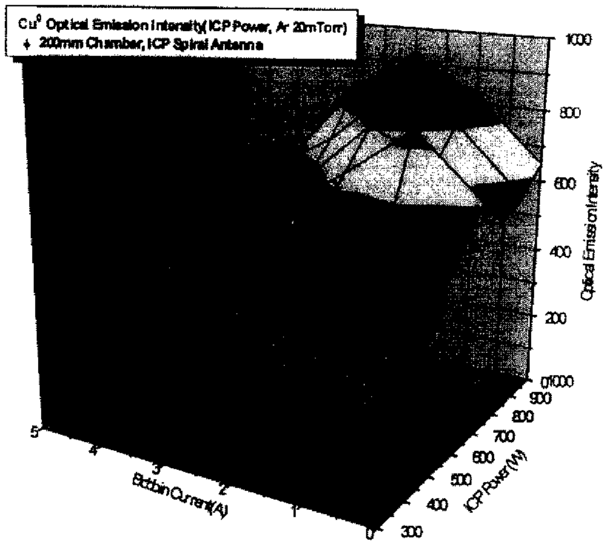

Fig. 9. Effect of axial magnetic field on Cu coil sputtering is measured by optical emission intensity change.

coupling with RF field. At higher Ar gas pressure, the necessary $B_z$ also increases. As the collision frequency between electrons and atoms increases, the mean free path of electrons gets shorter. So in order to deflect the electron's trajectory within that flying time, the increased magnetic field looks necessary. In experiments this appears as movement of peak point in OES intensity vs. axial magnetic field curves. At 30 mTorr, OES intensities of $Ar^0$, $Ar^+$ peak at 2A of coil current, which is 2 times of at 10 mTorr. In Fig. 9, the optical emission from sputtered $Cu^0$ is reduced at high RF power by bobbin current of 4A. More strong evidence for axial magnetic field effect is plasma's impedance characteristic change shown in Fig. 10. We used Advanced Energy's RFZ-60 just before RF feedthrough of our plasma chamber and the measured impedances are only from plasma and RF antenna. At the same RF power of 600 W, peak voltage drops down more than 20% at coil current 2A. We could guess that 2A, i.e. 8G of $B_z$ is the starting point of plasma wave interaction which gives lowest reflected power (virtually zero) and reactance. But at higher $B_z$, the coil voltage starts to increase again and all the other properties are getting worse. This may be closely related with the Magnetized Inductively Coupled Plasma (MICP) reported earlier by authors [4].

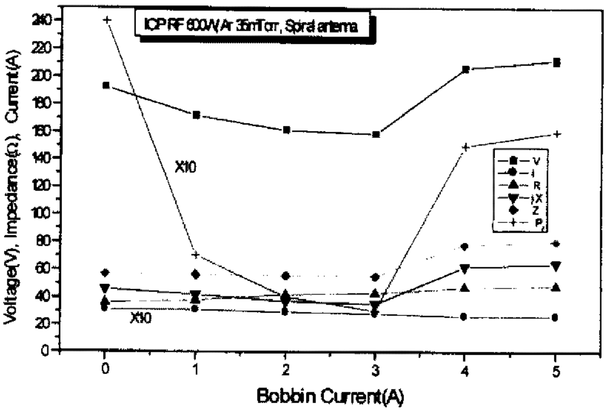

Fig. 10. Impedance characteristics of ICP change as axial magnetic field increases. About 3A, corresponding to 8G at RF antenna position, gives lowest coil voltage and reactance.

## IV. Conclusions

RF pulsed sputtering of the metal target could restore metal quenched ICP and also enhance the ionization of the sputtered atoms with 10 ms/10 ms and 100 ms/100 ms on/off time duration. At this time duration, the deposited Ag films have higher (200) preferred orientation over (111) from

XRD results. This time constant is suggested to be closely related with the characteristic diffusion length of the plasma chamber. OES diagnostics showed the wavelike dispersion structure exists in magnetic field - ion flux ratio relationship. This must be studied theoretically and modeled to get an insight into the underlying physics. At 600 W of RF and 30 mTorr Ar, 2A was an optimal coil current for $B_z$ with the lowest reflected power and coil voltage inducement, which gives very small coil sputtering and contamination.

## Acknowledgement

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