Transactions of the Materials Research Society of Japan 30[1] 291-294 (2005)

Measurement of Absolute Cu Atom Density in Magnetron Sputtering Plasmas

Junsi Gao, Nayan Nafarizal, Koichi Sasaki, Hirotaka Toyoda, Satoshi Iwata, Takeshi Kato, Shigeru Tsunashima, and Hideo Sugai

Department of Electrical Engineering and Computer Science, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan
Fax: 81-52-788-6075, Email: gao@nuee.nagoya-u.ac.jp

In this work, the dependences of the absolute density distribution of sputtered Cu atoms were investigated systematically on the input power and the gas pressure by laser-induced fluorescence (LIF). The sputtered Cu atoms were mainly distributed in the region adjacent to the target surface when the gas pressure was below 3 mTorr. The peak position of the density distribution was dependent on the discharge conditions. With increasing the gas pressure, the peak position moved toward the downstream area separated from the target. The distance between the peak position and the target was as far as 6 cm at a pressure of 10 mTorr and a discharge power of 50 W. The absolute Cu atom density in the vicinity of the target was 1.6 $\times 10^{10}$ cm^{-3} at 3 mTorr and 50 W, while they reached 9.9$\times 10^{11}$ cm^{-3} at 50 mTorr and 50 W. The mechanism for the movement of the peak position will be investigated continuously in the future study.

Key words: magnetron sputtering plasma, absolute density, distribution, laser-induced fluorescence

1. INTRODUCTION

Sputter deposition using magnetron plasma sources is frequently used in fabricating magnetic devices having multilayered structures of magnetic and non-magnetic metals [1-6] and in depositing thin metallic films such as Cu and Al for catalysts and semiconductor wiring [7-10], after their developments in the late 1970's [11-13]. Because of its magnetic field, a magnetron sputtering source can trap electrons in the vicinity of the cathode to generate high density plasmas. Ions in the plasma are accelerated toward the cathode by the sheath electric field, causing atoms of the cathode material to be sputtered and secondary electrons to be emitted. These secondary electrons enter the trapping region and cause sufficient ionization to maintain the discharge. The combination of high sputtering rates at moderate voltages and reduced scattering of sputtered atoms at low operating pressures allow high deposition rates to be realized in the magnetron sputtering deposition. However, the non-uniformity of the magnetic field causes the sputtering rate to vary considerably across the diameter of the cathode. Thus, non-uniform thickness distributions were produced in the deposited films on the substrate, which was attributed to the different angular distribution of the sputtered atom density [14-16]. Although the non-uniform erosion shape of the target and the non-uniform thickness distribution of the film were investigated in details, few studies were performed for investigating the density distribution of sputtered atoms in magnetron sputtering plasmas, which directly influences the uniformity of the deposited films.

In this study, two-dimensional laser-induced fluorescence (2D-LIF) was utilized to visualize the distribution of Cu atom density in magnetron sputtering plasmas. 2D-LIF has a high sensitivity and a high spatial resolution. It is, however, impossible to derive the absolute Cu atom density from the 2D-LIF signal with no calibration. In this measurement, we used ultraviolet absorption spectroscopy using a hollow cathode lamp for determining the absolute Cu atom density.

2. EXPERIMENT

A schematic diagram of the experimental setup for 2D-LIF is shown in Fig. 1, which consists of a tunable optical parametric oscillator (OPO) and a magnetron sputtering system. The OPO laser had a linewidth of approximately 1 pm at a wavelength of 324.75 nm. The laser beam passed through two cylindrical lenses, which arranged the laser beam to be a planar shape with 80 mm in width and 1 mm in thickness. This planar laser beam crossed through the plasma and excited Cu atoms on its pathway. The transition for excitation employed here is $^2P_{3/2}$-$^2S_{1/2}$ at 324.754 nm, which induced the fluorescence at 510.55 nm (the $^2P_{3/2}$-$^2D_{5/2}$ transition). The image of the fluorescence formed on the planar laser beam was taken by a gated CCD camera with an image intensifier. The tone of the picture taken by the CCD camera represented the two-dimensional distribution of the Cu atom density.

A dc-magnetron sputtering source was used for generating plasmas in a cylindrical chamber with a diameter of 300 mm and a length of 260 mm. Circular permanent magnets were located behind a planar Cu target with 50 mm in diameter and 2 mm in thickness. The magnetic field strength on the surface of the target was approximately 60 mT, which was measured at a radial distance of 15 mm where the magnetic field was

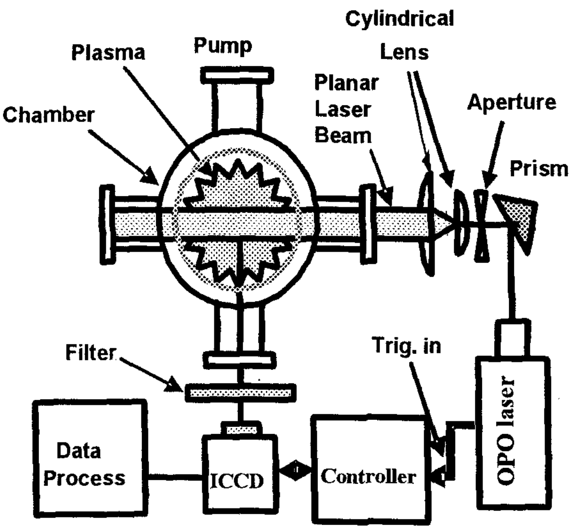

Fig. 1 Schematic diagram of the experimental setup for 2D-LIF measurement.

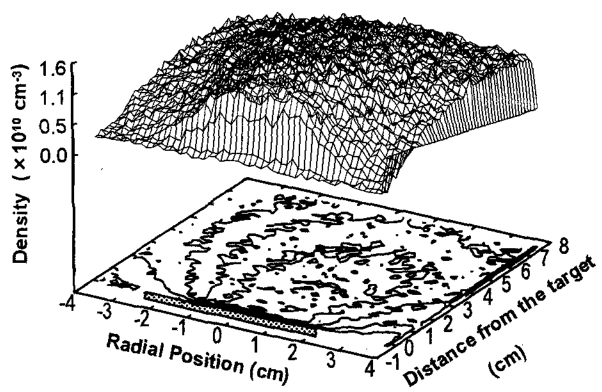

Fig. 2 Spatial distribution of the Cu atom density observed at a discharge power of 50 W and a gas pressure of 3 mTorr.

parallel to the target surface. The chamber was filled with Ar gas at pressures from 1 to 100 mTorr after the evacuation using a turbo molecular pump.

3. RESULTS AND DISCUSSION

There were different combinations of the current and the voltage for different gas pressures (P_g) although the dc power (P_{dc}) was fixed at the same value. For example, at P_{dc}=30 W, the current and the voltage were 0.08 A and 375 V at P_g=3 mTorr, respectively, while they were 0.1 A and 300 V at P_g=50 mTorr. In the present work, we investigated the spatial distribution of the Cu atom density as functions of the gas pressure and the discharge power. However, it is noted that the energies of sputtered atoms may be affected by the energy of sputtering ions which is determined by the sheath potential and multiple collisions in background Ar gas. The sheath potential and collisions are dependent on the discharge voltage and the gas pressure, respectively.

A typical distribution of the absolute Cu density is shown in Fig. 2, which was obtained at P_g=3 mTorr and P_{dc}=50 W. The origin of the r-z plane (r and z are the radial position and the distance from the target, respectively) is the center of the target surface. This distribution had a high-density area adjacent to the target surface. The peak value of the absolute Cu density in the vicinity of the target was 1.6×10^{10} cm^{-3}. The Cu density decreased monotonically with the distance from the target along the cylindrical axis, and it was 3.5×10^9 cm^{-3} at z=7 cm. The Cu density at z=0 cm and r=±4 cm was close to zero. This may be because Cu atoms are ejected into the chamber rather vertically. The mean free path at 3 mTorr is estimated to be approximately 20 mm. The high-density area may be thus formed near the target surface.

The measurement was repeated in the pressure range from 1 to 100 mTorr. As a result, it was found that not only the absolute density but also the distribution changed with the gas pressure significantly. Figure 3 shows the distribution of the Cu atom density observed at P_g=50 mTorr and P_{dc}=50 W. The peak value of the absolute Cu density was close to 1×10^{12} cm^{-3}, which was much higher than the Cu density at 3 mTorr. The Cu atom density in the vicinity of the target surface (1×10^{11} cm^{-3}) was lower than the peak value, but it was six times higher than the Cu density observed at 3 mTorr at the same position. The higher Cu atom density at the higher gas pressure is attributed partly to limited diffusion.

We should emphasize here the fact that the peak position of the density distribution was separated from the target surface. The peak position at 50 mTorr was located at z=3 cm as shown in Fig. 3. Since the source of Cu atoms is the target surface, the distribution of the Cu atom density shown in Fig. 3 is mysterious. An explanation for such distribution is spatial distribution of the speed and/or the temperature of Cu atoms. If there are spatial distributions of the speed and/or the temperature, the distribution of the Cu atom density shown in Fig. 3 is understood reasonably by considering the transport with a constant flux. However, experimental results on the spatial distribution of the sputtered atom speed suggest that Cu atoms are almost stationary in the entire observation space when the gas pressure is 50 mTorr [17]. This is reasonable since the mean free path is approximately 1.2 mm at 50 mTorr. Therefore, the distribution shown in Fig. 3 cannot be explained by the transport with a constant flux.

In the experiment, the peak position was dependent on the discharge conditions. At a low gas pressure such as 3 mTorr, the peak position was adjacent to the target surface as shown in Fig. 2. With increasing the gas pressure, the peak position moved from the target surface toward the downstream region gradually. The distance between the peak position and the target

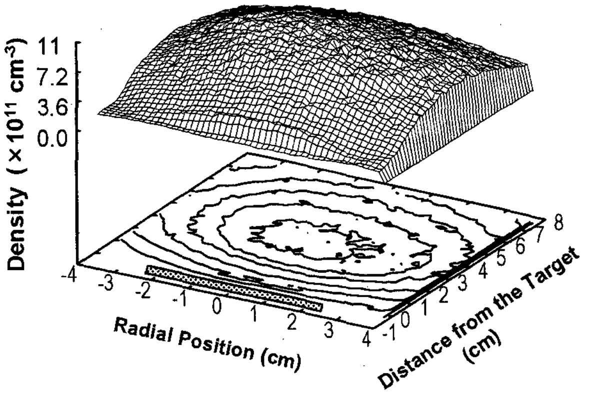

Fig. 3 The same as Fig. 2 but the gas pressure was 50 mTorr.

surface reached the maximum value of 60 mm at 10 mTorr. At gas pressures higher than 10 mTorr, the peak position moved toward the target surface again. The peak position was also a function of the discharge power, and the distance between the peak position and the target surface was longer at a higher discharge power. Further investigation is necessary to find a reasonable explanation for the peak position separated from the target surface.

Figure 4 shows the absolute Cu atom density at P_g=50 mTorr as a function of the discharge power. The Cu atom densities at four distances from the target are plotted. As shown in the figure, the Cu density increased with the discharge power significantly. This increase may be caused by the increase in the plasma density and by the increase in the irradiation energy of ions toward the target. The increase in the plasma density means the increase in the number of ions toward the target, and the higher irradiation energy of ions induces higher sputtering yield per an ion. It is noted that the increase in the Cu density is steeper at longer distances from the target, indicating the change of the spatial distribution of the Cu density with the discharge power.

Figure 5 shows the dependence of the absolute Cu density on the gas pressure at the same positions as those in Fig. 4. The discharge power was fixed at P_{dc}=50 W. The Cu density increased with the gas pressure, which is attributed partly to the increase in the plasma density with the gas pressure. It is noted that the discharge voltage decreased with the gas pressure at the constant power of P_{dc}=50 W, indicating that the sputtering yield per an ion decreased with the gas pressure. Considering the significant increase shown in Fig. 5, there would be another mechanism for the enhancement of the Cu density in high-pressure plasmas. As mentioned above, the vicinity of the target had the highest Cu density at a low gas pressures below of 3 mTorr. The increase in the Cu density with the gas pressure was steeper in the longer distance from the target, resulting in the movement of the peak position of the Cu atom density from the target surface toward the downstream region. The Cu densities in the downstream region (3 and 5 cm) were saturated at gas pressures above 40 mTorr, while the Cu densities at z=0.2 and 1 cm continued to increase, indicating the movement of the peak position toward the target. The decrease or the saturation of the Cu density in the downstream region may be due to limited diffusion of sputtered Cu atoms in the high gas pressure.

4. CONCLUSIONS

The dependence of the absolute density distribution of sputtered Cu atoms in magnetron sputtering plasmas was investigated on the gas pressure and the dc power systematically. The absolute Cu density ranged from 10^9 to 10^{12} cm^{-3}, depending on the position and the discharge conditions. The Cu density increased with both the discharge power and the gas pressure, which may be

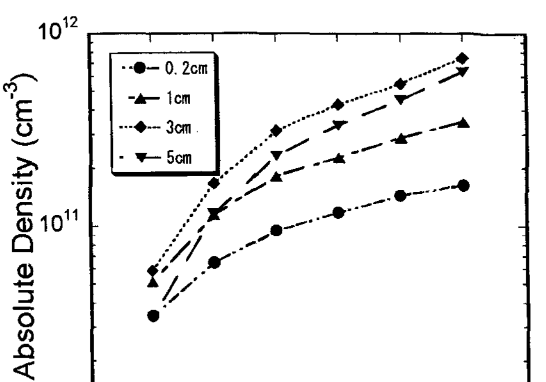

Fig. 4 Absolute Cu atom density at various distances from the target as a function of the discharge power. The gas pressure was fixed at 50 mTorr.

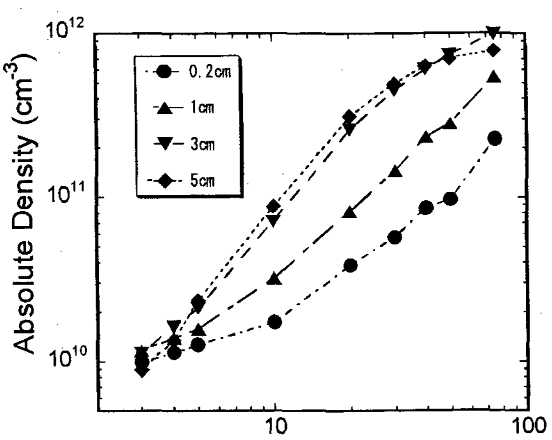

Fig. 5 Absolute Cu atom density at various distances from the target as a function of the gas pressure. The discharge power was fixed at 50 W.

related to the change in the plasma density and the irradiation energy of ions to the target. The local Cu density was also affected by the change in the spatial density distribution. We found that the peak position of the Cu density was adjacent to the target surface at low gas pressures below 3 mTorr. The peak position moved toward the downstream region with increasing the gas pressure from 3 to 10 mTorr. The distance between the peak position and the target surface was 60 mm at a gas pressure of 10 mTorr and a discharge power of 50 W. At gas pressures above 10 mTorr, the peak position moved toward the target surface. The mechanism for the peak position separated from the target surface has not been understood well, and further investigations on the kinetics and transport are necessary to understand the spatial distribution of the Cu atom density. Although we do not understand everything, we believe that the present experimental results are helpful to optimize thin film deposition using magnetron sputtering sources.

ACKOWLEDGEMENTS

This work was supported by 21st century COE (Center of Excellence) Program, "Information Nano-Devices Based on Advanced Plasma Science", of Nagoya University. The authors are grateful to Mr. N. Takada and Mr. H. Ushida for their technical help. We would also like to thank Dr. K. Shibagaki for his valuable discussion.

REFERENCES

[1] R.F. Carcia, J. Appl. Phys., vol. 63, pp. 5066-5073, 1988

[2] M.N.Baibich, J.M.Broto, A.Fert, F.Nguyen van Dau, F.Petroff, P.Etience, G.Creuzet, A.Friederich and J. Chazelas, Phys. Rev. Lett. 61 2472 (1988)

[3] S.S.P.Parkin, R.Bhadra and K.P.Roche, Phys. Rev. Lett. 66 2152 (1991)

[4] Stéphanie Capdeville, Pierre Alphonse, Corine Bonningue, Lionel Presmanes,a) and Philippe Tailhades, J. Appl. Phys., Vol. 96 (11), 6144 (2004)

[5] D. P. Makhnovskiy,a) N. Fry, L. V. Panina, and D. J. Mapps, J. Appl. Phys., Vol. 96(4), (2150)2004

[6] L. Castaldi, M. R. J. Gibbs and H. A. Davies, J. Appl. Phys., Vol. 93(11), (9165)2003

[7] S. M. Aouadia) and P. K. Shreeman and M. Williams

[8] J. Y. Gu,a) Chun-Yeol You,b) J. S. Jiang, and S. D.Bader, J. Appl. Phys., Vol. 93(10), (7696)2003

[9] S. Okamura, R. Goto, and S. Sugimoto, N. Tezuka and K. Inomata, J. Appl. Phys., Vol. 96(11), (6562)2004

[10] R.G.Lacerda, K. B. K. Teo, A. S. Teh, M.H.Yang, S. H. Dalal, D. A. Jefferson, J. H. Durrell, N. L. Rupesinghe, D. Roy, G. A. J. Amaratunga, and W. I. Milne, J. Appl. Phys., Vol. 96(8), (4456)2004

[11]G. M. Turner, S. M. Rossnagel, and J. J.Cuomo, J.Appl. Phys. **75**, 3611 (1994)

[12] J. J. Cuomo and S. M.Rossnagel, J. Vac.Sci. Technol. A **4**, 393(1986)

[13] D. B. Fraser, J. Vac. Sci. Technol. **15**, 178 (1978).

[14] J. A. Thornton, J. Vat. Sci. Technol. 15, 171 (1978).

[15] B. Chapman, Glow Discharge Processes (Wiley, New York, 1980)

[16] J. A. Thornton, in Deposition Technologies forFilms and Coatings, edited by R. F. Bunshah (Noyes,Park Ridge, NJ, 1982), Chap. 5

[17] K. Shibagaki, N. Nafarizal, K. Sasaki, H. Toyoda, T.Kato, S. Iwata, S. Tsunashima, and H. Sugai, to be submitted to J. Appl. Phys.

(Received December 23, 2004; Accepted January 31, 2005)