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The optical emission spectroscopy study of an rf-plasma-enhanced magnetron sputtering system

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Abstract

Optical emission spectroscopy has been performed for unbalanced DC magnetron sputtering of Cu in Ar atmosphere with the enhanced ionization of inductively coupled plasma. The intensities of Cu, Cu^+, Ar and Ar^+ lines were measured at various discharge parameters such as pressure and rf power. Both Cu and Cu^+ lines intensities initially increase and then decrease with increasing pressure. At the same time, Ar line intensity increases and the Ar^+ line intensity decreases with increasing pressure. With increasing rf power, all the lines intensities increase at different rates and become saturated when the rf power is greater than 700 W. The rf discharge exhibits mode jumping (E-mode to H-mode) and hysteresis phenomena. When the rf power increases to 400 W, the rf discharge mode jumps from E-mode to H-mode. When the rf power input decreases from 800 to 300 W, the rf discharge mode jumps back from H-mode to E-mode. However, during the mode change, the intensities of all lines are higher when switching from H-mode to E-mode than those when switching from E-mode to H-mode at the same rf power. In the rf power region, the ionization of Cu is significantly enhanced. The reasons of these phenomena are discussed.

Keywords: OES; DC magnetron sputtering; RF plasma; Cu; Ar

1. Introduction

Magnetron sputtering deposition was initially developed for high-rate deposition and excellent film structure and conformity. It has now been widely used to deposit copper seed layer prior to chemical vapor deposition or electroplating process for very large-scale integrated interconnects metallization [1–3]. But for conventional magnetron sputtering deposition, the ionization of sputtered atoms is low and it is difficult to control the deposition process. The use an rf coil to generate an inductively coupled plasma between sputtered target and substrate can ionize a large portion sputter atoms hence to enhance the control of the deposition process [4,5]. In order to obtain a better discharge parameter, the diagnosis of plasma is essential.

Optical emission from the plasma discharge reflects many important characteristics of plasma, such as the density of neutral/ion species, electron density and its energy distribution. Therefore, optical emission spectroscopy (OES) measurement has long been recognized as one of the suitable methods for plasma diagnostics [6,7]. In this paper, we report an OES diagnosis of the titled system to find a best working condition.

2. Experimental setup

The experimental setup consists of a high vacuum chamber, rf and dc power supplies, and a vacuum sputtering flange. A Cu target with a diameter of 20 cm is mounted at the top of the vacuum chamber. Two ring-shaped permanent magnets with opposite polarity are placed on the Cu target to produce magnetic field roughly parallel to the target (balanced magnetron field). Additional three ring-shaped permanent magnets are equipped outside the quartz vacuum chamber to produce unbalanced magnetic field roughly vertical to the sputtering target. With this magnetron system, the electrons can be confined inside the chamber so that the plasma can pass through the

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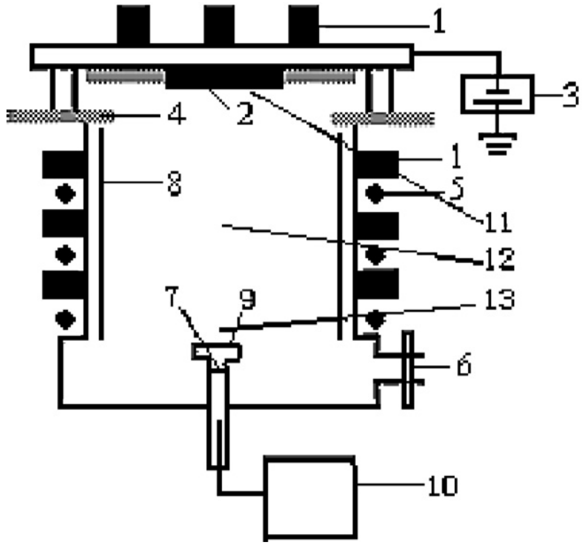

Fig. 1. The schematic construction of the experimental setup. 1. Magnetron; 2. cathode (target); 3. bias power supply; 4. anode; 5. RF electrode coil; 6. pump; 7. lens; 8. shield the cover; 9. poles; 10. monochrometer and photoelectronic acquisition system; 11. target area; 12. chamber area; 13. substrate area.

chamber and reach the substrate with little depression. A rf coil is wrapped outside the quartz chamber between the sputtering target and the substrate holder. A water-cooled system is equipped to avoid the target and the rf coil from overheating.

The optical emission spectrometer is composed of optical collection system, monochrometer and photo-electronic acquisition system. The output signal of the photoelectron multiplication tub (PMT) is sent to a computer for acquisition, after being amplified by a dc amplifier. The wavelength range of the monochrometer is 300–1000 nm and its highest resolution is 0.1 nm. A lens coupled with optical fibers is used to collect the lights and can be moved vertically to collect light from different areas. We use this system to collect light from three different areas as shown in Fig. 1: target area, chamber area and substrate area.

The base pressure of the vacuum chamber is 0.004 Pa, Ar is the working gas and the working pressure is 0.2–0.8 Pa. The highest dc voltage supplied on the Cu target is 1000 V. The frequency of the rf power is 13.56 MHz and the highest power is 1000 W. A matching network system is used between the rf power source and rf coil to reduce the reflected power.

3. Results and discussion

Emission lines were compared with the NIST Scientific and Technical atomic line database [8]. Many emission lines could be assigned to Cu neutrals, Cu ions, Ar neutrals and Ar ions. We chose some representative lines and they are listed in Table 1. We chose Cu atom line (324.7 nm), Cu ion (Cu^+) line (617.2 nm), Ar atom line (415.9 nm) and Ar ion (Ar^+) line (434.8 nm). These four lines are shown in Fig. 2, the scanning time of Cu^+ line is 500 ms and others

Table 1
Emission lines assigned by NIST Scientific and Technical atomic line database

Type	Wavelength (nm)	Upper level (eV)	Lower level (eV)
Ar	415.9	14.529	11.548
Ar^+	434.8	19.495	16.644
Cu	324.7	3.817	0
Cu^+	617.2		

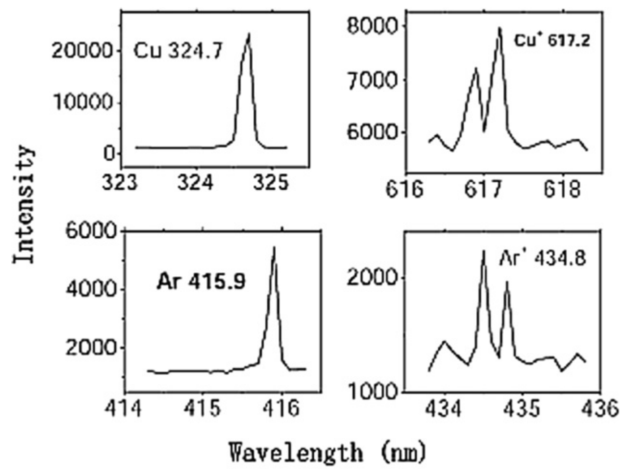

Fig. 2. The selected Ar atom, Cu atom, Ar ion and Cu ion lines.

are 100 ms, so in fact, the Cu^+ line intensity is weaker than Ar and Ar^+ lines. The intensities of these lines are studied as function of different chamber areas and discharge parameters, such as Ar pressure and rf power. As we used a lens to collect lights from the plasma source, Cu deposition on the lens decreases the transmission of the lens, therefore, signals from different lines were collected at the same time. Since the Cu^+ line intensity is weak, we chose a long scanning time (500 ms) to enhance the signal-to-noise ratio. From the variety of Cu^+ line intensity we can roughly evaluate the Cu^+/Cu in which we are most interested. From the variety of the ratio of Ar atom line and Ar ion line, we can analyze the influence of discharge parameters on the plasma parameters such as electron temperature and density.

3.1. *The influence of discharge pressure on emission line intensities*

In the present investigation, the sputtering dc magnetron discharge in Ar was operated at the pressure of 0.2, 0.4, 0.6 and 0.8 Pa with applied dc voltage of 490–400 V (the higher pressure, the lower voltage) to sustain about the same current (about 100 mA) collected from the target without rf power. With the increase of rf power the required dc voltage will decrease. For example, when the rf power is higher than 500 W, the required dc voltage decreases to about 100 V.