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Plasma property of inductively coupled discharge and substrate bias co-assisted very-high-frequency magnetron sputtering

Yi Liu [a], Chao Ye [a,b], Haijie He [a], Xiangying Wang [c], Shuibing Ge [a,b], Fupei Huang [a]

[a] *College of Physics, Optoelectronics and Energy, Soochow University, Suzhou 215006, People's Republic of China*
[b] *Key Laboratory of Thin Films of Jiangsu Province, Soochow University, Suzhou 215006, People's Republic of China*
[c] *Medical College of Soochow University, Suzhou 215123, People's Republic of China*

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ABSTRACT

Very-high-frequency (VHF) magnetron sputtering is an important method to deposit the polycrystalline films at low temperature. To increase the plasma density, ion flux and to control the ion energy, the inductively coupled plasma (ICP) and substrate bias co-assisted VHF magnetron sputtering was developed. The plasma properties of this system were measured by a Langmuir probe and a retarding field energy analyzer. In the VHF magnetron sputtering, the ICP discharge can increase the plasma density effectively but has a small influence on the ion energy and ion flux; the substrate bias can increase the plasma density and ion flux more effectively but result in the divergence of ion energy. When the ICP discharge and substrate bias are simultaneously applied, the divergence of ion energy can be suppressed, while the high plasma density (2.6×10^{17} m^{-3}) and ion flux (4.3×10^{20} $m^{-2} \cdot s^{-1}$) can be remained. Therefore, the ICP and substrate bias co-assisted VHF magnetron sputtering is a possible way to deposit the polycrystalline films at low temperature with a higher growth rate.

1. Introduction

Magnetron sputtering is a well known coating method. Progresses made in the magnetron sputtering system for the past several decades, particularly in the unbalanced magnetron system, have made it widely used. Recently, the very-high-frequency (VHF) magnetron sputtering has become an important technique to deposit the polycrystalline and nanocrystalline films at low temperature. The examples include the deposition of polycrystalline silicon films at low temperature using 182.5 MHz and 60 MHz VHF sputtering [1,2], and the formation of crystalline γ-Al_2O_3 using 71 MHz/13.56 MHz dual-frequency sputtering [3]. The formation of crystalline films by VHF magnetron sputtering is probably related to the higher ion energy because the ion energy was found to increase with the source frequency [4–6]. Therefore, the VHF magnetron sputtering is a possible way to control the crystallography and property of films. However, the low plasma density and ion flux were obtained in the VHF magnetron sputtering, as a result, leading to a small growth rate of films [2].

In order to increase the plasma density and ion flux in magnetron sputtering, the inductively coupled plasma (ICP) is usually used, which is generated by a RF (13.56 MHz) coil inserted in the process chamber between the substrate and magnetron target. The ICP discharge in the magnetron sputtering is thought to excite and ionize the sputtered species to a high degree effectively [7,8], thus creating high-density low-energy ion flux and activated species [9], and achieving a sufficient reaction [10,11]. As a result, this plasma can promote the formation of crystalline film [12] and dense microstructure [10,11] at lower deposition temperature. In order to control the ion energy in the magnetron sputtering, the substrate bias is also used. By applying a negative high DC bias, the pulse negative bias or an AC bias to the substrate [13–15], the ion energy can be effectively adjusted. The interaction between the positive ions in the plasma and the growing films [16] provides a combined benefit of both energetic ion-assisted deposition and a high deposition rate [17]. As a result, the crystallization, microstructure and property of the films are influenced [18,19]. However, the ICP-assisted discharge and substrate bias are usually used in the DC and RF (1 MHz, 13.56 MHz) magnetron sputtering, and seldom used in the VHF magnetron sputtering.

In this work, the RF (13.56 MHz) ICP and the RF (27.12 MHz) substrate bias co-assisted VHF (60 MHz) magnetron sputtering was developed. The plasma parameter, the electron energy probability function (EEPF) and the ion velocity distribution function (IVDF) of this system were investigated by a Langmuir probe measurement and a retarding

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E-mail address: cye@suda.edu.cn (C. Ye).

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field energy analyzer. The roles of ICP discharge and substrate bias in the VHF magnetron sputtering were discussed.

2. Experiments

2.1. The setup

Fig. 1 shows the schematic diagram of the 60 MHz VHF magnetron sputtering assisted by the 13.56 MHz ICP discharge and the 27.12 MHz substrate bias. The device was a cylindrical vacuum chamber made of stainless steel, had a diameter of 350 mm and a height of 300 mm. The circular water-cooled iron target with a diameter of 50 mm placed at the top of chamber with an angle of 45°, played the role of discharge cathode. The horseshoe-type annular magnetic field on the surface of the cathode was distributed by two permanent magnets placed behind the cathode. The intensity of magnetic field, measured using a Hall-probe gaussmeter, reached to a maximum value of about 780 G on the cathode surface. One-turn open loop coil made of stainless steel with a diameter of 200 mm was horizontally and centrally positioned below the cathode to produce the inductively coupled plasma. The coil was connected to RF (13.56 MHz) source at one end through a matching box, and the other was floated. This open loop configuration can effectively suppress the net extraction of electrons from the plasma to the grounding through the antenna and minimize the antenna RF voltage by satisfying the balance condition [20,21], thus reducing the floating potential and plasma potential. The electrically floated stainless steel substrate holder with a diameter of 100 mm was mounted away from the cathode to adjust the ion energy. The distances of the ICP coil and the substrate holder from the tilted magnetron are shown in Fig. 1. The sputtering target was biased by a 60 MHz VHF voltage through a matching box with a fixed input power of 150 W (reflected power about 20 W). The ICP coil was biased by a 13.56 MHz RF voltage through a matching box with the input power of 0–160 W (corresponding reflected power of 0–27 W). The substrate holder was biased by a 27.12 MHz RF voltage through a matching box with the input power of 0–150 W (corresponding reflected power of 0–13 W). The wall of the device was electrically grounded. The base pressure of the system, evacuated with a 600 l/s turbo-molecular pump backed up with a mechanical pump, was less than 5×10^{-4} Pa. Argon with a fixed flow rate of 30 sccm was used as the discharge gas and the operating pressure was maintained at 4.7–5.0 Pa.

2.2. Langmuir probe measurement

A Hiden Analytical RF compensated cylindrical ESPion Langmuir probe with a tungsten tip (0.15 mm diameter and 10 mm length) was used to acquire current–voltage (I–V) characteristic curves in the downstream zone. For the application of cylindrical Langmuir probe in the magnetron sputtering system, in order to avoid the depletion of low-energy electrons by the magnetic field, it was necessary that the radius of the probe (R) should be smaller than the Larmor radius of electrons (r_{ce}), i.e., $R << r_{ce}$. In our experiment, the Langmuir probe tip was positioned at the center of the reactor and 50 mm below the target surface, where the intensity of the magnetic field was about 10 G and the average electron temperature was 3 eV and so, thus the r_{ce} was about 5.7 mm. Therefore, the condition of R (0.075 mm) $<< r_{ce}$ was satisfied, and the probe measurement was sufficiently reliable in the downstream region. The I–V measurements were carried out for a probe bias voltage sweep of −100 V to 50 V. In order to reduce the RF distortion of the I–V characteristics, the probe system contained a resonance filter. The 13.56 MHz, 27.12 MHz and 60 MHz RF distortion of fundamental harmonics could be filtered. In order to eliminate the effect of deposition layer on I–V characteristic, the probe tip was automatically cleaned at a potential of −200 V with a 20 ms cleaning period before every data acquisition period. From the I–V characteristics, the electron density n_e, effective electron temperature T_{eff}, plasma potential V_p, ion flux Γ_i and the electron energy probability function (EEPF) were obtained. The smoothing and differentiation functions are based on the technique described by Savitzky and Golay [22,23]. To reduce the noise degradation of the result, five I–V scans were averaged and a wider filter width of 25 points was used for each discharge condition. Then, the electron energy distribution function (EEDF) $g_e(\varepsilon)$ is obtained from the Druyvesteyn formula [24,25]:

$$g_e(\varepsilon) = \frac{2m_e}{e^2 A}\left(\frac{2eV}{m_e}\right)^{1/2}\frac{d^2 I_e}{dV^2} \quad (1)$$

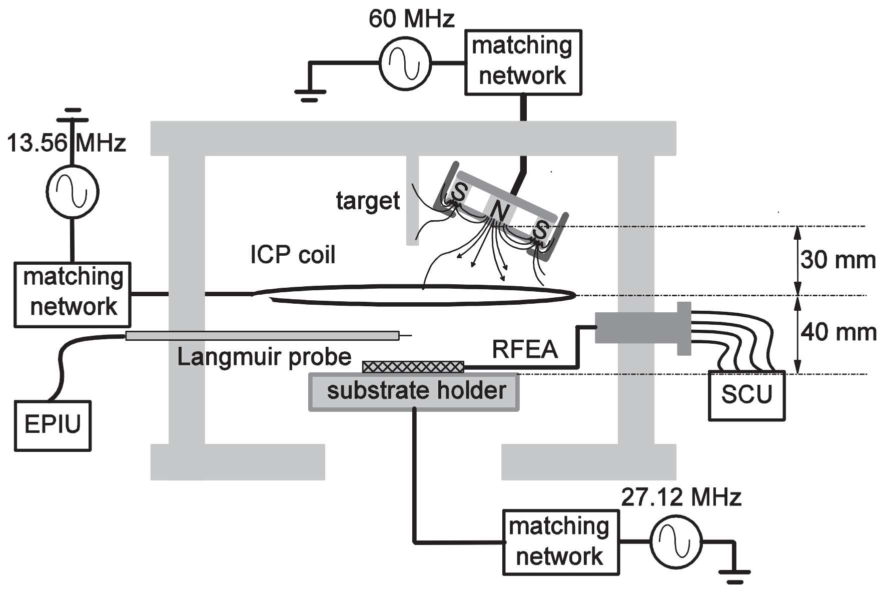

Fig. 1. Schematic diagram of the 60 MHz VHF magnetron sputtering assisted by the 13.56 MHz ICP discharge and the 27.12 MHz substrate bias.