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Best Paper of This Month

Improvement on Plasma Intensity Uniformity in Rectangular DC Magnetron Sputter by Optimizing Structures of Substrate Electrode

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ABSTRACT

DC magnetron sputtering is widely used for thin film deposition in the field of displays. By adding magnet arrays to a large rectangular magnetron sputtering system, while the ionization and deposition rate are increased, the film properties can be nonuniform, and the local target erosion rate can be increased. Film properties strongly depend on uniform plasma density and energy. Although the ferromagnetic shield has been used to decrease the magnetic field locally, the plasma remains nonuniform at the corners of the rectangular shape target. In this study, a plasma simulation was conducted to analyze the plasma distribution in a DC magnetron sputtering system. The plasma uniformity was improved by optimizing the thickness and shape of the substrate electrode, carefully controlling the distance between the target and substrate electrode based on Paschen's law, leading to the reduction of local high plasma intensity.

1. Introduction

DC magnetron sputtering is one of the most widely used techniques for the thin film deposition of both metals and compound materials in various fields of industrial applications[1]. It usually has magnet arrays at the back side of the target to increase the ionization rate in the plasma. The magnet array generates a magnetic field above the target, and the time varying magnetic field and electric field form the Lorentz force. Since electrons are trapped near the target surface by this Lorentz force, the collision between the discharging gas and electron has become more active. However, both plasma intensity and target erosion rate are not uniform in the whole target area[2]. Thus, there have been lots of approaches to improve these technical issues in the DC magnetron sputtering technique for increased target usage efficiency. In addition, fast deposition rate and film properties such as low sheet resistance and residual stress are required for reducing the processing cost and better device performance. Especially in the display industry, very large target and substrate were used for mass production. Thus, there is more difficulty to solve the non-uniformity of film properties and target erosion. To solve these problems, many researches have been studied. By optimizing magnet geometry at the corner, it was possible to control electron drift velocity to reduce target erosion rate at the corner[3]. In another study,

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a ferromagnetic bar was added between magnet arrays to make the erosion profile blunt[4]. In the other approach, extra magnets were added at the corner to realize the erosion rate uniform[5,6]. However, there is still a fast erosion rate due to the relatively higher magnetic field at the corners of the rectangular shape target. In this paper, thus we have designed and optimized the shape of substrate electrode at locally high plasma regions to control the target-substrate distance and potential difference, resulting in the improvement on the plasma uniformity such as plasma density and plasma energy in a DC magnetron sputter. And by optimizing the thickness and shape of the substrate electrode, plasma uniformity was improved based on the careful control of the distance between the target and substrate electrode based on Paschen's law through the reduction of local high plasma intensity.

2. Plasma in DC magnetron sputter

2.1 DC magnetron sputtering

A DC magnetron sputter is one of the core apparatuses for the film deposition. A schematic diagram of DC magnetron sputter is shown in Fig. 1. Some seed electrons are accelerated by the electric field generated by two electrodes and these moving electrons collide with the discharging gas. If the kinetic energy of electrons is higher than the ionization energy of gases, the discharging gas will be ionized and release an electron. After that, electrons are accelerated again in the electric field and the same process repeats. Positive ions generated by ionization also are accelerated by the electric field and head to the target. If the energy of the positive ion is higher than the binding energy of the target material, this collision knocks some atoms off the target surface to stick on the substrate. The magnet arrays behind the target make magnetic fields over the target. Due to this magnetic field and electric field, electrons near the target receive the Lorentz force. Then the number of collisions between the discharging gas and electrons increases for the higher ionization rate. Magnet arrays help more ionization and make the deposition rate increase[7].

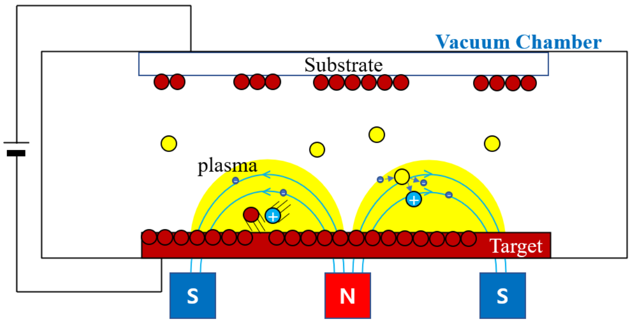


Fig. 1 Schematic diagram of DC magnetron sputtering

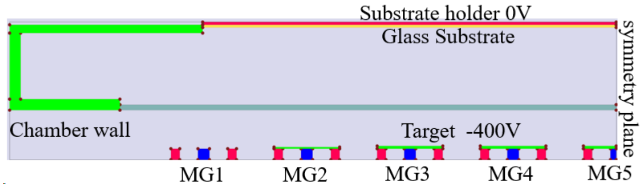
2.2 Particle-in-Cell Monte Carlo collision simulation

Particle-in-Cell (PIC) method is a general and powerful method for plasma simulation. The PIC method calculates the trajectories of electrons and positive ions in a self-consistent electromagnetic field determined by Maxwell's equations. In addition, Monte-Carlo collision (MCC) simulation is usually used for analyzing the collisions of particles such as ionization and scattering of particles[8]. PIC-MCC simulation includes Lorentz's equation of motion to analyze the position and velocity of each particle and Maxwell's equation to determine the electromagnetic fields[9]. However, since there are lots of particles in the domain, it is difficult to calculate the collisions and trajectories exactly for all particles. Thus, the PIC-MCC method uses the concept of "super-particle" to reduce the number of particles to tractable order, which represents a large number of particles in the plasma[9]. Since super-particles are tracked by solving the Newton-Lorentz equation for the motion of charged particles coupled with Maxwell equations for the self-consistent calculation of both electric and magnetic fields with less assumption, the kinetics of each species can be simulated with very little approximation[10].

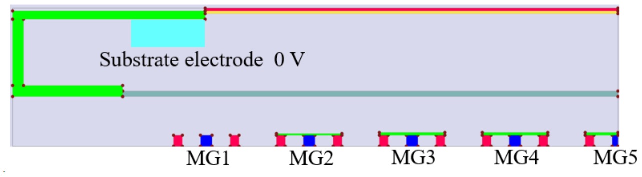
3. Plasma simulation condition

3.1 Plasma simulation condition

Plasma simulation was conducted by the "PEGASUS" simulation tool (PEGASUS Software Inc.). This software is based on the PIC method for the movement of charged particles in the electromagnetic field as well as the MCC method for the collision behaviors of particles such as ions, electrons, and neutrals in the plasma[11]. The schematic simulation geometry is shown in Fig. 2, where a cathode voltage on the target was applied with -400 V while both of



(a) Simulation geometry without substrate electrode



(b) Simulation geometry with substrate electrode

Fig. 2 Simulation geometry

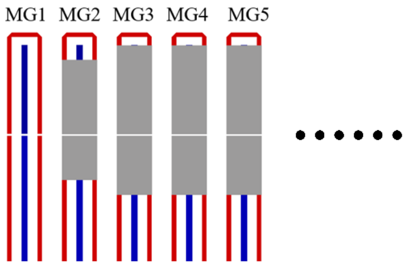


Fig. 3 Ferromagnetic shield and magnet array geometry

substrate holder and chamber wall were grounded. A glass substrate is located on the substrate holder. The discharging gas of argon was used with a pressure of 6 Pa. There are some magnet arrays behind the target and the magnitude of magnets is 1Tesla. And ferromagnetic shields exist at top of some magnet arrays to control the plasma intensity. This ferromagnetic shield geometry is also shown in Fig. 3, where the material of ferromagnetic shield is SUS430. In the simulation, the secondary electron emission coefficient (γ) was set as 0.115. The initial number of super particles was set as 20,000 and the initial plasma density was set as 10^{14} /m^3. The simulation domain is assumed as a quarter size of the total system with a symmetry plane condition. The distance between the two electrodes was kept at 155 mm while the target-magnet array distance is 30 mm.

3.2 Design of substrate electrode

From the simulation result of geometry without substrate electrode, plasma resulted in high intensity in the magnet array 1. At high plasma intensity regions, a relatively thick substrate electrode is applied to decrease the plasma intensity by the decreased inter-electrode distance. From Paschen's law, as shown in Fig. 4, it was understood that the breakdown voltage for generating plasma is a function of the product of operating pressure(p) and inter-electrode distance(d), $V_B = f(pd)$ [12]. As the inter-electrode distance is decreased as indicated by a blue arrow in Fig. 4, the required breakdown voltage increases, resulting in the decreased plasma intensity. Thus, if a thick substrate electrode is applied, it is possible to decrease the plasma intensity in a local high plasma region. In addition, if some voltage is applied to the substrate electrode, then we can decrease the plasma intensity again with the relatively lower local electric field. The designed substrate electrode geometry is shown in Fig. 5(a) with the

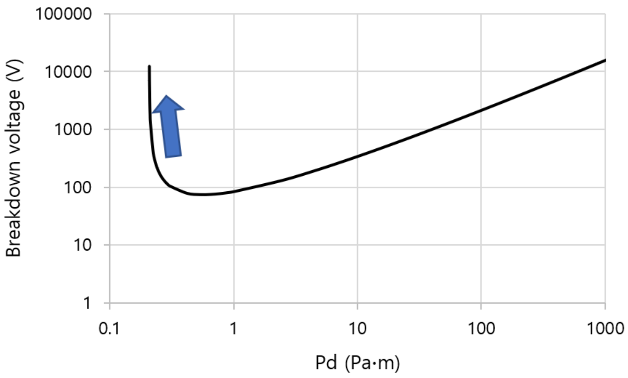
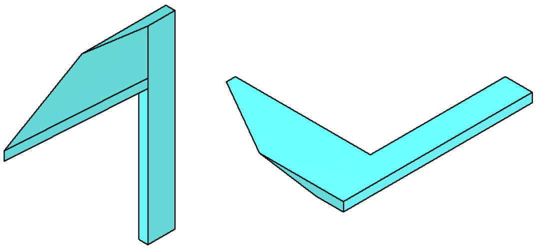
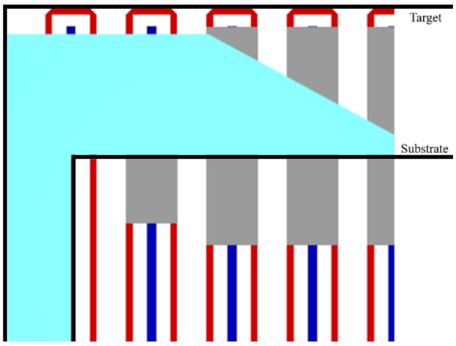


Fig. 4 Paschen curve



(a) Designed substrate electrode



(b) Position of substrate electrode on magnet arrays

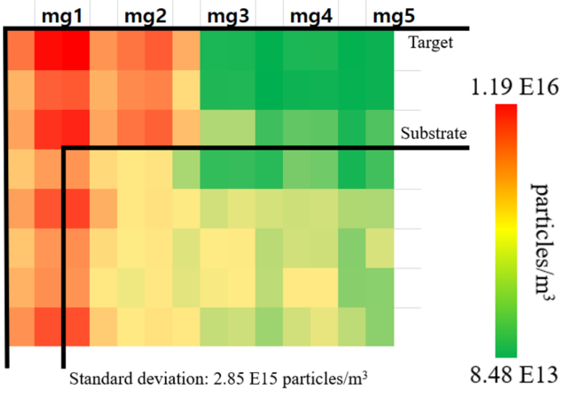
Fig. 5 Geometry and position of substrate electrode

position of the substrate electrode in Fig. 5(b).

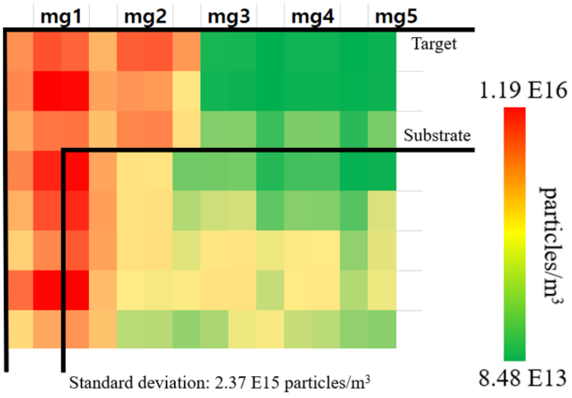
4. Simulation results

4.1 Effect of target-substrate distance

To evaluate the effect of target-substrate distance, simulations were conducted. The highest plasma density and energy were found at the position of magnet array 1, especially at a corner of the target. Fig. 6 shows plasma density distribution in the DC magnetron sputter without and with the substrate electrode. By decreasing the target-substrate distance, the plasma density is decreased by 29 % at the position of highest value while the standard deviation of plasma density is decreased by 16.8 %. Due to the increased electric field by decreasing target-substrate distance, plasma energy is increased and uniformity becomes a little worse as shown in Fig. 7.

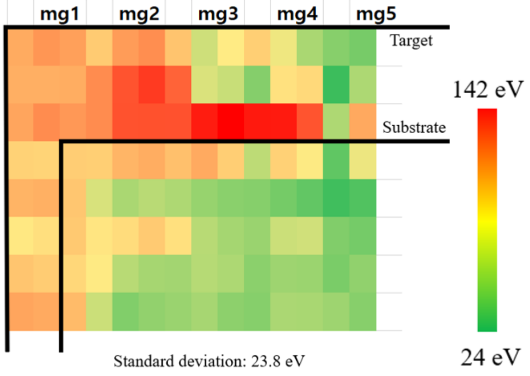


(a) Plasma density distribution without substrate electrode

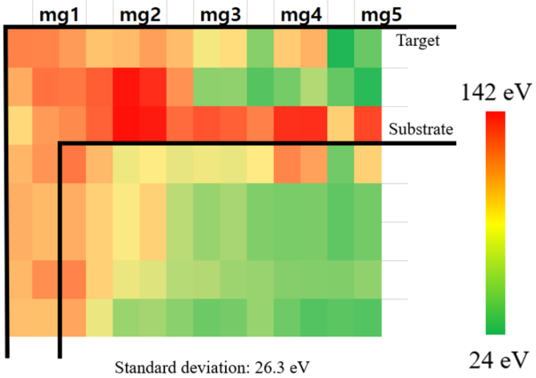


(b) Plasma density distribution with substrate electrode 0 V

Fig. 6 Comparison of plasma density distributions



(a) Plasma energy distribution without substrate electrode



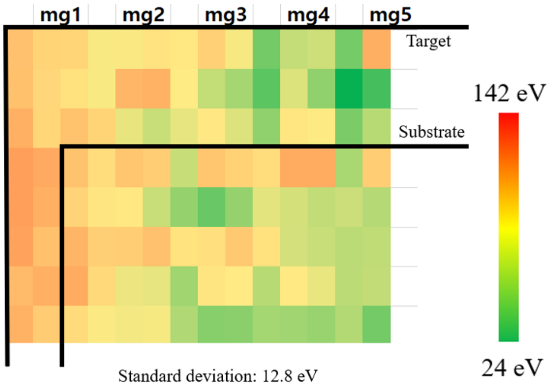
(b) Plasma energy distribution with substrate electrode 0 V

Fig. 7 Comparison of plasma energy distributions

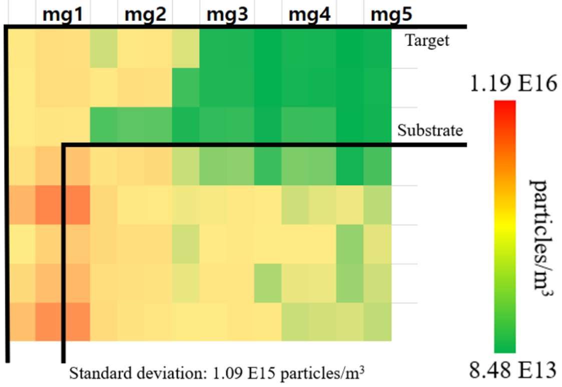
4.2 Effect of substrate electrode voltage

Applying voltage on the substrate electrode will be a solution to decrease the electric potential locally for better plasma energy uniformity. The simulation was conducted with the substrate electrodes after applying -200 V. The plasma energy distribution is shown in Fig. 8(a). After applying -200 V, high plasma energy at the corner area is decreased effectively. Then the standard deviation of plasma energy is decreased by 51 % after applying the -200 V. From Fig. 8(b), we also understood that the plasma density is decreased more effectively at the position of the highest value, resulting in the standard deviation of plasma density with the decreased value by 54 % after applying -200 V on the substrate electrode. Finally, it is confirmed that the uniformity of both the ionization rate and the plasma intensity was improved as the inter-electrode distance decreased with careful control on the electric potential.

When the distance between the target and the electrode decreases, the space between the two electrodes is reduced to



(a) Plasma energy distribution after applying substrate electrode −200 V



(b) Plasma density distribution after applying substrate electrode −200 V

Fig. 8 Plasma energy and density distribution after applying substrate electrode − 200 V

result in the decreased number of the discharge gas particles between the electrodes. Therefore, due to the reduced number of collisions for ionization, the plasma density will be decreased locally by decreasing the inter-electrode distance. In addition, the lowered electric field by applying negative voltage on the substrate electrode results in the reduced energy and number of electrons in the plasma, which means the decreased plasma intensity at the corners of rectangular target area.

5. Conclusions

To improve the uniformity of the plasma intensity and the target erosion rate in a rectangular DC magnetron sputter, the shape, and thickness of the substrate electrode were designed based on the careful control of the distance and electric potential between the target and substrate electrode based on Paschen's law. The plasma density and energy above the target surface were analyzed by PEGASUS simulation software based on the PIC-MCC. Since the plasma intensity shows the highest values at the corners of the rectangular target in the reference geometry, we tried to change the substrate electrode structure to decrease the plasma intensity at the local high plasma region. By decreasing the target-substrate distance locally and applying the negative voltage on that substrate electrode region, the plasma density and energy of the whole target area resulted in better uniformity. After optimizing the substrate electrode structure, the standard deviations of plasma density and energy are decreased by 62 % and 50 %, respectively. Thus, we believe that this study shows a guideline to increase the target usage efficiency of the rectangular DC magnetron sputter in the display industry.

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