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Ion current optimization in a magnetron with tunable magnetic field configuration

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Abstract. The response of the ion current in the substrate region to the magnetic system configuration of a circular magnetron was studied during direct current sputtering of aluminum target. The unbalancing degree induced by changing of magnets' positions was modelled with finite element methods. The ion saturation current in the substrate region showed more than twofold variation with unbalancing degree in the range 0.6–1.2. The dependence was non-monotonic, and the system was optimized to maximize the substrate ion current. The Langmuir probe diagnostics showed plasma density $\sim 10^{16} \text{ m}^{-3}$ in the optimized magnetic configuration.

1. Introduction

Magnetron sputtering is one of the most widespread methods for thin film deposition. There are numerous configurations and power regimes of magnetron sputtering that enhance the deposition process and boost the quality of produced coatings.

One of the methods to improve quality of films is to elevate the ionization degree and thus to arrange the ion assistance of coating growth. This is, for instance, useful for production of thin film electrodes for electrochemical sensors [1, 2]. Generally, it can be done in two ways: by optimizing the magnetic field configuration, and by changing the power supply regime (i.e. utilizing high power pulsed sputtering modes—HiPIMS [3], HCIMD [4], MPPMS [5], and others).

Changing the magnetic field configuration is often associated with so-called unbalancing of the magnetron i.e. varying the relationship between magnetic fluxes produced by inner and outer magnets [6, 7]. A number of studies report managing the ionization degree and deposition rate by permanent magnet unbalancing in direct current (DC), pulsed DC, and HiPIMS modes [8-10]. Tuning the magnetic field is also an appropriate solution for maintaining the stable deposition conditions when the target racetrack erosion triggers deviations in voltage and current. It is particularly worth doing when the erosion rate is extremely high, as in liquid/hot target sputtering modes [11, 12].



It is widely accepted to characterize the magnetic field of a magnetron with a ratio g (degree of unbalancing) $g = 2 z(B = 0) / d$, where $z(B = 0)$ —distance from the magnetron target to the magnetic field null, and d —target diameter [13]. The classification of magnetic configurations ranks them from “extremely balanced” ($g > 2$) to “extremely unbalanced” ones ($g < 1$) [13]. In case of balanced magnetic configurations, only small fraction of confined electrons can reach the substrate, and the ion bombardment of growing film is low. Unbalancing implies lowering of $z(B = 0)$ and facilitating electrons’ escape from the magnetic trap.

In present paper, we test the magnetic field dependence of DC discharge substrate current in a circular magnetron, which is capable of in situ magnetic field changing by independently varying the positions of inner and outer magnets.

2. Experimental setup

The measurements were made in a conventional circular magnetron sputtering configuration. 76.2 mm diameter aluminium (99.99%, Girmet) target was used. Argon gas (99.998%) was introduced through an automated mass-flow-controller (Bronkhorst). In all experiments, the argon pressure was 0.5 Pa (base pressure 10^{-4} Pa). DC magnetron discharge was generated by APEL-M series power supply (Applied Electronics). The magnetron (Pinch Magneto series) is capable of in situ magnetic field control by individually varying the positions of inner (cylinder) and outer (ring) magnets. This is in fact an old and proven concept for discharge operation tuning [4], yet the commercial presentation of such systems had no realization for quite a long time.

In saturation current measurements, a flat collector was used. It was located 8 cm above the target surface, in the typical substrate position. The bias voltage was fixed at -30 V with respect to the grounded vacuum chamber.

For the Langmuir probe diagnostics, a custom built probe was used. It was located 3 cm above the magnetron target surface on its symmetry axis. The probe tip was a Ta wire with 0.7 mm diameter and 3 mm length. It was encased in alumina housing covered with Ni foil. The collecting area of the probe was assumed to be equal to its geometrical area (7 mm^2). The probe voltage was supplied by a sweep generator consisting of low-voltage waveform generator (Tabor Electronics) and a custom amplifier. The sweep was asymmetric triangular (from -30 to 0 V) with repetition frequency 100 Hz.

3. Results

3.1. Modeling

Prior to the experiments, the electric and magnetic fields were calculated with a finite element method for different magnet arrangements, and the degree of unbalance was estimated for each configuration.

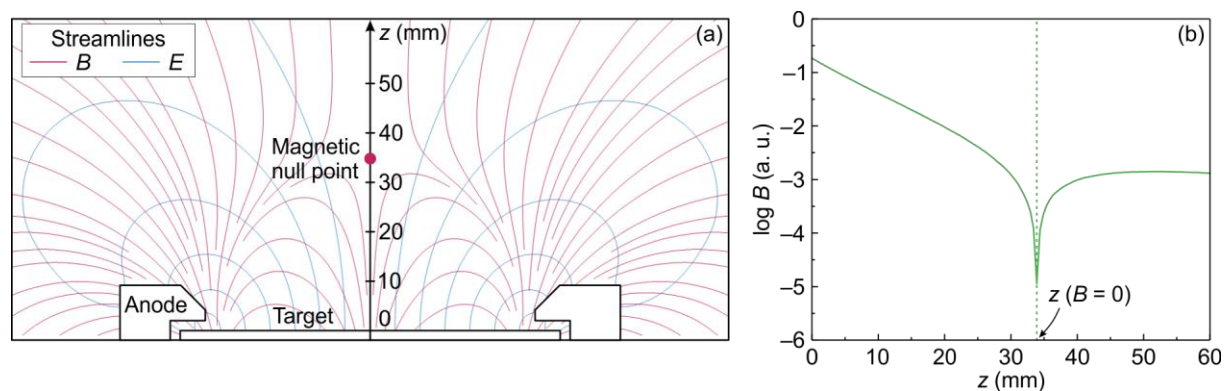


Figure 1. (a) Typical electric and magnetic field streamlines in the magnetron; (b) corresponding B -field dependence on the distance to target along the symmetry axis (log scale).

Electric and magnetic fields in front of the target are shown in figure 1a. Figure 1b demonstrates corresponding magnetic flux density profile along the z -axis above the magnetron target (log scale). This curve yields singularity coordinate $z(B = 0)$ that is needed to calculate the unbalancing factor g .

It was found that the magnetic system of our magnetron was capable of g variation in the range 0.6–1.2. Following the classification in [11], it means that possible configurations were limited to “very unbalanced” ($1.0 \leq g < 1.25$) and “extremely unbalanced” ($g < 1.0$) groups.

3.2. Effect of unbalancing

The dependence of ion saturation current on the relative position of magnets (Δz) is shown in figure 2 along with the unbalancing degree g calculated for a number of magnetic configurations. Discharge power P was fixed at 100 W.

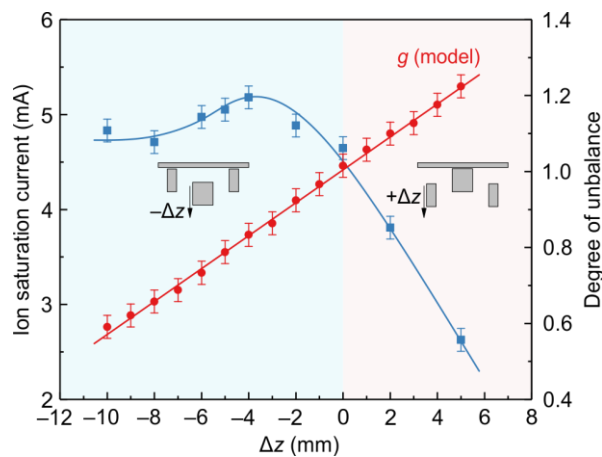


Figure 2. Ion saturation current and degree of unbalancing (g) for different positions of magnets.

The error in the calculated data is due to limited accuracy of $B = 0$ singularity derivation. One can observe that a local maximum exists around $\Delta z = -4$ mm relative position between magnets that corresponds to $g \approx 0.8$. The dependence is nonlinear, and after lowering the outer magnet below the inner one, the ion current rapidly decreases.

3.3. Power dependence

In the magnetic configuration with maximum ion current ($g \approx 0.8$), the electron temperature and density were measured with a Langmuir probe for a range of DC discharge power $P = 10$ –500 W. The dependence of electron temperature T_e and plasma density n on the discharge power for this case is shown in figure 3.

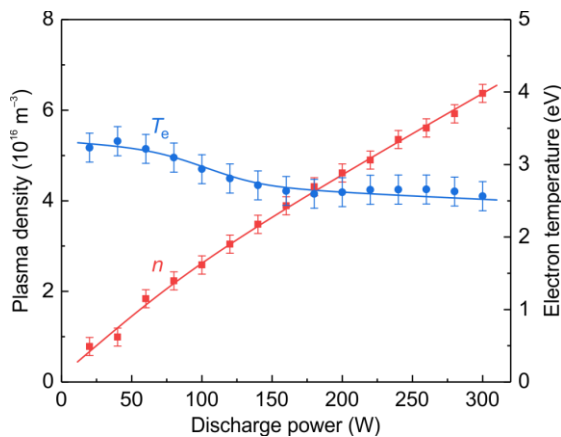


Figure 3. Discharge power dependence of electron temperature and plasma density.

One can notice that electron temperature slightly decreases with discharge power but stays in the order of 3 eV, while plasma density grows nearly 6 times with P increase from 20 to 300 W. The maximum recorded plasma density was $6.4 \times 10^{16} \text{ m}^{-3}$.

4. Conclusion

The magnetron with variable magnetic field option was tested. Ion saturation current in the substrate region was measured for unbalancing degree g values ranging from 0.6 to 1.2. The magnetron remained unbalanced in the whole tested range of magnet positions. The ion current changes non-linearly and non-monotonically with g . The optimal magnetic configuration with maximum ion current was found ($g \approx 0.8$). In this configuration, the plasma density was measured with a Langmuir probe yielding $n = 6.4 \times 10^{16} \text{ m}^{-3}$ at 300 W discharge power.

Varying the magnetic field configuration is a convenient tool for tuning the ion content in the substrate region. Having the capabilities of in situ magnet positioning ensures widening of film properties that can be prepared using the magnetron.

Acknowledgment

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