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The improvement of high power impulse magnetron sputtering performance by an external unbalanced magnetic field

Chunwei Li [a, b, *], Xiubo Tian [b, **], Chunzhi Gong [b], Jianping Xu [c]

[a] College of Engineering and Technology, Northeast Forestry University, Harbin, 150040, China
[b] State Key Laboratory of Advanced Welding and Joining, Harbin Institute of Technology, Harbin, 150001, China
[c] Department of Materials and Chemical Engineering, Heilongjiang Institute of Technology, Harbin, 150050, China

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ABSTRACT

High power impulse magnetron sputtering (HIPIMS) is an emerging technique that improves the ionization rate of magnetron-sputtered materials. However, HIPIMS often demands further improvement in the ionization rate in some applications. In this study, we applied an unbalanced magnetic field to enhance the HIPIMS discharge, using a conventional magnetron and a coaxial electro-solenoid coil. Vanadium target discharge currents and substrate ion currents were recorded using a digitizing oscilloscope at different coil currents. The elemental composition and temporal and spatial distributions of argon and vanadium atoms and ions in the high vacuum plasma were measured by optical emission spectroscopy. The results showed that the substrate ion current increased gradually with the coil current over the range 0–6 A, and that a high-density plasma beam was formed between the substrate and target. We explained this effect as the confinement of energetic electrons by the external magnetic field. Total ion production was also increased. Finally, we observed that the line intensities of Ar^0, Ar^{1+}, V^0, and V^{1+} increased gradually to varying degrees under the external magnetic field.

1. Introduction

The conventional direct current magnetron sputtering (DCMS) is a well-established method for thin film deposition, producing a high deposition rate with a low substrate temperature [1]. Its application has been constrained however by a low ionization rate (<10%) and plasma density (10^{14}-10^{16} m^{-3}) [2]. In many cases, the high ionization fraction of sputtered atoms is desired in order to improve the quality of the deposited films through the transfer of activation energy to the substrate from the incident ions [3]. To address this shortcoming, Kouznetsov et al. [4] developed high power impulse magnetron sputtering (HIPIMS). HIPIMS discharges usually have short pulse durations (20–200 μs) and low duty cycles (0.5–5%), producing a high peak current and power (0.5–10 kW cm^{-2}) while still maintaining an average power within the thermal budget of the cooling system [5–7]. This technique enables high film density and smoothness [8], high film-substrate bonding strength [9], and a uniform layer thickness on complex substrate shapes [10,11]. However, HIPIMS often demands further improvement in the ionization rate in some applications [12].

Magnetic field design is important in HIPIMS to affect the plasma and the film deposition. The magnetic field configurations with different field strengths, race track widths, and race track patterns may alter the plasma distribution from the target to the substrate [13]. Capek et al. proposed a simple approach for the stabilization of the HIPIMS discharge by controlling the target magnetic field using paramagnetic spacers with different thicknesses in between the magnetron surface and the target [14]. Bradley et al. reported that DC and pulsed-DC discharges showed the expected behavior that deposition rates decreased by ~25–40% with decreasing magnetic field strength (B); however, the opposite trend was observed in HIPIMS with deposition rates increasing by a factor of two over the same decrease in B [15]. Raman et al. found that higher deposition rates in HIPIMS and their variation with pulsing parameters originateD from the magnetic field topology [16]. Moreover, Greczynski and Hultman demonstrated that the peak amplitude of target current determined deposition rate loss during HIPIMS [17]. By analyzing the typical discharge waveforms of HIPIMS [18], it has been found that the pulse peak current can

* Corresponding author. College of Engineering and Technology, Northeast Forestry University, Harbin, 150040, China.
** Corresponding author.
E-mail addresses: lcwnefu@126.com (C. Li), xiubotian@163.com (X. Tian).

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reach 3.5 kA, i.e. a large ion flux/electron flow. The balanced magnetic field prevents electrons escaping to the vacuum chamber [19]. However, by using unbalanced magnetron configuration, electrons can easily move towards the anode. By controlling the electron deflection pathway, high density of electrons can be exploited to improve the material ionization rate. Starting from this principle, we have introduced unbalanced magnetron sputtering into the HIPIMS system. The magnetic field of unbalanced magnetron sputtering strengthened the outer ring of magnets. Some electrons in the plasma were no longer confined to the target region and were able to follow the magnetic field lines and flow out towards the substrate [1]. This resulted in the confinement of the electrons in the substrate region (the coating work interval) and produced higher density plasma, which was expected to improve the ion flux density.

In this study, we introduced an external magnetic field in the HIPIMS system to enhance discharge performance. The target discharge current and substrate ion current were recorded using a digitizing oscilloscope at different coil currents ranging from 0 to 6 A. The effect of the external magnetic field on the optical emission spectra obtained from the HIPIMS discharge plasma was investigated.

2. Experimental details

The experiments were performed in a cylindrical vacuum chamber 400 mm high and 400 mm in diameter, made of AISI 304 stainless steel. Fig. 1 shows a schematic illustration of the experimental setup. A vanadium target (99.99% purity) with a diameter of 50 mm and a thickness of 6 mm was fixed on the magnetron cathode. Argon gas (99.9997% purity) was introduced *via* a leak valve under the chamber. The base pressure was less than 5.0×10^{-3} Pa and the working pressure was 1.0 Pa. The pressure was monitored with a compound vacuometer. The magnetron cathode was driven by a hybrid pulsed power supply (State Key Laboratory of Advanced Welding Production and Technology, Harbin Institute of Technology) [20]. The substrate holder was powered by a DC power supply and the substrate bias was fixed at −90 V. The distance between the vanadium target and the substrate holder was 100 mm. Coils composed of varnished Cu wire were positioned around the magnetron cathode outside the vacuum chamber to create an external magnetic field. We adjusted the current passing through the coils between 0 and 6 A to modulate the magnetic field. The substrate holder ($80 \times 60 \times 3$ mm^3) could be negatively biased to repel the high-energy electrons produced during the discharge pulse. For ion flux distribution tests we placed a cylinder 355 mm long and 25 mm in diameter in the vacuum chamber at different positions to form different angles (0°, 45°, 90°, 135°, and 180°) with the magnetron cathode (Fig. 1). The target discharge current and substrate ion current were recorded using a digitizing oscilloscope (Tektronix TD420A). The elemental composition and temporal and spatial distributions of argon and vanadium atoms and ions in the high vacuum plasma were measured using optical emission spectroscopy (Avaspec-3648). Magnetic field intensity on the surface of the cathode target was measured using a Gauss-meter (HT20).

3. Results and discussion

3.1. Magnetic field configuration

Fig. 2 shows the axial magnetic strength distribution. Without an applied current ($I_c = 0$), the magnetic field peaks 30 mm from the magnetron cathode. An open magnetic field is formed. The magnetic field strength decreases gradually with increasing distance from the cathode, reaching approximately 0 mT at about 80 mm. Application of current increases the intensity and reach of the field. When the coil current is 6 A, an 8 mT field is maintained at the same position (80 mm), and an appreciable field persists out at 170 mm.

3.2. Target discharge characteristics

Fig. 3 reproduces the glow morphology images of the vanadium target during HIPIMS discharge. Without the external magnetic field, the glow close to the target cathode is diffuse and confined to the target region. When the external magnetic field is applied, the glow is focused and stronger. The unbalanced magnetic field also extends the glow to the substrate region. This phenomenon indicates that the change in the magnetic field configuration induced by the external magnetic field leads to the change in the macro-morphology of the glow. The intrinsic magnetic field concentrates close to the target cathode region, which limits the plasma diffusion toward the substrate. With the external magnetic field, the electrons can travel further away from the sputtered target along the magnetic induction lines and the glow discharge area thereby

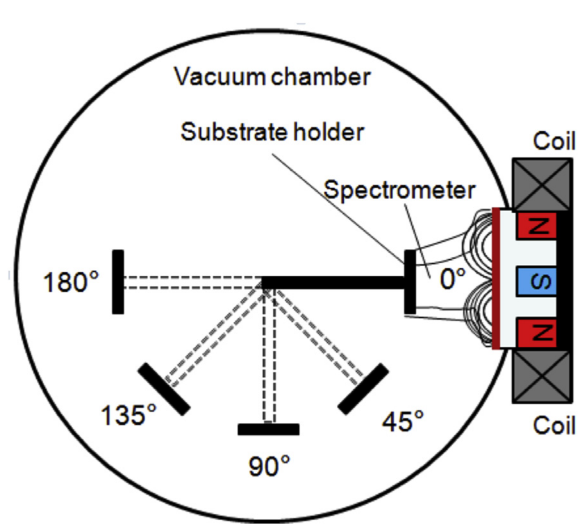

Fig. 1. Schematic illustration of the measurement of the substrate ion current at different positions in the vacuum system during HIPIMS discharge.

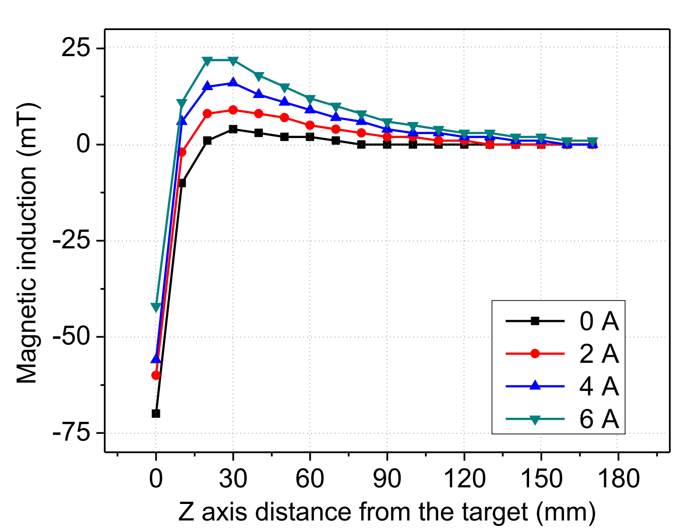

Fig. 2. Measurement of the axial magnetic strength distribution.