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External magnetic field increases both plasma generation and deposition rate in HiPIMS

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ABSTRACT

A widely recognised limitation of high power impulse magnetron sputtering (HiPIMS) is the lower deposition rate compared to that achieved using conventional DC sputtering. The HiPIMS deposition rate can be significantly increased by the application of an external magnetic field created by a solenoidal coil excited with a DC current pulse. However, the mechanisms causing enhancement of deposition rate are not fully understood. Here we investigate experimentally the influence of external magnetic fields on the sputtering conditions near the target and on the ion transport to the substrate, using an aluminium (Al) target as an example. The deposition rate was measured as a function of coil current and substrate bias voltage. We show that there is a favourable orientation of the applied field that increases the peak target current, substrate ion current, and deposition rate and an unfavourable one that inhibits the operation of the magnetron gun. To shed light on these observations and identify the mechanisms, we calculated magnetic field distributions using finite element methods. We show that a synergistic combination of the externally applied magnetic field and the inherent magnetron field expands and intensifies the ionisation zone. This increases the extent and density of the plasma leading to an increase in the deposition rate. We provide evidence that the external magnetic field also guides the ion flux towards the substrate and focuses it on the substrate, further increasing the deposition rate.

1. Introduction

The high power applied to the metal target in HiPIMS allows a high degree of ionisation of the sputtered material [1–6] providing increased energy at the substrate that leads to pinhole-free, dense thin films [7–9]. In HiPIMS, the deposition flux is limited by the duty cycle and electric field-driven attraction of metal ions back to the target [10–12]. This leads to low deposition rates in comparison to those achieved in conventional DC sputtering which is a widely recognised limitation of HiPIMS.

Capek et al. increased the HiPIMS deposition rate 4.5-fold [12] at constant power by weakening the magnetic field at the surface of the target by introducing Cu spacers under the target. However, the discharge current was reduced, leading to lower ion flux at the substrate, even though a higher voltage was required in this configuration. The reduced ion flux arises from the weaker confinement of the electrons in the vicinity of the target, reducing ionisation by electron impact in the confined plasma. Raman et al. [13–15] achieved an increase in the deposition rate by a factor of two using a customised configuration of permanent magnets in the magnetron, which they have termed a “TriPack”.

Bohlmark et al. [16] reported an enhancement of the deposition rate by a factor of two at the centre of the substrate by applying an external magnetic field using a solenoidal coil placed in front of the target and excited with a DC current. The enhancement of the deposition rate was position-dependent and decreased strongly away from the centre of the substrate. Anders proposed HiPIMS with a coil powered by DC or pulsed-DC [17,18] (pulse length ≥ 100 μs) currents with the aim of enhancing the transport of ions from target to substrate but an enhancement factor was not reported. We have recently demonstrated that an externally applied magnetic field can be used to tune the surface chemistry of the target material and increase the deposition rate in reactive HiPIMS [19]. The origin of the reported enhancements in increasing the deposition rate using an applied magnetic field is not yet known. There are two possible mechanisms for increases in the deposition rate: magnetic field guiding that increases the efficiency of

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transport of ion species; changes in magnetic field confinement conditions at the magnetron racetrack that increase the rate of sputtering and ionisation.

In this work, we first demonstrate experimentally an increased deposition rate from an Al metal target using an externally applied magnetic field. We use aluminium as a model target, because aluminium-based coatings have proven their ability to protect structural materials from corrosion attack [20]. Aluminium is also widely used as a finishing coating [21]. We investigate the origins of the deposition rate enhancement using measurements of film thickness and substrate current as a function of magnetic field strength, time delay between the triggering of the pulses and the application of field, and substrate bias voltage. To assist in the interpretation of these observations and to identify the underlying mechanisms, we calculate magnetic field distributions using finite element methods.

2. Experimental and simulation methods

The experiments were performed in a cylindrical shaped vacuum chamber, 67.6 cm in diameter and 50.8 cm in height. Prior to the experiments, the chamber was evacuated by a turbomolecular pump (Shimadzu 1003LM) to a base pressure of approximately 3.5×10^{-7} Torr. The magnetron (AJA International Inc., USA) configuration (target dimeter = 7.62 cm) is unbalanced with the outer magnets having a magnetic field strength of 0.5 T, which is ~10% stronger than that of the central one (manufacturer's specifications). The magnetron was powered by a RUP7 pulsed power supply manufactured by GBS-Electronik GmbH, Germany, capable of delivering a peak voltage and current of 1000 V and 400 A, respectively. However, the average output current and the operation frequency cannot exceed the limit of 3 A and 30 kHz, respectively. The power supply was voltage-regulated and the discharge current was determined by the plasma impedance. A schematic diagram of the apparatus including diagnostic equipment is shown in Fig. 1. The pulse length was set to 100 µs. The HiPIMS voltage source, spectrometer and the coil power supply were all triggered with settable delay times using the pulse generator and measured with a 200 MHz oscilloscope (DSO-X 2014A). Silicon wafer substrates were mounted on a conductive holder connected to a power supply for sustaining a constant DC bias potential. Because of the relatively large ion current pulses to the substrate, the intended bias was maintained during deposition with the assistance of a 900 uF capacitor. A current transformer was used to measure the current flowing from the substrate.

The cylindrical shaped solenoid coil was constructed by winding 20 turns of a hollow Cu tube, acting as the current conductor, around a cylindrical Teflon insulating support (inner diameter = 80 mm, outer dimeter = 90 mm, height = 160 mm). To create an external magnetic field, the coil was placed in front of the chimney of the magnetron gun at a distance of 17 mm from the magnetron target support surface. This distance is measured with reference to the closest point on the first turn. The chimney was electrically isolated from the magnetron and from the earthed chamber. A current of up to 150 A at 800 V was delivered through the coil to produce magnetic fields up to 14 mT with a short rise time of 1 µs. The time-dependence of a coil current pulse of 60 µs, applied with a delay time of 20 µs is shown in Fig. 2(a). The delay in applying current to the coil with respect to the HiPIMS voltage pulse was varied from 20 to 110 µs.

Through a viewport on the chamber, a 50-mm focal length lens was used to image a section of the region between the substrate and the coil (to monitor the plasma species along a line-of-sight perpendicular to the discharge axis) onto the entrance of a fused-silica optical fibre bundle (1 mm diameter). The other end of the fibre bundle was terminated in the 50 µm wide entrance slit of a spectrograph (Princeton Instruments, Acton, MA, USA, Acton SpectraPro 2750). The grating used had 1200 lines mm^{-1} resulting in a nominal resolution of 0.0140 nm at 300 nm, and 0.0120 nm at 750 nm. An intensified charge-coupled device (ICCD) with a 1024 × 1024 pixel array (Princeton Instruments PI-MAX) was located at the spectrometer's exit plane to capture the plasma emission spectra. The ICCD camera was triggered along with the HiPIMS pulse operated with a gate width of 120 µs. By collecting the light for the entire duration between the initiation of the HiPIMS pulse and 20 µs after the pulse, we were able to record the integrated intensity of light emitted by Al II ions (at 624.33 nm) over the period of the discharge pulse. The signal-to-noise ratio was maximized by averaging spectra acquired over 200 consecutive pulses.

The same synchronisation pulse triggered a framing streak camera (Hamamatsu C4187) fitted with a framing unit (M4189). A 35 mm Nikon lens was used to image the localized light intensity from the target plasma for a selected time window in the pulse. The images were taken at the end of the HiPIMS voltage pulse with an exposure time of 50 ns. A DC power supply was connected to the substrate to provide negative bias voltages to eliminate electrons and extract the ions to the substrate.

COMSOL was used to calculate the magnetic field distribution in the vicinity of the coil and the magnetron target. The geometrical layout, including the magnetron permanent magnets, target, and the coil, used for the simulations is shown in Fig. 2(b and c). The magnetic field

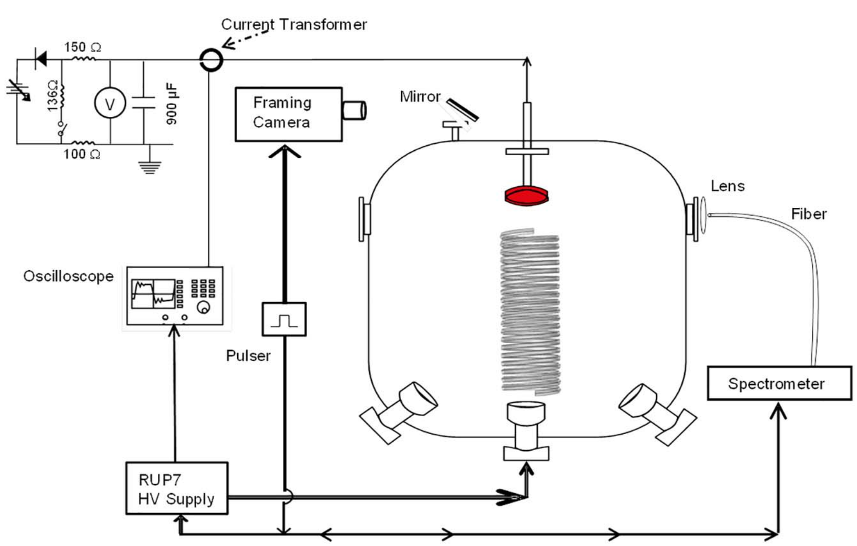

Fig. 1. A schematic diagram of the HiPIMS deposition system showing the additional solenoidal coil that provides an external magnetic field. The coil was wound on a Teflon cylinder to assist in electrically isolating the coil from the plasma.