A Plasma Lens for Magnetron Sputtering

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***Abstract*—A plasma lens, consisting of a solenoid and potential-defining ring electrodes, has been placed between a magnetron and substrates to be coated. Photography reveals qualitative information on excitation, ionization, and the transport of plasma to the substrate.**

***Index Terms*—Plasma devices, plasma materials processing, plasma transport processes, sputtering, thin films.**

MAGNETRON sputtering is a widely used coating technology [1]. In essence, a magnetically enhanced glow discharge with closed electron drift is operated at relatively low pressure, of order 1 Pa, such that the cathode of the discharge is "targeted" by positive ions. Surface atoms of the cathode (target) are removed and used for the deposition of thin films and coatings. Several distinct versions of magnetron sputtering have been developed over the years, and in particular, high-power impulse magnetron sputtering (HIPIMS) is a much talked about new addition to the family of sputtering technologies for the deposition of thin films [2].

In reactive deposition, the magnetron is operated in a mixture of noble gas (usually argon) and reactive gas, such as oxygen in case an oxide coating is desired. For example, aluminum-doped zinc oxide (AZO) [3] is a recently much researched transparent conducting oxide (TCO) because it is a low-cost alternative to the more costly indium–tin–oxide widely used in displays, solar cells, light-emitting diodes, etc.

The electric field that accelerates positive ions *to* the target also accelerates negative ions *away* from the target toward the substrate. Reactive deposition with oxygen implies that negative oxygen ions are present, and therefore, apparently unavoidable, the growing film is subject to bombardment of high-energy (> 100 eV) negative ions, causing "ion damage" [4], which is highly undesirable for some crystalline films such as TCOs.

A magnetron produces plasma of gas (and in the case of HIPIMS also of the target metal). A portion of the plasma can escape from the magnetron depending on the unbalancing of the magnetic field. Stronger unbalancing is used to intentionally assist film growth by (positive) ions of relative low energy (mostly < 20 eV).

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Fig. 1 shows an interesting approach to plasma utilization in magnetron sputtering. Here, a solenoid generates an essentially axial magnetic field which influences the degree of unbalancing the magnetron, promoting the escape of plasma. Apart from affecting the magnetic field near the target zone, the solenoid also aids the excitation and ionization of material and guides the plasma to the substrate. That is, while electrons and positive ions are confined and transported, negative ions are actually pushed out of the plasma stream: In this sense, the solenoid acts as a plasma lens with focusing properties for positive ions and defocusing properties for negative ions [5]–[7]. The guiding of plasma by solenoids has been much studied for filtered cathodic arc plasma deposition [8], [9], and the field of research has been dubbed plasma optics [10]. An image of arc plasma transport in a curved solenoid filter has been shown in one of the previous Special Issues on Images in Plasma Science [11]. In cathodic arcs, the motivation was to rid the plasma of the undesired so-called macroparticles. In HIPIMS, an axial magnetic field was shown to locally enhance the deposition rate [12]. Here, however, the main goal is to affect the ratio of positive and negative ions arriving on the substrate. The plasma lensing effect is based on the radial electric field that builds when electrons are magnetized and ions are not magnetized. One can go one step further and introduce ring electrodes near the solenoid's entrance and exit to aid in establishing a desired potential gradient. A curved version of such plasma lens has the advantage of also addressing macroparticle issues in case arcing occurs although the deposition rate is reduced.

The photo in Fig. 1 was taken through a window of the vacuum processing chamber using a Canon EOS Rebel T1i SRL camera with a 15 megapixel CMOS detector. The exposure time was 1/30 s, with $f/5$ aperture, at a sensitivity of ISO 1600. In the center part of the figure, we see a coil made of 1/4-in copper tubing, which is water cooled. Biasable electrode rings are placed near the entrance and exit of the solenoid. The 2-in (5 cm) diameter planar magnetron, shown on the right, with a 2-in (5 cm) diameter Zn4at%Al target was connected to a Pinnacle Plus magnetron supply (Advanced Energy). The medium-frequency discharge was run with 300 W average power, at 315 V and 0.95 A, 150 kHz, with a 0.5 μs reverse phase. The gas flow ratio of argon and oxygen was 30 : 9 resulting in a pressure of 0.53 Pa during deposition. The solenoid carried 400 A of current. The AZO films made at 200 °C were of good quality with a transmission of about 85% in the visible spectrum and an electrical conductivity in the high 10^{-4} $\Omega \cdot$ cm. Using HIPIMS and a 90° filter delivered even better films with 3.5×10^{-4} $\Omega \cdot$ cm at a reduced substrate temperature of only 160 °C, to be reported elsewhere. Research in the lensing effect and film optimization is still ongoing.

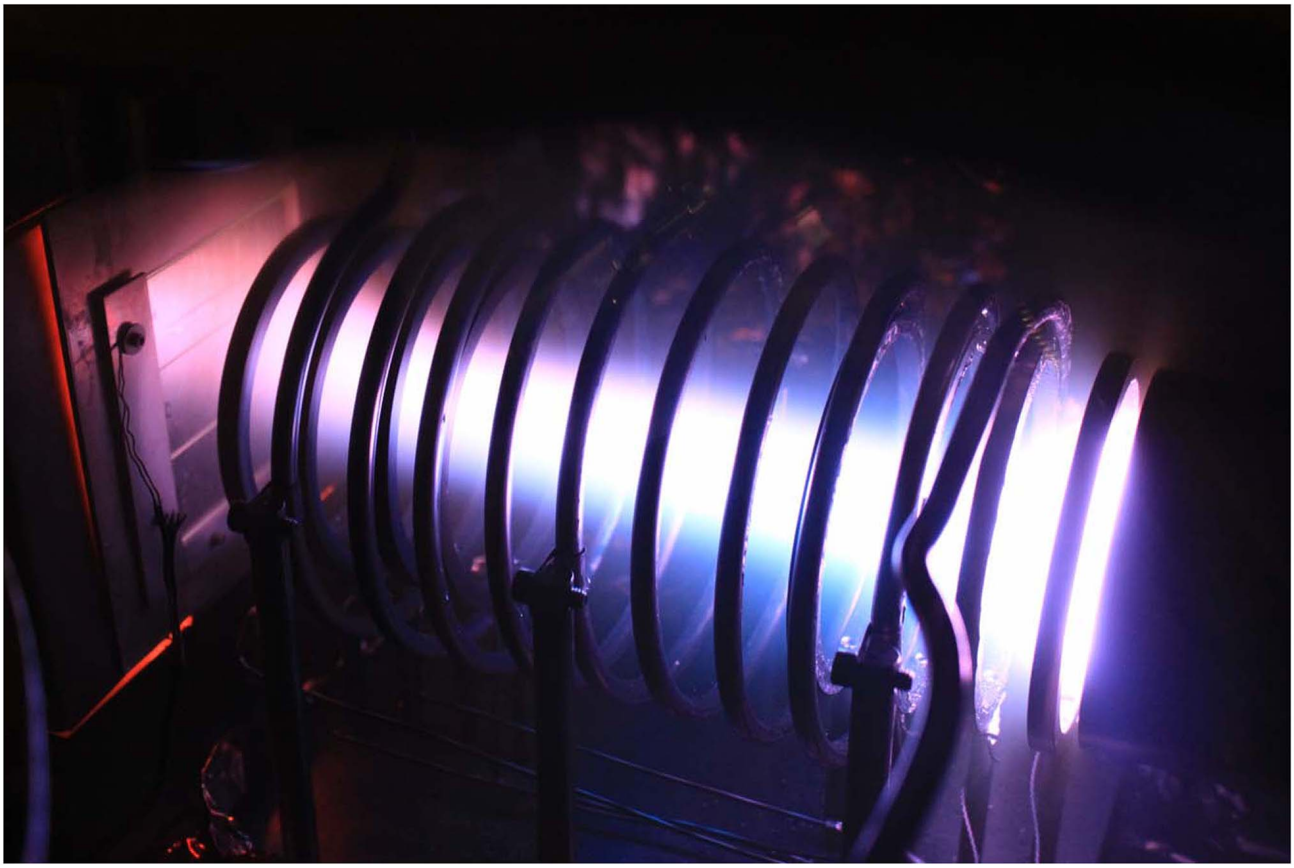

Fig. 1. Plasma lens placed between (right) magnetron and (left) substrate. The magnetron has a 2-in (5 cm) diameter aluminum-doped zinc target, operating in an argon–oxygen gas mixture. Microscope slide substrates are mounted on a heater; the goal is to deposit high-quality AZO films, a low-cost transparent conductor.

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