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Guiding the deposition flux in an ionized magnetron discharge

J. Bohlmark^{1,a}, M. Östbye^{1,2}, M. Lattemann¹, H. Ljungcrantz², T. Rosell², and U. Helmersson^{1,b}

¹ *IFM Material Physics, Linköping University, SE-581 83, Sweden*

² *Impact Coatings AB, Westmansgatan 29, SE-582 16, Sweden*

^a Present address: *Chemfilt Ionspattering AB, Diskettgatan 11C, SE-583 35, Linköping, Sweden.*

^b Email: contact person, ulfhe@ifm.liu.se

Abstract

A study of the ability to control the deposition flux in a high power impulse magnetron sputtering discharge using an external magnetic field is presented in this article. Pulses with peak power of 1.4 kWcm^{-2} were applied to a conventional planar magnetron equipped with an Al target. The high power creates a high degree of ionization of the sputtered material, which opens for an opportunity to control of the energy and direction of the deposition species. An external magnetic field was created with a current carrying coil placed in front of the target. To measure the distribution of deposition material samples were placed in an array surrounding the target and the depositions were made with and without the external magnetic field. The distribution is significantly changed when the magnetic field is present. An increase of 80 % in deposition rate is observed for the sample placed in the central position (right in front of the target center) and the deposition rate is strongly decreased on samples placed to the side of the target. The measurements were also performed on a conventional direct current magnetron discharge, but no major effect of the magnetic field was observed in that case.

Keywords: thin films, sputtering, IPVD, HIPIMS, HPPMS

Introduction

Magnetron sputtering is a widely used technique for production of various types of coatings. In conventional direct current (dc) magnetron sputtering, where the power level is kept relatively low ($\sim \text{W}/\text{cm}^2$), plasma densities of the order of 10^{16} - 10^{17} electrons/ m^3 develops [1]. Typically values of the ionized fractions are then low, usually less than 10 %, depending on the power level, the discharge geometry, the target material, and the magnetic field geometry [2]. When the majorities of sputtered particles are electrically neutral, it does not allow for much control over the direction and energy of the deposition material. For some applications it is a great advantage to gain control over the energy and direction of the deposition species. For example, in deposition of high aspect ratio structures, during integrated circuit fabrication, it is desired to obtain a collimated deposition flux that arrives normal to the wafer surface. This is achieved by a negative substrate bias and the depositing ions are accelerated gaining a speed component along the electric field lines that dominates over the lateral speed components [3]. For complex shaped substrates the same technique can be used to achieve a normal flux, and thereby an improved film quality, also on surfaces not directly facing the source [4]. The quality of the grown films is also strongly affected by the energy of incoming deposition species [5]. To increase the control over the deposition process, it is thus desirable to produce a deposition flux with high fractions of ionized material.

Today, several alternatives exist to produce highly ionized fluxes of deposition material. A commonly used technique is arc evaporation. Arc evaporation is known to produce dense coatings, often with good adhesion. The main drawback with this technique is the production of droplets. In the arc spot, small molten particles of metal

are produced. The droplets can seriously reduce the quality of the film. A promising alternative is high power impulse magnetron sputtering (HIPIMS) [6-9] that combines many of the benefits of arc evaporation and conventional dc magnetron sputtering. The plasma is highly ionized, but without formation of droplets. The technique relies on the creation of a high-density plasma in front of the sputtering source, ionizing a large fraction of the sputtered atoms. In magnetron sputtering, the increase in plasma density is simply achieved by increasing the applied power, but is limited by the thermal load of the target. The solution to this problem is to apply the power in pulses with a low duty factor. Since the thermal load of the target is limited by the average power rather than the peak power, the peak power during the active discharge can be very high. The applied peak voltage can be up to a couple of kV, resulting in peak discharge currents of the order of a few Acm^{-2} and a peak power density of several kWcm^{-2} on the target surface. The high power results in electron densities exceeding 10^{19} m^{-3} surrounding the magnetron [10,11]. The high density of electrons increases the probability for ionizing collisions drastically for the sputtered atoms, and results in a high degree of ionization of the sputtered material. Values of 5-70 % are reported [6,12], and optical emission studies suggest even higher peak values [8,13]. The HIPIMS technique has been shown to produce coatings with improved properties. CrN films prepared by HIPIMS have been shown to have excellent adhesion, high density, and high corrosion and wear protection capabilities [14]. The technique is also known as high power pulsed magnetron sputtering.

In this paper a study is presented on how the deposition material from a HIPIMS discharge can be guided with an external magnetic field. In this way the

deposition rate in front of the magnetron was increased and the deposition to the sides reduced.

Experimental details

The experiments were performed in a cylindrical shaped vacuum chamber, 44 cm in diameter and 70 cm in height. A 150 mm diameter Al plate was mounted as a sputtering target onto a weakly unbalanced magnetron in the top of the chamber. The chamber was, prior to the measurements, evacuated by a turbomolecular pump to a base pressure of about 10^{-4} Pa. Ar gas was introduced into the chamber through a mechanical leak valve to a pressure of 0.4 Pa. The cathode was operated by a pulsed power supply manufactured by Chemfilt Ion Sputtering AB, Sweden, capable of delivering 2000 V and 1200 A peak values at 50 Hz repetition frequency and duty cycle of ~ 0.5 %. The pulse length was about 100 μ s. An example of the pulse shape can be seen in Fig. 1. These traces correspond to a peak power value of 240 kW, while the average power reaches merely 400 W due to the low duty factor. The target current was measured with a Tektronix CT-04 high current transformer together with a Tektronix TCP202 current probe and a Tektronix P6015 high voltage probe was used to measure the cathode voltage.

A cylindrical shaped coil was placed in front of the magnetron, at a distance of 20 mm from the target surface, to create an external magnetic field. The coil was made of 120 turns of Cu wire and had an inner diameter of 189 mm, an outer diameter of 240 mm, and a height of 86 mm. When current was drawn through the coil it generated a magnetic field opposing the field from the centre pole of the magnetron. The magnetic field configurations are illustrated in Fig. 2 demonstrating the situation

without and with a coil current of 6 A, as simulated using a finite element method [15]. In this experiment two different field strengths were used, 3 and 6 A coil current. When a current of 6 A is drawn through the coil it generates a magnetic field of roughly 5 mT in the center of the coil (measured in the absence of the magnetic field of the magnetron).

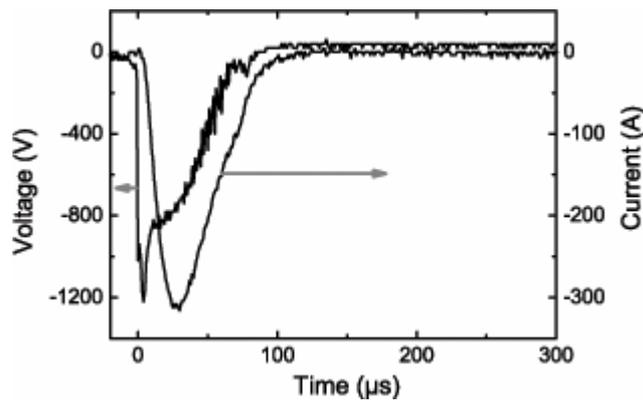


Fig. 1. The discharge current and target voltage applied to the magnetron with an Al target. These traces correspond to a peak power of 240 kW and an average power of 400 W.

A total of 11 Si samples were placed both facing the target and perpendicular to the target as illustrated in Fig. 2. The samples facing the target were placed at a distance of 150 mm from the target distributed along the radius, from the center out to 75 mm. The samples perpendicular to the target were distributed between 77.5 and 140 mm from the target at 90 mm from the center axis.

The film thicknesses were measured using X-ray-reflectometry (XRR). XRR is limited to film thicknesses of ~ 10 -100 nm for metals, due to absorption and resolution limitations. Because of the large variation in deposition rate depending on

substrate position, films were grown in two different runs (3 and 10 minutes) to obtain the right thickness interval for XRR measurements for all sample positions.

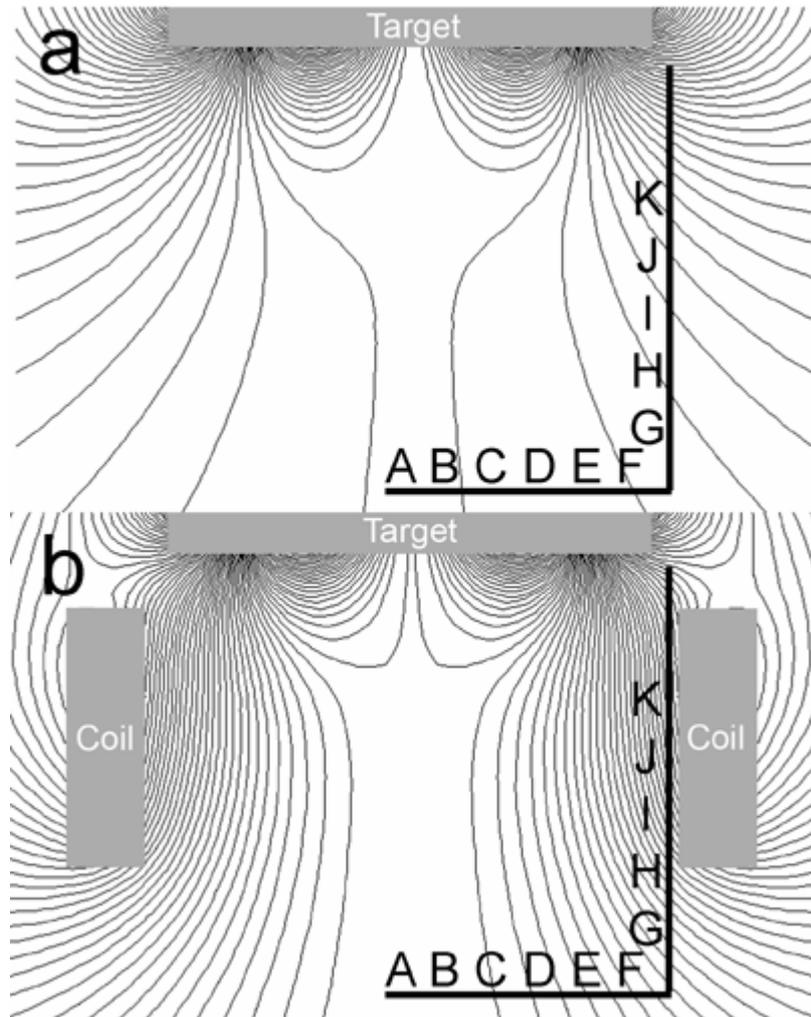


Fig. 2. (a) The magnetic field of the magnetron. (b) The field generated by the coil superimposed with the original field of the magnetron. The field was simulated by using a finite element method. A to K indicate substrate positions.

Results and discussion

The force acting on a charged particle moving with velocity v in the presence of a magnetic field is determined by the Lorentz force

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B}) \quad (1)$$

where q is the charge of the particle and E and B is the electric and magnetic fields. Inside the bulk plasma the motion of the charge carriers cancels out most of the externally applied electric field. The solution of Eq. 1 with $E = 0$ is a gyrating orbit perpendicular to the magnetic field. The radius of such an orbit is called the Larmor radius and is defined as

$$r_L = \frac{mv}{qB} \quad (2)$$

where m is the mass of the particle. To confine the particle it is necessary that the Larmor radius is much smaller than the dimension of the experimental setup. In our experimental setup we typically generate magnetic field strengths of a few mT. As a reference we use the following values of the electron energy, ion energy, and the magnetic field strength; $E_e \sim 1$ eV, $E_i \sim 1$ eV, $B \sim 5$ mT. In this example the electrons will have a Larmor radius of less than 1 mm, while an ion will have a Larmor radius of about 10 cm. Due to the large ion Larmor radius, at energies ions are not confined by the magnetic field. Although these ions are not magnetized they cannot move independently but are bound to the electron motion by the plasma internal electric field. If the gyro orbit of the ions “sticks out” of the plasma, internal electric fields develop in order to keep the plasma quasi neutral, which in turns keeps the ions back with the magnetized electrons. Even a very slight charge separation generates internal fields in the plasma, and the associated electrostatic forces keep electrons and ions together. This is known as ambipolar diffusion. Similar arguments and observations are used to explain the plasma confinement in magnetically filtered arc discharges [16,17]. Thus, the motion of the ions, thermalized or not, is determined by the effect of the magnetic field on the electrons. Due to this **phenomenon** it should be possible to control the spatial distribution of the deposition material for the HIPIMS discharge, even with a relatively weak external magnetic field.

For comparison, the spatial distribution of sputtered Al was recorded for a conventional dc discharge with and without the presence of the external magnetic field. The result can be seen in Fig. 3 where the deposition rates have been normalized with the rate for sample position A. Note that the overall deposition rate is lower for the HIPIMS deposition as is discussed by Christie [18]. It can be seen that the externally applied magnetic field only to a small degree affects the distribution of material for the dc discharge. This is an expected outcome, since the majority of the sputtered particles are electrically neutral, and not affected by the external magnetic field. The distribution of material for the conventional dc discharge is also compared to the distribution of material for the HIPIMS discharge in the absence of the magnetic field. In Fig. 3 it can be seen that there is no major difference in the spatial distribution of material between the conventional dc discharge and the HIPIMS discharge when no external field is applied.

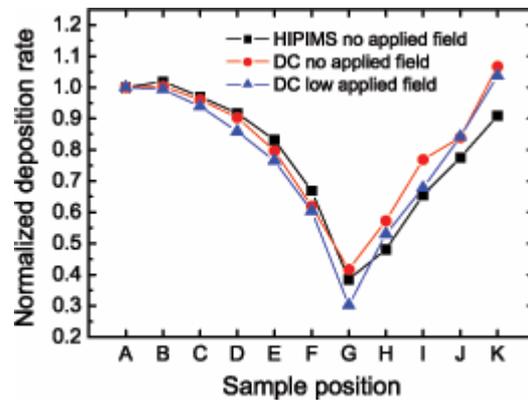


Fig. 3. The distribution of deposited material onto substrates positioned at position A to K for a conventional dc discharge with and without the external field, and for the HIPIMS discharge without the externally applied field. Each deposition is normalized by setting the thickness of the film on position A to 1.

In contrast to conventional dc magnetron sputtering the spatial distribution of the deposition material is significantly affected by the magnetic field from the coil for the HIPIMS depositions. The result can be seen in Fig. 4 in which two different magnetic field strengths were used, one with 3 A, and one with 6 A coil current. The deposition rate is increased with about 80 % for the sample placed on the center axis (sample A) when 6 A is drawn through the coil. The deposition rate increases on all the samples facing the target (A – F), and decreases on the samples situated on the side wall (samples G – K). The applied magnetic field acts as a focusing lens for the deposition material. The focusing effect is less pronounced when a weaker field is applied.

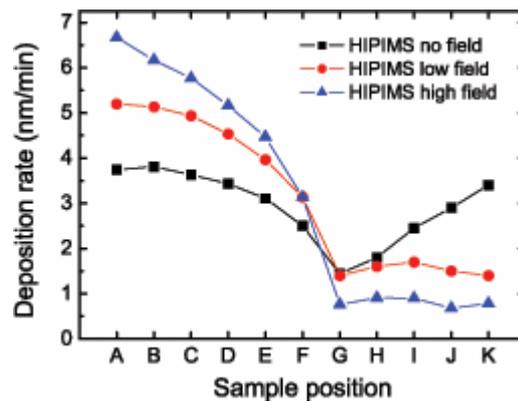


Fig. 4. The distribution of deposited material onto substrates positioned at position A to K for the HIPIMS discharge depending on the externally applied field.

The results presented in this paper are useful as a tool for increasing the deposition rate for HIPIMS, and increasing the target utilization, since less material is lost to the chamber walls. The results presented in this paper not only show the possibilities to control the spatial distribution of material, but are also one more indication that the HIPIMS discharge is highly ionized since the magnetic field affects only ionized Al.

Conclusions

The spatial distribution of deposition material for the HIPIMS discharge has been measured and an external magnetic field were used to focus the flux. The spatial distribution of material is significantly changed when the plasma is exposed to an external magnetic field. The deposition rate was increased with about 80 % for a sample placed on the center axis. For a conventional dc discharge only a minor effect of the magnetic field was observed. The redistribution of material in the HIPIMS discharge not only shows the possibilities to control the flux of material, but also verifies a high degree of ionization of the sputtered material.

Acknowledgements

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