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Deposition rate enhancement in HiPIMS through the control of magnetic field and pulse configuration

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ABSTRACT

In high power impulse magnetron sputtering (HiPIMS) process, the magnetic field and unbalance degree and pulsing configuration are key factors in controlling metal ionization rate and flux of sputtered species towards the substrate. This work reports results on the effect of pulsing configuration (pulse duration) and an auxiliary magnetic field on the deposition rate of ten technologically-relevant elemental target materials (C, Al, Ti, Mn, Ni, Cu, Zn, Mo, Ta, and W) sputtered using HiPIMS. An auxiliary magnetic field was created with a toroidal-shaped permanent magnet placed in front of a strong balanced magnetron. Deposition rates in HiPIMS assisted by this auxiliary magnetic field were compared to those obtained in direct current magnetron sputtering (dcMS) and HiPIMS without an external magnetic field, under the same experimental conditions (average power, gas pressure). It was found that in the case of HiPIMS assisted by the external magnetic field, the deposition rates were approximately 40% to 140% higher compared to HiPIMS without auxiliary magnetic field and, for some materials, even higher compared to those found in dcMS. For copper (Cu) target, total ion current, ion-to-metal flux ratio and ion energy distribution function were measured at the substrate position. Experimental results indicate that during HiPIMS operation (without external magnetic field), the ionized Cu flux fraction increases by 10 to 50% as the pulse duration decreases from 50 to 3 μs, while, in the presence of the external magnetic field, the ionized Cu flux fraction further increases, with values in the range of 40–80% higher. Beside higher deposition rates and increased metal ionization rate, the HiPIMS assisted by the external magnetic field significantly improves Cu target utilization from 20 to 32%. Therefore, deposition rate, metal ion flux towards substrate and target utilization may be optimized by using an appropriate magnetic field and pulsing design.

1. Introduction

In plasma-assisted physical vapour deposition (PVD) process, the energy and amount of ion species are the most effective factors influencing thin film's properties, such as density and adherence. High-power impulse magnetron sputtering (HiPIMS) is a magnetron sputtering technique which uses high power density impulses to provide a high plasma density and a high degree of ionization of sputtered material [1]. Because a large fraction of the sputtered metals is ionized, thin films properties can be tuned by controlling the energy and direction of target material ion flux using electric and/or magnetic fields. As a result, the HiPIMS-deposited coatings are denser, smoother, and have better adhesion to the deposition substrate than the films grown by conventional direct current (*dc*) magnetron sputtering (dcMS) [2].

The lower deposition rate for HiPIMS as compared to dcMS for the same average discharge power is a major drawback of this deposition technique and it's still one of the most discussed topics in this field of research [3,4]. This drawback overshadows the economic perspective of HiPIMS and its development on industrial-scale. The most common explanation given for the deposition rate reduction is the back-attraction of metal ions to the target, followed by a self-sputtering process [5–8]. Gas rarefaction [9], a less than linear increase in sputtering yields with target voltage [10] and side-wall loss of metal ions [11,12] represent other important factors responsible for the deposition rate decrease in HiPIMS. In the last decade, extensive studies were performed to increase the deposition rate in HiPIMS by the proper choice of pulse configuration (pulse duration, repetition frequency, target voltage, peak current, etc.) or by changing the magnetic field design (shape and magnitude) of the magnetron cathode. It was observed that operating the HiPIMS discharge in short pulse mode allows increasing

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the deposition rate due to the reduced gas rarefaction and ion back-attraction effects [13]. Moreover, the operation of HiPIMS discharge with very short pulses offers the possibility to control the current peak, and therefore, the ionization degree of sputtered material and plasma composition [14]. Another method to increase deposition rates is exciting the HiPIMS plasma with sequence of pulse packets consisting of several micro-pulses separated by several tens of microseconds. Operating the HiPIMS discharge in multi-pulse mode, the target atoms sputtered during successive micro-pulses are overlapped and they get ionized when cross the electron confinement zone, leading to higher plasma density away from the target, while ultra-short pulses ($< 5\,\mu s$) prevent metal ion back-attraction and improve the transport of metal ions towards the substrate [15].

Beside pulse configuration, the shape and magnitude of the magnetic field above the target surface have a major contribution to the deposition rate in HiPIMS. Generally, it was found that weakening the magnetic field at the cathode surface can have a significant effect on increasing the normalized deposition rate. Capek et al. found that lowering the magnetic field strength at the target surface by adding paramagnetic spacers with different thickness behind the target leads to an increase in deposition rate by a factor of 4.5 [5]. Similar effect was observed by other researchers who found a significant increase in deposition rate as the magnetic field strength of the magnetron cathode is reduced [16,17]. They argue that the increase in deposition rate with lowering magnetic field is a direct consequence of reduced height of the potential barrier existing in the trap region, allowing more metallic ions to arrive at the substrate. As a general remark, weakening the magnetic field strength leads to a lower electron confinement efficiency and a reduced target current. In a previous paper, we have proved that there is an inverse relationship between peak target current and normalized deposition rate [7]. We successfully managed to manipulate the deposition rate through the peak target current which in turn was controlled by certain operation parameters such as: target voltage, pulse duration, magnetic field strength and target erosion depth.

Beside deposition rate, charged particles energy and spatial-distribution [18] and, therefore, thin film properties, are also affected by the magnetron's magnetic field design. To summarize, the movement of ions and their energy are controlled by the electric field distribution inside the plasma volume during the HiPIMS discharge, which in turn, is strongly influenced by the magnetic field design. Therefore, a careful design of the magnetron's magnetic field configuration (magnetic balance, shape and magnitude) should be considered in order to optimize the deposition rates and thin film's properties.

An effort to optimize the magnetic field configuration, specifically for HiPIMS, was made by Yu et al. They used a large target (35 cm in diameter), with spiral magnet pack assembly, in order to produce superior plasma uniformity on the substrate and to improve target utilization [19]. Experimental results on spiral magnet pack design have shown that the discharge doesn't work in the high current mode, cannot be ignited at pressures lower than 5 Pa and it's not operating even in magnetron mode when the cathode is scaled down to a smaller size (10 cm in diameter). The reason is the low electron trapping efficiency due to the open magnetic field lines in this magnetic field configuration.

In order to overcome these drawbacks, Raman et al. proposed new designs of the magnetic field configurations, namely “ε” magnet pack [20] and “TriPack” magnet pack [21], respectively, which produce deposition rates twice higher than the conventional magnetron's dipole magnetic field configuration (10 cm in diameter) and also superior deposition uniformity. The increase in deposition rate is attributed to the confinement of the electrons at larger distance from the target surface, where the electric field is smaller and allows metallic ions to escape from the magnetic trap and to arrive at the substrate. Fast imaging measurements have shown that, in the case of ‘ε’ and ‘TriPack’ magnet pack configurations, the ionization zones expand more than in the case of conventional magnet pack configuration. Although the results obtained with these configurations are encouraging, however the scale down to a smaller cathode size is still an issue.

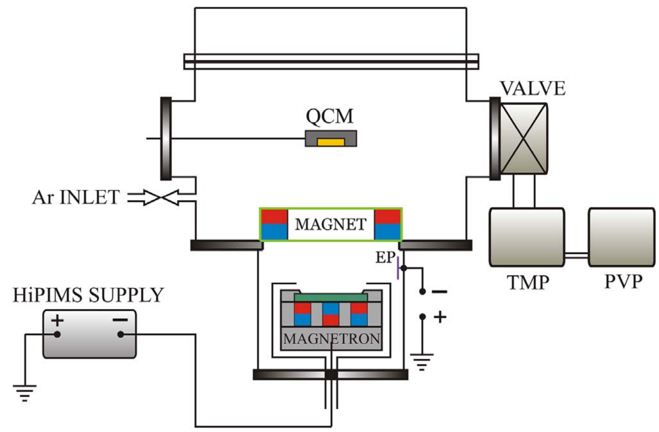

Fig. 1. Sketch of the experimental set-up.

In this work, ten different target materials (C, Al, Ti, Mn, Ni, Cu, Zn, Mo, Ta, and W), comprising a wide range of atomic masses, ionization energies, melting temperatures and sputtering yields, were sputtered in order to study the influence of pulsing configuration (pulse duration) and external magnetic field on the deposition rate. The target materials were selected for their relevance in technological applications, as well as to investigate a wide range of materials sputtered in ultra-short HiPIMS conditions that would allow us to draw material-specific conclusions. The values of the deposition rates measured in HiPIMS were compared with those measured by sputtering target materials under equivalent experimental conditions using dcMS.

2. Experimental device, methods and materials

Direct current magnetron sputtering and high power impulse magnetron sputtering of selected target materials were performed in a stainless steel cylindrical vacuum chamber (diameter of 40 cm, height of 40 cm) equipped with a magnetic balanced magnetron cathode (Kurt J. Lesker TORUS 2″). A schematic of the experimental device is shown in Fig. 1. The deposition chamber was evacuated to the base pressure of 2×10^{-5} Pa using a turbomolecular pump (TMP, Turbo V 750, Agilent Technologies) backed by a dry scroll pump (PVP, IDP-15, Agilent Technologies). The system pressure was maintained at 0.6 Pa, in argon gas (purity 99.999%) atmosphere, supplied at constant flow rate of 20 sccm.

The magnetic field's strength and configuration in the vicinity of the magnetron cathode was changed by adding a permanent magnet with thoroidal shape (external diameter of 10 cm, internal diameter of 6 cm and height of 3 cm). The permanent magnet, placed axially, with the bottom part at 5 cm from the target's surface, weakens the magnetic flux density of the inner pole and raises the magnetic flux density of the outer pole of the magnetron by 600 G, shifting the magnetic field configuration towards an unbalanced magnetron of type II, according to the classification made by Window and Savvides [22]. Strengthening the magnetic flux density of the outer permanent magnet allows an increasing fraction of electrons escaping the magnetic trap to be channeled towards the substrate. This, in turn, increases the plasma density in the vicinity of the substrate and further enhances the ion flux incident at the substrate.

Fig. 2 shows the variation of axial and radial magnetic flux density on a line above the racetrack. It is worth mentioning that when the auxiliary magnet is added the radial component of the magnetic flux, above the racetrack region, remains the same up to a distance of 2.5 cm from the target surface. For the sake of simplicity, for the additional magnetic field and for the HiPIMS discharge assisted by this additional magnetic field, *m.f.* and *m.f.*-HiPIMS notations will be used in this paper.