Optimization of deposition rate in High Power Impulse Magnetron Sputtering

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Despite many useful properties and advantages of High Power Impulse Magnetron Sputtering (HiPIMS) process, it was often reported that one of its major drawbacks is a typically lower deposition rate compared to the conventional dc magnetron sputtering, at the same applied average power. The main cause for reducing the deposition rate in HIPIMS is due to the fact that a large fraction of sputtered atoms is ionized, and some of the newly formed ions are returned to the target by the negative potential, causing self-sputtering. In this contribution, the effects of target potential, pulse duration and magnetic balance of the magnetron on the ion return effect and deposition rate are investigated. It was found that the deposition rate increases from 20% to 80% of dcMS values as the magnetic balance of the magnetron was changed from unbalanced magnetron of type II to unbalanced magnetron of type I for the same average power of 100 W, during the sputtering process of a tungsten target in argon at 1 Pa argon pressure.

1. Introduction

Over the past 20 years, a major interest was focused on developing the conventional magnetron sputtering process in order to increase both metal ionization and deposition rates, avoid target poisoning in reactive sputtering, and minimize electrical instabilities. High power impulse magnetron sputtering (HiPIMS) is one of the most promising alternative techniques, characterized by a very high power density at the target and dense plasma, with high ionization degree of the sputtered material [1]. However, as many researchers reported, HiPIMS processing results in lower deposition rates compared to the conventional dc magnetron sputtering system, at the same average power [2]. The physical reasons for lower deposition rate, including ion return, sputtering yield, ion species, film density, power loss in the switch module, hot target, magnetic unbalancing, and guiding effects are discussed by Anders [3].

In order to explain the lower deposition rates in HiPIMS, Christie *et al.* developed a phenomenological model which predicts back-attraction of the sputtered atoms that are ionized in the dense plasma region, close to the target [4]. There have been some attempts to increase the deposition rate in the HiPIMS discharge by reducing the ion return effect. Recently, Antonin *et al.* demonstrated that using very short pulses or sequences of consecutive very short high-power pulses significantly increases the deposition rate compared to standard HiPIMS [5].

In this contribution, the effects of target potential, pulse duration, and magnetic balance of the magnetron on the ion return effect and deposition rate were investigated.

2. Experimental device, methods and techniques

The experiments were performed in a cylindrical shaped vacuum chamber, 400 mm in diameter and 400 mm in height. The chamber was, prior to the sputtering process, evacuated by a turbomolecular pump to a base pressure of about 10^{-4} Pa. Two type of magnetron were used in this work, one of them was a balanced magnetron and other was a strongly unbalanced magnetron of type I (according to the standard classification [6]). For the unbalanced magnetron, the radial component of magnetic field at the target surface was about 1300 Gauss at a radial position of r = 19 mm, while the axial component was about 4000 Gauss.

The target was a tungsten disk with a thickness of 2 mm and a diameter of 56 mm and was sputtered in pure argon at 1 Pa pressure and 100 W average power. The cathode was operated in HiPIMS regime by a pulsed power supply capable of delivering 1 kV and 50 A peak current values at 1 kHz repetition frequency.

In order to study the influence of the magnetic balance of the magnetron on the deposition rate, an external coaxially-mounted coil having 100 turns of copper wire was used. The supplementary magnetic field created in the cathode sheath region of the magnetron allows changing the magnetic field strength and degree of unbalance of the magnetron from type I to type II. The center of the coil corresponds with the center of the target surface. The magnetic field strength and direction was changed from -100 to 500 Gauss by controlling the coil current intensity between -20 A and +100 A. The deposition rate of the tungsten was monitored using a Quartz Crystal Microbalance placed axially at 100 mm from the target surface.

3. Results and discussions

3.1. The pulse duration effect

The effect of the pulse duration on the deposition rate was investigated and the results are presented in Fig. 1. The target was sputtered using a balanced magnetron in argon gas at pressures of 1 Pa and time-averaged powers of 100 W. The peak voltage during the pulse was set to -1 kV. The deposition rate, measured *in situ* by a QCM, is directly related to pulse duration and increases with the pulse duration decreasing. This is due to the fact that using very short pulse duration less metal ions will be attracted back to the target surface by the cathode fall and the self-sputtering process will be reduced. Decreasing the pulse duration, the plasma composition is changed and the discharge evolves from metal self-sputtering mode to dominant gas sputtering mode.

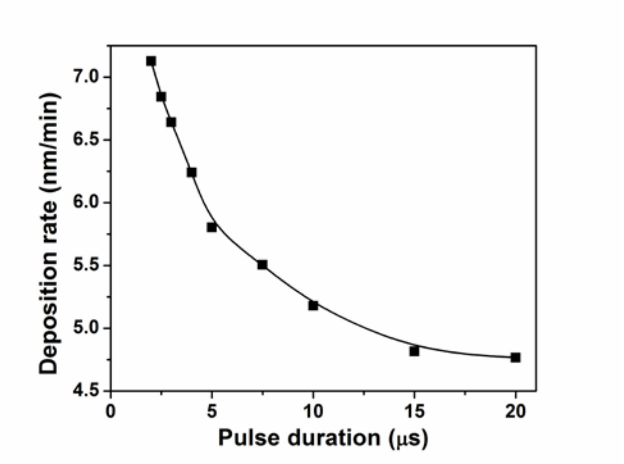

Fig. 1. Tungsten deposition rate versus pulse duration.

The ion current and the relative neutral metal atoms density versus pulse duration were measured and reported in previous works [5,7] and showed the same decreasing profile as the deposition rate when the pulse length is enlarged from 2 to 20 μs. For longer pulse duration, the sputtered atoms spend enough time in the high plasma density region and their probability to be ionized and back attracted to the target is higher. For short pulse duration the residence time of the metallic ions in ionization region is low and they may escape from the magnetic trap region and participate to the deposition process.

3.2. The target voltage effect

The effect of the back-attracted ions on the deposition rate is highlighted in this section by changing the target voltage during HiPIMS operation. The experimental conditions (gas pressure, average power) were the same with those used in previous section. Using pulse duration of 15 µs and decreasing the target voltage from 1000 V to 400 V, but maintaining the same average power to 100 W, the deposition rate increases from 4.2 to 19.2 nm/min (Fig. 2.). This value is very close to the deposition rate of the tungsten sputtered in dc mode at the same applied power. For lower target voltage, the instantaneous power within the pulse decreases constantly via discharge voltage and current from 22.6 kW to 1.2 kW and the operating regime weakens from HiPIMS to dcMS regime. This increase in deposition rate is usually accompanied by a decrease in ionization fraction of the sputtered atoms, influencing the microstructure and film quality, such as density, hardness, adhesion, surface roughness [8]. The lower ionization fraction of the sputtered atoms and lower target voltage diminish the ion return effect.

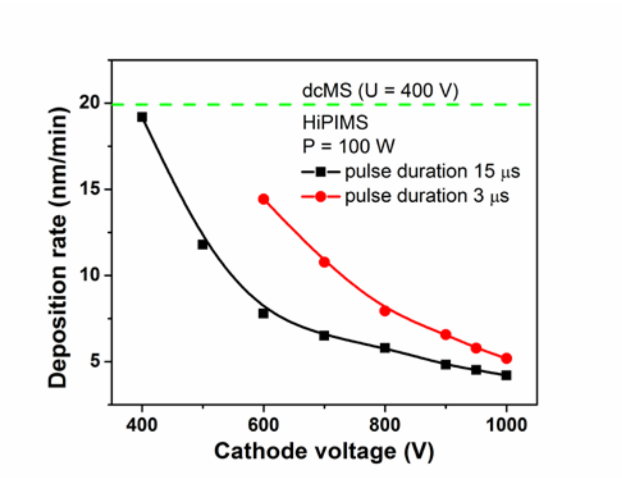

Fig. 2. Tungsten deposition rate versus target voltage. (Green dash line indicates the deposition rate in dc mode at 100 W average power).

The deposition rate increases significantly when HiPIMS operates with very short pulses and low target voltage. In this case, there is a cumulative effect between target voltage and pulse length.

3.3. The magnetic balance effect

The effect of the magnetic balance on the deposition rate was investigated by using an unbalanced magnetron of type I and an external magnetic coil. By strengthening the mean magnetic field in the trap region of the cathode the deposition rate decreases, while by weakening the magnetic field results in an increased deposition rate (Fig. 3.).

One explanation for the reduction in deposition rate when the magnetron is balanced or unbalanced of type II is that the sputtered material is ionized close to the target and the negative potential can extend far into the plasma as an extended pre-sheath [9]. The decrease in deposition rate is related to an increase in the effective potential barrier in the trap region, which avoids the ions leaving the trap, increasing therefore their probability to be back-attracted to the target.

In the case of an unbalanced magnetron of type I, as the magnetic field strength is reduced, electric field over the trap region is reduced and helps ions to escape and more efficiently assist in film growth than in the balanced case or unbalanced of type II [10].

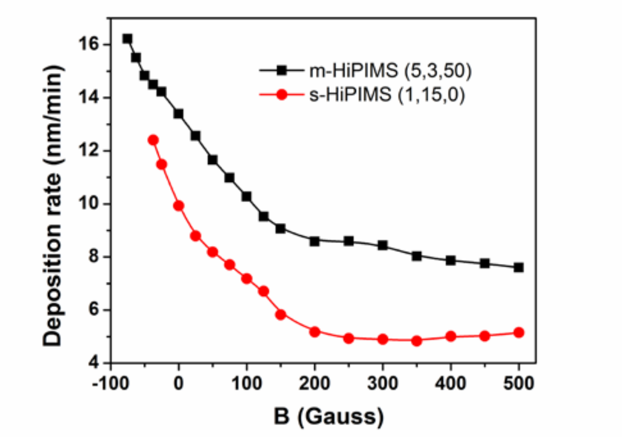

Fig. 3. Tungsten deposition rate versus external magnetic field strength. The multi-pulse is a sequence of 5 pulses of 3 μs duration, separated by 50 μs. The average power is 100 W and argon pressure is 1 Pa.

In Fig. 3 is illustrated the evolution of the tungsten deposition rate when magnetic balance of the cathode is switched from strongly unbalanced magnetron type I to type II, for two different HiPIMS operation mode. In standard HiPIMS mode (s-HiPIMS) the pulse duration was 15 μs, while in multi-pulse HiPIMS mode (m-HiPIMS) a sequence of 5 pulses of 3 μs duration, separated by 50 μs was used. The gas pressure was 1 Pa and average power 100 W. In both HiPIMS operation modes the deposited rate is at least two times higher when the magnetic balance of the magnetron is switched from unbalanced of type II to unbalanced of type I. Also, the deposition rate in m-HiPIMS mode is always higher than in the s-HiPIMS mode, for the same average power and the same magnetic balance of the cathode.

4. Conclusions

Applying an external magnetic field in the cathode sheath region of the magnetron can change the unbalancing degree of the magnetron and enhances the deposition rate by relaxation of the ion trapping and reducing the metal ions return effect. Moreover, by operating the HiPIMS with very short pulses or in multi-pulse mode, it is possible to increase more the deposition rate by taking advantages of the high ion fraction of the sputtered material in HiPIMS pulse and plasma behavior in the afterglow, but drastically limiting the metal ion back-attraction to the target.

Controlling and optimizing the magnetic balance of the magnetron and using standard HiPIMS with very short pulses or multi-pulse HiPIMS it is possible to overcome the deposition rate limitation, without losing the HiPIMS benefits. It was found that the deposition rate increases from 20% to 80% of dcMS values as the magnetic balance of the magnetron was changed from unbalanced magnetron of type II to unbalanced magnetron of type I.

5. References

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