Introduction

In the high power impulse magnetron sputtering (HiPIMS) the discharge is created by applying a high power unipolar pulse of low duty cycle to the cathode target (Holmenson et al., 2005, 2006). The pulse length is typically 50 - 500 µs and the pulse frequency 1 - 100 kHz. The high power pulse has a peak cathode voltage in the range 500 - 2000 V which gives peak power densities in the range 1 - 3 kW/cm². A high fractional ionization has been demonstrated and values higher than 90 % have been reported (Bolmán et al. 2005).

The measured ionized flux fraction from Cu target was estimated roughly 70 % (Kouznetsov et al., 1999), from a Ti target around 5 % (Macák et al., 2003) and from Cu and Al target 4.5 % and 5.5 % respectively (DeKoven et al., 2003).

The reported measured values are highly inconsistent. The ionization mechanism and the temporal behavior of the plasma parameters in a high power impulse magnetron sputtering (HiPIMS) discharge is investigated using a time dependent global (volume averaged) model.

The global (volume averaged) model

The discharge is assumed to consist of electrons, Ar atoms in the ground state, metastable Ar atoms, Ar⁺ ions, metal atoms, M, and metal ions, M⁺.

Electrons are assumed to have a Maxwellian energy distribution in the range 1 - 7 eV.

The power balance equation, which equates the absorbed power to power losses due to elastic and inelastic collisions and losses due to the charged particle flow to the discharge walls is given as

$$\frac{d}{dV} \left( \frac{P_{abs}}{n_e} \right) = \frac{P_{ion}}{n_e} + \frac{P_{coll}}{n_e} + \frac{P_{loss}}{n_e}$$

where

- $P_{abs}$ is the mean kinetic energy per electron lost and $P_{ion}$ is the mean kinetic energy per ion lost.
- $n_e$ is the argon ion mass, and $n_{Ar}^+$ is the density of argon ions.
- The collisional energy loss per electron-ion pair created and is defined as

$$\Delta E = \Delta E_{ion} + \sum \Delta E_{exc},$$

where

- $\Delta E_{ion}$ is the ionization energy, $\Delta E_{exc}$ is the threshold energy and $\Delta E_{exc}$ is the rate coefficient for the i-th excitation process, respectively, $\Delta E_{ion}$ is the ionization rate coefficient for single-step ionization.

The pulse balance for the metal ions gives

$$\frac{d}{dV} n_{Al} = \frac{\Delta E_{ion}}{n_e} = \frac{\Delta E_{exc}}{n_e}$$

where $n_{Al}$ is the neutral metal density, $n_{Al}^+$ is the metal ion density, $n_{Al}^+$ is the density of metastable argon atoms, and $n_{Al}^+$ is the metal ion mass.

The pulse balance for metal atoms is

$$\frac{d}{dV} n_{Al} = \frac{\Delta E_{ion}}{n_e} = \frac{\Delta E_{exc}}{n_e}$$

where $\Delta E_{ion}$ is the yield of sputtered atoms per incident argon ion, $\Delta E_{exc}$ is the yield of sputtered atoms per incident metal ion, $r_\gamma$ is the target radius.

- The particle balance equation for generation and loss of metastable argon atoms is

$$\frac{dn_{Ar}}{dt} = \frac{1}{n_e} \frac{dn_{Ar}}{dt} = \frac{\Delta E_{ion}}{n_e}$$

- The particle balance for argon ions is

$$\frac{dn_{Ar}}{dt} = \frac{1}{n_e} \frac{dn_{Ar}}{dt} = \frac{\Delta E_{ion}}{n_e}$$

- The temporal variation of the particle density and the electron temperature was obtained by solving the differential equations (1), (3), (4), (5) and (6) simultaneously and self-consistently. Once the density of Ar²⁺ and M⁺ ions is found the quasi-neutrality condition gives the electron density $n_e = n_{Ar}^+ + n_{M}^+$.

Results and discussion

To explore the ionization processes in a high power impulse magnetron sputtering discharge we assume a discharge chamber of radius $R = 15$ cm and length $L = 15$ cm with a target of radius 7.5 cm made of aluminum.

We assume the power pulse to be the same as shown in figure 1 and the discharge pressure to be 10 mTorr (after Gudmundsson et al. 2002).

Conclusions

- The metal ion fraction and the ionized flux fraction are very high, the sputtered metal is almost fully ionized.
- During the pulse on period, electron impact ionization is the most effective process in creating metal ions while charge exchange becomes the dominant process in creating metal ions after the pulse is off.

Acknowledgments

This work was partially supported by the Icelandic Research Fund and the University of Iceland Research Fund.

References


