On recycling in high power impulse magnetron sputtering discharges

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Abstract

Here we discuss the large discharge currents observed in HPIMS discharges. We discuss the current composition and the role of self-sputter recycling (SS-recycling) and working gas recycling within the discharge. We find that above a critical current density, $J_{crit}$, a combination of self-sputter recycling and working gas recycling is the general case. For high self-sputtering yields, above $Y_{SS} < 1$, the discharges become dominated by SS-recycling, and contain only a few hot secondary electrons that have been accelerated across the cathode sheath. For low sputtering yields, below $Y_{SS} \approx 0.2$, the discharges above $I_{crit}$ are dominated by working gas recycling and have a significant sheath electrification of secondary electrons.

Introduction

The high power impulse magnetron sputtering (HPIMS) discharge is a recent addition to plasma assisted physical vapor deposition (PVD) methods. A high density plasma is created by applying high power pulses at low frequency and low duty cycle to a magnetron sputtering device [1].

Here we focus on the ion current at the target surface, where the electron fraction of the discharge current is insignificant due to an effective secondary electron emission yield typically below 0.1. A primary current $I_{prim}$ is defined as ions of the working gas, here Ar⁺, that are ionized for the first time and then drawn to the target. This is the dominating current in conventional dc magnetron sputtering discharges. This current has a critical upper limit

$$I_{crit} = \frac{q}{\epsilon} \sqrt{\frac{2}{\pi m_e}} \frac{1}{\xi g \beta g}$$

Discharge currents $I_{SS}$ above $I_{crit}$ are only possible if there is some kind of recycling of atoms that leave the target, become subsequently ionized and then are drawn back to the target.

In Figure 1 we see the current composition at the target surface of a HiPIMS discharge with Al target measured by Anders et al. [2] and analyzed by the ionization region model (IRM) [3]. For the 50 nm diameter Al target the critical current is $I_{crit} \approx 7 \, A$.

When the discharge is operated at 400 V the contributions of $\alpha^+$ and $Ar^+$-ions to the discharge current are very similar. At 800 V $\alpha^+$-ions dominate the discharge current (self-sputtering) while the contribution of $Ar^+$ is below 10% except at the initiation of the pulse.

With increasing discharge current the primary current, $I_{prim}$, gradually becomes a very small fraction of the total discharge current $I_{total}$.

The generalized recycling model

The generalized recycling model (GRM) is a scheme to understand the current evolution to high discharge currents by analyzing and quantifying the individual contributions of SS-recycling and working gas-recycling [4,5].

The total current carried by working gas ions is

$$I_{g} = I_{prim} + I_{SS-recycle} = I_{SS}(1 + \frac{\eta_{SS}}{Y_{SS}})$$

where the self-sputtering parameter is

$$\eta_{SS} = \alpha_{SS} Y_{SS}$$

The total discharge current is

$$I_{total} = I_{g} + \sum I_{SS} = I_{SS} \left( 1 + \frac{\eta_{SS}}{Y_{SS}} \right)$$

where $\eta_{SS}$ is ionization probability

$\beta_{SS}$ is back addition probability

$Y_{SS}$ is self-sputter yield

The total discharge current is

$$I_{total} = I_{prim} + I_{SS-recycle} + I_{SS} = I_{SS} \left( 1 + \frac{\eta_{SS}}{Y_{SS}} \right) (1 + \epsilon_{SS})$$

Thus $I_{SS}$ acts as a seed to the whole discharge current and has an upper limit $I_{SS} \leq I_{total}$

Similarly $I_{SS}(1 + \epsilon_{SS})$ is the seed current for the self-sputtering process.

Figure 1: The temporal variation of the discharge current composition at the target surface for an argon discharge at 1.8 Pa with 50 mm diameter Al target for discharge voltages (a) 400 V, and (b) 800 V, where we define a working gas-sputtering parameter

$$\epsilon_{SS} = \alpha_{SS} Y_{SS}$$

Figure 2: The recycling map, a graph in which the ion current mix of $I_{prim}$, $I_{SS-recycle}$, and $I_{SS}$ to the target in a magnetron sputtering discharge is defined by a point. $I_{prim}/I_{crit} = 0.5$ defines the dCMS regime, while $I_{SS}/I_{SS-recycle} < 0.5$ defines the recycling regime (diagonal lines). For $I_{SS}/I_{SS-recycle} > 0.5$ we have the SS-recycle dominated regime B, and for $I_{SS}/I_{SS-recycle} < 0$, the gas-recycle dominated range B.

Recycling map is a graph in which the ion current mix of $I_{prim}$, $I_{SS-recycle}$, and $I_{SS}$ to the target in a magnetron sputtering discharge is defined by a point. The value of $I_{SS}/I_{SS-recycle} = 0.5$ can be read on the diagonal lines ($Y_{SS} = 0.5$)

$\eta_{SS}/I_{SS} = 0.5$ defines the dCMS regime

For $I_{SS}/I_{SS-recycle} > 0.5$ we have the SS-recycle dominated range A

For $I_{SS}/I_{SS-recycle} > 0.5$ we have the gas-recycle dominated range B

As seen in Figure 3 the discharge with Al target moves from the dCMS regime to the HiPIMS discharge regime with increased discharge voltage – type A.

A discharge with carbon target jumps from the dCMS regime to the HiPIMS regime – both SS recycling and working gas recycling play a role – intermediate type AB

References