On recycling in high power impulse magnetron sputtering discharges

N. Brenning[1], J. T. Gudmundsson[1,2], M. A. Raadu[1], T. J. Petty[3], T. M. Minea[3] and D. Lundin[3]

[1] Department of Space and Plasma Physics, KTH–Royal Institute of Technology, Stockholm, Sweden

[2] Science Institute, University of Iceland, Reykjavík, Iceland

[3] Laboratoire de Physique des Gaz et Plasmas - LPGP, Université Paris-Sud, Orsay Cedex, France

Abstract

Here we discuss the large discharge currents observed in HiPIMS discharges. We discuss the current composition and the role of self-sputter (SS-) recycling and working gas recycling within the discharge. We find that above a critical current density $J_D \approx 0.2$ A/cm^2, a combination of self-sputter recycling and working gas-recycling is the general case. For high self-sputtering yields, above $Y_{SS} \approx 1$, 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 self-sputter yields, below $Y_{SS} \approx 0.2$, the discharges above J_{crit} are dominated by working gas recycling and have a significant sheath energization of secondary electrons.

Introduction

The high power impulse magnetron sputtering (HiPIMS) 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

$$I_{crit} = S_{RT} e p_g \sqrt{\frac{1}{2\pi m_g k_B T_g}} = S_{RT} e n_g \sqrt{\frac{k_B T_g}{2\pi m_g}}$$

Discharge currents I_D 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 mm diameter Al target the critical current is $I_{crit} \approx 7$ A.

When the discharge is operated at 400 V the contributions of Al$^+$ and Ar$^+$-ions to the discharge current are very similar.

At 800 V Al$^+$-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_D.

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

$$I_g = I_{prim} + I_{gas-recycle} = I_{prim}\left(1 + \frac{\pi_g}{1-\pi_g}\right)$$

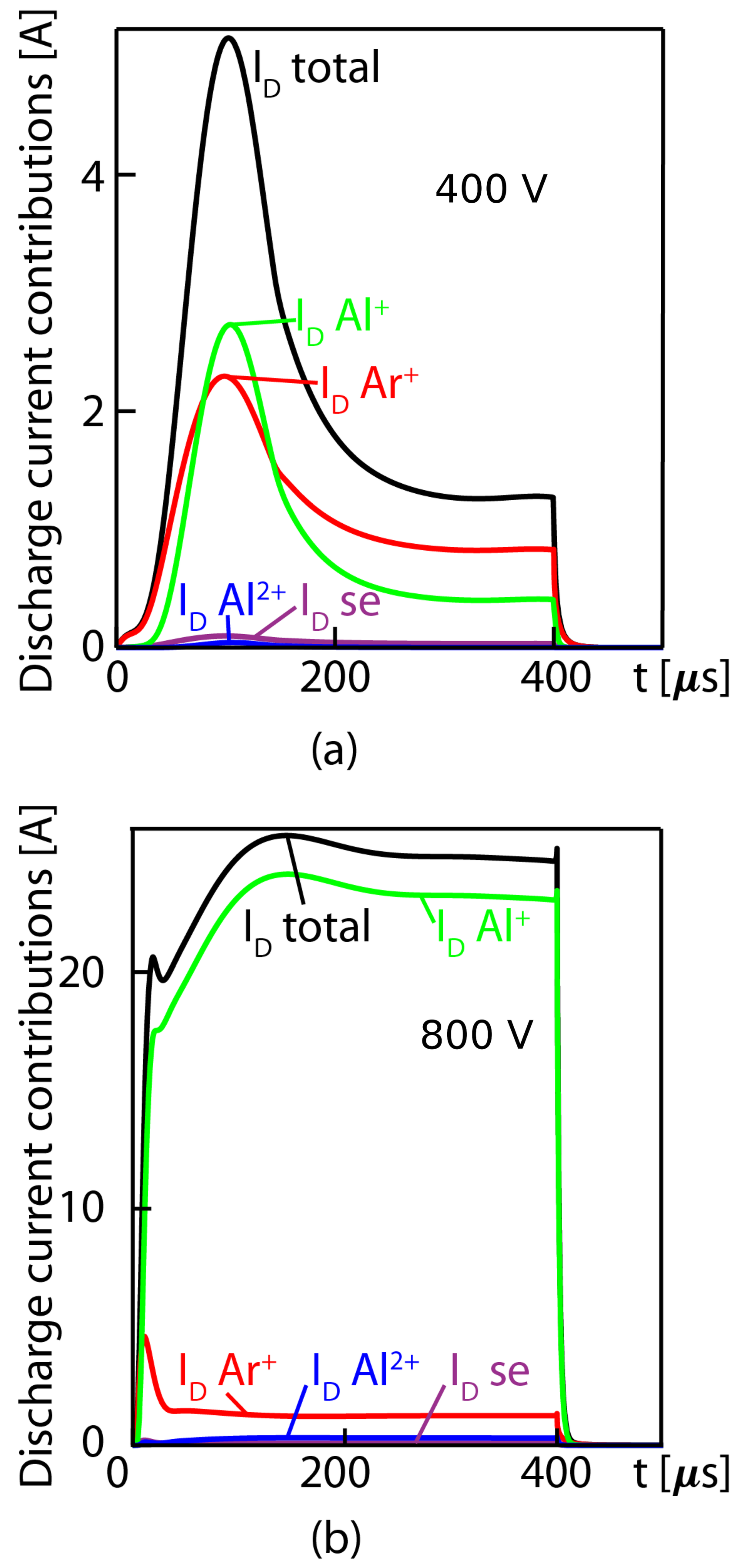

Figure 1: The temporal variation of the discharge current composition at the target surface for an argon discharge at 1.8 Pa with 50 mm diameter Al target for discharge voltage (a) 400V, and (b) 800 V.

where we define a working gas-sputtering parameter

$$\pi_g = \alpha_g \beta_g \xi_{pulse}$$

where

- α_g is ionization probability
- β_g is back attraction probability
- $\xi_{pulse} = 1$ is return fraction in a pulse

The total self-sputter current is

$$I_{SS} = I_g\left(\frac{Y_g}{Y_{SS}}\frac{\pi_{SS}}{1-\pi_{SS}}\right)$$

where the self-sputter parameter is

$$\pi_{SS} = \alpha_t \beta_t Y_{SS}$$

where

- α_t is ionization probability
- β_t is back attraction probability
- Y_{SS} is self-sputter yield

The total discharge current is

$$I_D = I_{prim} + I_{gas-recycle} + I_{SS} = I_{prim}\left(1 + \frac{\pi_g}{1-\pi_g}\right)\left(1 + \frac{Y_g}{Y_{SS}}\frac{\pi_{SS}}{1-\pi_{SS}}\right)$$

or

$$I_D = I_{prim}\Pi_{gas-recycle}\Pi_{SS-recycl}$$

Thus I_{prim} acts as a seed to the whole discharge current and has an upper limit I_{crit}.

Similarly $I_{prim}\Pi_{gas-recycle}$ is the seed current for the self-sputter process.

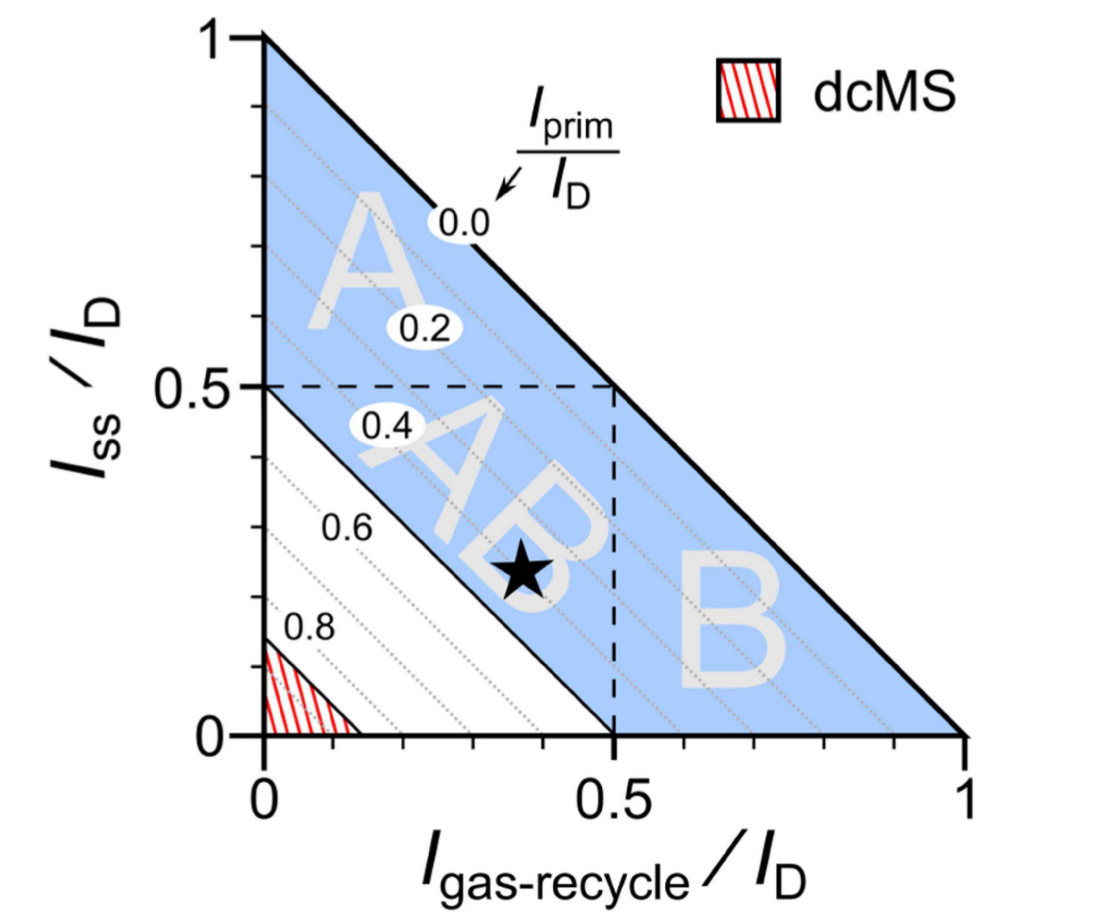

Figure 2: The recycling map, a graph in which the ion current mix of I_{prim}, $I_{gas-recycle}$, and I_{SS} to the target in a magnetron sputtering discharge is defined by a point. $I_{prim}/I_D \geq 0.85$ defines the dcMS regime, while $I_{prim}/I_D < 0.5$ defines the recycling regime (blue-shaded region). For $I_{SS}/I_D > 0.5$, we have the SS-recycle dominated range A and for $I_{gas-recycle}/I_D > 0.5$ the gas-recycle dominated range B.

Recycling map is a graph in which the ion current mix of I_{prim}, $I_{gas-recycle}$, and I_{SS} to the target in a magnetron sputtering discharge is defined by a point. The value of $I_{prim}/I_D = 39$ %, can be read on the diagonal lines ($Y_{SS} = 0.5$)

- $I_{prim}/I_D \geq 0.85$ defines the dcMS regime
- For $I_{SS}/I_D > 0.5$ we have the SS-recycle dominated range A
- For $I_{gas-recycle}/I_D > 0.5$ 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**

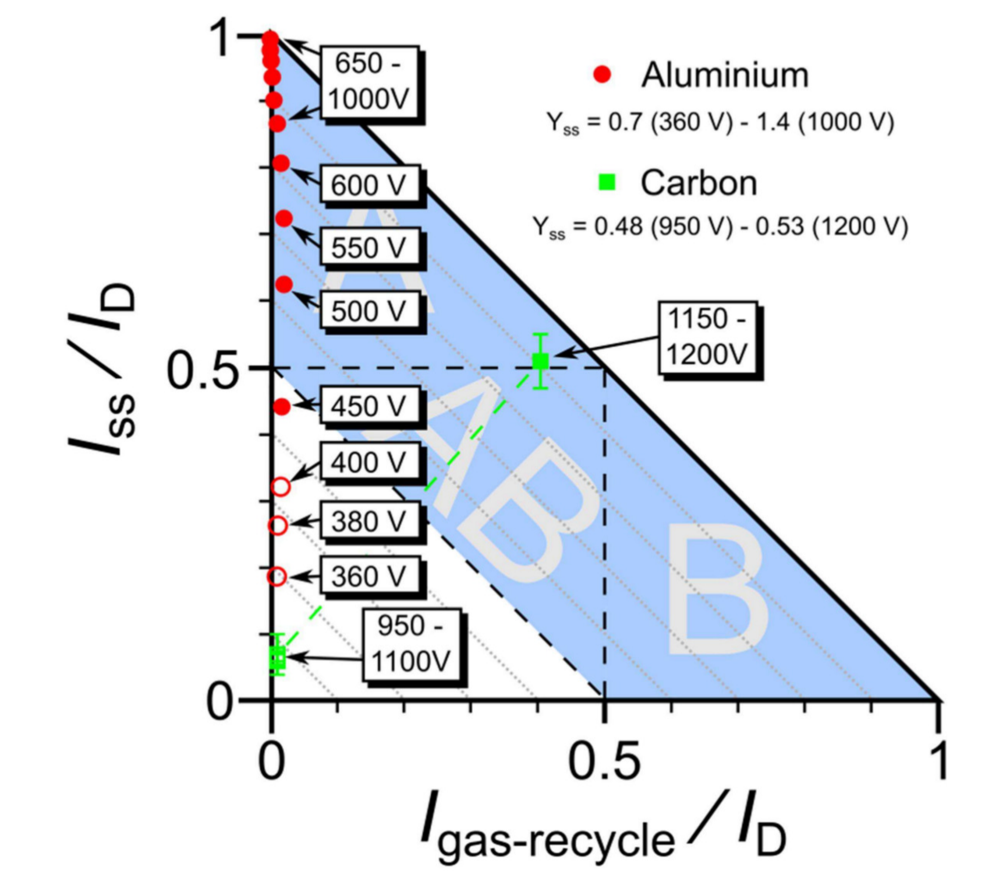

Figure 3: A recycling map with the roads from the dcMS regime to the HiPIMS regime for the two discharges, evaluated at the current plateaus (300 μs for the Al case and 150 μs for the C case) when equilibrium is well established. The symbols are drawn open at discharge currents I_D below I_{crit} and filled for $I_D > I_{crit}$.

For very high self-sputter yields $Y_{SS} > 1$, the discharges above I_{crit} are of **type A** with dominating **SS-recycling**

For very low self-sputter yields $Y_{SS} < 0.2$, the discharges above I_{crit} are of **type B** with dominating **working gas recycling**

- Cu – $Y_{SS} = 2.6$
- Al – $Y_{SS} = 1.1$
- Ti – $Y_{SS} = 0.7$
- C – $Y_{SS} = 0.5$
- TiO_2 – $Y_{SS} = 0.04 - 0.25$

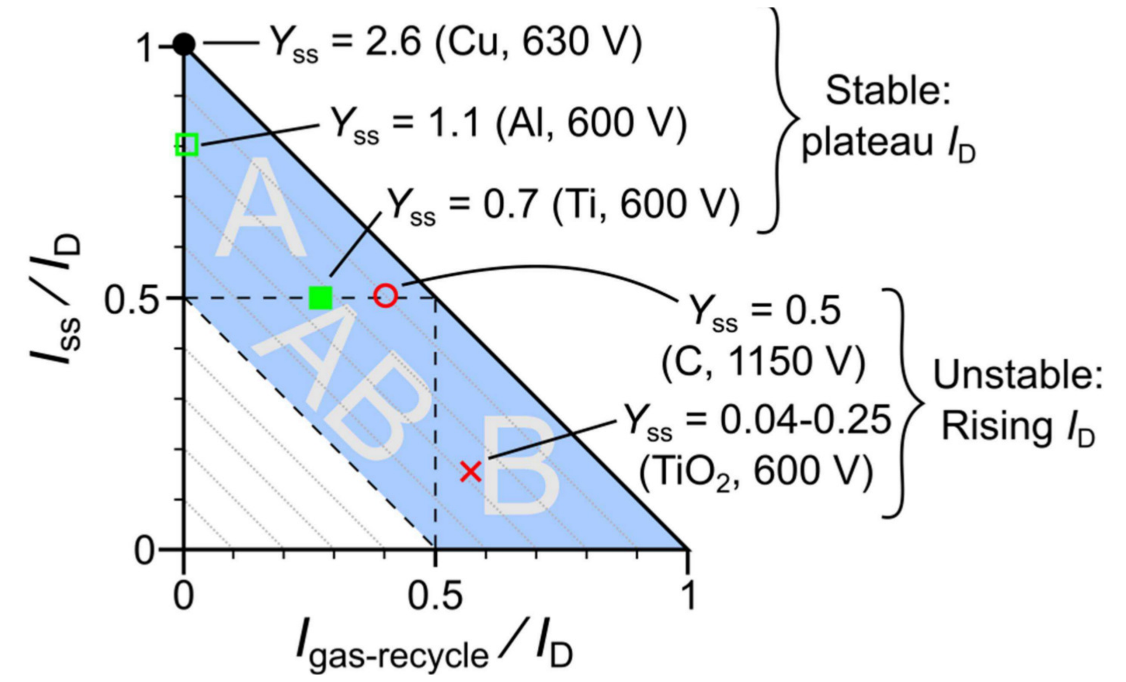

Figure 4: A recycling map showing five discharges with typical HiPIMS current densities of $J_D \approx 0.6 - 3.1$ A/cm^2 taken over the whole target, and with self-sputter yields in the range from about 0.1 (TiO_2) to 2.6 (Cu).

References

[1] J. T. Gudmundsson et al., J. Vac. Sci. Technol. A, **30** (2012) 030801.
[2] A. Anders et al., J. Appl. Phys., **102** (2007) 113303.
[3] C. Huo et al. J. Phys. D: Appl. Phys., **50** (2017) 354003
[4] N. Brenning et al., Plasma Sources Sci. Technol., **26** (2017) 125003.
[5] J. T. Gudmundsson et al., Plasma Sources Sci. Technol., **25** (2017) 065004.