The High Power Impulse Magnetron Sputtering (HiPIMS) Discharge

Jón Tómas Guðmundsson

University of Michigan – Shanghai Jiao Tong University Joint Institute,
Shanghai Jiao Tong University, Shanghai, China
and
Science Institute, University of Iceland, Iceland

tumi@hi.is

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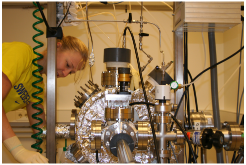
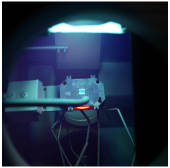
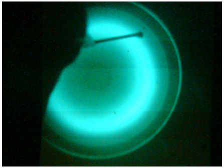
Introduction



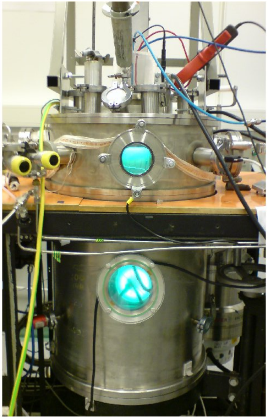




- Magnetron sputtering has been the workhorse of plasma based sputtering methods for over three decades
- For many applications a high degree of ionization of the sputtered vapor is desired
  - controlled ion bombardment of the growing film
  - ion energy can be controlled by a negative bias applied to the substrate
  - collimation – enhanced step coverage
- Ionized flux of sputtered vapor therefore introduces an additional control parameter into the deposition process

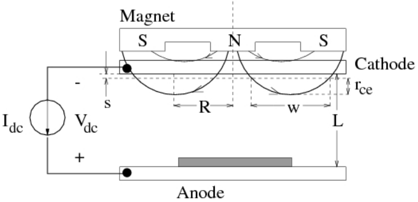
Outline

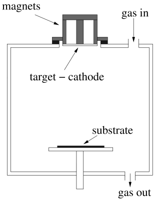
- Magnetron Sputtering Discharge
- Ionized Physical Vapor Deposition (IPVD)
- High power impulse magnetron sputtering discharge (HiPIMS)
    - Power supply
    - Electron density
    - Plasma dynamics
    - Electron energy
    - Ionization fraction
    - Ion energy
    - Deposition rate
    - Applications
- Summary



Planar Magnetron Sputtering Discharge

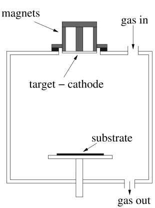
Planar Magnetron Sputtering Discharge

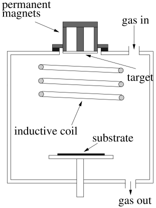


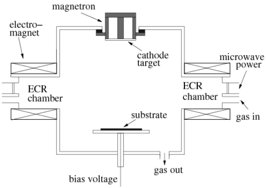


- For a typical dc planar magnetron discharge
  - pressure of 1 – 10 mTorr
  - a magnetic field strength of 0.01 – 0.05 T
  - cathode potentials 300 – 700 V
  - average power 200 – 600 W
  - electron density in the substrate vicinity is $10^{15} - 10^{17}$ m^{-3}
  - low fraction of the sputtered material is ionized $\sim$ 1 %
  - the majority of ions are the ions of the inert gas
  - the sputtered vapor is mainly neutral

Planar Magnetron Sputtering Discharge







- In magnetron sputtering discharges increased ionized flux fraction is achieved by
  - a secondary discharge between the target and the substrate (rf coil or microwaves)
  - reshaping the geometry of the cathode to get more focused plasma (hollow cathode)
  - increasing the power to the cathode (high power pulse)
- Common to all highly ionized magnetron sputtering techniques is a very high density plasma

Ionized Physical Vapor Deposition (IPVD)

Ionized Physical Vapor Deposition (IPVD)

- When the flux of ions is higher than the flux of neutrals or $\Gamma_{\rm i} > \Gamma_{\rm m}$ the process is referred to as ionized physical vapor deposition (IPVD)
- The metal ions can be accelerated to the substrate by means of a low voltage dc bias
  - The metal ions arrive at the substrate at normal incidence and at specific energy
  - The energy of the ions can be tailored to obtain impinging particles with energies comparable to typical surface and molecular binding energies

Ionized Physical Vapor Deposition (IPVD)

- Ionizing the sputtered vapor has several advantages:
  - improvement of the film quality, increased film density (Kusano (2006) 49th SVC, p. 15, Lim et al. (2000) JVSTA **18** 524, Samuelsson et al. (2010) SCT **202** 591)
  - improved adhesion (Ehiasarian et al. (2007) JAP **101** 054301)
  - improved surface roughness (Sarakinos et al. (2007) JPD **40** 2108)
  - deposition on substrates with complex shapes and high aspect ratio (Alami et al. (2005) JVSTA **23** 278)
  - phase tailoring (Alami et al. (2007) TSF **515** 3434)
  - guiding of the deposition material to the desired areas of the substrate (Bohlmark et al. (2006) TSF **515** 1928)
  - hysteresis free reactive sputtering has been demonstrated in a HiPIMS discharge (Wallin and Helmersson (2008) TSF **516** 6398)

Ionized Physical Vapor Deposition (IPVD)

- The system design is determined by the average distance a neutral particle travels before being ionized
- The ionization mean free path is

$$\lambda_{\mathrm{iz}} = \frac{v_{\mathrm{s}}}{k_{\mathrm{iz}} n_{\mathrm{e}}}$$

  where
    - v_{s} is the velocity of the sputtered neutral metal
    - k_{iz} is the ionization rate coefficient
    - n_{e} is the electron density

Ionized Physical Vapor Deposition (IPVD)

- This distance has to be short
  - v_s has to be low - thermalize the sputtered flux - increase discharge pressure
  - n_e has to be high
- Typical parameters for argon gas and copper target

Gas	v_s [m/s]	T_e [V]	n_e [m^{-3}]	λ_{iz} [cm]	Discharge
Ar	1000[a]	3	10^{17}	162	
Ar	300	3	10^{17}	49	dcMS
Ar	300	3	10^{18}	4.9	ICP-MS/ECR-MS
Ar	300	3	10^{19}	0.5	HiPIMS
Cu	300	1.5	10^{19}	7.5	SSS-HiPIMS

[a] (Britun et al. (2008) APL **92** 141503)

Ionized Physical Vapor Deposition (IPVD)

- Another important parameter is the fraction of ionized metal flux

$$\frac{\Gamma_{\rm i}}{\Gamma_{\rm i} + \Gamma_{\rm n}}$$

- The ion flux to the substrate is

$$\Gamma_{\rm i} \approx 0.61 n_{\rm m+} u_{\rm B} \sim \sqrt{T_{\rm e}}$$

- The flux of thermalized neutrals is

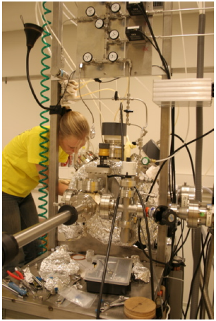
$$\Gamma_{\rm n} = \frac{1}{4} n_{\rm m} v_{\rm Th} \sim \sqrt{T_{\rm g}}$$

- Since $T_{\rm e} \gg T_{\rm g}$ the fraction of ionized metal flux is larger than the fraction of ionized metal in the plasma
- It is not necessary to completely ionize the sputtered metal to create a highly ionized flux to the substrate

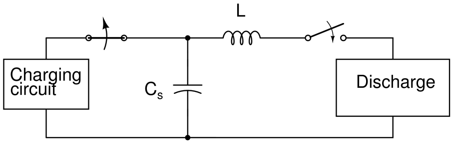
High Power Impulse Magnetron Sputtering (HiPIMS)

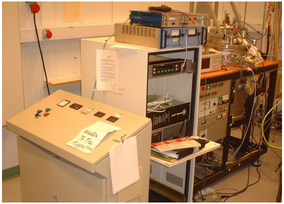
High Power Impulse Magnetron Sputtering (HiPIMS)

- In a conventional dc magnetron discharge the power density is limited by the thermal load on the target
- In a HiPIMS discharge a high power pulse is supplied for a short period
  - low frequency
  - low duty cycle
  - low average power
- The HiPIMS discharge uses the same sputtering apparatus except the power supply



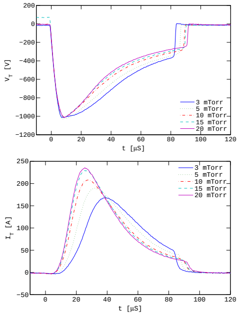
HiPIMS - Power supply

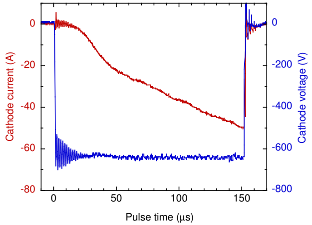




- The high power pulsed discharge operates with a
  - Cathode voltage in the range of 500 – 2000 V
  - Current densities of 3 – 4 A/cm^2
  - Power densities in the range of 1 – 3 kW/cm^2
  - Average power 200 – 600 W
  - Frequency in the range of 50 – 5000 Hz
  - Duty cycle in the range of 0.5 – 5 %

HiPIMS - Power supply





From Magnus et al. (2011), TSF **519** 5861

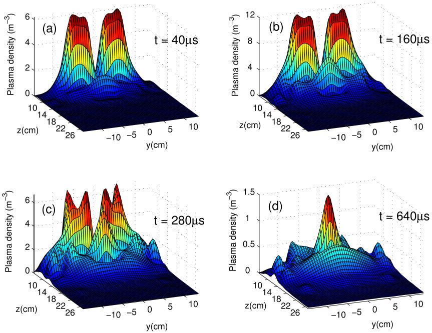
From Sigurjonsson et al. (2009) 52nd SVC, p. 234

- The exact pulse shape is determined by the load
  - the discharge formed
  - it depends on the gas type and gas pressure

  and the electronics of the power supply

High Power Impulse Magnetron Sputtering (HiPIMS) - Electrons

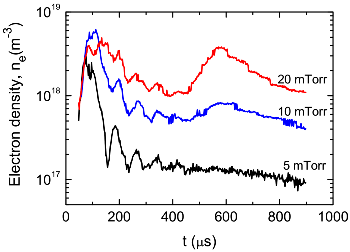
HiPIMS - Electron density



(After Bohlmark et al. (2005), IEEE Trans. Plasma Sci. **33** 346)

- Temporal and spatial variation of the electron density
- Ar discharge at 20 mTorr, Ti target, pulse length 100 μs
- The electron density in the substrate vicinity is of the order of $10^{18} - 10^{19}$ m^{-3}

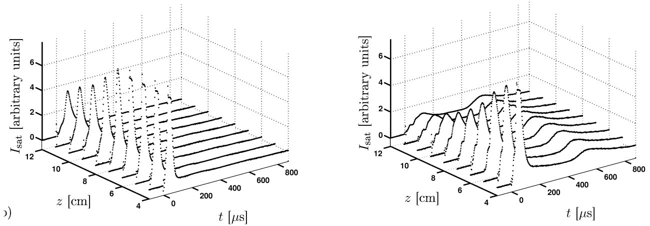
HiPIMS - Electron density



(After Gudmundsson et al. (2002), SCT **161** 249)

- The electron density versus time from the initiation of the pulse 9 cm below the target
- The pulse is 100 μs long and the average power 300 W and the target made of tantalum
- A strong initial peak appears
- A second peak appears later in time at higher pressure

HiPIMS - Plasma dynamics



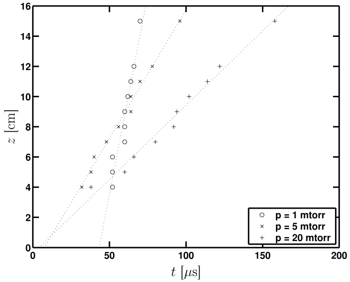
5 mTorr

20 mTorr

From Gylfason et al. (2005) JPD **38** 3417

- The electron saturation current as a function of location and time from pulse initiation
- The argon pressure was 5 mTorr and 20 mTorr, the target was made of titanium, and the pulse energy 6 J

HiPIMS - Plasma dynamics

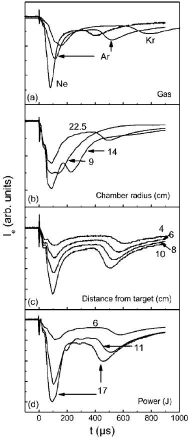


From Gylfason et al. (2005) JPD **38** 3417

- Each peak travels with a fixed velocity through the chamber
- The peaks travel with a velocity of 5.3×10^3 m/s at 1 mTorr, 1.7×10^3 m/s at 5 mTorr, and 9.8×10^2 m/s at 20 mTorr

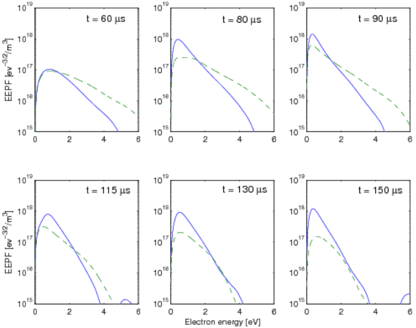
HiPIMS - Plasma dynamics

- The plasma density versus time while varying the
  - sputtering gas
  - chamber dimension
  - distance to target
  - applied power
- The first peak appears immediately after the plasma ignition
- The peaks increase with increased applied power



From Alami et al. (2005) PSST **14** 525

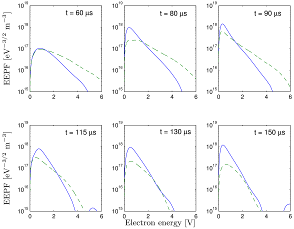
HiPIMS - Electron energy



From Gudmundsson et al. (2009) JAP **105** 123302

- The electron energy probability function (EEPF) under the race-track 100 mm below the target for an argon discharge at 3 (dashed) and 20 (solid) mTorr with a copper target

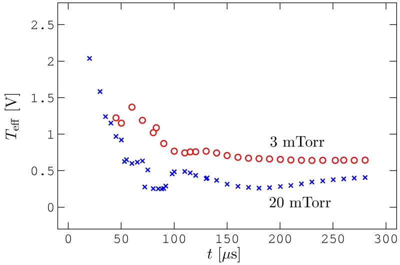
HiPIMS - Electron energy



From Gudmundsson et al. (2009) JAP **105** 123302

- The measured EEPF is Maxwellian-like during the pulse
  - high electron density leads to a Maxwellian-like low energy part of the EEPF
  - the depletion in the high energy part is due to the escape of high energy electrons to the chamber walls and inelastic collisions of high energy electrons
- The EEPF is more broad at low pressure and early in the pulse

HiPIMS - Electron energy



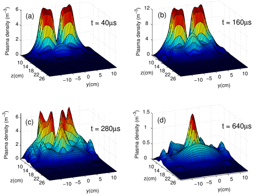
From Gudmundsson et al. (2009) JAP **105** 123302

- Temporal variation of the effective electron temperature 100 mm below the target under the race-track ($r = 40$ mm)
- The electron energy decreases with increased discharge pressure

HiPIMS - Electron density - summary

- The peak electron density is of the order of $10^{18} - 10^{19}$ m^{-3}
  Gudmundsson et al. (2001) APL **78** 3427
  Gudmundsson et al. (2002) SCT **161** 249
- A monotonic rise in plasma density
  - with discharge gas pressure
    Gudmundsson et al. (2002) SCT **161** 249
  - applied power Alami et al. (2005) PSST **14** 525
- A linear increase in electron density with increased discharge current

  Ehiasarian et al. (2008) JAP **104** 083305



After Bohlmark et al. (2005)

HiPIMS - Electrons - summary

- The electron density depends on the target material
  - Cr target gives higher density than Ti

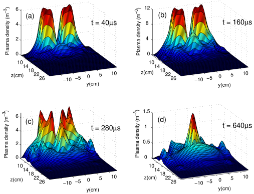
    Vetushka and Ehiasarian (2008) JPD **41** 015204

- The peak electron density travels away from the target with fixed velocity

  Gylfason et al. (2005) JPD **38** 3417

- The electron energy distribution function (EEDF) during the pulse is Maxwellian-like

  Gudmundsson et al. (2009) JAP **105** 123302

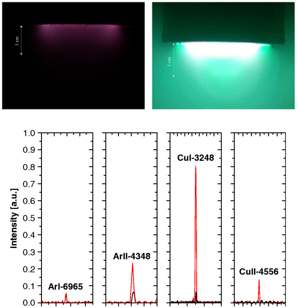


After Bohlmark et al. (2005)

High Power Impulse Magnetron Sputtering (HiPIMS) - Ions

HiPIMS - Ionization fraction

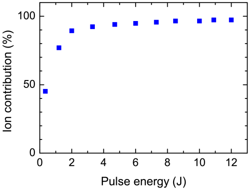
- Conventional dc magnetron discharge - Pre-ionization - violet argon discharge
- HiPIMS discharge averaged over several pulses - green discharge characteristic of Cu vapour
- The Cu^+ lines are only observed in HiPIMS mode



From Vašina et al. (2007) PSST **16** 501

HiPIMS - Ionization fraction

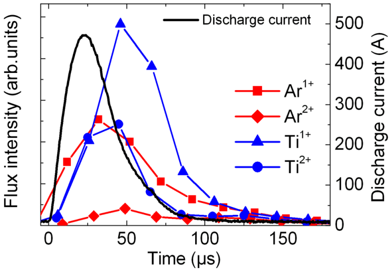
- There have been conflicting reports on the fraction of ionized metal flux
  - 70 % for Cu Kouznetsov et al. (1999) SCT **122** 290
  - 56 % for Cu Vlček et al. (2007a) JVSTA **25** 42
  - 99 % for Ti Kudláček et al. (2008) PSST **17** 025010
  - 40 % for $Ti_{0.5}Al_{0.5}$ Macák et al. (2000) JVSTA **18** 1533
  - 9.5 % for Al DeKoven et al. (2003) 46th SVC p. 158
  - 4.5 % for C DeKoven et al. (2003) 46th SVC p. 158
- The degree of ionization
  - 90 % for Ti Bohlmark et al. (2005) JVSTA **23** 18
- The fraction of ionized metal flux depends on applied power, pulse frequency and pulse length, and distance from the target



From Bohlmark et al. (2005)

HiPIMS - Ionization fraction

- The ion flux versus time measured by a mass spectrometer (20 μs windows)
- The gas pressure was 3 mTorr, pulse energy 8 J and the target made of Ti
- Highly metallic ion flux during the active phase of the discharge

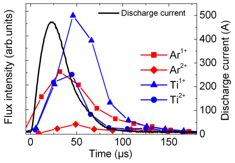


From Bohlmark et al. (2006) TSF **515** 1522

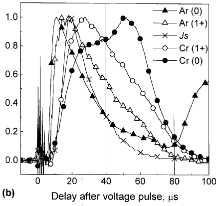
HiPIMS - Ionization fraction

- The discharge develops from an argon dominated discharge to a metal dominated discharge during the active phase of the discharge.
- This has been observed both by optical emission spectroscopy and mass spectroscopy
- Cu-ions have been measured to be up to 92 % of the total ion flux at the substrate (Vlček et al. (2007) EPL **77** 45002)
- Ti-ions are up to 29 % of the total ion flux at the same conditions

(Kudláček et al. (2008) PSST **17** 025010)



From Bohlmark et al. (2006) TSF **515** 1522



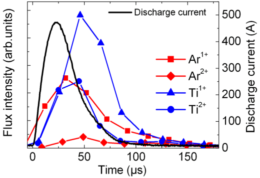
From Ehiasarian et al. (2002) Vacuum **65**

HiPIMS - Ionization fraction

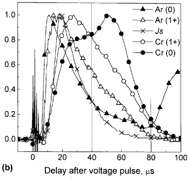
- During the initial stages of the pulse Ar^+ ions dominate the discharge
- Later in the pulse metal ions build up and become the abundant ion species
- Multiply charged ions have been observed
- Significant fraction of the ion flux is Ti^{2+}

  Bohlmark et al. (2006) TSF **515** 1522
- Ti^{4+} ions have been observed

  Andersson et al. (2008) APL **93** 071504



From Bohlmark et al. (2006) **515** 1522

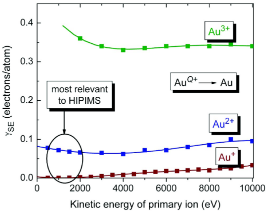


From Ehiasarian et al. (2002) Vacuum **65** 147

HiPIMS - Multiply charged ions

- Multiply charged metal ions are crucial for the transition of the discharge from argon ion sputtering to self-sputtering
- Singly charged metal ions cannot create the secondary electrons necessary to maintain metal self-sputtering (γ_{SE} is practically zero)
- The first ionization energies of many metals are insufficient to overcome the workfunction of the target material

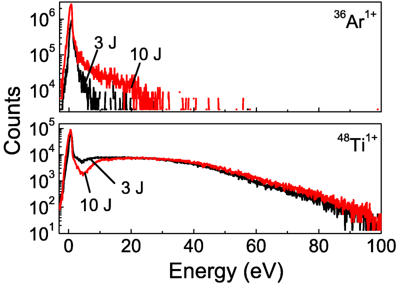
Anders et al. (2007) JAP **102** 113303, Anders (2008) APL **92** 201501



Anders (2008) APL **92** 201501

HiPIMS - Ion energy

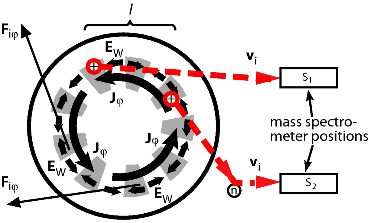
- The time averaged ion energy distribution for Ar^+ and Ti^+ ions
- The gas pressure was 3 mTorr, pulse energy 3 J and 10 J and the target made of Ti
- The ion energy distribution is broad to over 100 eV
- About 50 % of the Ti^+ ions have energy > 20 eV



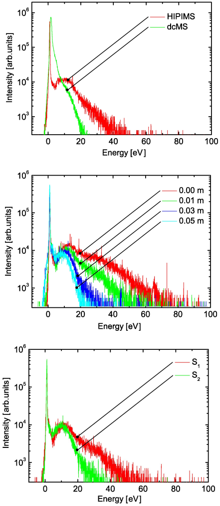
From Bohlmark et al. (2006) TSF **515** 1522

HiPIMS - Ion energy

- Significant fraction of the Ti^+ ions are transported radially outwards
- Direction dependent high energy-tail



From Lundin et al. (2008) PSST **17** 035021

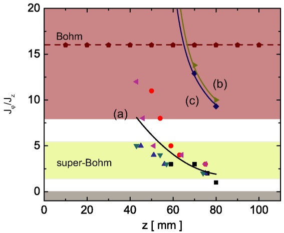


HiPIMS - Charged particle transport

- It has been observed that the electron cross-**B** transport in HiPIMS discharges is much faster than classical collision theory predicts
- The diffusion coefficient is roughly a factor 5 greater than what Bohm diffusion would predict

Brenning et al. (2009) PRL **103** 225003

Lundin et al. (2011) PSST **20** 045003



From Lundin et al. (2011) PSST **20** 045003

HiPIMS - Ionization fraction

- Gasless self-sputtering of copper has been demonstrated

  Andersson and Anders (2009) PRL **102** 045003

- This self-sputtering in vacuum can deliver extraordinarily high metal-ion current
- The usable ion current increased exponentially with increasing discharge voltage

PRL **102,** 045003 (2009) PHYSICAL REVIEW LETTERS week ending 30 JANUARY 2009

Self-Sputtering Far above the Runaway Threshold: An Extraordinary Metal-Ion Generator

Joakim Andersson and André Anders

Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, California 94720, USA

(Received 12 September 2008; published 27 January 2009)

When self-sputtering is driven far above the runaway threshold voltage, energetic electrons are made available to produce "excess plasma" far from the magnetron target. Ionization balance considerations show that the secondary electrons deliver the necessary energy to the "remote" zone. Thereby, such a system can be an extraordinarily prolific generator of usable metal ions. Contrary to other known sources, the ion current to a substrate can exceed the discharge current. For gasless self-sputtering of copper, the usable ion current scales exponentially with the discharge voltage.

DOI: 10.1103/PhysRevLett.102.045003 PACS numbers: 52.80.Vp, 52.25.Jm, 52.40.Hf, 81.15.Cd

Large fluxes of ions are of interest to a number of plasma-based technologies such as self-ion assisted deposition of films and high-current and large-area ion sources. The generation of large ion fluxes is a challenging task because plasma systems tend to produce just as many ions as necessary to maintain the discharge. Hence, only a small fraction of the generated ions can be utilized for processing. Among the most prolific generators of ions are cathodic arc discharges, where the available ion current is generally quantified by normalizing it to the discharge current; the ratio is typically about 0.1 [1]. In this contribution we will demonstrate that high-power impulse magnetron sputtering (HIPIMS) can be an extremely prolific generator of metal ions that, under certain conditions, can deliver ion currents that even exceed the discharge current. We will show that this very high level is consistent with common particle and energy balance considerations.

HIPIMS was developed with the goal to at least partially ionize the sputtered atoms and thereby to provide a means for self-ion assisted deposition of thin films [2–5]. In HIPIMS, and depending on several parameters such as power density, target material, and gas pressure, the magnetron discharge plasma contains a large fraction of ionized sputtered material, and therefore HIPIMS processes are closely related to self-sputtering. Self-sputtering is an intriguing subject of research since the early reports by Hosokawa and co-workers [6,7] because, after initiating the magnetron in a gas atmosphere at high-power density, self-sputtering can sustain itself for a few target materials under certain conditions [8,9].

The *current-voltage-time* characteristics of HIPIMS discharges in background gas [10,11] show that for sufficiently long pulses (typically $>100\ \mu s$) at constant voltage, the current may go through a maximum and then settle at an equilibrium value. The current reduction after the initial peak is due to gas rarefaction. However, if the power density is high, the current evolution may look completely different in that, at a well-defined voltage threshold, the current does not reduce but jumps to a new, much higher value. This is the threshold of sustained self-sputtering [7]. At the threshold, self-sputtering amplifies itself and the self-sputtering parameter exceeds unity, $\Pi = \alpha\beta\gamma_{SS} > 1$, where α is the probability that a sputtered atom is ionized, β is the probability that the newly formed ion returns to the target, and γ_{SS} is the self-sputtering yield. All three quantities are time dependent but the system evolves towards a new steady state, with $\Pi = 1$, provided the power supply can supply the necessary current at constant voltage.

Copper is a preferred material for studying sustained self-sputtering because the sustained situation, $\Pi = 1$, can be obtained at manageable, relative low power densities (e.g., $\sim 1\ kW/cm^2$ averaged over the target area). Recently, it was shown that copper allows gasless (high vacuum) self-sputtering to occur when the magnetron discharge pulses are "kickstarted" via short vacuum-arc plasma pulses [12]. We will focus here on "gasless" sputtering because it avoids the modeling complications associated with plasmas containing both gas and metal species.

The current to a negatively biased ion collector, i.e., large probe operating in the ion saturation current, is given by the area integral over the current density $I_i = \int j_i dA$, with the Bohm current [13]

$$j_i = 0.61 n_{i0} \bar{Q} e \left(\frac{kT_{e0}}{m_i}\right)^{1/2}, \tag{1}$$

where n_{i0} is the ion density at the edge of the sheath (index "0") of the collector, $\bar{Q}$ is the mean ion charge state number, e is the elementary charge, $(kT_{e0}/m_i)^{1/2}$ is the local ion sound velocity which depends on the electron temperature, T_{e0}, and the ion mass; k is the Boltzmann constant. In the derivation of (1), the magnetic field was neglected, and it is assumed that the collector is flat, i.e., that the sheath is much thinner than the collectors curvature. There are ample descriptions of refinement in the literature [14,15] but this approximation will suffice to discuss the physics.

To determine the ion density in (1), we should consider the ion balance equation at the collector's sheath edge (omitting the index 0 for simplicity)

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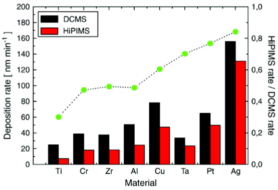
High Power Impulse Magnetron Sputtering (HiPIMS) - Deposition rate

HiPIMS - Deposition rate

- Several groups report on a significantly lower deposition rate for HiPIMS as compared to dcMS
  - a factor of 2 lower deposition rate for Cu and Ti thin films

    (Bugaev et al., 1996) XVIIth Symp. Disc. Elec. Ins. Vac., p. 1074
  - a factor of 3 – 7 lower deposition rate for reactive sputtering of TiO_2 from a Ti target and AlO_x from an Al target

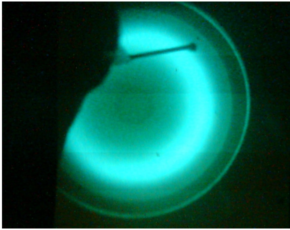
    Davis et al. (2004) 47th SVC, p. 215, Sproul et al. (2004) 47th SVC, p. 96
  - the reduction in deposition rate decreases with decreased magnetic confinement (weaker magnetic field) Bugaev et al. (1996)
  - a detailed study of various target materials confirms a consistently lower deposition rate Samuelsson et al. (2010) SCT **202** 591



From Samuelsson et al. (2010)

HiPIMS - Deposition rate

- One explanation is that the sputtered material is ionized close to the target and many of the metallic ions will be attracted back to the target surface by the cathode potential
  - A reduction in the deposition rate would occur mainly for metals with a low self-sputtering yield
- The deposition rate in the self sputtering mode is lower than when argon sputtering is dominating



Horwat and Anders (2008) JPD **41** 135210

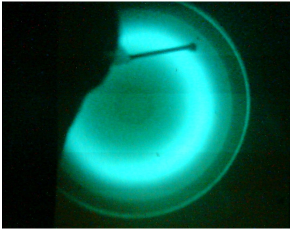
HiPIMS - Deposition rate

- It has been claimed that the magnetic confinement influences the deposition rate

  Bohlmark et al. (2006) TSF **515** 1928, Bugaev et al. (1996)
- A significant fraction of the ions of the sputtered material are transported sideways

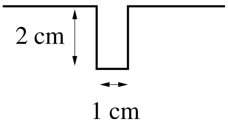
  Lundin et al. (2008) PSST **17** 035021
- Also when comparing dcMS and HiPIMS discharges at the same average power the non-linear scaling of the sputter yield with the applied voltage is not taken into account

  Emmerlich et al. (2008) Vacuum **82** 867
- The reduced deposition rate observed in the HiPIMS discharge is likely to be a combination of these factors



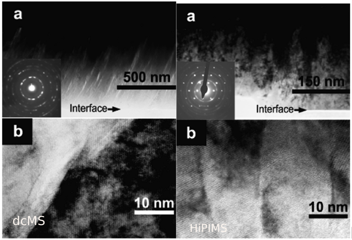
High Power Impulse Magnetron Sputtering (HiPIMS) - Applications

Application - Trench filling



- Ta thin films grown on Si substrates placed along a wall of a 2 cm deep and 1 cm wide trench
  - conventional dc magnetron sputtering (dcMS)
  - high power impulse magnetron sputtering (HiPIMS)
- Average power is the same 440 W
- Substrate bias of - 50 V
- They were compared by scanning electron microscope (SEM), transmission electron microscope (TEM)

Application - Trench filling



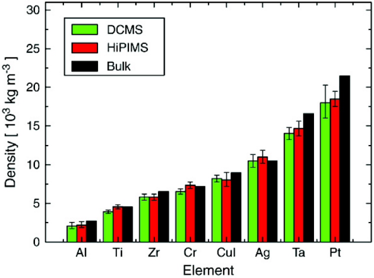
From Alami et al. (2005) JVSTA **23** 278

dc magnetron HiPIMS

- dcMS grown films exhibit rough surface, pores between grains and inclined columnar structure, leaning toward the aperture
- Ta films grown by HiPIMS have smooth surface, and dense crystalline structure with grains perpendicular to the substrate

Other applications

- The HiPIMS gives consistently denser films
- This illustrates how the bombarding ions transfer momentum to the surface allowing the microstructure to be modified



From Samuelsson et al. (2010) SCT **202** 591

HiPIMS - Applications

- HiPIMS has already been demonstrated on an industrial scale

  (Ehiasarian et al., 2006) 49th SVC, p. 349

- Due to the absence of a secondary discharge in the reactor an industrial reactor can be upgraded to become IPVD device by changing the power supply

Summary

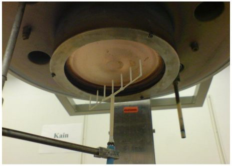
Summary

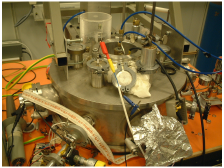
- The design parameters for Ionized Physical Vapor Deposition (IPVD) were discussed
- The high power impulse magnetron sputtering discharge (HIPIMS) has been demonstrated as an Ionized Physical Vapor Deposition (IPVD) tool
- Power supply
  - Essentially the same sputtering apparatus except for the power supply
- Electron density
  - Roughly 2 orders of magnitude higher in the substrate vicinity than for a conventional dc magnetron sputtering discharge

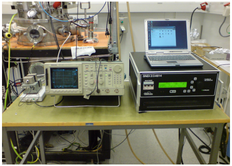
Summary

- Ionization fraction
  - Ionization fraction is high, mainly due to the high electron density
  - The ions on the inert gas and the ions of the sputtered vapor are separated in time
- Deposition rate
  - Deposition rate is lower than in a conventional dc magnetron sputtering discharge, maybe due to self sputtering

Acknowlegdements







http://www.raunvis.hi.is/~tumi/hipims.html

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