High Power Impulse Magnetron Sputtering (HiPIMS)

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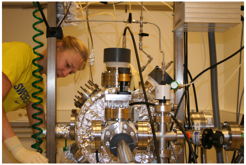
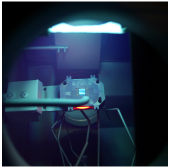
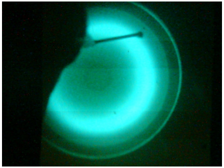
Introduction



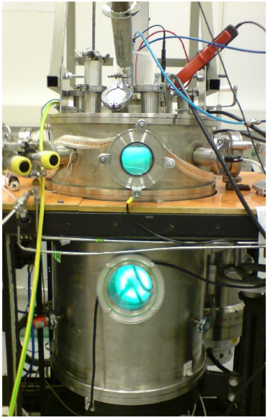




- Magnetron sputtering has been the workhorse of plasma based sputtering methods for over three decades
- For many applications a high degree of ionization of the sputtered vapor is desired
  - controlled ion bombardment of the growing film – controlled by a negative bias applied to the substrate
  -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

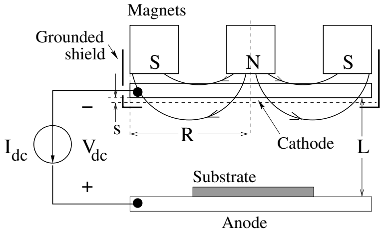
Outline

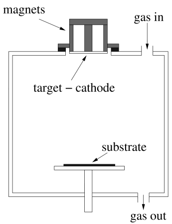
- Magnetron Sputtering Discharge
- Ionized Physical Vapor Deposition (IPVD)
- High power impulse magnetron sputtering discharge (HiPIMS)
    - Power supply
    - Voltage - Current - time
    - Electrons
    - Ions
    - Deposition rate
    - Applications
- Summary



Planar Magnetron Sputtering Discharge

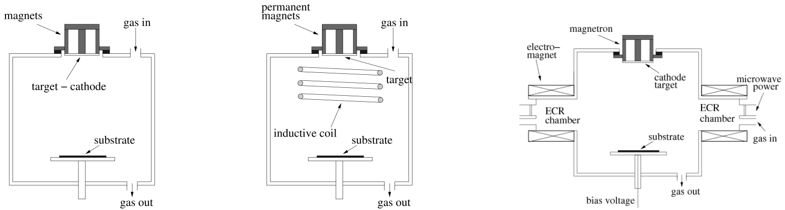
Planar Magnetron Sputtering Discharge





- 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



From Gudmundsson (2008), J. Phys.: Conf. Ser. **100** 082002

- 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 $\Gamma_{\mathrm{i}} > \Gamma_{\mathrm{m}}$ 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 (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)

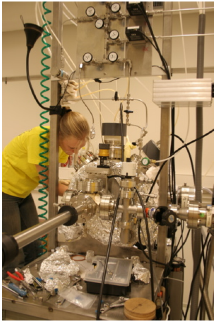
Ionized Physical Vapor Deposition (IPVD)

- 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

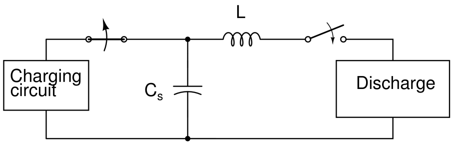
High Power Impulse Magnetron Sputtering (HiPIMS)

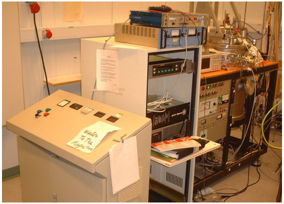
High Power Impulse Magnetron Sputtering (HiPIMS)

- 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 high power pulsed magnetron sputtering discharge uses the same sputtering apparatus except the power supply



HiPIMS - Power supply

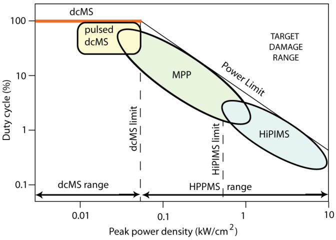




- The high power pulsed discharge operates with a
  - Cathode voltage in the range of 500 – 2000 V
  - Current densities of 3 – 4 A/cm^2
  - Power densities in the range of 0.5 – 3 kW/cm^2
  - Average power 200 – 600 W
  - Frequency in the range of 50 – 5000 Hz
  - Duty cycle in the range of 0.5 – 5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

HiPIMS - Power supply

- High power pulsed magnetron sputtering (HPPMS)
- HiPIMS
  - a pulse of very high amplitude, an impulse, is applied to the cathode and a long pause exists between the pulses
- Modulated pulse power (MPP)
  - the initial stages of the pulse (few hundred μs) the power level is moderate (typical for a dcMS) followed by a high power pulse (few hundred μs up to a ms)



From Gudmundsson et al. (2012), JVSTA **30** 030801

- Power density limits
  $p_t = 0.05$ kW/cm^2 dcMS limit
  $p_t = 0.5$ kW/cm^2 HiPIMS limit

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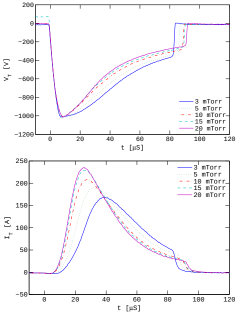
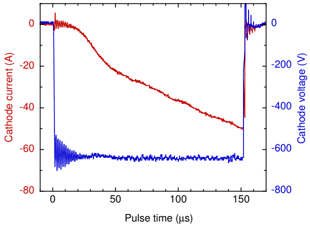
HiPIMS - Power supply





From Magnus et al. (2011a), TSF **520** 1621

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

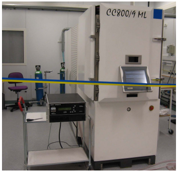
and the electronics of the power supply

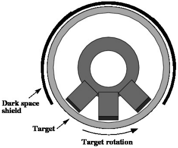
HiPIMS - Power supply

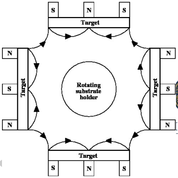
- HiPIMS has already been demonstrated on an industrial scale

  (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
- This may include both rotating magnetron sputtering discharge and unbalanced multimagnetron sputtering systems referred to as closed field unbalanced multimagnetron systems (CFUBMS)



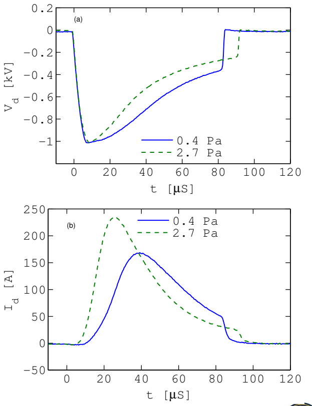




High Power Impulse Magnetron Sputtering (HiPIMS) - Voltage - Current - Time characteristics

HiPIMS - Voltage - Current - time

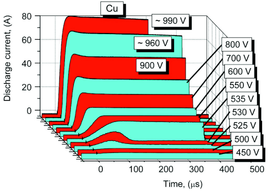
- To describe the discharge current-voltage characteristics the current-voltage-time space is required
- The early work on HiPIMS used 50 – 100 μs pulses
- The cathode voltage and the discharge current depend on the discharge gas pressure

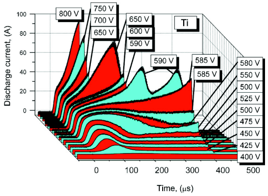


From Gudmundsson et al. (2012), JVSTA **30** 030801

HiPIMS - Voltage - Current - time

- For longer pulses the initial pressure dependent current peak is followed by a second phase that is power and material dependent
- The initial phase is dominated by gas ions, whereas the later phase has a strong contribution from self-sputtering
- For some materials, the discharge switches into a mode of sustained self-sputtering



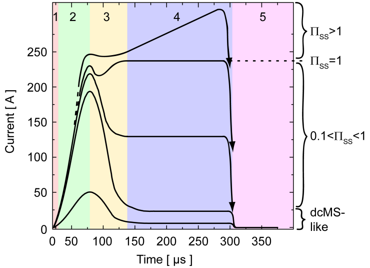


From Anders et al. (2007, 2008),

JAP **102** 113303 and JAP **103** 039901

HiPIMS - Voltage - Current - time

- A schematic illustration of the discharge current assuming square shaped voltage pulses
- The current is generally characterized by an initial peak followed by a more or less stable current plateau (bottom current curves)
- In other cases it shows an initial peak followed by a second increase of the discharge current (top current curves)



From Gudmundsson et al. (2012), JVSTA **30** 030801

HiPIMS - Voltage - Current - time

- The self-sputtering can operate in a self-sustained mode, when the ions of the sputtered vapor are created at high enough rate that the ions of the working gas are not needed
- The condition for sustained self-sputtering is expressed as

$$\Pi_{\mathrm{ss}} = \alpha \beta_{\mathrm{t}} Y_{\mathrm{ss}} = 1$$

  where
  - α is the probability of ionization of the sputtered atom
  - β_{t} in the probability that the newly formed ion of the sputtered vapor returns to the target
  - Y_{ss} is the self-sputter yield of the ion
- This is a steady state situation and the current remains constant

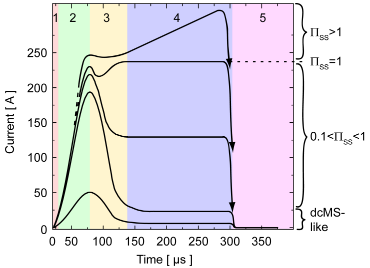
HiPIMS - Voltage - Current - time

- Note that since $\alpha < 1$ and $\beta_t < 1$ the condition $Y_{ss} > 1$ is necessary but not sufficient for achieving sustained self-sputtering
- The transient phase of self-sputtering runaway occurs when $\Pi_{ss} > 1$
- Self-sputtering runaway occurs at a well-defined threshold power, determined by the discharge voltage and is readily obtained for high sputter yield materials
- But runaway can also occur at lower threshold voltages than for pure self-sputtering as well as for ransition metals and target materials of low sputter yield due to what is referred to as 'gas recycling' runaway

Anders (2011), SCT **205** S1, Anders et al. (2012) JPD **45** 012003

HiPIMS - Voltage - Current - time

- The bottom curve represents a range of low self-sputtering, $\Pi_{ss} < 0.1$ and the discharge physics in the plateau/runaway phase is dcMS-like
- The middle range of power densities, with $0.1 < \Pi_{ss} < 1$, represents partially self-sputtering discharge
- The top curve represents self-sputtering runaway which requires $\Pi_{ss} > 1$ and a self-sputter yield $Y_{ss} > 1/(\alpha\beta_t) > 1$



From Gudmundsson et al. (2012), JVSTA **30** 030801

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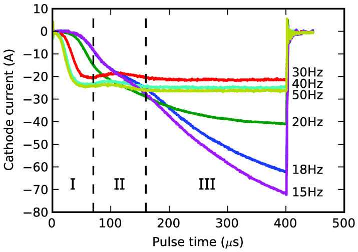
HiPIMS - Voltage - Current - time

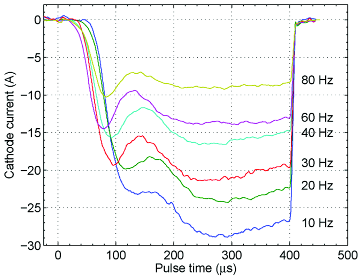
- During reactive sputtering, a reactive gas is added to the inert working gas
- This changes the plasma composition by adding new ion species, and the target condition can also change due to the formation of a compound on its surface
- The current waveform of Ar/O_2 discharge is highly dependent on the repetition frequency and applied voltage which is linked to oxide formation on the target



From Magnus et al. (2012), JVSTA submitted

HiPIMS - Voltage - Current - time

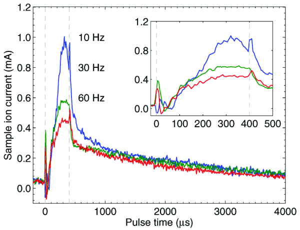
- Similarly the current waveform in the reactive Ar/N_2 HiPIMS discharge is highly dependent on the pulse repetition frequency, unlike for pure Ar
- The current is found to increase significantly as the frequency is lowered
- This is attributed to an increase in the secondary electron emission yield during the self-sputtering phase, when the nitride forms on the target at low frequencies



From Magnus et al. (2011b) JAP **110** 083306

HiPIMS - Voltage - Current - time

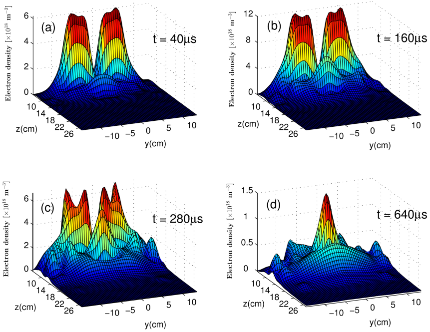
- At high frequencies, a nitride is not able to form between pulses, and self-sputtering by Ti^+-ions (singly and multiply charged) from a Ti target is the dominant process
- At low frequency, the long off-time result in a nitride layer being formed on the target surface and self-sputtering by Ti^+- and N^+-ions from TiN takes place
- The observed changes in the discharge current are reflected in the flux of ions impinging on the substrate



From Magnus et al. (2011b), JAP **110** 083306

High Power Impulse Magnetron Sputtering (HiPIMS) - Electrons

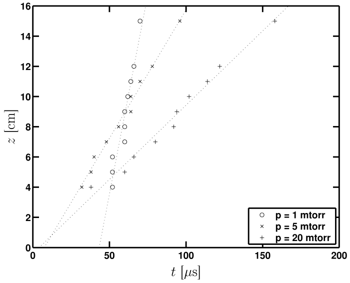
HiPIMS - Electron density



(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}

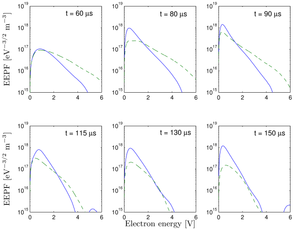
HiPIMS - Electron density



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

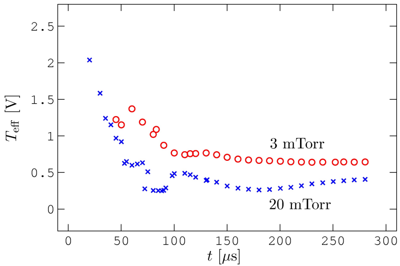
HiPIMS - Electron energy



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

- The measured EEPF is Maxwellian-like during the pulse at 3 (dashed) and 20 (solid) mTorr with a copper target
  - 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

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

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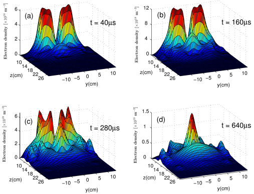
HiPIMS - Electron density - summary

- 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)

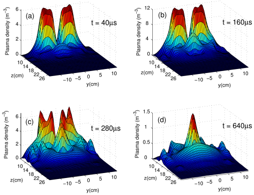
HiPIMS - Electrons - summary

- 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)

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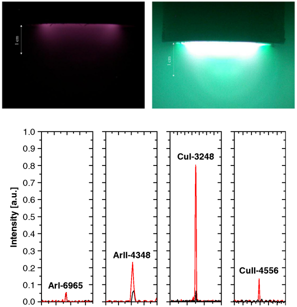
High Power Impulse Magnetron Sputtering (HiPIMS) - Ions

HiPIMS - Ionization fraction

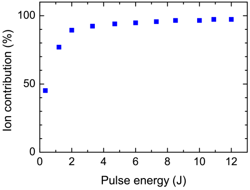
- Conventional dc magnetron discharge - Pre-ionization - violet argon discharge
- HiPIMS discharge averaged over several pulses - green discharge characteristic of Cu vapor
- The Cu^{+} lines are only observed in HiPIMS mode



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

HiPIMS - Ionization fraction

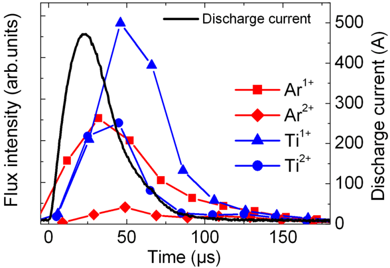
- There have been conflicting reports on the fraction of ionized metal flux
  - 70 % for Cu Kouznetsov et al. (1999) SCT **122** 290
  - 56 % for Cu Vlček et al. (2007a) JVSTA **25** 42
  - 99 % for Ti Kudláček et al. (2008) PSST **17** 025010
  - 40 % for $Ti_{0.5}Al_{0.5}$ Macák et al. (2000) JVSTA **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



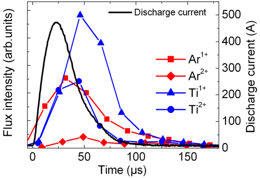
From Bohlmark et al. (2006) TSF **515** 1522

HiPIMS - Ionization fraction

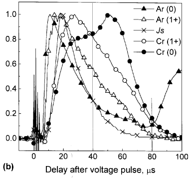
- During the initial stages of the pulse Ar^{+} ions dominate the discharge
- Later in the pulse metal ions build up and become the abundant ion species
- Multiply charged ions have been observed
- Significant fraction of the ion flux is Ti^{2+}

  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

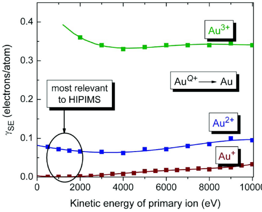


From Ehiasarian et al. (2002) Vacuum **65** 147

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

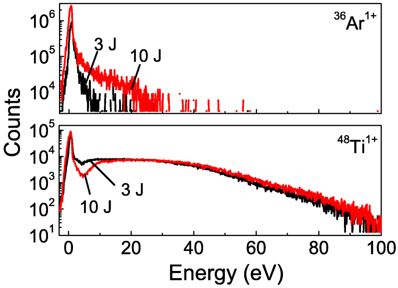
Anders et al. (2007) JAP **102** 113303, Anders (2008) APL **92** 201501



From Anders (2008) APL **92** 201501

HiPIMS - Ion energy

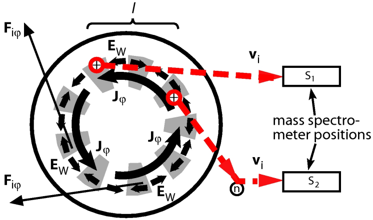
- The time averaged ion energy distribution for Ar^+ and Ti^+ ions
- The gas pressure was 3 mTorr, pulse energy 3 J and 10 J and the target made of Ti
- The ion energy distribution is broad to over 100 eV
- About 50 % of the Ti^+ ions have energy > 20 eV



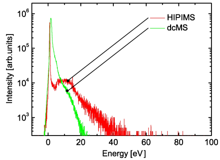
From Bohlmark et al. (2006) TSF **515** 1522

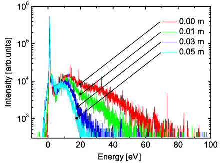
HiPIMS - Ion energy

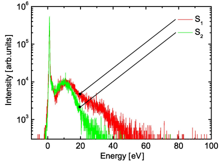
- Significant fraction of the Ti^+ ions are transported radially outwards
- Direction dependent high energy-tail



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

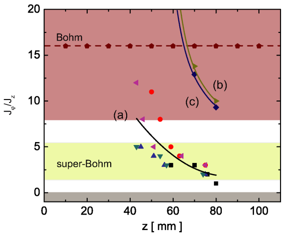






HiPIMS - Charged particle transport

- 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



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

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

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

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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)

High Power Impulse Magnetron Sputtering (HiPIMS) - Deposition rate

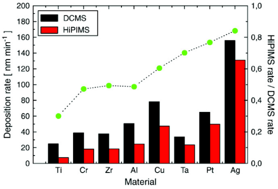
HiPIMS - Deposition rate

- 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

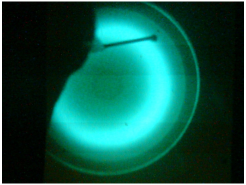
    Davis et al. (2004) 47th SVC, p. 215, Sproul et al. (2004) 47th SVC, p. 96
  - the reduction in deposition rate decreases with decreased magnetic confinement (weaker magnetic field) Bugaev et al. (1996)
  - a detailed study of various target materials confirms a consistently lower deposition rate

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



From Samuelsson et al. (2010)

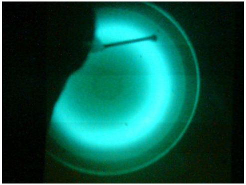
HiPIMS - Deposition rate



- 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

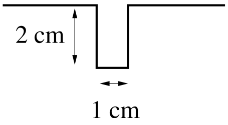
- Also when comparing dcMS and HiPIMS discharges at the same average power the non-linear scaling of the sputter yield with the applied voltage is not taken into account

  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

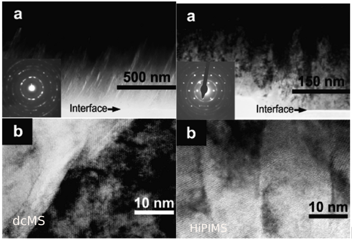
High Power Impulse Magnetron Sputtering (HiPIMS) - Applications

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



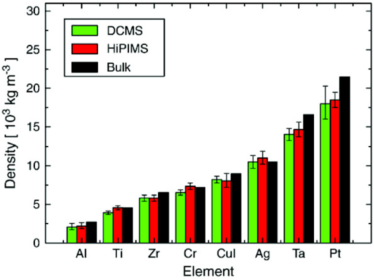
From Alami et al. (2005) JVSTA **23** 278

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

Application – Film Density

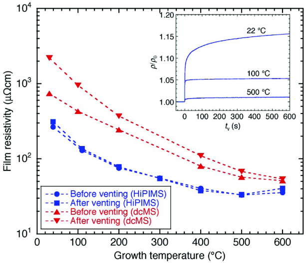
- The HiPIMS gives consistently denser films
- This illustrates how the bombarding ions transfer momentum to the surface allowing the microstructure to be modified



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

Application – Film Resistivity

- TiN as diffusion barriers in copper and aluminum interconnects
- HiPIMS deposited films have significantly lower resistivity than dcMS deposited films on SiO_2 at all growth temperatures due to reduced grain boundary scattering
- Thus, ultrathin continuous TiN films with superior electrical characteristics can be obtained with HiPIMS at reduced temperatures



From Magnus et al. (2012) IEEE EDL accepted

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
- Film quality
  - Films deposited by HiPIMS are denser, more resistant to oxidation, smoother surfaces etc. – higher quality films are achieved at lower depostion temperature than by dcMS

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  - Dr. Johan Bohlmark (Linköping University, Sweden now Sandvik A.B. Sweden)
  - Dr. Sveinn Olafsson (University of Iceland)
  - Prof. Ulf Helmersson (Linköping University, Sweden)
  - Prof. Nils Brenning (KTH Stockholm)
  - Dr. Friðrik Magnus (University of Iceland, now Uppsala University, Sweden)
  - Dr. Daniel Lundin (Linköping University, Sweden)
  - Petter Larsson (Linköping University, Sweden)
  - Mattias Samuelsson (Linköping University, Sweden)
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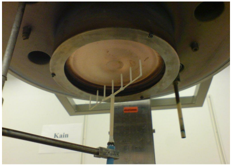 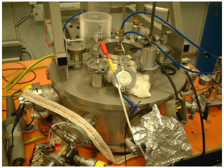 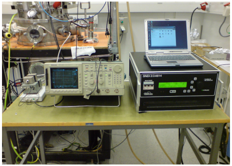

http://langmuir.raunvis.hi.is/∼tumi/hipims.html

- J. T. Gudmundsson, N. Brenning, D. Lundin and U. Helmersson, High power impulse magnetron sputtering discharge, Journal of Vacuum Science and Technology A, **30**(3) (2012) 030801

- The photographs were taken by Árni S. Ingason, Páll Sigurjónsson, Kristinn B. Gylfason and Markus Baur.

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