On the Plasma Parameters in the High Power Impulse Magnetron Sputtering (HiPIMS) Discharge

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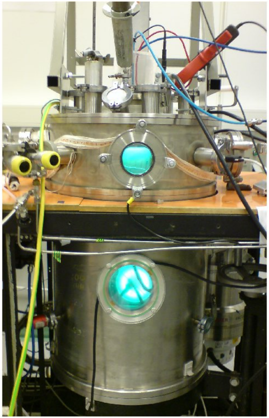
Introduction

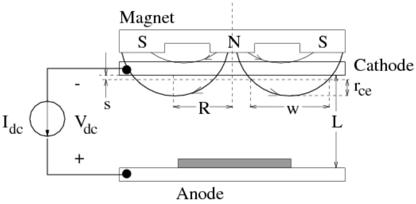
- The demand for new materials and layer structures has lead to development of more advanced sputtering systems
- One such sputtering system is the
  - high power pulsed magnetron sputtering discharge (HPPMS)
  - high power impulse magnetron sputtering discharge (HiPIMS)
- It gives high electron density and highly ionized flux of the sputtered material
- The plasma parameters in the HiPIMS discharge will be reviewed

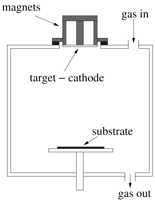
Introduction

- 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



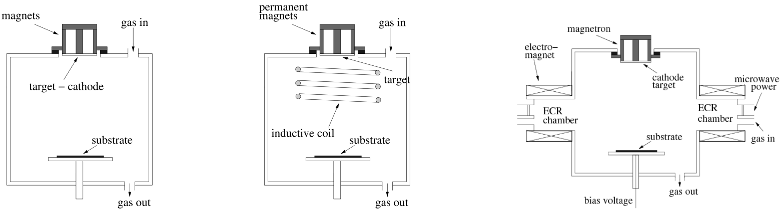
Planar Magnetron Sputtering Discharge





- 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
  - electron density in the substrate vicinity is $10^{15} - 10^{16}$ 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)

- 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
- Ionizing the sputtered vapor has several advantages:
  - improvement of the film quality
  - control of the reactivity
  - deposition on substrates with complex shapes and high aspect ratio

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

$$\lambda_{iz} = \frac{v_s}{k_{iz} n_e}$$

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

v_s [eV]	T_e [eV]	n_e [m^{-3}]	λ_{iz} [cm]
1.5	3	1×10^{17}	333
0.05	3	1×10^{17}	61
0.05	3	1×10^{18}	6.1
0.05	3	1×10^{19}	0.61

Ionized Physical Vapor Deposition (IPVD)

- Another important parameter is the fractional ionization of the metal flux

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

- The ion flux to the substrate is

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

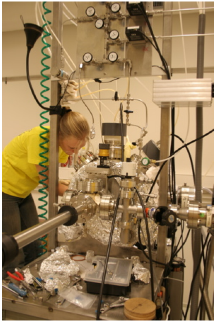
- The flux of thermalized neutrals is

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

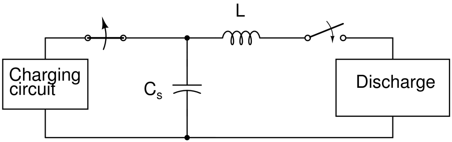
- Since $T_{\rm e} \gg T_{\rm g}$ the fractional ionization of the metal flux is larger than the fraction of ionized metal in the plasma
- It is not necessary to completely ionize the sputtered metal to create a highly ionized flux to the substrate

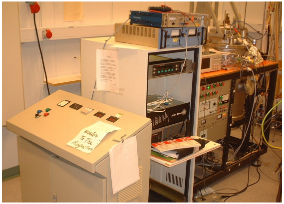
High Power Impulse Magnetron Sputtering (HiPIMS)

- 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



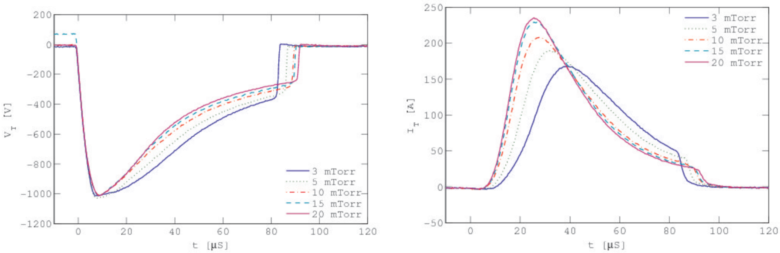
HiPIMS - Power supply





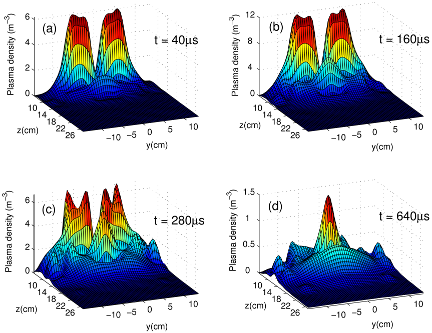
- The high power pulsed discharge operates with a
  - Cathode voltage in the range of 500 – 2000 V
  - Current densities of 3 – 4 A/cm^2
  - Power densities in the range of 1 – 3 kW/cm^2
  - Average power 200 – 600 W
  - Frequency in the range of 50 – 1000 Hz
  - Duty cycle in the range of 0.5 – 5 %

HiPIMS - Power supply



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

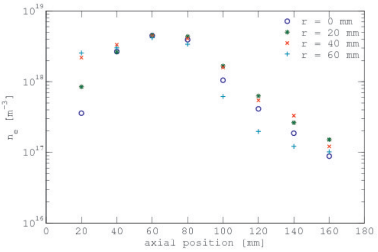
HiPIMS - Electron density



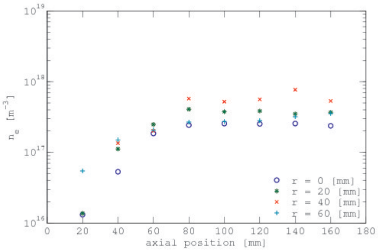
(After Bohlmark et al. (2005) and Guðmundsson et al. (2006))

- Temporal and spatial variation of the electron density
- Argon discharge at 20 mTorr with a titanium target
- The electron density in the substrate vicinity is of the order of $10^{18} - 10^{19}$ m^{-3}

HiPIMS - Electron density



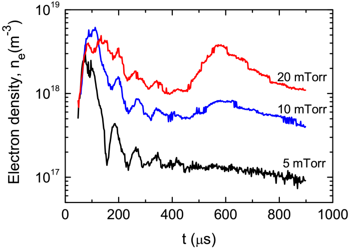
65 μs



230 μs

- The spatial variation of the electron density at 65 μs and 230 μs from the initiation for gas pressure of 10 mTorr.
- The pulse is 90 μs long and the average power 270 W and the target made of copper
- The electron density is uniform along the radius of the discharge

HiPIMS - Electron density

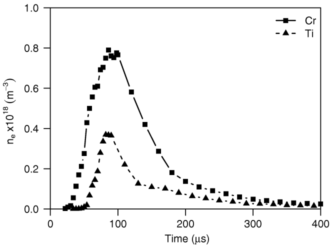


(After Gudmundsson et al. (2002))

- 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

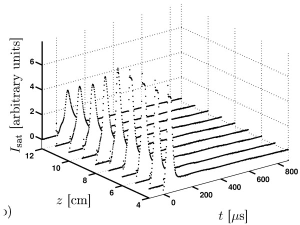
HiPIMS - Electron density

- The electron density depends on the target material
  - Cr target gives higher density than Ti
  - higher $[Cr^{+}]/[Ar^{+}]$ than $[Ti^{+}]/[Ar^{+}]$ ratio
- The ionization of metal atoms plays an important role in the creation of electrons

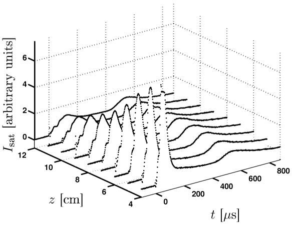


(From Vetushka and Ehiasarian (2008))

HiPIMS - Plasma dynamics



5 mTorr

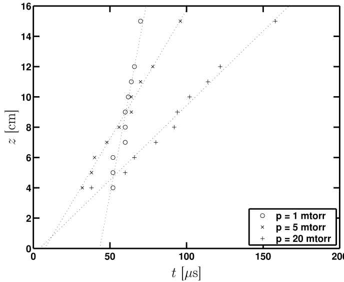


20 mTorr

(From Gylfason et al. (2005))

- 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
- A monotonic rise in plasma density with discharge gas pressure and applied power is generally observed

HiPIMS - Plasma dynamics

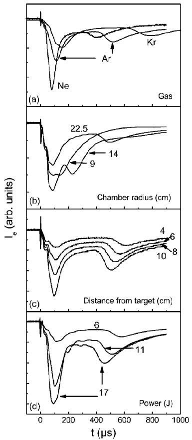


(From Gylfason et al. (2005))

- 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

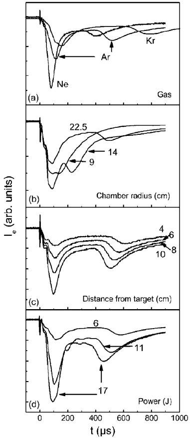


(From Alami et al. (2005))

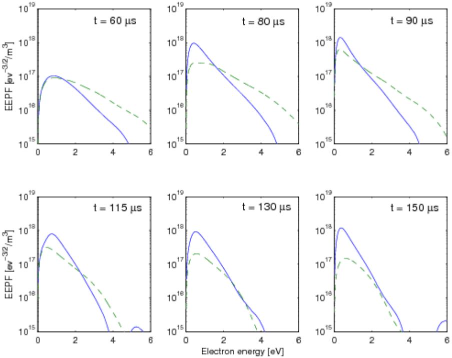
HiPIMS - Plasma dynamics

- The second peak appears only for pressures above 5 mTorr
- The lighter the gas atom the earlier the peaks appear
- Decreased chamber radius results in earlier appearance of the second peak
    - we propose that the charged particles travel as sound waves
    - the second peak is a reflection from the walls

(From Alami et al. (2005))

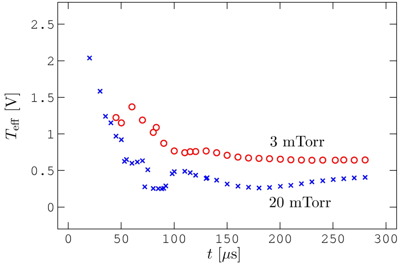


HiPIMS - Electron energy



- 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
- The EEPF is more broad at low pressure and early in the pulse

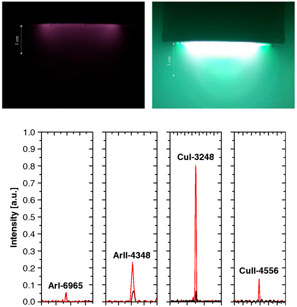
HiPIMS - Electron energy



- 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 - Ionization fraction

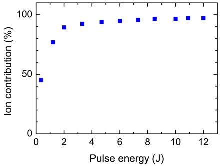
- Conventional dc magnetron discharge - Pre-ionization - violet argon discharge
- HiPIMS discharge averaged over several pulses - green discharge characteristic of Cu vapour
- The Cu^+ lines are only observed in HiPIMS mode



(From Vašina et al. (2007))

HiPIMS - Ionization fraction

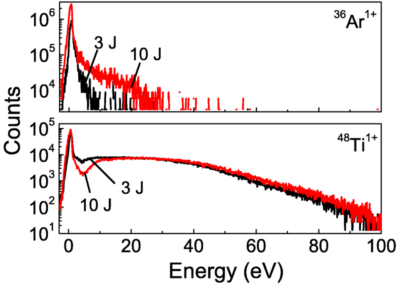
- There have been conflicting reports on the ionized flux fraction
  - 70 % for Cu (Kouznetsov et al., 1999)
  - 92 % for Cu (Vlček et al., 2007)
  - 40 % for $Ti_{0.5}Al_{0.5}$ (Macák et al., 2000)
  - 9.5 % for Al (DeKoven et al., 2003)
  - 4.5 % for C (DeKoven et al., 2003)
- The degree of ionization
  - 90 % for Ti (Bohlmark et al., 2005)
- The ionization flux fraction depends on applied power, pulse frequency and pulse length



(From Bohlmark et al. (2005))

HiPIMS - Ion energy

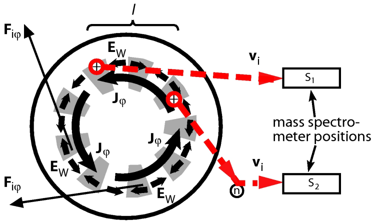
- The time averaged ion energy distribution for Ar^+ and Ti^+ ions
- The gas pressure was 3 mTorr, pulse energy 3 J and 10 J and the target made of Ti
- The ion energy distribution is broad to over 100 eV
- About 50 % of the Ti^+ ions have energy > 20 eV



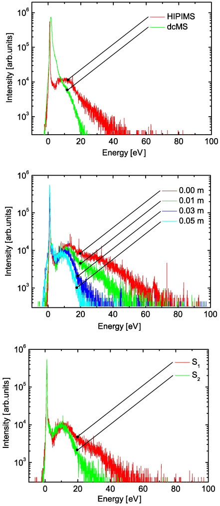
(From Bohlmark et al. (2006))

HiPIMS - Ion energy

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

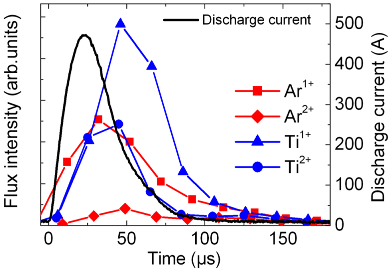


(From Lundin et al. (2008))



HiPIMS - Ionization fraction

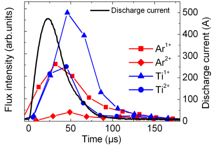
- The ion flux versus time measured by a mass spectrometer (20 μs windows)
- The gas pressure was 3 mTorr, pulse energy 8 J and the target made of Ti
- Highly metallic ion flux during the active phase of the discharge



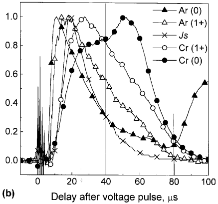
(From Bohlmark et al. (2006))

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)
- Ti^{4+} ions have been observed (Andersson et al., 2008)



From Bohlmark et al. (2006)



From Ehiasarian et al. (2002)

HiPIMS - Ionization fraction

- Gasless self-sputtering of copper has been demonstrated

  (Andersson and Anders, 2009)

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

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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]

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

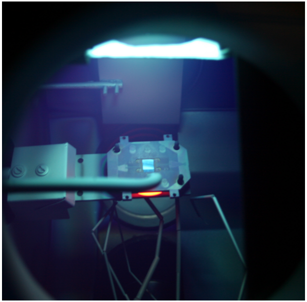
where n_{i0} is the ion density at the edge of the sheath (index "0") of the collector, $\bar{Q}$ is the mean ion charge state number, e is the elementary charge, $(kT_{e0}/m_i)^{1/2}$ is the local ion sound velocity which depends on the electron temperature, T_{e0}, and the ion mass; k is the Boltzmann 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)

HiPIMS - Deposition rate

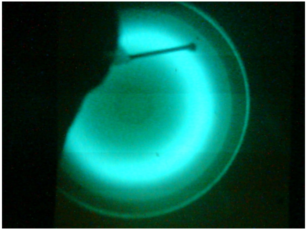
- Several groups report on a significantly lower deposition rate for HiPIMS as compared to dcMS
  - a factor of 2 lower deposition rate for Cu and Ti thin films (Bugaev et al., 1996)
  - a factor of 4 – 7 lower deposition rate for reactive sputtering of TiO_2 from a Ti target (Davis et al., 2004)
  - a factor of 3 – 4 lower deposition rate for reactive sputtering of AlO_x from an Al target (Sproul et al., 2004)
  - the reduction in deposition rate decreases with decreased magnetic confinement (weaker magnetic field)

    (Bugaev et al., 1996)

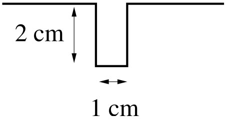


HiPIMS - Deposition rate

- 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
- A significant fraction of the ions of the sputtered material are transported sideways
- Maybe this can be reduced by optimized magnetic confinement

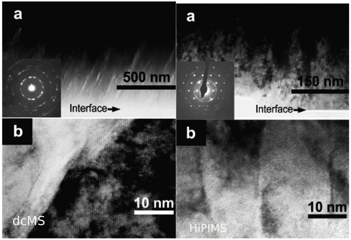


Application - Trench filling



- 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
- They were compared by scanning electron microscope (SEM), transmission electron microscope (TEM)

Application - Trench filling



(From Alami et al. (2005))

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

HiPIMS - Applications

- HiPIMS has already been demonstrated on an industrial scale

  (Ehiasarian et al., 2006)

- 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

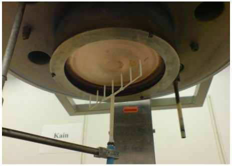
- We reviewed the measured plasma parameters of the high power impulse magnetron sputtering discharge (HIPIMS)

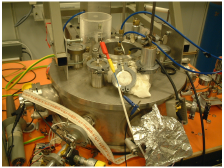
- Power supply
  - Essentially the same sputtering apparatus except for the power supply
- Electron density
  - Roughly 2 orders of magnitude higher in the substrate vicinity than for a conventional dc magnetron sputtering discharge
- Plasma dynamics
  - The peak electron density travels away from the target with fixed velocity

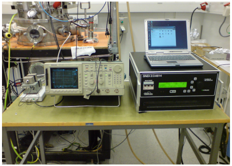
Summary

- 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







Can be downloaded at

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

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References

Alami, J., J. T. Gudmundsson, J. Bohlmark, J. Birch, and U. Helmersson (2005). Plasma dynamics in a highly ionized pulsed magnetron discharge. *Plasma Sources Science and Technology 14*(3), 525–531.

Alami, J., P. O. A. Petersson, D. Music, J. T. Gudmundsson, J. Bohlmark, and U. Helmersson (2005). Ion-assisted physical vapor deposition for enhanced film deposition on non-flat surfaces. *Journal of Vacuum Science and Technology A 23*, 278–280.

Andersson, J., and A. Anders (2009). Self-Sputtering Far above the Runaway Threshold: An Extraordinary Metal-Ion Generator. *Physical Review Letters 102*(4), 045003.

Andersson, J., A. P. Ehiasarian, and A. Anders (2008). Observation of Ti^{4+} ions in a high power impulse magnetron sputtering plasma. *Applied Physics Letters 93*(7), 071504.

Bohlmark, J., J. Alami, C. Christou, A. P. Ehiasarian, and U. Helmersson (2005). Ionization of sputtered metals in high power pulsed magnetron sputtering. *Journal of Vacuum Science and Technology A 23*(1), 18–22.

Bohlmark, J., J. T. Gudmundsson, J. Alami, M. Latteman, and U. Helmersson (2005). Spatial electron density distribution in a high-power pulsed magnetron discharge. *IEEE Transactions on Plasma Science 33*(2), 346–347.

Bohlmark, J., M. Lattemann, J. T. Gudmundsson, A. P. Ehiasarian, Y. A. Gonzalvo, N. Brenning, and U. Helmersson (2006). The ion energy distributions and ion flux composition from a high power impulse magnetron sputtering discharge. *Thin Solid Films 515*(5), 1522–1526.

Bugaev, S. P., N. N. Koval, N. S. Sochugov, and A. N. Zakharov (1996, July 21-26). Investigation of a high-current pulsed magnetron discharge initiated in the low-pressure diffuse arc plasma. In *XVIIth International Symposium on Discharges and Electrical Insulation in Vacuum, 1996*, Berkeley, CA USA, pp. 1074–1076. IEEE.

Davis, J. A., W. D. Sproul, D. J. Christie, and M. Geisler (2004). High power pulse reactive sputtering of TiO_2. In *47th Annual Technical Conferenece Proceedings*, Dallas, TX, USA, pp. 215–218. Society of Vacuum Coaters.

DeKoven, B. M., P. R. Ward, R. E. Weiss, D. J. Christie, R. A. Scholl, W. D. Sproul, F. Tomasel, and A. Anders (2003). Carbon thin film deposition using high power pulsed magnetron sputtering. In *46th Annual Technical Conferenece Proceedings*, San Francisco, CA, USA, pp. 158–165. Society of Vacuum Coaters.

Ehiasarian, A. P., R. New, W.-D. Münz, L. Hultman, U. Helmersson, and V. Kouznetzov (2002). Influence of high power densities on the composition of pulsed magnetron plasmas. *Vacuum 65*, 147–154.

References

Ehiasarian, A. P., C. Reinhard, P. E. Hovsepian, and J. M. Colton (2006). Industrial-scale production of corrosion-resistant CrN/NbN coatings deposited by combined high power impulse magnetron sputtering etching unbalanced magnetron sputtering deposition (HIPIMS/UBM) process. In *49th Annual Technical Conferenece Proceedings*, Washington DC, USA, pp. 349–353. Society of Vacuum Coaters.

Gudmundsson, J. T., J. Alami, and U. Helmersson (2002). Spatial and temporal behavior of the plasma parameters in a pulsed magnetron discharge. *Surface and Coatings Technology 161*(2-3), 249–256.

Guðmundsson, J. T., J. Bohlmark, J. Alami, K. B. Gylfason, and U. Helmersson ((2005-2006)). Dreifing rafeinda í tíma og rúmi í há aflpúlsaðri segulspætu. *Tímarit um raunvísindi og stærðfræði 3*(1), 75–79.

Gylfason, K. B., J. Alami, U. Helmersson, and J. T. Gudmundsson (2005). Ion-acoustic solitary waves in a pulsed magnetron sputtering discharge. *Journal of Physics D: Applied Physics 38*(18), 3417–3421.

Kouznetsov, V., K. Macák, J. M. Schneider, U. Helmersson, and I. Petrov (1999). A novel pulsed magnetron sputter technique utilizing very high target power densities. *Surface and Coatings Technology 122*(2-3), 290–293.

Lundin, D., P. Larsson, E. Wallin, M. Lattemann, N. Brenning, and U. Helmersson (2008). Cross-field ion transport during high power impulse magnetron sputtering. *Plasma Sources Science and Technology 17*(3), 035021.

Macák, K., V. Kouznetzov, J. M. Schneider, U. Helmersson, and I. Petrov (2000). Ionized sputter deposition using an extremely high plasma density pulsed magnetron discharge. *Journal of Vacuum Science and Technology A 18*(4), 1533–1537.

Sproul, W., D. J. Christie, and D. C. Carter (2004). The reactive sputter deposition of aluminum oxide coatings using high power pulsed magnetron sputtering (hppms). In *47th Annual Technical Conferenece Proceedings*, Dallas, TX, USA, pp. 96–100. Society of Vacuum Coaters.

Vašina, P., M. Meško, J. C. Imbert, M. Ganciu, C. Boisse-Laporte, L. de Poucques, M. Touzeau, D. Pagnon, and J. Bretagne (2007). Experimental study of a pre-ionized high power pulsed magnetron discharge. *Plasma Sources Science and Technology 16*(3), 501–510.

Vetushka, A. and A. P. Ehiasarian (2008). Plasma dynamic in chromium and titanium HIPIMS discharges. *Journal of Physics D: Applied Physics 41*(1), 015204.

Vlček, J., P. Kudláček, K. Burcalová, and J. Musil (2007). Ion flux characteristics in high-power pulsed magnetron sputtering discharges. *Europhysics Letters 77*(4), 45002.