Ionization Processes in the High Power Impulse Magnetron Sputtering Discharge (HiPIMS)

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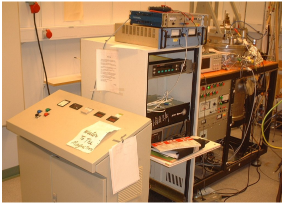
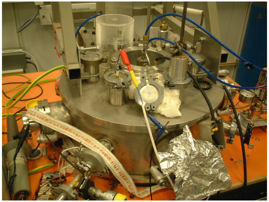
Introduction

- 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 energy of the ions can be tailored to obtain impinging particles with energies comparable to typical surface and molecular binding energies

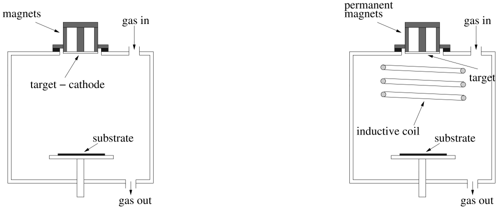
Introduction





- This work is a result of collaboration with
  - Kristinn B. Gylfason (now at Royal Institute of Technology in Stockholm)
  - Dr. Jones Alami (now at RWTH Aachen, Germany)
  - Dr. Johan Bohlmark (now at Chemfilt Ionsputtering AB)
  - Dr. Arutiun Ehiasarian (Sheffield Hallam University, UK)
  - Prof. Ulf Helmersson (Linköping University, Sweden)

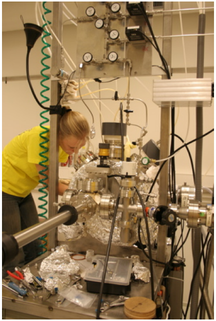
Planar Magnetron Sputtering Discharge



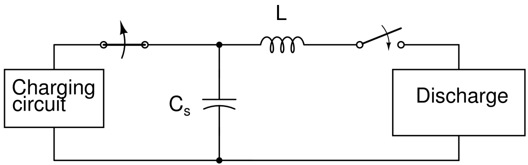
- A typical dc planar magnetron discharge operates at a pressure of 1 – 10 mTorr with a magnetic field strength of 0.01 – 0.05 T and at cathode potentials 300 – 700 V
- Electron density in the substrate vicinity is in the range $10^{15} - 10^{16}$ m^{-3}
  - low fraction of the sputtered material is ionized ($\sim$ 1 %)
  - the majority of ions are the ions of the inert gas
  - additional ionization by a secondary discharge (rf or microwave)

High Power Impulse Magnetron Sputtering (HiPIMS)

- In a conventional dc magnetron discharge the power density is limited by the thermal load on the target
- Most of the ion bombarding energy is transformed into heat at the target
- In unipolar pulsing the power supply is at low (or zero) power and then a high power pulse is supplied for a short period
- The high power pulsed magnetron sputtering discharge uses the same sputtering apparatus except the power supply

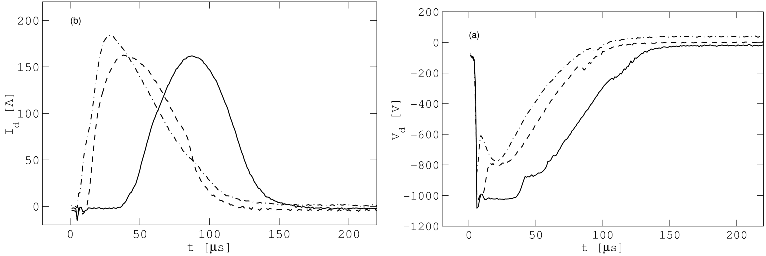


HiPIMS - Power supply



- 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
  - Frequency in the range of 50 – 500 Hz
  - Duty cycle in the range of 0.5 – 5 %

HiPIMS - Power supply

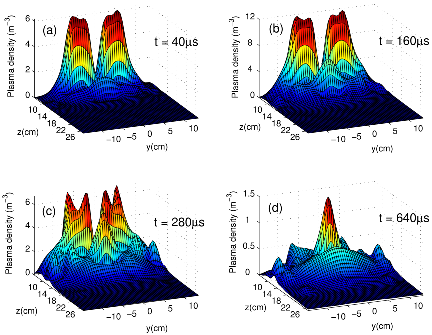


0.5 mTorr (solid line), 2 mTorr (dashed line) and 20 mTorr (dot dashed line)

(After Gudmundsson et al. (2002))

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

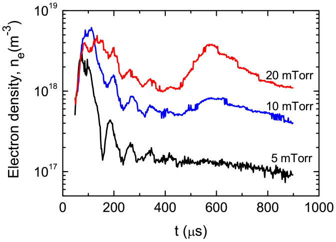
HiPIMS - Electron density



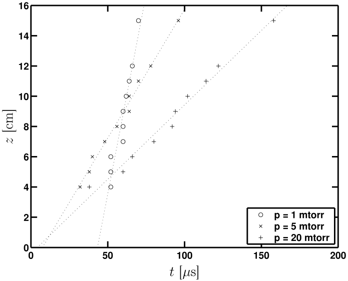
(After Bohlmark et al. (2005b))

- 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} m^{-3}

HiPIMS - Electron density



(After Gudmundsson et al. (2002))

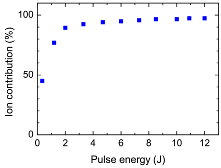


(From Gylfason et al. (2005))

- 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
- Each peak travels with a fixed velocity through the chamber

HiPIMS - Ionization fraction

- There have been conflicting reports on the ionized flux fraction
  - 70 % for Cu (Kouznetsov et al., 1999)
  - 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., 2005a)



(From Bohlmark et al. (2005a))

HiPIMS - Ionization fraction

- To explore the ionization mechanism and the temporal behavior of the plasma parameters a time dependent global (volume averaged) model was developed
- The discharge is assumed to consist of
  - electrons, e
  - argon atoms in the ground state, Ar
  - metastable argon atoms, Ar^*
  - argon ions, Ar^+
  - metal atoms, M
  - metal ions, M^+

HiPIMS - Ionization fraction

- Metal ions are generated by electron impact ionization

$$e + \mathrm{M} \longrightarrow \mathrm{M}^{+} + 2e$$

  by Penning ionization by collision with an electronically excited argon atom

$$\mathrm{Ar}^{*} + \mathrm{M} \longrightarrow \mathrm{M}^{+} + \mathrm{Ar} + 2e$$

  by charge exchange

$$\mathrm{Ar}^{+} + \mathrm{M} \longrightarrow \mathrm{M}^{+} + \mathrm{Ar}$$

- The metal ions are assumed to be lost by diffusion to solid surfaces such as the chamber walls

HiPIMS - Ionization fraction

- Particle balance for metal ions

$$\frac{dn_{\mathrm{m+}}}{dt} = \underbrace{k_{\mathrm{miz}} n_{\mathrm{e}} n_{\mathrm{m}}}_{\text{electron impact}} + \underbrace{k_{\mathrm{P}} n_{\mathrm{Ar^*}} n_{\mathrm{m}}}_{\text{Penning}} + \underbrace{k_{\mathrm{chexc}} n_{\mathrm{Ar^+}} n_{\mathrm{m}}}_{\text{charge exchange}} - \underbrace{k_{\mathrm{wall,m+}} n_{\mathrm{m+}}}_{\text{loss to wall}}$$

- Particle balance for metal atoms

$$\frac{dn_{\mathrm{m}}}{dt} = \underbrace{\frac{\gamma_{\mathrm{sput}} h_{\mathrm{L}} u_{\mathrm{B}} n_{\mathrm{Ar^+}} r_{\mathrm{T}}^2}{R^2 L}}_{\text{sputtering from target}} + \underbrace{\frac{\gamma_{\mathrm{selfsput}} h_{\mathrm{L}} u_{\mathrm{B,m}} n_{\mathrm{m+}} r_{\mathrm{T}}^2}{R^2 L}}_{\text{selfsputtering from target}}$$

$$- \underbrace{k_{\mathrm{miz}} n_{\mathrm{e}} n_{\mathrm{m}}}_{\text{ionization}} - \underbrace{k_{\mathrm{P}} n_{\mathrm{Ar^*}} n_{\mathrm{m}}}_{\text{Penning}} - \underbrace{k_{\mathrm{chexc}} n_{\mathrm{Ar^+}} n_{\mathrm{m}}}_{\text{charge exchange}} - \underbrace{k_{\mathrm{diff,m}} n_{\mathrm{m}}}_{\text{loss to wall}}$$

HiPIMS - Ionization fraction

- Particle balance for argon ions, Ar^+

$$\frac{dn_{\mathrm{Ar}^+}}{dt} = k_{\mathrm{iz}} n_{\mathrm{e}} n_{\mathrm{Ar}} + k_{\mathrm{exc,iz}} n_{\mathrm{e}} n_{\mathrm{Ar}^*} - k_{\mathrm{chexc}} n_{\mathrm{m}} n_{\mathrm{Ar}^+} - k_{\mathrm{wall,Ar}+} n_{\mathrm{Ar}^+}$$

- Particle balance for metastable argon atoms, Ar^*

$$\frac{dn_{\mathrm{Ar}^*}}{dt} = k_{\mathrm{exc}} n_{\mathrm{e}} n_{\mathrm{Ar}} - (k_{\mathrm{exc,iz}} + k_{\mathrm{deexc}}) n_{\mathrm{e}} n_{\mathrm{Ar}^*} - k_{\mathrm{loss,Ar}^*} n_{\mathrm{Ar}^*} - k_{\mathrm{P}} n_{\mathrm{Ar}^*} n_{\mathrm{m}}$$

- Quasi-neutrality condition

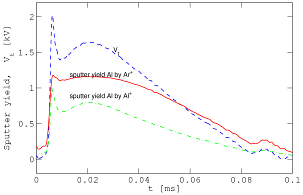
$$n_{\mathrm{e}} = n_{\mathrm{Ar}^+} + n_{\mathrm{m}+}$$

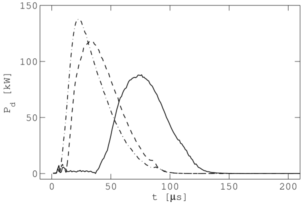
- Power balance

$$\frac{d}{dt}\left(\frac{3}{2} e n_{\mathrm{e}} T_{\mathrm{e}}\right) = \frac{P_{\mathrm{abs}}}{V} - e\mathcal{E}_{\mathrm{c}} k_{\mathrm{iz}} n_{\mathrm{Ar}} n_{\mathrm{e}} - e k_{\mathrm{wall,Ar}^+} (\mathcal{E}_{\mathrm{e}} + \mathcal{E}_{\mathrm{i}}) n_{\mathrm{Ar}^+}$$

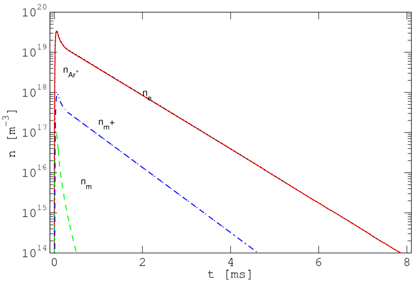
HiPIMS - Ionization fraction

- The temporal variation of the particle density and the electron temperature was obtained by solving the differential equations simultaneously and self-consistently
- We assume a discharge chamber of radius $R = 15$ cm and length $L = 15$ cm with a target of radius 7.5 cm made of aluminum.
- The electron energy distribution is assumed to be Maxwellian
- The power pulse is the measured pulse at 10 mTorr (dash dot line)

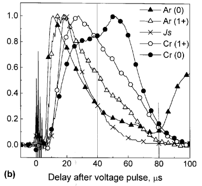




HiPIMS - Ionization fraction



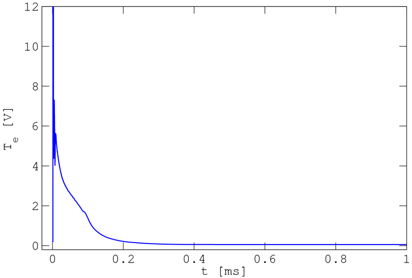
- The calculated electron and ion density versus time



From Ehiasarian et al. (2002)

- The measured emission from a discharge with a Cr target

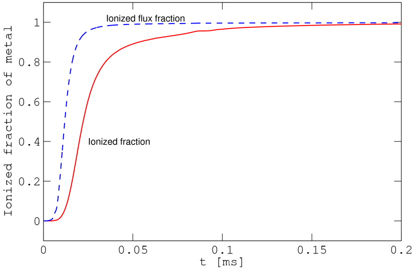
HiPIMS - Ionization fraction



- The calculated electron temperature

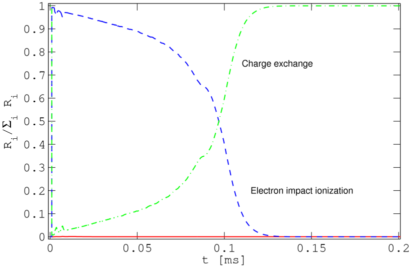
HiPIMS - Ionization fraction

- For aluminum
  - The integrated ionized fraction is 97 %
  - The integrated ionized flux fraction is 99 %
- For carbon
  - The integrated ionized fraction is 89 %
  - The integrated ionized flux fraction is 97 %



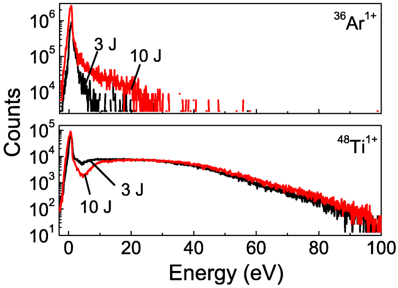
HiPIMS - Ionization fraction

- The first 100 μs (while the pulse is “on”) electron impact ionization is the most effective process in creating metal ions
- Then charge exchange becomes the dominant process in creating metal ions



HiPIMS - Ion energy

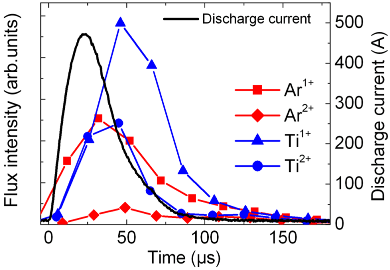
- The time averaged ion energy distribution for Ar^{+} and Ti^{+} ions
- The gas pressure was 3 mTorr, pulse energy 3 J and 10 J and the target made of Ti
- The ion energy distribution is broad to over 100 eV
- About 50 % of the Ti^{+} ions have energy > 20 eV



(From Bohlmark et al. (2006))

HiPIMS - Ionization fraction

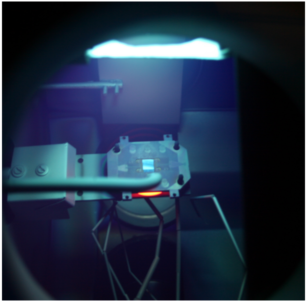
- The ion flux versus time measured by a mass spectrometer (20 μs windows)
- The gas pressure was 3 mTorr, pulse energy 8 J and the target made of Ti



(From Bohlmark et al. (2006))

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
- Maybe this can be reduced by optimized magnetic confinement

Summary

- We reviewed the physics 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

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