The High Power Impulse Magnetron Sputtering Discharge

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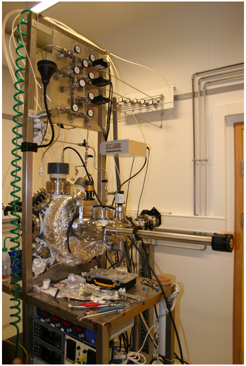
49th Annual SVC Technical Conference, April 24. 2006

Introduction

- Magnetron sputtering discharges are widely used in thin film processing

- Applications include
  - thin films in integrated circuits
  - magnetic material
  - hard, protective, and wear resistant coatings
  - optical coatings
  - decorative coatings
  - low friction films

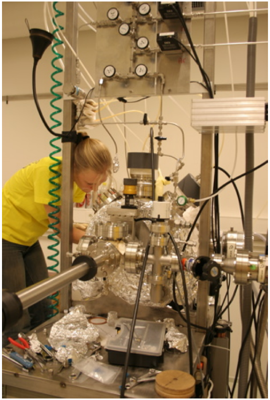


Introduction

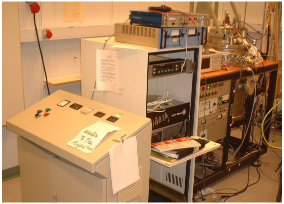
- The demand for new materials and layer structures has lead to development of more advanced sputtering systems
- One such sputtering system is the
  - high power pulsed magnetron sputtering discharge (HPPMS)
  - high power impulse magnetron sputtering discharge (HiPIMS)
- It gives high electron density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

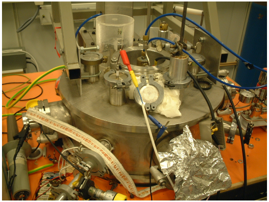
Introduction

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



Introduction

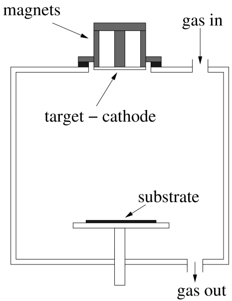




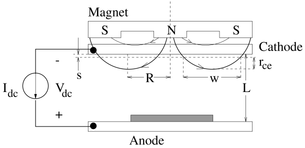
- This work is a result of collaboration with
  - Kristinn B. Gylfason (University of Iceland)
  - Dr. Jones Alami (Linköping University, Sweden)
  - Johan Bohlmark (Linköping University, Sweden)
  - Dr. Arutiun Ehiasarian (Sheffield Hallam University, UK)
  - Prof. Ulf Helmersson (Linköping University, Sweden)
  - Dr. Martina Latteman (Linköping University, Sweden)

Planar Magnetron Sputtering Discharge

- Sputtering in a dc glow discharge is a slow process
- The planar magnetron was developed to enhance the sputtering and increase the deposition rate
- A typical planar magnetron discharge consist of a planar cathode (sputtering source or target) parallel to an anode surface

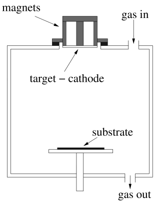


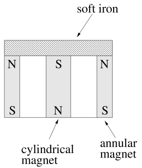
Planar Magnetron Sputtering Discharge

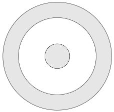


- A magnet is placed at the back of the cathode target with the pole pieces at the center and perimeter
- It generates magnetic field lines that enter and leave through the cathode plate
- The magnetic field confines the energetic electrons near the cathode, where they undergo numerous ionizing collisions before being lost to a grounded surface

Planar Magnetron Sputtering Discharge







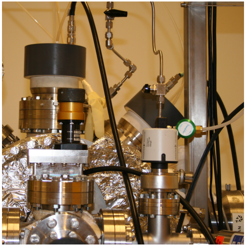
- A typical dc planar magnetron discharge operates at a pressure of 1 – 10 mTorr with a magnetic field strength of 0.01 – 0.05 T and at cathode potentials 300 – 700 V
- Electron density in the substrate vicinity is in the range $10^{15} - 10^{16}$ m^{-3}

Planar Magnetron Sputtering Discharge

- Conventional magnetron sputtering processes suffer from fundamental problems such as
  - low target utilization
  - target poisoning
  - poor deposition rates for dielectric and ferromagnetic materials
  - target thermal load limits the available current
  - electrical instabilities or arcs cause process instability
  - low fraction of the sputtered material is ionized

Planar Magnetron Sputtering Discharge

- Several sputtering systems have been designed to overcome these obstacles
- They include
  - pulsing the applied target voltage
  - additional ionization by a secondary discharge (rf or microwave)
  - increased magnetic confinement
  - reshaping the cathode for more focused plasma (hollow cathode)



Ionized Physical Vapor Deposition (IPVD)

- In sputtering the majority of ions are the ions of the inert gas
- The sputtered vapor is mainly neutral, the ionization fraction of the sputtered material is low ($\sim 1\%$)
- Over the last decade new ionized vapor deposition techniques have appeared that achieve 50 – 90 % ionization 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

Ionized Physical Vapor Deposition (IPVD)

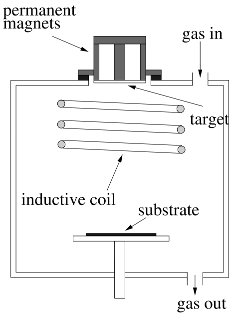
- When the flux of ions is higher than the flux of neutrals or $\Gamma_{+} > \Gamma_{\mathrm{m}}$ the process is referred to as ionized physical vapor deposition (IPVD)
- This is achieved by
  - increasing the power to the cathode (high power pulse)
  - a secondary discharge between the target and the substrate (rf coil or microwaves)
  - reshaping the geometry of the cathode to get more focused plasma (hollow cathodes)
- Common to all highly ionized techniques is very high density plasma

Ionized Physical Vapor Deposition (IPVD)

- The development of ionized physical vapor deposition (IPVD) devices was mainly driven by the need to deposit metal layers and diffusion barriers into trenches or vias of high aspect ratios
- 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

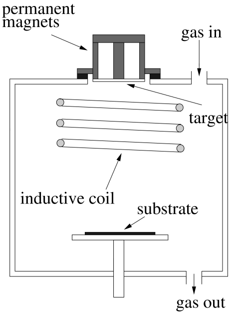
rf Inductive Coil in a Magnetron

- In order to generate highly ionized discharge a radio-frequency discharge can be added in the region between the cathode and the anode
- The metal ions can then be accelerated to the substrate by means of a low voltage dc bias
- Metal atoms sputtered from the cathode transit the rf plasma and can be ionized



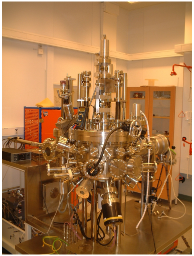
rf Inductive Coil in a Magnetron

- The metal atoms have low ionization potential (6 – 8 eV) compared to the inert Ar (15.8 eV)
- The metal ions can then 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

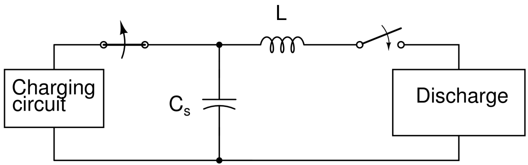


HiPIMS

- 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

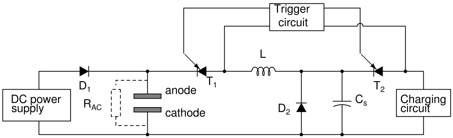


HiPIMS - Power supply



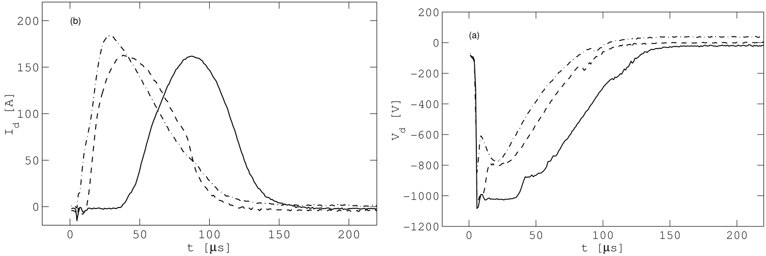
- The high power pulsed discharge operates with a
  - Cathode voltage in the range of 500-2000 V
  - Current densities of 3-4 A/cm^2
  - Power densities in the range of 1-3 kW/cm^2
  - Frequency in the range of 50 – 500 Hz
  - Duty cycle in the range of 0.5 – 5 %

HiPIMS - Power supply



- A pulse generator with a pre-ionizer
- A dc power supply maintains a conventional dc magnetron discharge
- The storage capacitor C_s is charged through a thyristor switch (T_2) from a charging circuit and a trigger circuit discharges the capacitor through a thyristor switch (T_1)
- The coil L reduces the rate of current rise

HiPIMS - Power supply

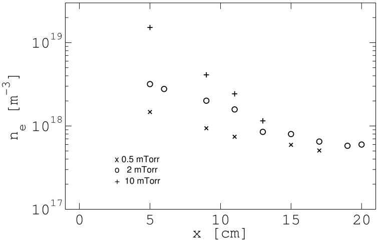


0.5 mTorr (solid line), 2 mTorr (dashed line) and 20 mTorr (dot dashed line)

(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

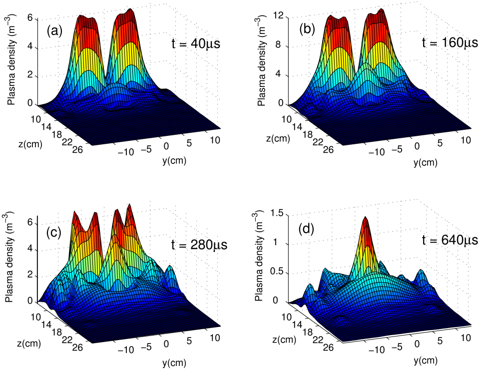
HiPIMS - Electron density



(After Gudmundsson et al. (2002))

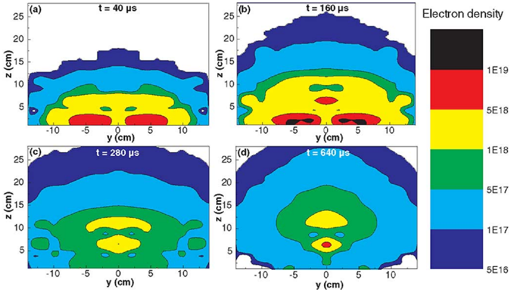
- The peak plasma density (electron density), n_{e} as a function of distance from Ta target for average power 300 W
- The electron density in the substrate vicinity is of the order of 10^{18} m^{-3}

HiPIMS - Electron density



- Temporal and spatial variation of the electron density
- Argon discharge at 20 mTorr with a titanium target

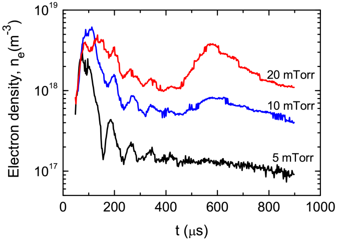
HiPIMS - Electron density



(From Bohlmark et al. (2005b))

- Temporal and spatial variation of the electron density
- Argon discharge at 20 mTorr with a titanium target

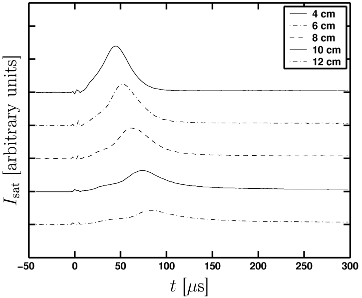
HiPIMS - Electron density



(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

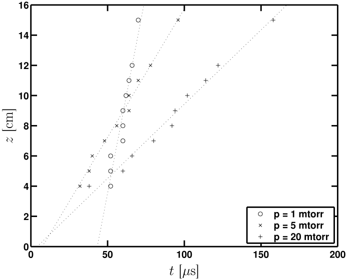
HiPIMS - Plasma dynamics



(From Gylfason et al. (2005))

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

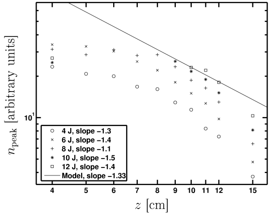
HiPIMS - Plasma dynamics



(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



(From Gylfason et al. (2005))

- Intuitively a spherical symmetry is expected, since the diameter of the target (15 cm) is only one third of that of the chamber (44 cm)
- In such a configuration, the amplitude of expanding solitons will decay, just due to the spherical geometry, as

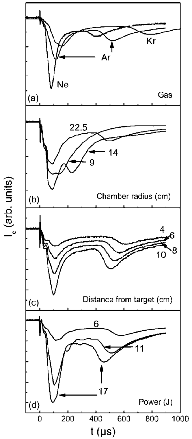
$$n_{\mathrm{peak}} \propto z^{\frac{-4}{3}}$$

where z is the radius of the soliton

HiPIMS - Plasma dynamics

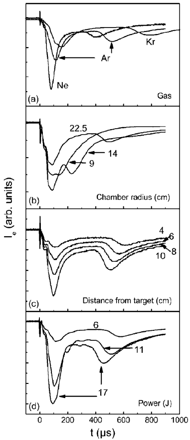
- The plasma density versus time while varying the
  - sputtering gas
  - chamber dimension
  - distance to target
  - applied power

(From Alami et al. (2005a))



HiPIMS - Plasma dynamics

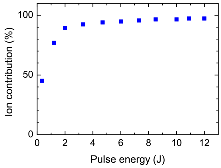
- The first peak appears immediately after the plasma ignition
- The second peak appears only for pressures above 5 mTorr
- The lighter the gas atom the earlier the peaks appear
- Decreased chamber radius results in earlier appearance of the second peak
    - We propose that the charged particles travel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



(From Alami et al. (2005a))

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

$$\frac{dn_{\mathrm{m}}}{dt} = \underbrace{\frac{\gamma_{\mathrm{sput}} h_{\mathrm{L}} u_{\mathrm{B}} n_{\mathrm{Ar}^+} r_{\mathrm{T}}^2}{R^2 L}}_{\text{sputtering from target}} - \underbrace{k_{\mathrm{miz}} n_{\mathrm{e}} n_{\mathrm{m}}}_{\text{ionization}} - \underbrace{k_{\mathrm{P}} n_{\mathrm{Ar}^*} n_{\mathrm{m}}}_{\text{Penning}}$$

$$- \underbrace{k_{\mathrm{chexc}} n_{\mathrm{Ar}^+} n_{\mathrm{m}}}_{\text{charge exchange}} - \underbrace{k_{\mathrm{diff,m}} n_{\mathrm{m+}}}_{\text{loss to wall}}$$

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

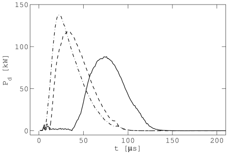
$$n_{\mathrm{e}} = n_{\mathrm{Ar}^+} + n_{\mathrm{m}+}$$

- Power balance

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

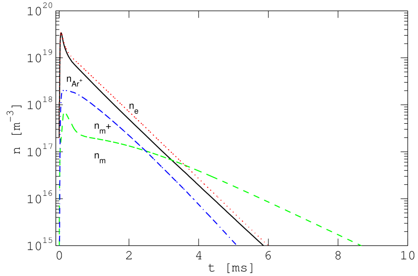
HiPIMS - Ionization fraction

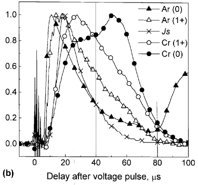
- The temporal variation of the particle density and the electron temperature was obtained by solving the differential equations simultaneously and self-consistently
- We assume a discharge chamber of radius $R = 15$ cm and length $L = 15$ cm with a target of radius 7.5 cm made of aluminum.
- The electron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



- The power pulse was the measured pulse at 10 mTorr

HiPIMS - Ionization fraction



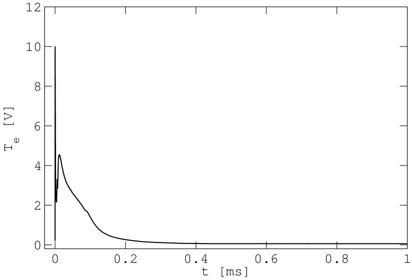


From Ehiasarian et al. (2002)

- The calculated electron and ion density versus time

- The measured emission from a discharge with a Cr target

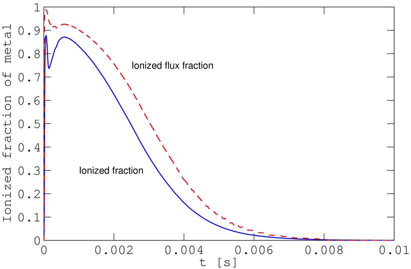
HiPIMS - Ionization fraction



- The calculated electron temperature

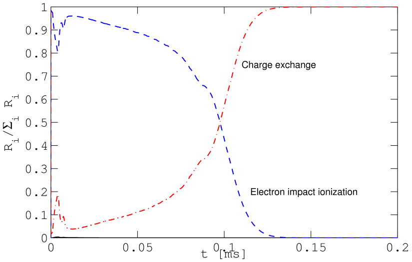
HiPIMS - Ionization fraction

- The ionization fraction of the sputtered aluminum and the ionized flux fraction
  - The integrated ionized fraction during the pulse is 0.76
  - The integrated ionized flux fraction during the pulse is 0.89



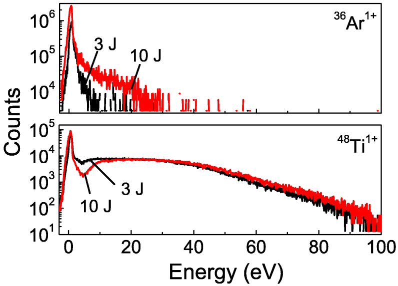
HiPIMS - Ionization fraction

- The first 100 μs electron impact ionization is the most effective process in creating metal ions
- Then exchange becomes the dominant process in creating metal ions



HiPIMS - Ion energy

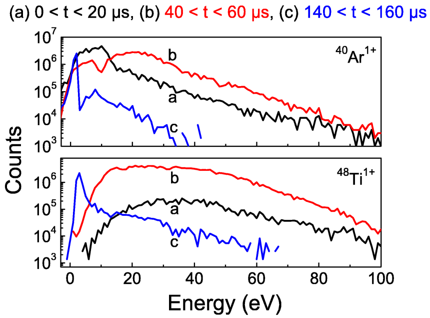
- The time averaged ion energy distribution for Ar^+ and Ti^+ ions
- The gas pressure was 3 mTorr, pulse energy 3 J and 10 J and the target made of Ti
- The ion energy distribution is broad to over 100 eV
- About 50 % of the Ti^+ ions have energy > 20 eV



(From Bohlmark et al. (2006))

HiPIMS - Ion energy

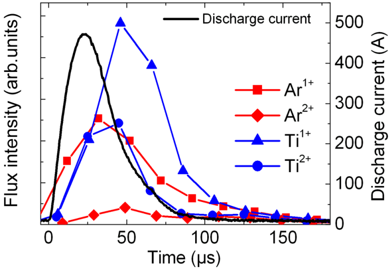
- The measured ion energy distribution for Ar^+ and Ti^+ ions over 20 μs time windows
- The gas pressure was 3 mTorr, pulse energy 9 J and the target made of Ti



(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



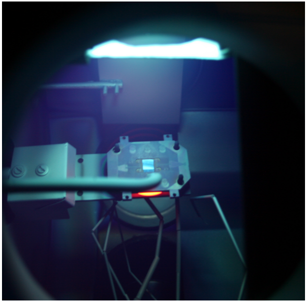
(From Bohlmark et al. (2006))

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

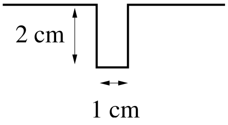
- and compared to mid frequency pulsed magnetron discharge
  - a factor of 4 lower deposition rate for reactive sputtering of zirconium oxide from Zr target (Glocker et al., 2004)
  - no reduction in deposition rate for reactive sputtering of tantalum oxide from Ta target (Glocker et al., 2004)



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

Application - Trench filling

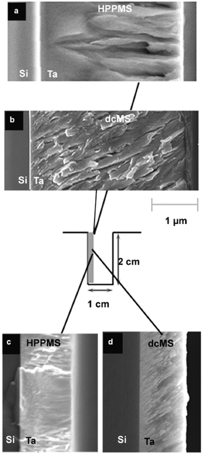


- Ta thin films grown on Si substrates placed along a wall of a 2 cm deep and 1 cm wide trench
  - conventional dc magnetron sputtering (dcMS)
  - high power impulse magnetron sputtering (HiPIMS)
- Average power is the same 440 W
- They were compared by scanning electron microscope (SEM), transmission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

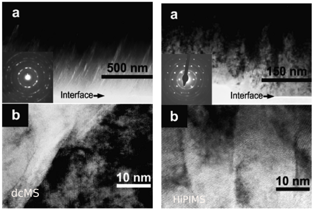
Application - Trench filling

- SEM images of Ta films grown by dc MS show columnar structures leaning toward the aperture

(From Alami et al. (2005b))



Application - Trench filling



(From Alami et al. (2005b))

- 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 advantage of high power pulsed magnetron discharge for film growth has been demonstrated by several groups
  - ultra-thin carbon films grown by HIPIMS have significantly higher densities (2.7 g/cm^3), than films grown by a conventional dcMS discharge (< 2.0 g/cm^3) Furthermore, the surface roughness is lower (DeKoven et al., 2003)
  - TiO_2 thin films grown by reactive sputtering by HIPIMS have higher index of refraction than grown by dcMS discharge - maybe due to higher density (Davis et al., 2004)
- This illustrates how the bombarding ions transfer momentum to the surface allowing the microstructure to be modified

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
- We demonstrated the use of a high power pulsed magnetron sputtering discharge
  - for trench filling
  - to grow denser films

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