Second Sheffield HIPIMS and ABS Days: Advances in Industrial PVD Technologies, Sheffield Hallam University:

The high power impulse magnetron sputtering discharge: A brief review

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Introduction

- Magnetron sputtering discharges are widely used in thin film processing
- 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) or high power impulse magnetron sputtering discharge (HIPIMS)
- It gives high electron density and highly ionized flux of the sputtered material

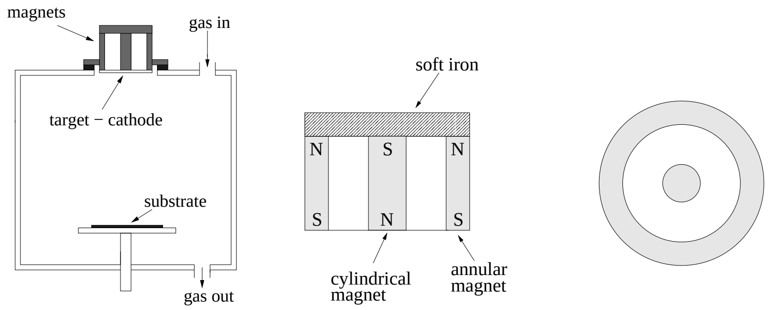
Introduction

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

Introduction

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

Planar Magnetron Sputtering Discharge

- Conventional magnetron sputtering processes suffer from fundamental problems such as
  - low target utilisation
  - 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
- Some of these problems have been alleviated by
  - pulsing the applied target voltage
  - additional ionization by rf or microwave power
  - increased magnetic confinement.
  - reshaping the cathode for more focused plasma (hollow cathode)

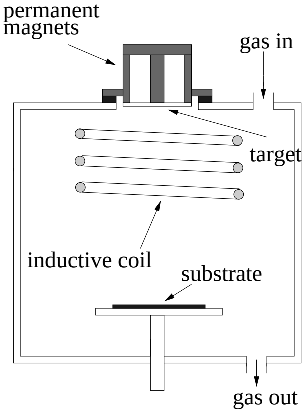
Ionized Physical Vapour Deposition (IPVD)

- The development of ionized physical vapour 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 vapour has several advantages:
  - improvement of the film quality
  - control of the reactivity
  - deposition on substrates with complex shapes and high aspect ratio

Ionized Physical Vapour 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 vapour deposition (IPVD)
- This is achieved by
  - increased power to the cathode (high power pulse)
  - external supply of energy through 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

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

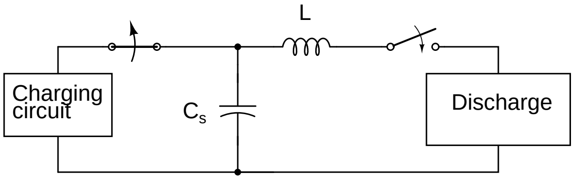
rf Inductive Coil in a Magnetron

- Metal atoms sputtered from the cathode transit the rf plasma and can be ionized
- 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

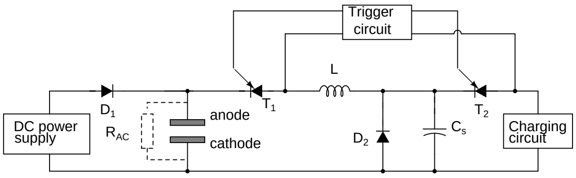
- In a conventional dc magnetron discharge the power density is limited by the thermal load on the target
- Most of the ion bombarding energy is transformed into heat at the target
- In unipolar pulsing the power supply is at low (or zero) power and then a high power pulse is supplied for a short period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

HIPIMS - Power supply



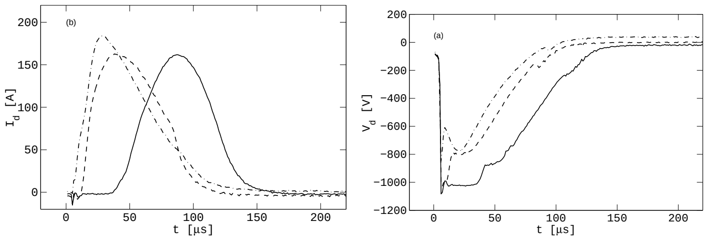
- The high power pulsed discharge operates with a
  - Cathode voltage in the range of 500-2000 V
  - Current densities of 3-4 A/cm^2
  - Power densities in the range of 1-3 kW/cm^2
  - Frequency in the range of $50 - 500$ Hz
  - Duty cycle in the range of $0.5 - 5$ %

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

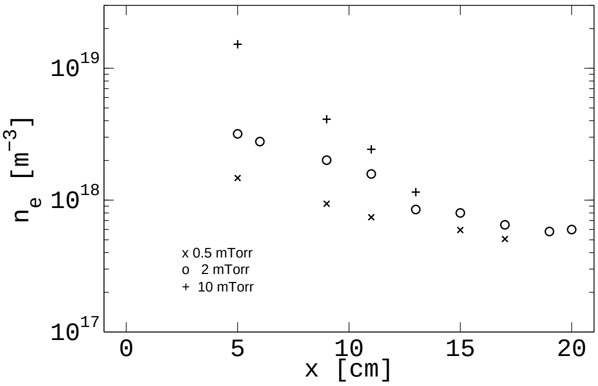


0.5 mTorr (solid line), 2 mTorr (dashed line) and 20 mTorr (dot dashed line)

(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

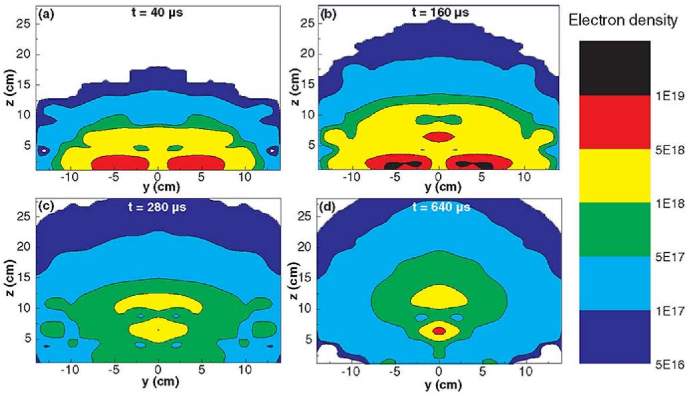
HIPIMS - Electron density



(After Gudmundsson et al. (2002))

- The peak plasma density (electron density), n_{e} as a function of distance from the Ta target
- The average power was 300 W

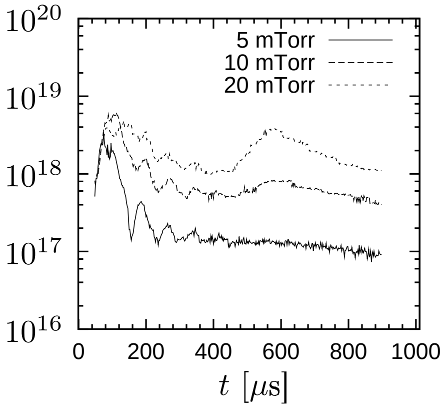
HIPIMS - Electron density



(From Bohlmark et al. (2005b))

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

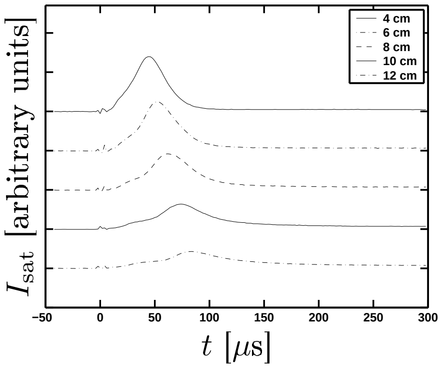
HIPIMS - Electron density



(From 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

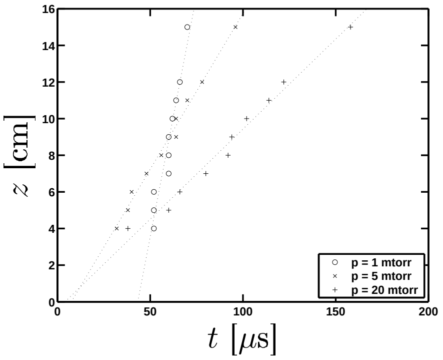
HIPIMS - Plasma dynamics



(From Gylfason et al. (2004))

- 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

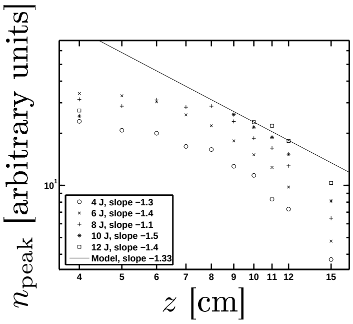
HIPIMS - Plasma dynamics



(From Gylfason et al. (2004))

- 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

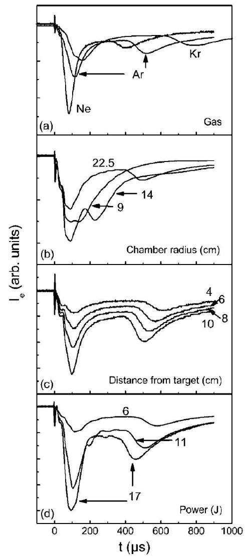


(From Gylfason et al. (2004))

- Intuitively one would expect a spherical symmetry of expanding waves in our system, 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

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

HIPIMS - Plasma dynamics

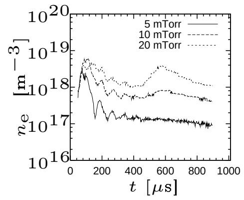


while varying the

- (a) sputtering gas
- (b) chamber dimension
- (c) distance to the target
- (d) 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

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)

HIPIMS - Ionization fraction

- The high electron density created during the pulse is the key to achieve the highly ionized flux fraction of the sputtered material
- The metal ions are generated by electron impact ionization

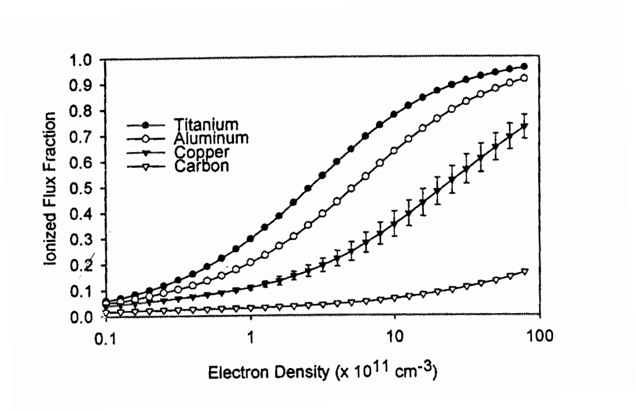
$$e + \mathrm{M} \longrightarrow \mathrm{M}^{+} + 2e$$

and by Penning ionization by collision with metastable argon atom

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

- For low electron density ($n_\mathrm{e} \ll 10^{17}\ \mathrm{m}^{-3}$) Penning ionization dominates and fractional ionization is low
- For high electron density ($n_\mathrm{e} \gg 10^{17}\ \mathrm{m}^{-3}$) electron impact ionization dominates and fractional ionization is high

HIPIMS - Ionization fraction



(From Hopwood (2000))

- The low value for C can be explained by the high ionization potential and low rate coefficient for electron impact ionization

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 an Zr target (Glocker et al., 2004)
  - no reduction in deposition rate for reactive sputtering of tantalum oxide from an Ta target (Glocker et al., 2004)

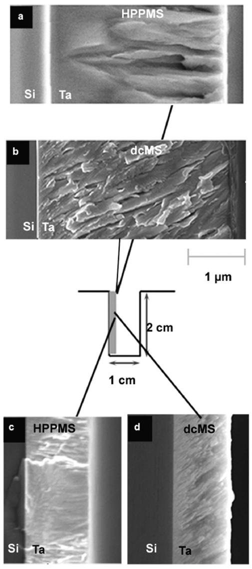
HIPIMS - Deposition rate

- 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 optimised magnetic confinement

Application - Trench filling

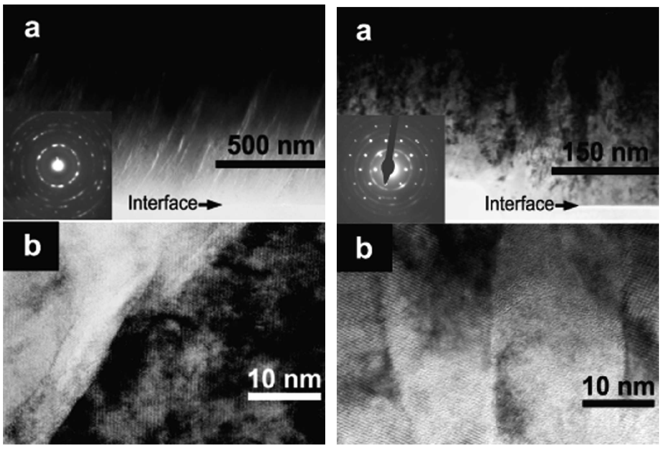
- Ta thin films grown on Si substrates placed along a wall of a 2 cm deep and 1 cm wide trench
  - conventional dc magnetron sputtering (dcMS)
  - high power pulsed magnetron sputtering (HPPMS)
- Average power is the same 440 W
- They were compared by scanning electron microscope (SEM), transmission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

Application - Trench filling



(From Alami et al. (2005b))

Application - Trench filling



dc magnetron HPPMS

(From Alami et al. (2005b))

Application - Trench filling

- TEM images 1 mm from the opening
- dcMS grown films exhibit rough surface, pores between grains and inclined columnar structure, leaning toward the aperture
- Ta films grown by HPPMS have smooth surface, and dense crystalline structure with grains perpendicular to the substrate
- We relate this to the high ionization fraction of the sputtered species

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
  - Electron density
  - Plasma dynamics
  - Ionization fraction
  - Deposition rate
- We demonstrated the use of a high power pulsed magnetron sputtering discharge
  - for trench filling
- A brief review has been submitted by Helmersson et al. (2005)

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