California Nanosystems Institute (CNSI)
University of California Santa Barbara:

The Magnetron Sputtering Discharge: Variations and Applications in a Shrinking World

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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
- The demand for new materials and layer structures has lead to development of more advanced sputtering systems

Introduction

- Introduction to dc Sputtering
- The Magnetron Sputtering Discharge
- Variations of the Magnetron Sputtering Discharge
- Examples of Applications
  - superlattice
  - MIM
  - trench filling

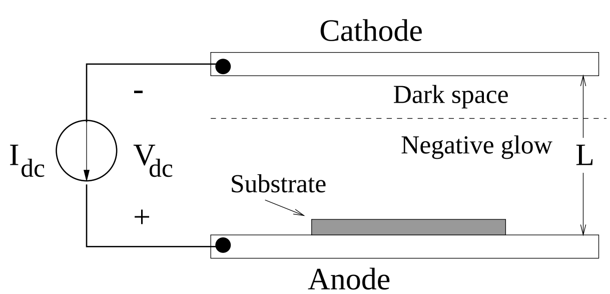
Introduction

- This work is a result of collaboration with
  - Kristinn B. Gylfason (University of Iceland)
  - Ivar Meyvantsson (University of Iceland)
  - Jones Alami (Linkoping University, Sweden)
  - Johan Bohlmark (Linkoping University, Sweden)
  - Jon Skirnir Agustsson (University of Iceland)
  - Gudmundur Reynaldsson (University of Iceland)
  - Dr. Sveinn Olafsson (University of Iceland)
  - Prof. Ulf Helmersson (Linkoping University, Sweden)

Weakly Ionized Plasmas

- Plasma is a partially or fully ionized gas that includes electrons, ions, neutral atoms and molecules
- The electrons, neutral species and ions are not in thermal equilibrium in a partially ionized plasma
- The following parameters describe the discharge
  - Electron density $n_{\rm e}$ and ion density $n_{\rm i}$
  - Electron temperature $T_{\rm e}$
- We want to know and control
  - Flux of ions and neutrals to the substrate, $\Gamma_{\rm i}, \Gamma_{\rm n}$
  - The ion energy distribution (IED) $f(\mathcal{E}_{\rm i})$
  - The electron energy distribution (EEDF) $f(\mathcal{E}_{\rm e})$

dc Sputtering



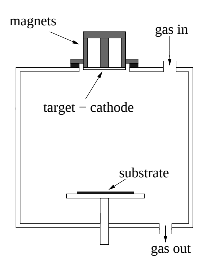
- Sputtering was discovered in 1852
- An ion sputters an atom and/or releases electrons from a target
- This can be done by accelerating ions from a plasma which is created between electrodes when a dc voltage of 1000 – 3000 V is applied

dc Sputtering

- Disadvantages of dc sputtering
  - Slow film growth
  - Low ionization
  - Heating of the substrate
- It is beneficial to have the sputtering discharge work at
  - higher current density
  - lower operating voltage
  - lower gas pressure

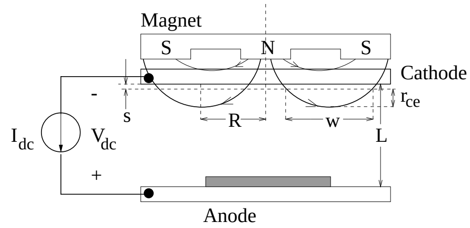
  than is possible in a dc sputtering discharge

Planar Magnetron Sputtering Discharge



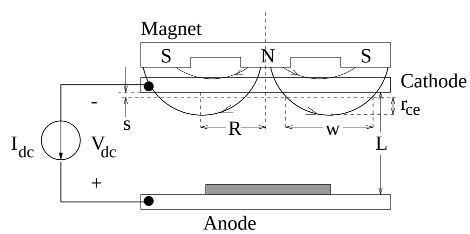
- The planar magnetron was developed to enhance the sputtering and increase the deposition rate
- A typical planar magnetron discharge consist of a planar cathode (sputtering source or target) parallel to an anode surface
- In a magnetron sputtering discharge the anode is of secondary importance

Planar Magnetron Sputtering Discharge



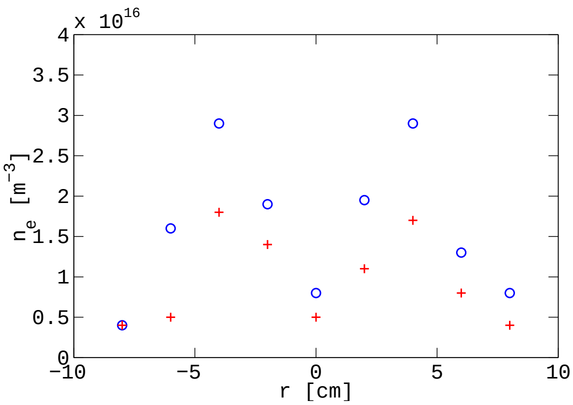
- A magnet is placed at the back of the cathode target with the pole pieces at the center and perimeter
- It generates magnetic field lines that enter and leave through the cathode plate
- The magnetic field confines the energetic electrons near the cathode, where they undergo numerous ionizing collisions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

Planar Magnetron Sputtering Discharge



- Ions, not confined by the magnetic field, are accelerated toward the cathode and strike it at high energy
- The impact of the ions on the cathode (target) results in sputtering of metal atoms and secondary electron emission from the cathode surface
- Energy gained in the cathode sheath by secondary electrons emitted from the cathode goes into the ionization necessary to maintain the discharge

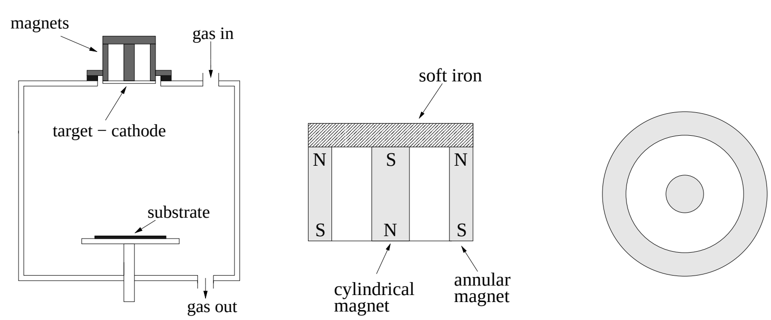
Planar Magnetron Sputtering Discharge



(After Field et al. (2002))

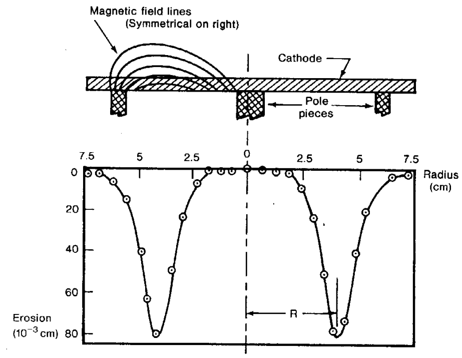
- The discharge forms as a high-density, bright, circular plasma that sits just below the cathode

Planar Magnetron Sputtering Discharge



- A typical dc planar magnetron 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
- The magnetic field can be created by permanent magnets, electromagnets or combination of both

Planar Magnetron Sputtering Discharge



(From Chapin (1974))

- A major problem in magnetron sputtering is the formation of a "racetrack"
- Due to this only about 25 – 30 % of the target is normally used during sputtering

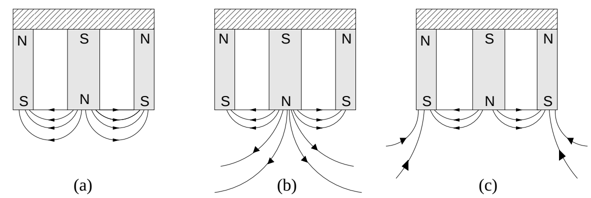
Planar Magnetron Sputtering Discharge

- 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

Planar Magnetron Sputtering Discharge

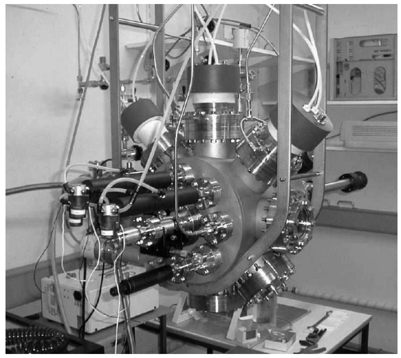
- Several sputtering systems have been designed to overcome these obstacles
- Some of these problems have been alleviated by
  - pulsing the applied target voltage
  - additional ionization by rf or microwave power
  - increased magnetic confinement.
  - reshaping the cathode for more focused plasma (hollow cathode)

Unbalanced Magnetron Sputtering Discharge



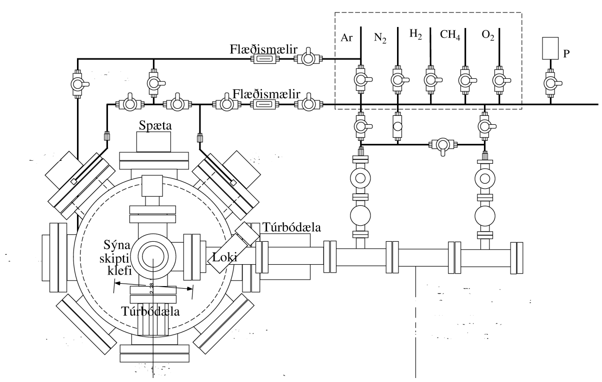
- The unbalanced magnetron was developed as an attempt to increase the ion current density in the vicinity of the substrate
- Thus the ion current density in the vicinity of the substrate can be varied by varying the intensity of the magnetic flux through the pole faces
- As a consequence the energy of the ions bombarding the substrate during film growth can be tuned by the substrate bias

Reactive Magnetron Discharge



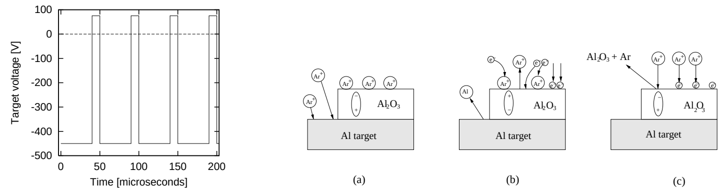
- Conventional dc magnetron sputtering is ideal for depositing thin metallic films
- Compounds such as oxides and nitrides must be deposited with reactive sputtering in which a metal target is sputtered inside a discharge of reactive gas

Reactive Magnetron Sputtering Discharge



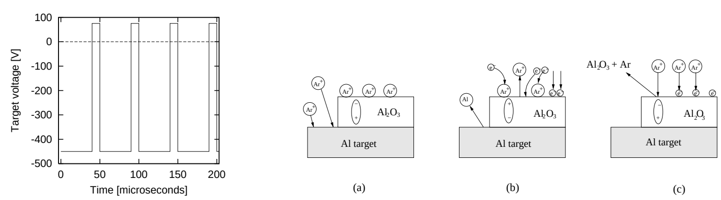
- The reactive process has required the development of more sophisticated sputtering systems such as
  - rf magnetron sputtering discharge
  - pulsed rf magnetron sputtering discharge
  - asymmetric bipolar magnetron sputtering discharge

Asymmetric Bipolar Pulsed Magnetron



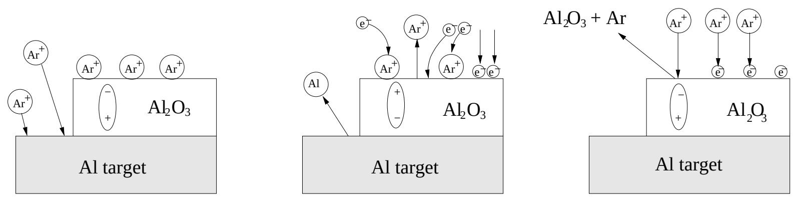
- Reactive dc sputtering for the deposition of dielectrics from conductive targets is limited by target poisoning and the consequent arcing and process instability
- Poisoning is the build-up of insulating layers on the target surface

Asymmetric Bipolar Pulsed Magnetron



- Asymmetric bipolar pulsing of the magnetron sputtering discharge has grown rapidly to become one of the main techniques for deposition of high quality dielectric films such as SiO_2, TiO_2, Al_2O_3, and MgO by reactive sputtering
- The magnetron discharge is pulsed in the medium frequency range (10 – 350 kHz) when depositing insulating films
- This significantly reduces the formation of arcs and, reduces the number of defects in the resulting film

Asymmetric Bipolar Pulsed Magnetron



(a) (b) (c)

- The target is sputtered at normal operating voltage (typically -400 to -500 V) for a fixed "pulse on" time
- The pulse on time is limited, such that charging of the poisoned regions does not reach the point where breakdown and arching occurs
- The charge is then dissipated through the plasma during "pulse off" period by switching the target voltage to a positive value

Ionized Physical Vapour Deposition (IPVD)

- In sputtering the majority of ions are the ions of the inert gas and the sputtered vapour is mainly neutral
- The ion density of the sputtered material is significantly lower
- Over the last decade new ionized vapour deposition techniques have appeared that achieve 50 – 90 % ionization of the sputterend material
- The energy of the ions can be tailored to obtain impinging particles with energies comparable to typical surface and molecular binding energies
- This is an advantage over evapouration techniques such as molecular beam epitaxy (MBE)

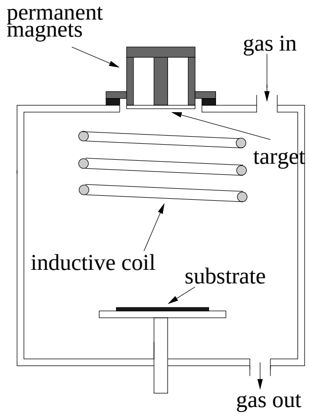
Ionized Physical Vapour Deposition (IPVD)

- 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 $\Gamma_+ > \Gamma_m$ 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 a very high density plasma

rf Inductive Coil in a Magnetron

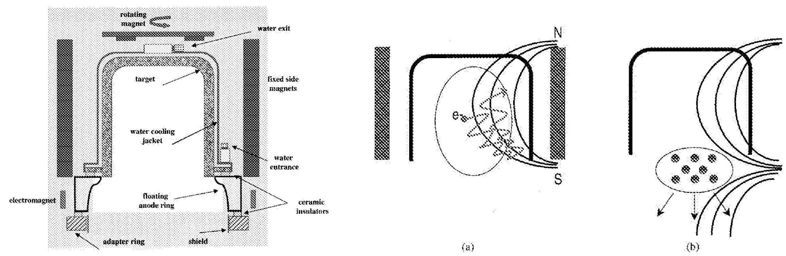


- In order to generate highly ionized discharge a radio-frequency discharge can be added in the region between the cathode and the anode

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

Hollow Cathode Magnetron



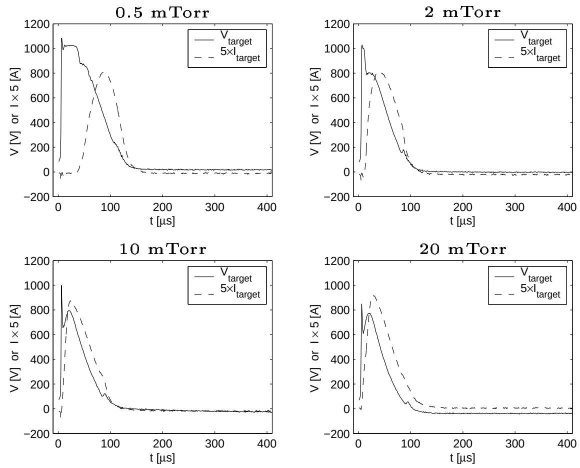
(From Klawuhn et al. (2000))

- A hollow-cathode magnetron source employs a magnetron discharge confined in an inverted cup-shaped target
- Due to the cup shaped target geometry, the electrons are electrostatically (target negatively biased) or magnetically confined within the volume of the source

Unipolar High Power Pulsed Magnetron

- 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

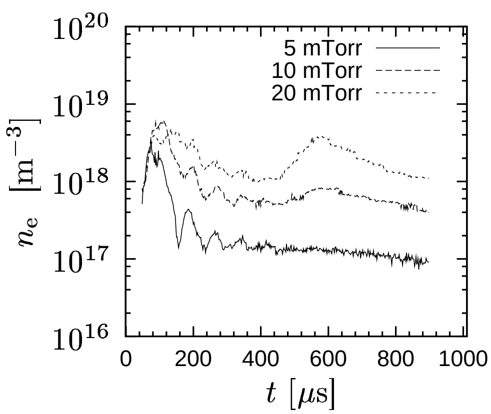
Unipolar High Power Pulsed Magnetron



(From Gudmundsson et al. (2002))

- A discharge with a power supply that can deliver up to 2.4 MW of power in 100 μs pulses at frequency of 50 Hz

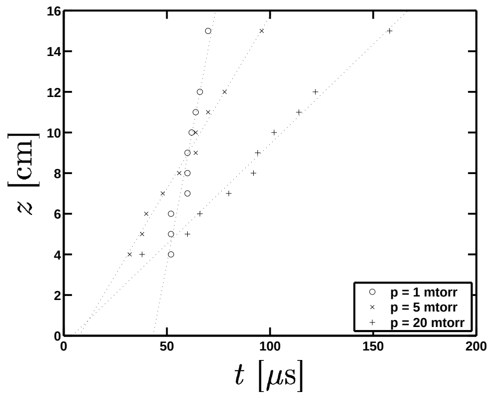
Unipolar High Power Pulsed Magnetron



(From Gudmundsson et al. (2002))

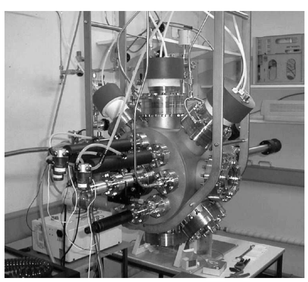
- The electron density versus time from the initiation of the pulse 9 cm below the target for gas pressure 5, 10 and 20 mTorr. The pulse is 100 μs long and the average power 300 W

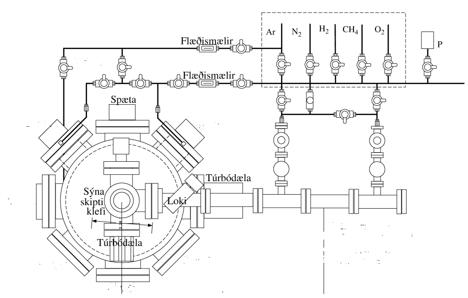
Unipolar High Power Pulsed Magnetron



- The position of the initial density peaks versus the time from pulse initiation
- The argon pressure was 5 mTorr, the target made of titanium, and the pulse energy 8 J

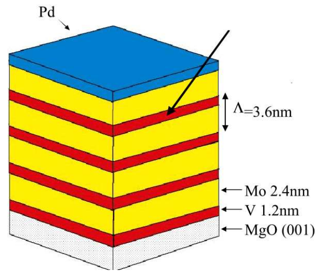
Applications





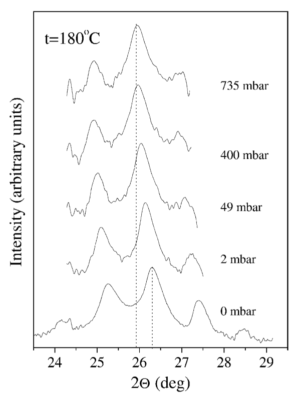
- The target voltage is either dc or asymmetric bipolar pulsed
- The magnetron sputtering discharge has 3 targets
  - Growth of alloys
  - Growth of layers of different metals or alloys
  - Growth of oxides and nitrides (reactive sputtering)

Applications - Superlattice



- Mo/V superlattices were grown in a dc magnetron sputtering discharge on MgO (0 0 1) substrate
- The dc magnetron has three targets, Mo, V and Pd
- Layers of Mo and V, a few nanometers thick were grown alternatively
- Hydrogen interactions in two-dimensional superlattice

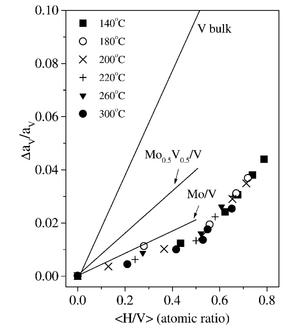
Applications - Superlattice



(From Reynaldsson et al. (2003))

- The shift in the Bragg peak originates from the out of plane expansion of the Mo/V 8/4 u.c. superlattice as hydrogen enters the vanadium layers

Applications - Superlattice



(From Reynaldsson et al. (2003))

- The expansion is linear with hydrogen concentration
- The expansion is temperature independent which indicates that there is no phase change

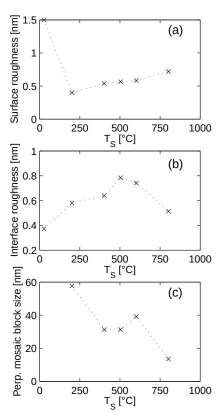
Application - Alloy and MIM

- The goal is to create a MIM device that is on the nanoscale
  - an ultra-thin conducting film on an insulating substrate
  - an ultra-thin dielectric layer
  - another ultra-thin conducting film
- Lattice mismatch between film and substrate causes strain in the film
- Strain increases the free energy of the interface and leads to island formation and thus greater minimal thickness for film formation and increased roughness
- The roughness increases the resistivity of the ultra-thin film

Application - Alloy and MIM

- Thus we choose a thin film material with a crystal structure compatible to that of the substrate
- The first choice was an Cr-Mo alloy and MgO insulator
- We use Mo, Cr, and Mg targets in the magnetron sputtering discharge
- Ultra-thin lattice matched heteroepitaxial $Cr_{0.63}Mo_{0.37}$ alloy were grown on a MgO (100) substrate by sputtering the Cr and Mo targets simultaneously
- MgO insulator is grown by reactive sputtering in Ar/O_2 discharge from a Mg target

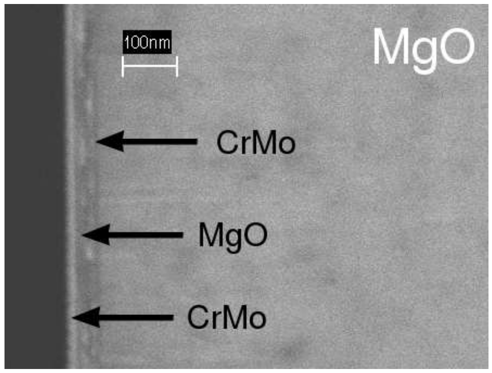
Application - Alloy and MIM



(From Meyvantsson et al. (2004))

- The optimum temperature for the growth of $Cr_{0.63}Mo_{0.37}$ alloy is determined 200°C

Application - Alloy and MIM

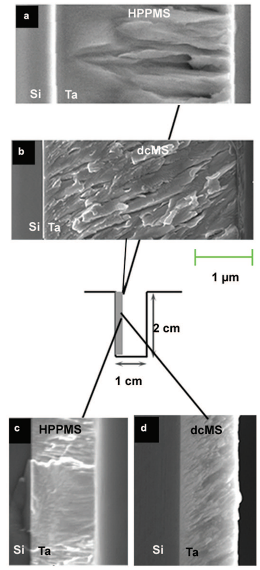


- A SEM image of $Cr_{0.63}Mo_{0.37}/MgO/Cr_{0.63}Mo_{0.37}$ MIM grown on MgO with 20 nm / 5 nm / 20 nm

Application - Trench filling

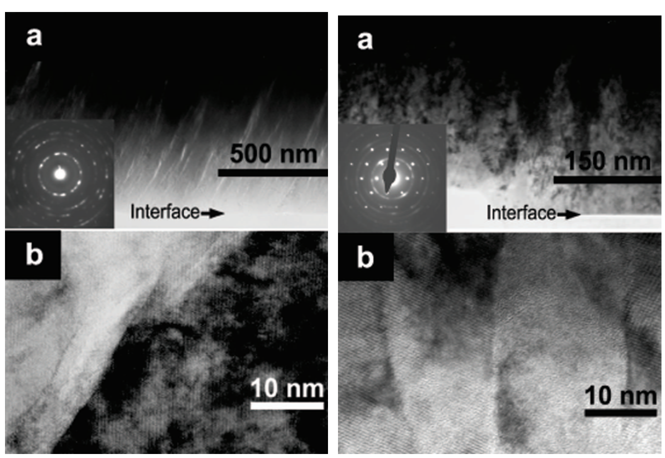
- Ta thin films grown on Si substrates placed along a wall of a 2 cm deep and 1 cm wide trench
  - conventional dc magnetron sputtering (dcMS)
  - high power pulsed magnetron sputtering (HPPMS)
- Average power is the same 440 W
- They were compared by scanning electron microscope (SEM), transmission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

Application - Trench filling



(From Alami et al. (2004))

Application - Trench filling



dc magnetron HPPMS

(From Alami et al. (2004))

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

Summary

- We reviewed
  - dc sputtering
  - dc magnetron sputtering
  - asymmetric bipolar magnetron sputtering

  and introduced
  - unipolar high power pulsed magnetron sputtering
- We demonstrated the use of a magnetron sputtering discharge
  - to grow superlattices
  - to grow alloys and simple devices on the nanoscale
  - for trench filling

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