Ionized physical vapor deposition (IPVD): Technology and applications

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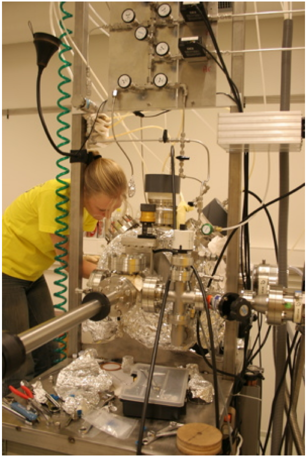
17th International Vacuum Congress,
Stockholm, Sweden, July 3. 2007

Introduction

- The demand for new materials and layer structures has lead to development of more advanced sputtering systems
- 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)
- In magnetron sputtering discharges 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 magnetron sputtering techniques is a very high density plasma

Introduction

- Ionized Physical Vapor Deposition (IPVD)
- Introduction to magnetron sputtering
- Magnetron sputtering with a secondary discharge
    - Inductively coupled discharge
    - Electron cylclotron resonance discharge
- High power impulse magnetron sputtering discharge (HiPIMS)
- Hollow cathode
- Summary



Ionized Physical Vapor Deposition (IPVD)

- In conventional dc magnetron 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%)
- The neutral metal ejected exhibits a cosine angular velocity distribution
- Over the last decade new ionized vapor deposition techniques have appeared that achieve 50 – 90 % ionization of the sputtered material
- 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. (Hopwood, 1998)

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

$$\lambda_{\mathrm{iz}} = \frac{v_{\mathrm{s}}}{k_{\mathrm{iz}} n_{\mathrm{e}}}$$

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

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

- The ion flux to the substrate is

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

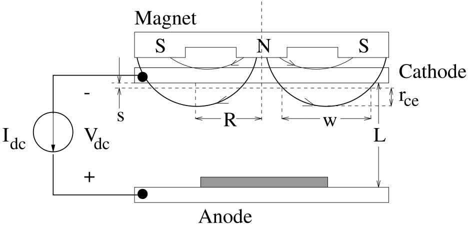
- The flux of thermalized neutrals is

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

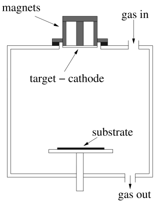
- Since $T_{\mathrm{e}} \gg T_{\mathrm{g}}$ the fractional ionization of the metal flux is larger than the fraction of ionized metal in the plasma
- It is not necessary to completely ionize the sputtered metal to create a highly ionized flux to the substrate

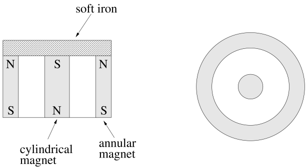
Planar magnetron sputtering discharge

- Magnetron sputtering discharges are widely used in thin film processing
- A magnet is placed at the back of the cathode target with the pole pieces at the center and perimeter
- A 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



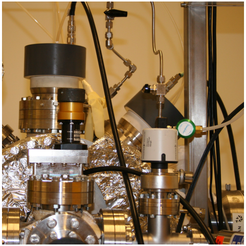


- A typical dc planar magnetron discharge operates at a pressure of 1 – 10 mTorr with a magnetic field strength of 0.01 – 0.05 T and at cathode potentials 300 – 700 V
- Electron density in the substrate vicinity is in the range $10^{15} - 10^{16}$ m^{-3}

Planar magnetron sputtering discharge

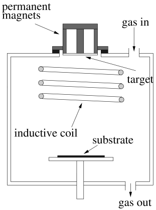
- Conventional magnetron sputtering processes are limited
  - low target utilization
  - target thermal load limits the available current
  - low fraction of the sputtered material is ionized

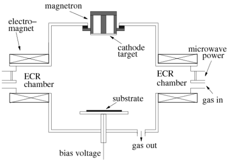
- Several sputtering systems have been designed to increase the ion flux at the substrate
- They include
  - pulsing the applied target voltage
  - additional ionization by a secondary discharge (rf or microwave)
  - increased magnetic confinement
  - reshaping the cathode for more focused plasma (hollow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



Secondary discharge in a magnetron sputtering discharge

- A secondary discharge is placed between the target and the substrate in a magnetron sputtering discharge
  - Inductively coupled plasma (ICP) discharge
  - Electron cyclotron resonance (ECR) discharge

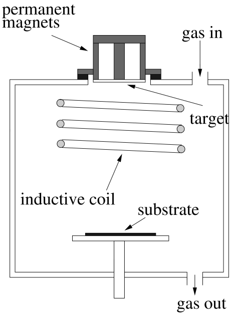




Secondary - Inductively coupled discharge (ICP-MS)

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

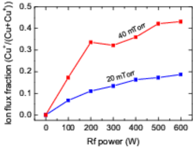
(Rossnagel and Hopwood, 1993, 1994; Wang et al., 1997)



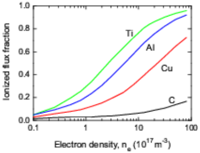
Secondary - Inductively coupled discharge (ICP-MS)

- The ionization fraction increases and saturates with increased rf power
- The ionization fraction saturates in the range 20 – 80 % depending on the discharge pressure and target material
- Global (volume averaged) model study
  - confirms the measured ionization fraction
  - indicates that electron impact ionization of the metal atoms dominates for electron density above 10^{17} m^{-3}

(Hopwood, 2000)



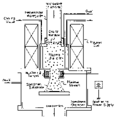
(After Wang et al. (1999))



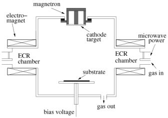
(After Hopwood (2000))

Secondary - Electron cylclotron resonance discharge (ECR-MS)

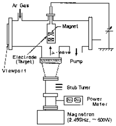
- A supplementary electron cyclotron resonance (ECR) discharge can be used to increase the ionization of the sputtered metal.
- ECR discharges are typically operated at microwave frequencies (e.g., $\sim$ 2.45 GHz) with a strong magnetic field B, giving high plasma densities ($10^{17} - 10^{18}$ m^{-3}) and are commonly operated at low working pressures (0.1–10 mTorr).



(From Takahashi et al. (1988))



(After Xu et al. (2001))

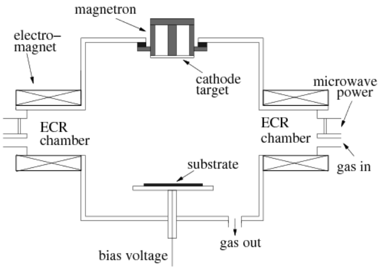


(From Yonesu et al. (1999))

Secondary - Electron cylclotron resonance discharge (ECR-MS)

- An ECR-MS apparatus, the two ECR discharge chambers are located at the opposite sites of the main processing chamber.
- A highly ionized plasma is created in the region between the target and the substrate.

(Musil et al., 1991; Takahashi et al., 1988; Xu et al., 2001)



(After Xu et al. (2001))

Secondary discharge in a magnetron sputtering discharge

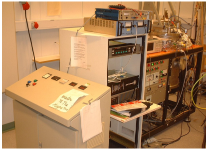
- In these discharges $n_{\mathrm{Ar}} \gg n_{\mathrm{M}}$ and the particle balance for the Ar plasma dictates the the electron temperature.
- For ICP and ECR discharges $n_{\mathrm{e}} \sim 10^{17} - 10^{18}$ m^{-3} so

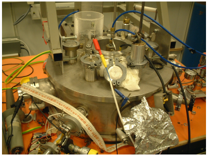
$$\lambda_{\mathrm{iz}} \sim \text{a few cm}$$

  if the sputtered vapor is thermalized
  - For $n_{\mathrm{e}} \ll 10^{17}$ m^{-3}, Penning ionization is the dominating process for metal ionization
  - for $n_{\mathrm{e}} \gg 10^{17}$ m^{-3} the metal ions are generated by electron impact ionization. (Hopwood, 2000)
- A high level of metal ionization is to be expected since the metals (Cu, Ti, Al, Ta) have ionization potentials in the range 6 – 8 V, significantly lower than for the used inert sputtering gas atoms used.

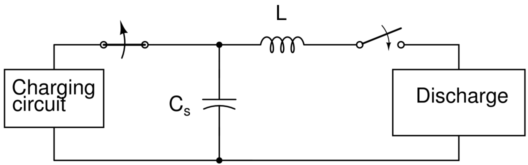
High power impulse magnetron sputtering discharge (HiPIMS)

- 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



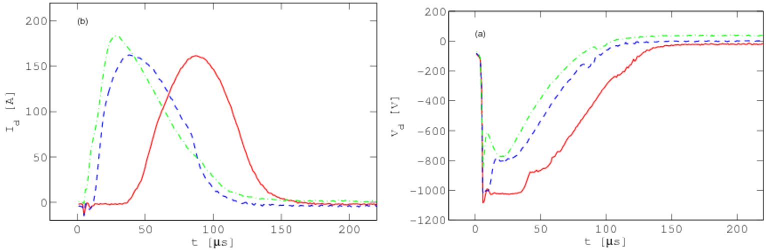


HiPIMS - Power supply



- 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 – 1000 Hz
  - Duty cycle in the range of 0.5 – 5 %

HiPIMS - Power supply

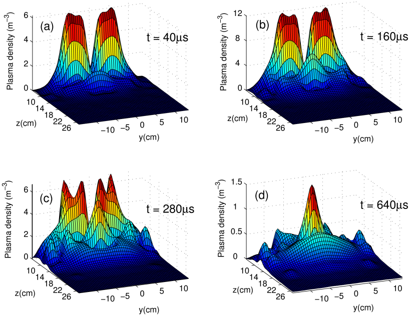


0.5 mTorr (solid line), 2 mTorr (dashed line) and 20 mTorr (dot dashed line)

(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

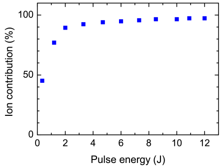


(After Bohlmark et al. (2005))

- 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 - 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., 2005)

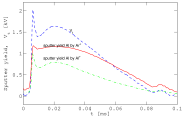


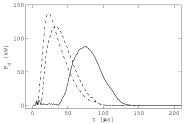
(From Bohlmark et al. (2005))

HiPIMS - Ionization fraction

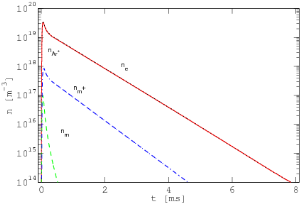
- To explore the ionization mechanism and the temporal behavior of the plasma parameters a time dependent global (volume averaged) model was developed

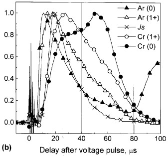
- The discharge is assumed to consist of
    - electrons, e
    - argon atoms in the ground state, Ar
    - metastable argon atoms, Ar^*
    - argon ions, Ar^+
    - metal atoms, M
    - metal ions, M^+





HiPIMS - Ionization fraction





From Ehiasarian et al. (2002)

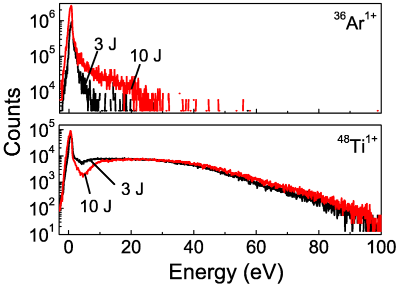
- The calculated electron and ion density versus time for Al target
- The first 100 μs electron impact ionization is the most effective process in creating metal ions
- The ionized flux fraction is $\sim$ 99 %

(Gudmundsson, 2007)

- The measured emission from a discharge with a Cr target

HiPIMS - Ion energy

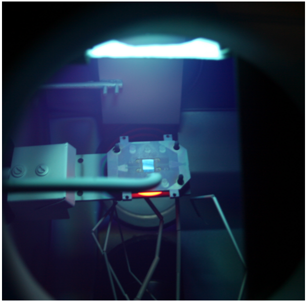
- The time averaged ion energy distribution for Ar^+ and Ti^+ ions
- The gas pressure was 3 mTorr, pulse energy 3 J and 10 J and the target made of Ti
- The ion energy distribution is broad to over 100 eV
- About 50 % of the Ti^+ ions have energy > 20 eV



(From Bohlmark et al. (2005))

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

HiPIMS - Applications

- HiPIMS has already been demonstrated on an industrial scale

  (Ehiasarian et al., 2006)

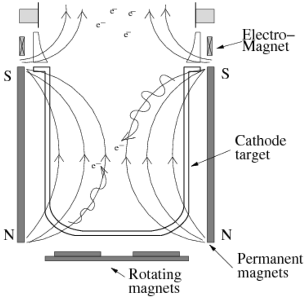
- Due to the absence of a secondary discharge in the reactor an industrial reactor can be upgraded to become IPVD device by changing the power supply

Other IPVD magnetron sputtering techniques

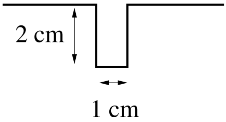
- Other IPVD methods include shaping the cathode target in a particular way referred to as hollow cathode magnetron (HCM) discharge

  (Klawuhn et al., 2000)

- An intense glow discharge forms in the cup-shaped cathode which confines the discharge both physically and electrostatically
- The HCM is capable of operating at an order of magnitude higher power densities than a conventional planar magnetron discharge and can be operated at very low pressures

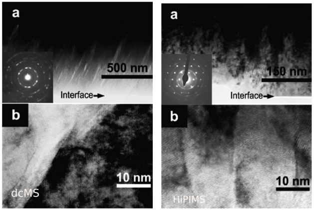


Application - Trench filling



- 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



(From Alami et al. (2005))

- 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 IPVD 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)
  - TiN thin film show increased microhardness and Yong's modulus with increaed rf power in ICP-MS (Lim et al., 2000)
- This illustrates how the bombarding ions transfer momentum to the surface allowing the microstructure to be modified

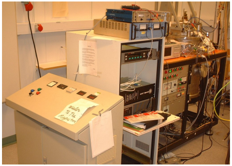
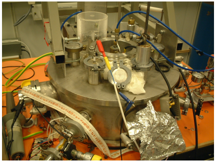
Summary

- The technology of ionized physical vapor deposition (IPVD) has been reviewed
  - Addition of a secondary discharge to a magnetron sputtering discharge
    - Ionization fraction is controlled by power to the secondary discharge and discharge pressure
  - The high power impulse magnetron sputtering discharge (HIPIMS)
    - Essentially the same sputtering apparatus except for the power supply
    - Roughly 2 orders of magnitude higher plasma density is achieved in the substrate vicinity than for a conventional dc magnetron sputtering discharge
    - Ionization fraction is high, mainly due to the high electron density

Summary

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

Acknowlegdements

- This work is a result of collaboration with
  - Dr. Jones Alami (Linköping University, Sweden now CemeCon A.G., Germany)
  - Dr. Johan Bohlmark (Linköping University, Sweden now Chemfilt A.B. Sweden)
  - Dr. Arutiun Ehiasarian (Sheffield Hallam University, UK)
  - Prof. Ulf Helmersson (Linköping University, Sweden)
  - Dr. Martina Latteman (Linköping University, Sweden)
  - Daniel Lundin (Linköping University, Sweden)
  - Páll Sigurjónsson (University of Iceland)
  - Kristinn B. Gylfason (University of Iceland now KTH Stockholm)
- The photographs were taken by Árni S. Ingason, Kristinn B. Gylfason and Markus Baur.
- This work was partially supported by the Icelandic Research Fund and the University of Iceland Research Fund.

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