Raunvísindaþing í Reykjavík 2006:

The high power impulse magnetron sputtering discharge: A brief review

J. T. Gudmundsson

Science Institute and
Department of Electrical and Computer Engineering,
University of Iceland
tumi@hi.is

3.-4. March 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) or high power impulse magnetron sputtering discharge (HiPIMS)
- It gives high electron density and highly ionized flux of the sputtered material

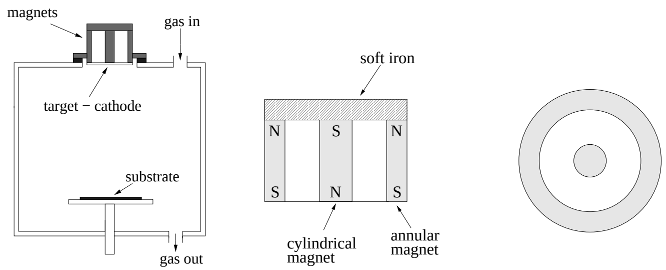
Introduction

- 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

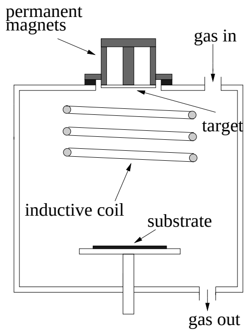
Ionized Physical Vapour Deposition (IPVD)

- When the flux of ions is higher than the flux of neutrals or $\Gamma_+ > \Gamma_{\rm m}$ the process is referred to as ionized physical vapour deposition (IPVD)
- This is achieved by
  - increased 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 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

rf Inductive Coil in a Magnetron

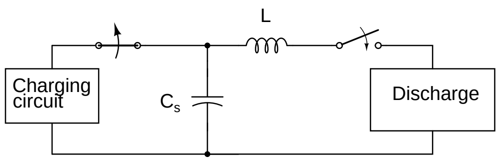


- In order to generate highly ionized discharge a radio-frequency discharge can be added in the region between the cathode and the anode
- The metal ions can then be accelerated to the substrate by means of a low voltage dc bias

HiPIMS

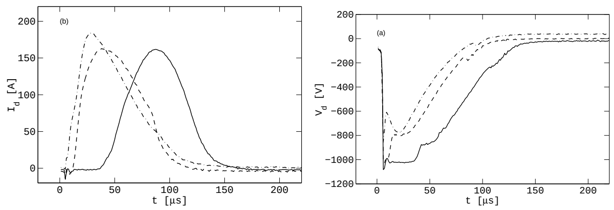
- In a conventional dc magnetron discharge the power density is limited by the thermal load on the target
- Most of the ion bombarding energy is transformed into heat at the target
- In unipolar pulsing the power supply is at low (or zero) power and then a high power pulse is supplied for a short period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

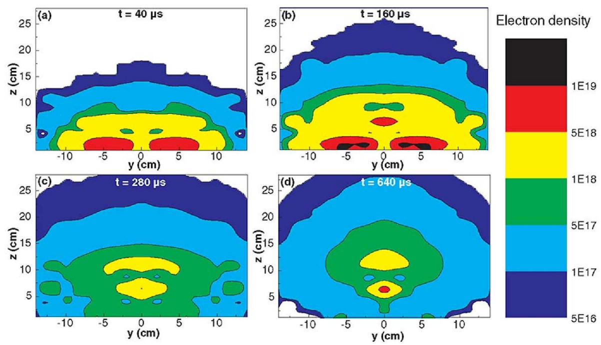


0.5 mTorr (solid line), 2 mTorr (dashed line) and 20 mTorr (dot dashed line)

(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

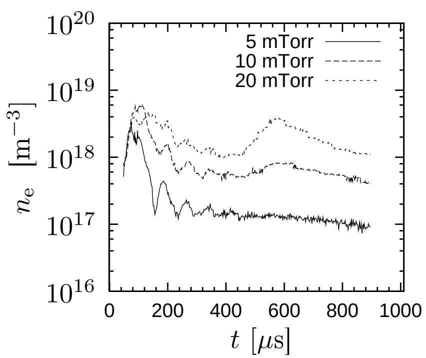
HiPIMS - Electron density



(From Bohlmark et al. (2005b))

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

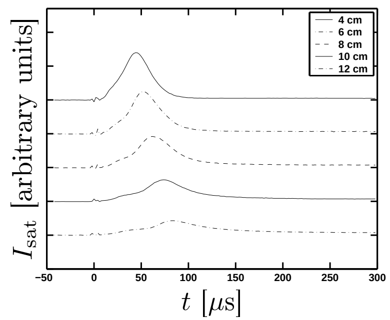
HiPIMS - Electron density



(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

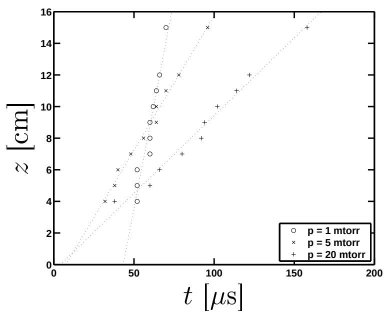
HiPIMS - Plasma dynamics



(From Gylfason et al. (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 - 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)

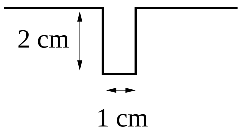
HiPIMS - Deposition rate

- 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

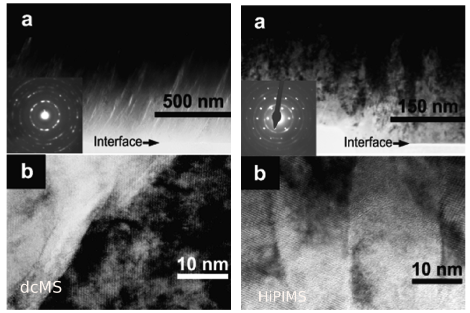
- One explanation is that the sputtered material is ionized close to the target and many of the metallic ions will be attracted back to the target surface by the cathode potential
- A reduction in the deposition rate would occur mainly for metals with a low self-sputtering yield
- Maybe this can be reduced by 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 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 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. (2005a,b)

References

Alami, J., Petersson, P. O. A., Music, D., Gudmundsson, J. T., Bohlmark, J., and Helmersson, U. (2005). Ion-assisted physical vapor deposition for enhanced film deposition on non-flat surfaces. *Journal of Vacuum Science and Technology A*, 23:278–280.

Bohlmark, J., Alami, J., Christou, C., Ehiasarian, A. P., and Helmersson, U. (2005a). Ionization of sputtered metals in high power pulsed magnetron sputtering. *Journal of Vacuum Science and Technology A*, 23(1):18–22.

Bohlmark, J., Gudmundsson, J. T., Alami, J., Latteman, M., and Helmersson, U. (2005b). Spatial electron density distribution in a high-power pulsed magnetron discharge. *IEEE Transactions on Plasma Science*, 33(2):346–347.

Bugaev, S. P., Koval, N. N., Sochugov, N. S., and Zakharov, A. N. (1996). Investigation of a high-current pulsed magnetron discharge initiated in the low-pressure diffuse arc plasma. In *XVIIth International Symposium on Discharges and Electrical Insulation in Vacuum, 1996*, pages 1074–1076, Berkeley, CA USA. IEEE.

Davis, J. A., Sproul, W. D., Christie, D. J., and Geisler, M. (2004). High power pulse reactive sputtering of TiO_2. In *47th Annual Technical Conferenece Proceedings*, pages 215–218, Dallas, TX, USA. Society of Vacuum Coaters.

DeKoven, B. M., Ward, P. R., Weiss, R. E., Christie, D. J., Scholl, R. A., Sproul, W. D., Tomasel, F., and Anders, A. (2003). Carbon thin film deposition using high power pulsed magnetron sputtering. In *46th Annual Technical Conferenece Proceedings*, pages 158–165, San Francisco, CA, USA. Society of Vacuum Coaters.

Gudmundsson, J. T., Alami, J., and Helmersson, U. (2002). Spatial and temporal behavior of the plasma parameters in a pulsed magnetron discharge. *Surface and Coatings Technology*, 161(2-3):249–256.

Gylfason, K. B., Alami, J., Helmersson, U., and Gudmundsson, J. T. (2005). Ion-acoustic solitary waves in a pulsed magnetron sputtering discharge. *Journal of Physics D: Applied Physics*, 38(18):3417–3421.

Helmersson, U., Lattemann, M., Alami, J., Bohlmark, J., Ehiasarian, A. P., and Gudmundsson, J. T. (2005a). High power impulse magnetron sputtering discharges and thin film growth: A brief review. In *48th Annual Technical Conferenece Proceedings*, pages 458 – 464, Denver, CO, USA. Society of Vacuum Coaters.

Helmersson, U., Lattemann, M., Bohlmark, J., Ehiasarian, A. P., and Gudmundsson, J. T. (submitted for publication 2005b). Ionized physical vapor deposition (IPVD): A review of technology and applications. *Thin Solid Films*.

Kouznetsov, V., Macák, K., Schneider, J. M., Helmersson, U., and Petrov, I. (1999). A novel pulsed magnetron sputter technique utilizing very high target power densities. *Surface and Coatings Technology*, 122(2-3):290–293.

Macák, K., Kouznetzov, V., Schneider, J. M., Helmersson, U., and Petrov, I. (2000). Ionized sputter deposition using an extremely high plasma density pulsed magnetron discharge. *Journal of Vacuum Science and Technology A*, 18(4):1533–1537.

Sproul, W. D., Christie, D. J., Carter, D. C., Tomasel, F., and Linz, T. (2004). Pulsed plasmas for sputtering applications. *Surface Engineering*, 20:174–176.