The High Power Impulse Magnetron Sputtering (HiPIMS) Discharge

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Magnetron sputtering has been the workhorse of plasma based sputtering methods for over three decades. For many applications a high degree of ionization of the sputtered vapor is desired:

- controlled ion bombardment of the growing film
- ion energy can be controlled by a negative bias applied to the substrate
- collimation – enhanced step coverage

Ionized flux of sputtered vapor therefore introduces an additional control parameter into the deposition process.
Outline

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

- For a typical dc planar magnetron discharge
  - pressure of $1 - 10$ mTorr
  - a magnetic field strength of $0.01 - 0.05$ T
  - cathode potentials $300 - 700$ V
  - average power $200 - 600$ W
  - electron density in the substrate vicinity is $10^{15} - 10^{17}$ m$^{-3}$
  - low fraction of the sputtered material is ionized $\sim 1\%$
  - the majority of ions are the ions of the inert gas
  - the sputtered vapor is mainly neutral
Planar Magnetron Sputtering Discharge

- In magnetron sputtering discharges increased ionized flux fraction is achieved by
  - 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 cathode)
  - increasing the power to the cathode (high power pulse)
- Common to all highly ionized magnetron sputtering techniques is a very high density plasma
Ionized Physical Vapor Deposition (IPVD)
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When the flux of ions is higher than the flux of neutrals or \( \Gamma_i > \Gamma_m \) the process is referred to as 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.
Ionized Physical Vapor Deposition (IPVD)

- Ionizing the sputtered vapor has several advantages:
  - improvement of the film quality, increased film density
    - Kusano (2006) 49th SVC, p. 15, Lim et al. (2000) JVSTA 18 524,
    - Samuelsson et al. (2010) SCT 202 591
  - improved adhesion
    - Ehiasarian et al. (2007) JAP 101 054301
  - improved surface roughness
    - Sarakinos et al. (2007) JPD 40 2108
  - deposition on substrates with complex shapes and high aspect ratio
    - Alami et al. (2005) JVSTA 23 278
  - phase tailoring
    - Alami et al. (2007) TSF 515 3434
  - guiding of the deposition material to the desired areas of the substrate
    - Bohlmark et al. (2006) TSF 515 1928
  - hysteresis free reactive sputtering has been demonstrated in a HiPIMS discharge
    - Wallin and Helmersson (2008) TSF 516 6398
The system design is determined by the average distance a neutral particle travels before being ionized. The ionization mean free path is

\[ \lambda_{iz} = \frac{v_s}{k_{iz} n_e} \]

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

- Typical parameters for argon gas and copper target

| Gas | $v_s$ [m/s] | $T_e$ [V] | $n_e$ [m$^{-3}$] | $\lambda_{iz}$ [cm] | Discharge         |
|-----|-------------|-----------|------------------|----------------------|-------------------|
| Ar  | 1000$^a$    | 3         | $10^{17}$        | 162                  | dcMS              |
| Ar  | 300         | 3         | $10^{17}$        | 49                   | ICP-MS/ECR-MS     |
| Ar  | 300         | 3         | $10^{18}$        | 4.9                  | HiPIMS            |
| Ar  | 300         | 3         | $10^{19}$        | 0.5                  | SSS-HiPIMS        |
| Cu  | 300         | 1.5       | $10^{19}$        | 7.5                  |                   |

$^a$(Britun et al. (2008) APL 92 141503)
Another important parameter is the fraction of ionized metal flux

\[ \frac{\Gamma_i}{\Gamma_i + \Gamma_n} \]

The ion flux to the substrate is

\[ \Gamma_i \approx 0.61 n_m u_B \sim \sqrt{T_e} \]

The flux of thermalized neutrals is

\[ \Gamma_n = \frac{1}{4} n_m v_{Th} \sim \sqrt{T_g} \]

Since \( T_e \gg T_g \) the fraction of ionized 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.
High Power Impulse Magnetron Sputtering (HiPIMS)
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- In a conventional dc magnetron discharge, the power density is limited by the thermal load on the target.
- In a HiPIMS discharge a high power pulse is supplied for a short period:
  - low frequency
  - low duty cycle
  - low average power
- The HiPIMS discharge uses the same sputtering apparatus except the 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/cm²
- Power densities in the range of 1 – 3 kW/cm²
- Average power 200 – 600 W
- Frequency in the range of 50 – 5000 Hz
- Duty cycle in the range of 0.5 – 5 %
The exact pulse shape is determined by the load:
- the discharge formed
- it depends on the gas type and gas pressure
- and the electronics of the power supply
High Power Impulse Magnetron Sputtering (HiPIMS) - Electrons
HiPIMS - Electron density

Temporal and spatial variation of the electron density

- Ar discharge at 20 mTorr, Ti target, pulse length 100 $\mu$s
- The electron density in the substrate vicinity is of the order of $10^{18} - 10^{19}$ m$^{-3}$

(After Bohlmark et al. (2005), IEEE Trans. Plasma Sci. 33 346)
HiPIMS - Electron density

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 and the target made of tantalum. A strong initial peak appears. A second peak appears later in time at higher pressure.

(After Gudmundsson et al. (2002), SCT 161 249)
The electron saturation current as a function of location and time from pulse initiation

The argon pressure was 5 mTorr and 20 mTorr, the target was made of titanium, and the pulse energy 6 J
Each peak travels with a fixed velocity through the chamber.

- The peaks travel with a velocity of $5.3 \times 10^3$ m/s at 1 mTorr, $1.7 \times 10^3$ m/s at 5 mTorr, and $9.8 \times 10^2$ m/s at 20 mTorr.
HiPIMS - Plasma dynamics

- The plasma density versus time while varying the
  - sputtering gas
  - chamber dimension
  - distance to target
  - applied power
- The first peak appears immediately after the plasma ignition
- The peaks increase with increased applied power

From Alami et al. (2005) PSST 14 525
HiPIMS - Electron energy

The electron energy probability function (EEPF) under the race-track 100 mm below the target for an argon discharge at 3 (dashed) and 20 (solid) mTorr with a copper target.

From Gudmundsson et al. (2009) JAP 105 123302
The measured EEPF is Maxwellian-like during the pulse.
- High electron density leads to a Maxwellian-like low energy part of the EEPF.
- The depletion in the high energy part is due to the escape of high energy electrons to the chamber walls and inelastic collisions of high energy electrons.

The EEPF is more broad at low pressure and early in the pulse.
Temporal variation of the effective electron temperature 100 mm below the target under the race-track ($r = 40$ mm)

- The electron energy decreases with increased discharge pressure
The peak electron density is of the order of $10^{18} - 10^{19} \text{ m}^{-3}$

Gudmundsson et al. (2001) APL 78 3427
Gudmundsson et al. (2002) SCT 161 249

A monotonic rise in plasma density
- with discharge gas pressure
  Gudmundsson et al. (2002) SCT 161 249
- applied power Alami et al. (2005) PSST 14 525

A linear increase in electron density with increased discharge current

Ehiasarian et al. (2008) JAP 104 083305

After Bohlmark et al. (2005)
The electron density depends on the target material
- Cr target gives higher density than Ti
  Vetushka and Ehiasarian (2008) JPD 41 015204

The peak electron density travels away from the target with fixed velocity
Gylfason et al. (2005) JPD 38 3417

The electron energy distribution function (EEDF) during the pulse is Maxwellian-like
Gudmundsson et al. (2009) JAP 105 123302
High Power Impulse Magnetron Sputtering (HiPIMS) - Ions
HiPIMS - Ionization fraction

- Conventional dc magnetron discharge - Pre-ionization - violet argon discharge
- HiPIMS discharge averaged over several pulses - green discharge characteristic of Cu vapour
- The Cu$^+$ lines are only observed in HiPIMS mode

From Vašina et al. (2007) PSST 16 501
There have been conflicting reports on the fraction of ionized metal flux:

- 70 % for Cu, Kouznetsov et al. (1999) SCT 122 290
- 56 % for Cu, Vlček et al. (2007a) JVSTA 25 42
- 99 % for Ti, Kudláček et al. (2008) PSST 17 025010
- 40 % for Ti$_{0.5}$Al$_{0.5}$, Macák et al. (2000) JVSTA 18 1533
- 9.5 % for Al, DeKoven et al. (2003) 46th SVC p. 158
- 4.5 % for C, DeKoven et al. (2003) 46th SVC p. 158

The degree of ionization:
- 90 % for Ti, Bohlmark et al. (2005) JVSTA 23 18

The fraction of ionized metal flux depends on applied power, pulse frequency and pulse length, and distance from the target.

From Bohlmark et al. (2005)
HiPIMS - Ionization fraction

- The ion flux versus time measured by a mass spectrometer (20 $\mu$s windows)
- The gas pressure was 3 mTorr, pulse energy 8 J and the target made of Ti
- Highly metallic ion flux during the active phase of the discharge

From Bohlmark et al. (2006) TSF 515 1522
HiPIMS - Ionization fraction

- The discharge develops from an argon dominated discharge to a metal dominated discharge during the active phase of the discharge.
- This has been observed both by optical emission spectroscopy and mass spectroscopy.
- Cu-ions have been measured to be up to 92% of the total ion flux at the substrate (Vlček et al. (2007) EPL 77 45002)
- Ti-ions are up to 29% of the total ion flux at the same conditions (Kudláček et al. (2008) PSST 17 025010)
HiPIMS - Ionization fraction

- During the initial stages of the pulse Ar$^+$ ions dominate the discharge
- Later in the pulse metal ions build up and become the abundant ion species
- Multiply charged ions have been observed
- Significant fraction of the ion flux is Ti$^{2+}$
  
  Bohlmark et al. (2006) TSF 515 1522

- Ti$^{4+}$ ions have been observed

  Andersson et al. (2008) APL 93 071504

From Bohlmark et al. (2006) 515 1522

From Ehiasarian et al. (2002) Vacuum 65 147
HiPIMS - Multiply charged ions

- Multiply charged metal ions are crucial for the transition of the discharge from argon ion sputtering to self-sputtering.
- Singly charged metal ions cannot create the secondary electrons necessary to maintain metal self-sputtering ($\gamma_{SE}$ is practically zero).
- The first ionization energies of many metals are insufficient to overcome the workfunction of the target material.

Anders et al. (2007) JAP 102 113303, Anders (2008) APL 92 201501
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) TSF 515 1522
**HiPIMS - Ion energy**

- Significant fraction of the Ti$^{+}$ ions are transported radially outwards
- Direction dependent high energy-tail

From Lundin et al. (2008) PSST 17 035021
HiPIMS - Charged particle transport

- It has been observed that the electron cross-\( \mathbf{B} \) transport in HiPIMS discharges is much faster than classical collision theory predicts.

- The diffusion coefficient is roughly a factor 5 greater than what Bohm diffusion would predict.

Brenning et al. (2009) PRL \textbf{103} 225003

Lundin et al. (2011) PSST \textbf{20} 045003

From Lundin et al. (2011) PSST \textbf{20} 045003
Gasless self-sputtering of copper has been demonstrated 

Andersson and Anders (2009) PRL 102 045003

This self-sputtering in vacuum can deliver extraordinarily high metal-ion current 

The usable ion current increased exponentially with increasing discharge voltage.
High Power Impulse Magnetron Sputtering (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) XVIIth Symp. Disc. Elec. Ins. Vac., p. 1074

- A factor of 3 – 7 lower deposition rate for reactive sputtering of TiO$_2$ from a Ti target and AlO$_x$ from an Al target
  Davis et al. (2004) 47th SVC, p. 215, Sproul et al. (2004) 47th SVC, p. 96

- The reduction in deposition rate decreases with decreased magnetic confinement (weaker magnetic field)
  Bugaev et al. (1996)

- A detailed study of various target materials confirms a consistently lower deposition rate
  Samuelsson et al. (2010) SCT 202 591
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.

- The deposition rate in the self sputtering mode is lower than when argon sputtering is dominating.

Horwat and Anders (2008) JPD 41 135210
HiPIMS - Deposition rate

- It has been claimed that the magnetic confinement influences the deposition rate
  Bohlmark et al. (2006) TSF 515 1928, Bugaev et al. (1996)

- A significant fraction of the ions of the sputtered material are transported sideways
  Lundin et al. (2008) PSST 17 035021

- Also when comparing dcMS and HiPIMS discharges at the same average power the non-linear scaling of the sputter yield with the applied voltage is not taken into account
  Emmerlich et al. (2008) Vacuum 82 867

- The reduced deposition rate observed in the HiPIMS discharge is likely to be a combination of these factors
High Power Impulse Magnetron Sputtering (HiPIMS) - Applications
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
- Substrate bias of -50 V
- They were compared by scanning electron microscope (SEM), transmission electron microscope (TEM)
Application - Trench filling

- 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.

From Alami et al. (2005) JVSTA 23 278
Other applications

- The HiPIMS gives consistently denser films.
- This illustrates how the bombarding ions transfer momentum to the surface allowing the microstructure to be modified.

From Samuelsson et al. (2010) SCT 202 591
HiPIMS - Applications

- HiPIMS has already been demonstrated on an industrial scale (Ehiasarian et al., 2006) 49th SVC, p. 349

- 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
Summary
Summary

- The design parameters for Ionized Physical Vapor Deposition (IPVD) were discussed.
- The high power impulse magnetron sputtering discharge (HIPIMS) has been demonstrated as an Ionized Physical Vapor Deposition (IPVD) tool.

- 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.
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
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