High power impulse magnetron sputtering discharge (HIPIMS)

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The high power impulse magnetron sputtering (HIPIMS) discharge is a recent addition to plasma based sputtering technology. In HIPIMS, high power is applied to the magnetron target in unipolar pulses at low duty cycle and low repetition frequency while keeping the average power about 2 orders of magnitude lower than the peak power [1]. This results in a high plasma density, and high ionization fraction of the sputtered vapor, which allows better control of the film growth by controlling the energy and direction of the deposition species. This is a significant advantage over conventional dc magnetron sputtering where the sputtered vapor consists mainly of neutral species. The HIPIMS discharge is now an established ionized physical vapor deposition technique [2,3], which is easily scalable and has been successfully introduced into various industrial applications. An overview of the development of the HIPIMS discharge and the underlying mechanisms that dictate the discharge properties is given. The development and properties of the high power pulsed power supply will be discussed, followed by an overview of the measured plasma parameters in the HIPIMS discharge, the electron energy and density, the ion energy, ion flux and plasma composition, and a discussion on the deposition rate. Then a brief overview of the benefits and applications of the HIPIMS technique is given.


High Power Impulse Magnetron Sputtering (HiPIMS)

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Introduction

- 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 – 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
  - Voltage - Current - time
  - Electrons
  - Ions
  - Deposition rate
  - Applications
- Summary

Planar Magnetron Sputtering Discharge
High Power Impulse Magnetron Sputtering (HiPIMS)

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

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.**
High Power Impulse Magnetron Sputtering (HiPIMS)  

Ionized Physical Vapor Deposition (IPVD)

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 (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
High Power Impulse Magnetron Sputtering (HiPIMS)

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

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

$^a$ (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
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 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/cm²
  - Power densities in the range of 0.5 – 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 %

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HiPIMS - Power supply

- High power pulsed magnetron sputtering (HPPMS)
- HiPIMS
  - a pulse of very high amplitude, an impulse, is applied to the cathode and a long pause exists between the pulses
- Modulated pulse power (MPP)
  - the initial stages of the pulse (few hundred µs) the power level is moderate (typical for a dcMS) followed by a high power pulse (few hundred µs up to a ms)

From Gudmundsson et al. (2012), JVSTA 30 030801

- Power density limits
  - $p_1 = 0.05$ kW/cm² dcMS limit
  - $p_1 = 0.5$ kW/cm² HiPIMS limit
HiPIMS - Power supply

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

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

This may include both rotating magnetron sputtering discharge and unbalanced multimagnetron sputtering systems referred to as closed field unbalanced multimagnetron systems (CFUBMS)
High Power Impulse Magnetron Sputtering (HiPIMS) - Voltage - Current - Time characteristics

To describe the discharge current-voltage characteristics, the current-voltage-time space is required.

The early work on HiPIMS used 50 – 100 µs pulses.

The cathode voltage and the discharge current depend on the discharge gas pressure.

From Gudmundsson et al. (2012), JVSTA 30 030801
For longer pulses the initial pressure dependent current peak is followed by a second phase that is power and material dependent. The initial phase is dominated by gas ions, whereas the later phase has a strong contribution from self-sputtering. For some materials, the discharge switches into a mode of sustained self-sputtering.

A schematic illustration of the discharge current assuming square shaped voltage pulses. The current is generally characterized by an initial peak followed by a more or less stable current plateau (bottom current curves). In other cases it shows an initial peak followed by a second increase of the discharge current (top current curves).
The self-sputtering can operate in a self-sustained mode, when the ions of the sputtered vapor are created at high enough rate that the ions of the working gas are not needed.

The condition for sustained self-sputtering is expressed as

$$\Pi_{ss} = \alpha \beta_t Y_{ss} = 1$$

where

- $\alpha$ is the probability of ionization of the sputtered atom
- $\beta_t$ is the probability that the newly formed ion of the sputtered vapor returns to the target
- $Y_{ss}$ is the self-sputter yield of the ion

This is a steady state situation and the current remains constant.

Note that since $\alpha < 1$ and $\beta_t < 1$ the condition $Y_{ss} > 1$ is necessary but not sufficient for achieving sustained self-sputtering.

The transient phase of self-sputtering runaway occurs when $\Pi_{ss} > 1$.

Self-sputtering runaway occurs at a well-defined threshold power, determined by the discharge voltage and is readily obtained for high sputter yield materials.

But runaway can also occur at lower threshold voltages than for pure self-sputtering as well as for transition metals and target materials of low sputter yield due to what is referred to as ‘gas recycling’ runaway.

Anders (2011), SCT 205 S1, Anders et al. (2012) JPD 45 012003
**HiPIMS - Voltage - Current - time**

- The bottom curve represents a range of low self-sputtering, \( \Pi_{ss} < 0.1 \) and the discharge physics in the plateau/runaway phase is dcMS-like.
- The middle range of power densities, with \( 0.1 < \Pi_{ss} < 1 \), represents partially self-sputtering discharge.
- The top curve represents self-sputtering runaway which requires \( \Pi_{ss} > 1 \) and a self-sputter yield \( Y_{ss} > 1/(\alpha \beta t) > 1 \).

From Gudmundsson et al. (2012), JVSTA 30 030801

**HiPIMS - Voltage - Current - time**

- During reactive sputtering, a reactive gas is added to the inert working gas.
- This changes the plasma composition by adding new ion species, and the target condition can also change due to the formation of a compound on its surface.
- The current waveform of Ar/O\(_2\) discharge is highly dependent on the repetition frequency and applied voltage which is linked to oxide formation on the target.

From Magnus et al. (2012), JVSTA submitted
Similarly the current waveform in the reactive Ar/N₂ HiPIMS discharge is highly dependent on the pulse repetition frequency, unlike for pure Ar. The current is found to increase significantly as the frequency is lowered. This is attributed to an increase in the secondary electron emission yield during the self-sputtering phase, when the nitride forms on the target at low frequencies.

At high frequencies, a nitride is not able to form between pulses, and self-sputtering by Ti⁺-ions (singly and multiply charged) from a Ti target is the dominant process. At low frequency, the long off-time result in a nitride layer being formed on the target surface and self-sputtering by Ti⁺ and N⁺-ions from TiN takes place. The observed changes in the discharge current are reflected in the flux of ions impinging on the substrate.

From Magnus et al. (2011b), JAP 110 083306.
High Power Impulse Magnetron Sputtering (HiPIMS) - Electrons

Temporal and spatial variation of the electron density
Ar discharge at 20 mTorr, Ti target, pulse length 100 µs
The electron density in the substrate vicinity is of the order of $10^{18} - 10^{19}$ m$^{-3}$
HiPIMS - Electron density

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 - Electron energy

The measured EEPF is Maxwellian-like during the pulse at 3 (dashed) and 20 (solid) mTorr with a copper target.

- 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.
HiPIMS - Electron energy

- 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

HiPIMS - Electron density - summary

- The peak electron density is of the order of $10^{18} - 10^{19}$ 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
**HiPIMS - Electrons - summary**

- 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

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**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

There have been conflicting reports on the fraction of ionized metal flux:
- 70% for Cu Koznetsov 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 Bohmárik 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.
High Power Impulse Magnetron Sputtering (HiPIMS)

**HiPIMS - Ionization fraction**

- The ion flux versus time measured by a mass spectrometer (20 µs 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

- 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 Ehiasarian et al. (2002) Vacuum 65 147 1522
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.


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
High Power Impulse Magnetron Sputtering (HiPIMS)

**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

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**HiPIMS - Charged particle transport**

- It has been observed that the electron cross-\(B\) 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 103 225003
Lundin et al. (2011) PSST 20 045003

From Lundin et al. (2011) PSST 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
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
- A factor of 3 – 7 lower deposition rate for reactive sputtering of TiO₂ from a Ti target and AlOₓ from an Al target
- 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

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)

**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)

From Alami et al. (2005) JVSTA 23 278

dc magnetron | HiPIMS

- 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
**Application – Film Density**

- 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

**Application – Film Resistivity**

- TiN as diffusion barriers in copper and aluminum interconnects
- HiPIMS deposited films have significantly lower resistivity than dcMS deposited films on SiO₂ at all growth temperatures due to reduced grain boundary scattering
- Thus, ultrathin continuous TiN films with superior electrical characteristics can be obtained with HiPIMS at reduced temperatures

From Magnus et al. (2012) IEEE EDL accepted
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
- Film quality
  - Films deposited by HiPIMS are denser, more resistant to oxidation, smoother surfaces etc. – higher quality films are achieved at lower deposition temperature than by dcMS

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http://langmuir.raunvis.hi.is/~tumi/hipims.html


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