Reactive High Power Impulse Magnetron Sputtering (HiPIMS)

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60th AVS International Symposium & Exhibition,
Long Beach, California
October 28., 2013
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.

In a HiPIMS discharge a high power pulse is supplied for a short period:
- low frequency
- low duty cycle
- low average power

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

- 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
  - $p_t = 0.05 \text{ kW/cm}^2$ dcMS limit
  - $p_t = 0.5 \text{ kW/cm}^2$ HiPIMS limit
Reactive HiPIMS - Applications
Reactive High Power Impulse Magnetron Sputtering (HiPIMS)

Application – Film Resistivity

- TiN as diffusion barriers for 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 and high resistance towards oxidation can be obtained with HiPIMS at reduced temperatures

From Magnus et al. (2012) IEEE EDL 33 1045
Application – Bragg mirror

- Multilayer structures containing a high-contrast (TiO$_2$/SiO$_2$) Bragg mirror fabricated on fused-silica substrates
  - reactive HiPIMS TiO$_2$ (88 nm)
  - reactive dcMS SiO$_2$ (163 nm)
  - capped with semitransparent gold
- Rutile TiO$_2$ ($n = 2.59$) and SiO$_2$ ($n = 1.45$) provide a large index contrast
- Smooth rutile TiO$_2$ films can be obtained by HiPIMS at relatively low growth temperatures, without post-annealing


Agnarsson et al. (2013) TSF 545 445
Reactive 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 and a pulse repetition frequency in the range 50–1000 Hz.

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**.

From Anders et al. (2007), JAP 102 113303 and JAP 103 039901
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**HiPIMS - Voltage - Current - time**

- 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).

From Gudmundsson et al. (2012), JVSTA 30 030801
HiPIMS - Voltage - Current - time

- 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.
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
Reactive High Power Impulse Magnetron Sputtering (HiPIMS)

**HiPIMS - Voltage - Current - time**

- Ar discharge with Ti target
- The initial peak in current results in a large flux of atoms from the target
- Collisions of the sputtered atoms with the working gas result in heating and expansion of the working gas – **rarefaction**
- A significant fraction of the sputtered atoms experience electron impact ionization (the ionization mean free path $\sim 1$ cm) and are attracted back to the target to participate in the sputtering process – **self-sputtering**

From Magnus et al. (2011) JAP 110 083306
During reactive sputtering, a reactive gas is added to the inert working gas.

The current waveform in the reactive Ar/N\textsubscript{2} HiPIMS discharge is highly dependent on the pulse repetition frequency, unlike for pure Ar.

N\textsubscript{2} addition changes the plasma composition and the target condition can also change due to the formation of a compound on its surface.

From Magnus et al. (2011) JAP 110 083306
Similarly for the Ar/O$_2$ discharge, the current waveform is highly dependent on the repetition frequency and applied voltage which is linked to oxide formation on the target.

The current is found to increase significantly as the frequency is lowered.

From Magnus et al. (2012), JVSTA 30 050601
The observed changes in the discharge current are reflected in the flux of ions impinging on the substrate.

From Magnus et al. (2011), JAP 110 083306
The discharge current $I_d$ is the sum of the ion current $I_i$ and the secondary electron current $I_i \gamma_{SE}$ or

$$I_d = I_i (1 + \gamma_{SE})$$

where $\gamma_{SE}$ is the secondary electron emission coefficient of the target material.

Also

$$I_i \propto n_i \propto \frac{1}{\varepsilon_T}$$

The total energy loss per electron-ion pair lost from the system $\varepsilon_T$ is expected to increase with the addition of nitrogen.

We must turn to the secondary electron emission yield to explain the self-sputtering runaway and observed frequency dependence of the current in the reactive discharge.
HiPIMS differs significantly from dcMS, due to the fact that self-sputtering quickly becomes dominant and the working gas ions (mostly Ar\(^+\) and N\(_2\)^+ or O\(_2\)^+) are depleted from the area in front of the target, due to rarefaction.

The secondary electron emission yield is governed by the composition of the target (Ti or TiN or TiO\(_2\)) and the type of ions that are bombarding it.

From Magnus et al. (2011), JAP 110 083306
and Magnus et al. (2012), JVSTA 30 050601
Reactive High Power Impulse Magnetron Sputtering (HiPIMS)

HiPIMS - Voltage - Current - time

- $\gamma_{SE}$ is practically zero for singly charged metal ions impacting a target of the same metal.
- $\gamma_{SE}$ will be higher for self-sputtering from a TiN or TiO$_2$ target, where N$^+$-ions or O$^+$-ions are also present, than for self-sputtering from a Ti target, where multiply charged Ti ions are needed to create secondary electrons.

From Magnus et al. (2011), JAP 110 083306
and Magnus et al. (2012), JVSTA 30 050601
At high frequencies, nitride or oxide 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 results in a nitride or oxide layer being formed on the target surface and self-sputtering by Ti\(^{+}\) and N\(^{+}\)-ions or O\(^{+}\)-ions from TiN or TiO\(_2\) takes place.

From Magnus et al. (2011), JAP 110 083306 and Magnus et al. (2012), JVSTA 30 050601
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- As the oxygen flow is increased a transition to oxide mode is observed – The delay in the onset of the current increases, the initial current peak is lowered and a transition to a self-sputtering runaway occurs.

- It has been confirmed that in the oxide mode, the discharge is dominated by O\(^+\)-ions, due to oxygen atoms sputtered off the target surface.

![Graph showing current waveforms for an Ar/O\(_2\) discharge with a Ti target where the oxygen flow rate is varied.

The current waveforms for an Ar/O\(_2\) discharge with a Ti target where the oxygen flow rate is varied – 600 V, 50 Hz and 0.6 Pa.

Aiempanakit et al. (2013), JAP 113 133302
Summary
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- The current-voltage-time waveforms in a reactive discharge exhibit similar general characteristics as the non-reactive case.
  - The current rises to a peak, then decays because of rarefaction before rising to a self-sputtering dominated phase.
- At low repetition frequency, the long off-time results in a nitride or oxide layer being formed on the target surface and self-sputtering by Ti\(^+\) and N\(^+\) or O\(^+\)-ions from TiN or TiO\(_2\) takes place with an increase in secondary electron emission yield and a corresponding increase in discharge current.
References

The slides can be downloaded at

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


