Reactive High Power Impulse Magnetron Sputtering (HiPIMS)

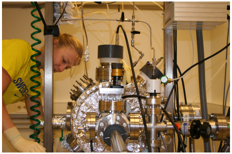
Jón Tómas Guðmundsson[1], Friðrik Magnus[1,2], Tryggvi K. Tryggvason[1,3], Ólafur B. Sveinsson[1,4], S. Shayestehaminzadeh[1], and Sveinn Ólafsson[1]

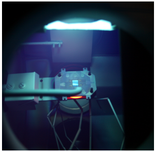
[1] Science Institute, University of Iceland, Iceland
[2] Uppsala University, Sweden
[3] Lund University, Sweden
[4] Linköping University, Sweden

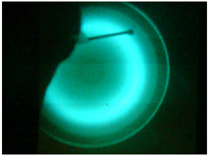
tumi@hi.is

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

Introduction



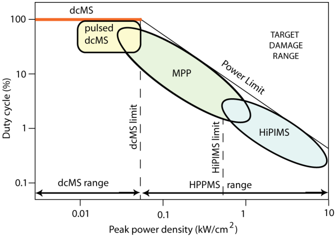




- Magnetron sputtering has been the workhorse of plasma based sputtering methods for over three decades
- For many applications a high degree of ionization of the sputtered vapor is desired
- In a HiPIMS discharge a high power pulse is supplied for a short period
  - low frequency
  - low duty cycle
  - 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)



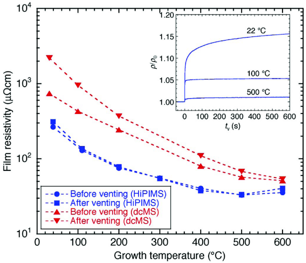
From Gudmundsson et al. (2012), JVSTA **30** 030801

- Power density limits
  $p_t = 0.05$ kW/cm^2 dcMS limit
  $p_t = 0.5$ kW/cm^2 HiPIMS limit

Reactive HiPIMS - Applications

Application – Film Resistivity

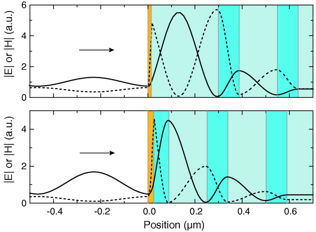
- TiN as diffusion barriers for interconnects
- HiPIMS deposited films have significantly lower resistivity than dcMS deposited films on SiO_2 at all growth temperatures due to reduced grain boundary scattering
- Thus, ultrathin continuous TiN films with superior electrical characteristics and high resistance 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



From Leosson et al. (2012) Opt. Lett. **37** 4026

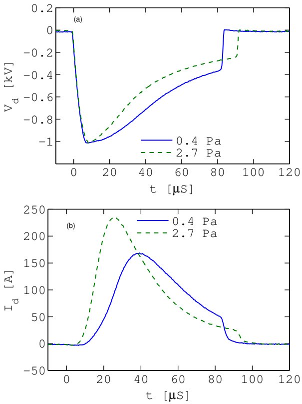
Magnus et al. (2011) Mater. Res. Soc. Symp. Proc. Vol. 1352

Agnarsson et al. (2013) TSF **545** 445

Reactive HiPIMS - Voltage - Current - Time characteristics

HiPIMS - Voltage - Current - time

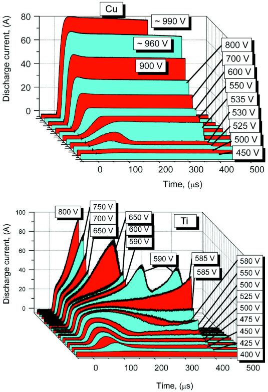
- To describe the discharge current-voltage characteristics the current-voltage-time space is required
- The early work on HiPIMS used 50 – 100 μs pulses and a pulse repetition frequency in the range 50–1000 Hz
- The cathode voltage and the discharge current depend on the discharge gas pressure



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

HiPIMS - Voltage - Current - time

- 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**

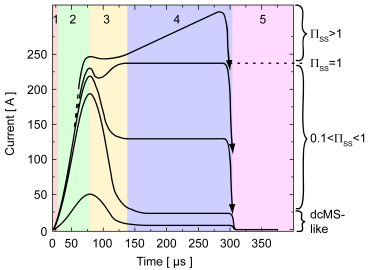


From Anders et al. (2007),

JAP **102** 113303 and JAP **103** 039901

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

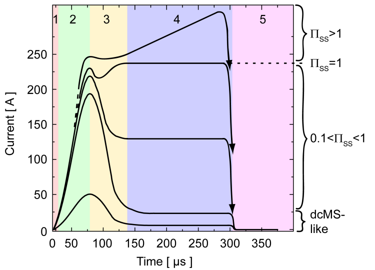
- The self-sputtering can operate in a self-sustained mode, when the ions of the sputtered vapor are created at high enough rate that the ions of the working gas are not needed
- The condition for sustained self-sputtering is expressed as

$$\Pi_{\rm ss} = \alpha\beta_{\rm t} Y_{\rm ss} = 1$$

  where
  - α is the probability of ionization of the sputtered atom
  - $\beta_{\rm t}$ in the probability that the newly formed ion of the sputtered vapor returns to the target
  - $Y_{\rm ss}$ is the self-sputter yield of the ion
- This is a steady state situation and the current remains constant

HiPIMS - Voltage - Current - time

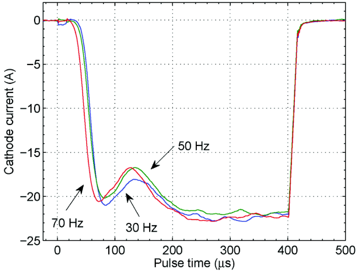
- The bottom curve represents a range of low self-sputtering, $\Pi_{ss} < 0.1$ and the discharge physics in the plateau/runaway phase is dcMS-like
- The middle range of power densities, with $0.1 < \Pi_{ss} < 1$, represents partially self-sputtering discharge
- The top curve represents self-sputtering 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

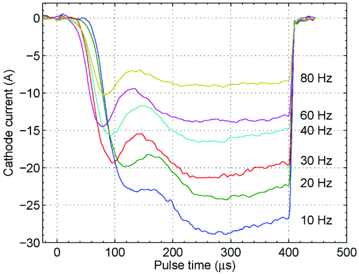
- Ar discharge with Ti target
- The initial peak in current results large flux of atoms from the target
- Collisions of the sputtered atoms with the working gas result in heating and expansion of the working gas – **rarefaction**
- A significant fraction of the sputtered atoms experience electron impact 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

HiPIMS - Voltage - Current - time

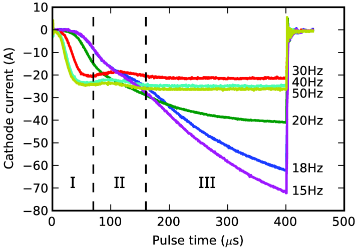
- During reactive sputtering, a reactive gas is added to the inert working gas
- The current waveform in the reactive Ar/N_2 HiPIMS discharge is highly dependent on the pulse repetition frequency, unlike for pure Ar
- N_2 addition changes the plasma composition and the target condition can also change due to the formation of a compound on its surface



From Magnus et al. (2011) JAP **110** 083306

HiPIMS - Voltage - Current - time

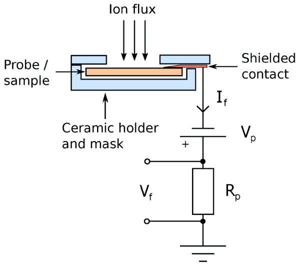
- Similarly for the Ar/O_2 discharge, the current waveform is highly dependent on the repetition frequency and applied voltage which is linked to oxide formation on the target
- The current is found to increase significantly as the frequency is lowered

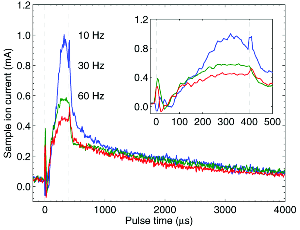


From Magnus et al. (2012), JVSTA **30** 050601

HiPIMS - Voltage - Current - time

- 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

HiPIMS - Voltage - Current - time

- The discharge current $I_{\rm d}$ is the sum of the ion current $I_{\rm i}$ and the secondary electron current $I_{\rm i}\gamma_{\rm SE}$ or

$$I_{\rm d} = I_{\rm i}(1 + \gamma_{\rm SE})$$

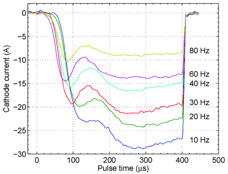
  where $\gamma_{\rm SE}$ is the secondary electron emission coefficient of the target material
- Also

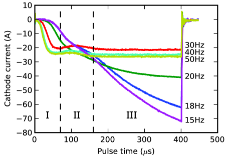
$$I_{\rm i} \propto n_{\rm i} \propto \frac{1}{\mathcal{E}_{\rm T}}$$

- The total energy loss per electron-ion pair lost from the system $\mathcal{E}_{\rm T}$ 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 - Voltage - Current - time

- 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



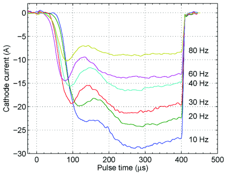


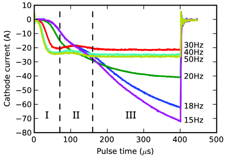
From Magnus et al. (2011), JAP **110** 083306

and Magnus et al. (2012), JVSTA **30** 050601

HiPIMS - Voltage - Current - time

- γ_{SE} is practically zero for singly charged metal ions impacting a target of the same metal
- γ_{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



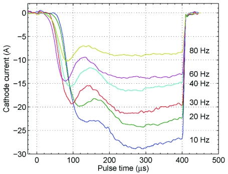


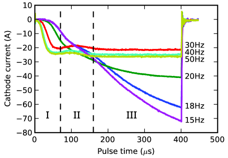
From Magnus et al. (2011), JAP **110** 083306

and Magnus et al. (2012), JVSTA **30** 050601

HiPIMS - Voltage - Current - time

- 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





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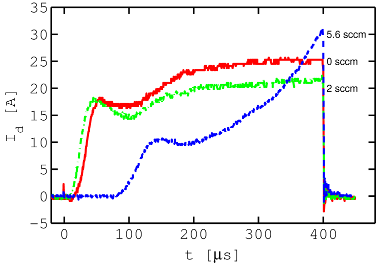
HiPIMS - Voltage - Current - time

- 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

Aiempanakit et al. (2013), JAP **113** 133302



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

Summary

Summary

- 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

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