Ionized Physical Vapor Deposition: Technology and Applications

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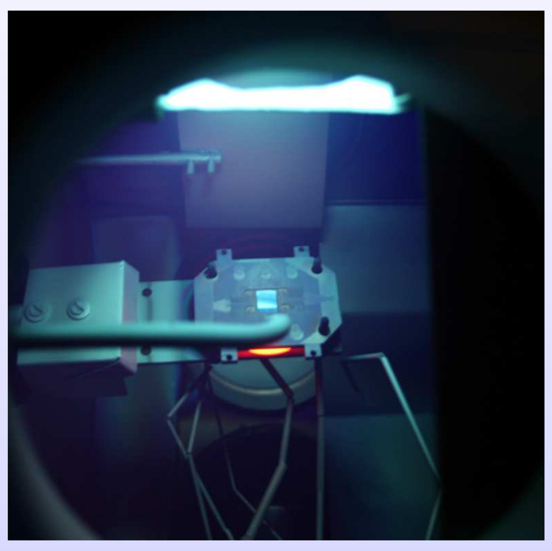

Introduction

- The demand for new materials and layer structures has lead to development of more advanced sputtering systems
  - in particular to increase the ionization of the sputtered vapor
  - traditionally by adding a secondary discharge between the target and the substrate
- A recent addition is the
  - high power pulsed magnetron sputtering discharge (HPPMS)
  - high power impulse magnetron sputtering discharge (HiPIMS)
- It gives high electron density and highly ionized flux of the sputtered material

Ionized Physical Vapor Deposition (IPVD)

- The system design is determined by the average distance a neutral particle travels before being ionized
- The ionization mean free path is

$$\lambda_{\rm iz} = \frac{v_{\rm s}}{k_{\rm iz} n_{\rm e}}$$

where
  - $v_{\rm s}$ is the velocity of the sputtered neutral metal
  - $k_{\rm iz}$ is the ionization rate coefficient
  - $n_{\rm e}$ is the electron density
- This distance has to be short
  - $v_{\rm s}$ has to be low - thermalize the sputtered flux - increase discharge pressure
  - $n_{\rm e}$ has to be high
- Typical parameters for argon gas and copper target

Gas	$v_{\rm s}$ [m/s]	$T_{\rm e}$ [V]	$n_{\rm e}$ [m^{-3}]	$\lambda_{\rm iz}$ [cm]	Discharge
Ar	1000	3	10^{17}	162	
Ar	300	3	10^{17}	49	dcMS
Ar	300	3	10^{18}	4.9	ICP-MS/ECR-MS
Ar	300	3	10^{19}	0.5	HiPIMS
Cu	300	1.5	10^{19}	7.5	SSS-HiPIMS

Magnetron Sputtering with a Secondary Discharge

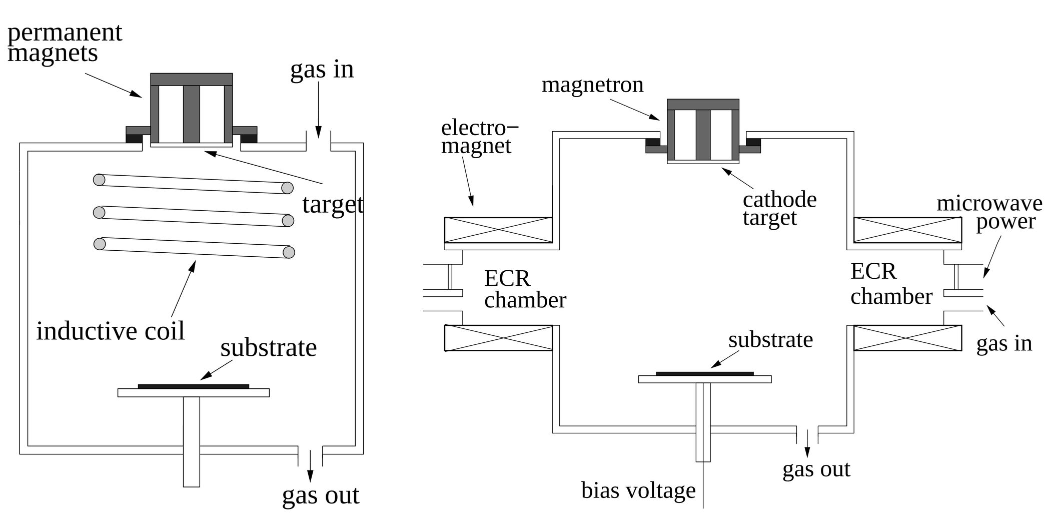

Figure 1: (Right) An ICP-MS where a radio-frequency-driven inductively coupled discharge is placed parallel to the cathode in between the cathode and the substrate. (Left) An ECR-MS apparatus, the two ECR discharge chambers are located at the opposite sites of the main processing chamber. (From Gudmundsson (2008)).

- 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)

High Power Impulse Magnetron Sputtering (HiPIMS)

- In high power impulse magnetron sputtering (HiPIMS) the discharge is created by applying a high power unipolar pulse of low duty cycle to the cathode target (Helmersson et al., 2005, 2006).
- The high power pulse has a peak cathode voltage in the range 500 – 2000 V which gives peak power densities in the range 1 – 3 kW/cm^2.
- For the high power impulse magnetron sputtering (HiPIMS) discharge
  - Peak power ~ kW/cm^2.
  - Average power, ~ W/cm^2, no significant target heating.
  - Repetition frequency 50 – 500 Hz.
  - Duty cycle 0.5 – 5 %
- Electron density of the order of $10^{18} - 10^{19}$ m^{-3} has been reported in the substrate vicinity (Gudmundsson et al., 2001; Bohlmark et al., 2005a)
- A high fractional ionization of the sputtered vapor has been demonstrated and values higher than 90 % have been reported (Bohlmark et al., 2005b).

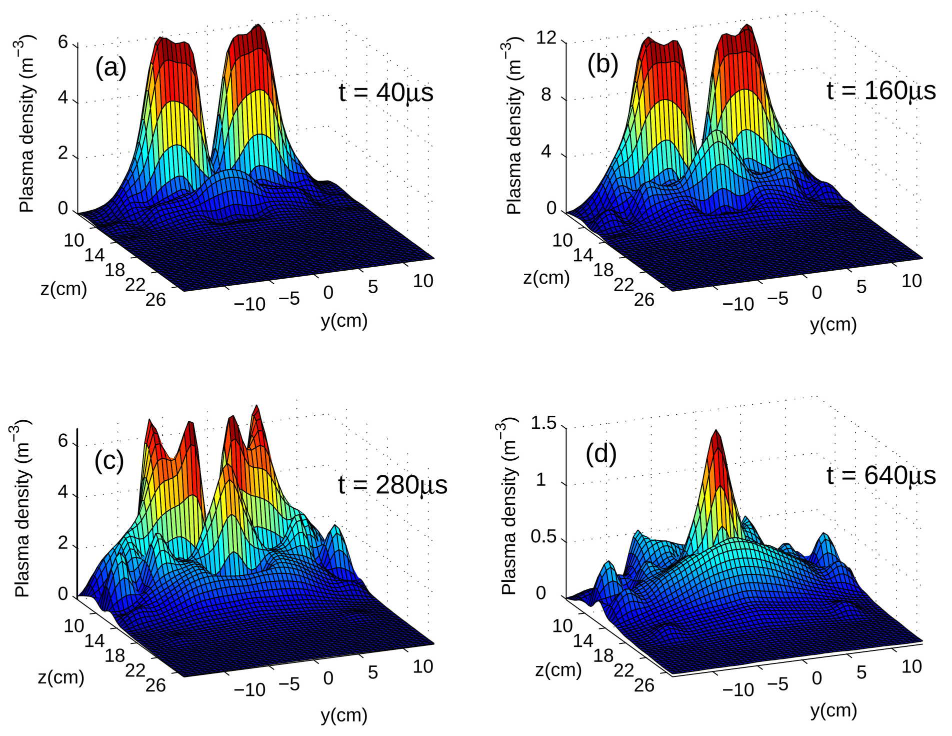

Figure 2: The spatial and temporal variation of the electron density in an argon discharge at 20 mTorr at (a) 40 μs, (b) 160 μs, (c) 280 μs and, (d) 640 μs, from initiating the 100 μs long pulse. The target was made of titanium 150 mm in diameter. (After Bohlmark et al. (2005a))

- A monotonic rise in plasma density
  - with discharge gas pressure
  - applied power
- A linear increase in electron density with increased discharge current
- The electron density depends on the target material
  - Cr target gives higher density than Ti (Vetushka and Ehiasarian, 2008)
- The peak electron density travels away from the target with fixed velocity
- The electron energy distribution function (EEDF) during the pulse is Maxwellian-like (Gudmundsson et al., 2009)
- The discharge develops from an argon dominated discharge to a metal dominated discharge during the active phase of the discharge.
- Cu-ions have been measured to be up to 92 % of the total ion flux at the substrate (Vlček et al., 2007)
- Several groups report on a significantly lower deposition rate for HiPIMS as compared to conventional dc magnetron sputtering (dcMS)
  - maybe due to self sputtering

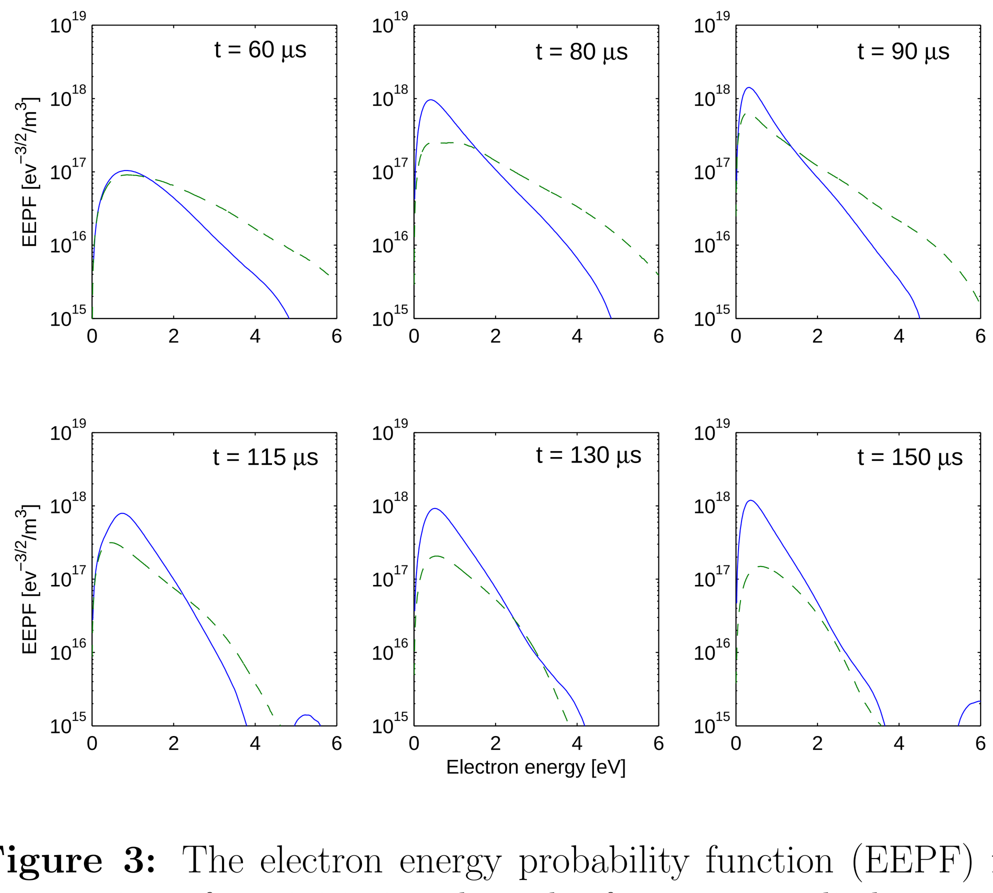

Figure 3: The electron energy probability function (EEPF) for various times from initiating the pulse for an argon discharge at 3 (green dotted line) and 20 (blue solid line) mTorr. The Langmuir probe is located under the race track 80 mm from the target surface. (From Gudmundsson et al. (2009)).

- Ionizing the sputtered vapor has several advantages:
  - improvement of the film quality, increased film density
  - improved adhesion
  - improved surface roughness
  - deposition on substrates with complex shapes and high aspect ratio
  - phase tailoring
  - guiding of the deposition material to the desired areas of the substrate
  - hysteresis free reactive sputtering has been demonstrated in a HiPIMS discharge (Wallin and Helmersson, 2008)

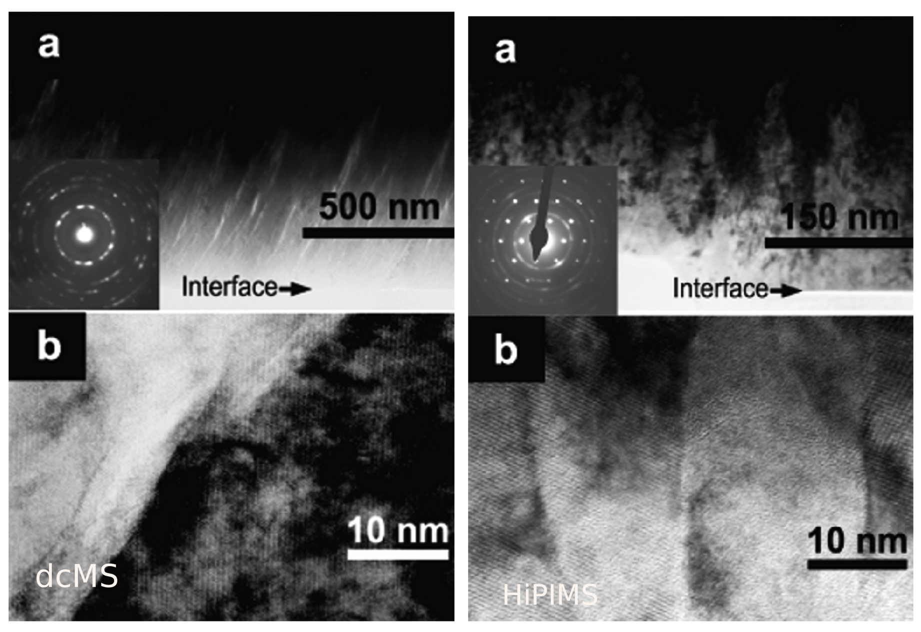

Figure 4: Ta thin films grown on Si substrates placed along a wall of a 2 cm deep and 1 cm wide trench by a dcMS and HiPIMS. (Left) dcMS grown films exhibit rough surface, pores between grains and inclined columnar structure, leaning toward the aperture and (Right) films grown by HiPIMS have smooth surface, and dense crystalline structure with grains perpendicular to the substrate. (From Alami et al. (2005)).

Summary

- The early IPVD tools were based on adding a secondary discharge between the target and the substrate
- The HiPIMS discharge is based on applying a high power pulse of low frequency and low duty cycle to the cathode target
- The HiPIMS discharge has roughly 2 orders of magnitude higher plasma density in the substrate vicinity than for a conventional dcMS discharge and the ionization fraction is high
- 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

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