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Impact of Chamber Pressure on Sputtered Particle Energy

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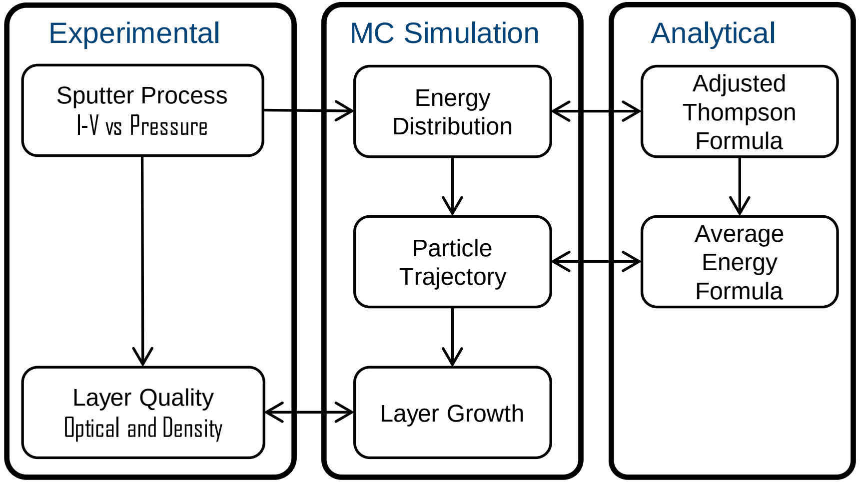
Background

Why Sputtering at Various Pressure Points?

- Generate dense/porous films: controlled diffusion rate
- Relax stresses in harder or thicker layers
- Control energy and flux of charged particles
    - Typically desired for harder coatings
    - Typically avoided for TCO layers
    - Typically limited for temperature sensitive substrates

Outline

- Test Set-up
- I-V Behavior from Experiments
- Monte Carlo Simulations and Analytical Approximation of Energy Distribution on Target and Substrate
- Fitting the Results with Optical Data
- Layer Growth Simulations and Confirm Optical Data
- Conclusions



Testing Set-up

- Planar or **Rotating Cylindrical** Magnetron
- Stationary or **Moving** Substrate
- Various Magnetic Systems
  - **Standard Field**
  - High Field
  - Online Adjustable Field
- Typically Metallic Process (in Ar gas only)
  - Metal targets: **Al**, Zn, Sn
  - Ceramic targets: ZrO_x, ZTO

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Results

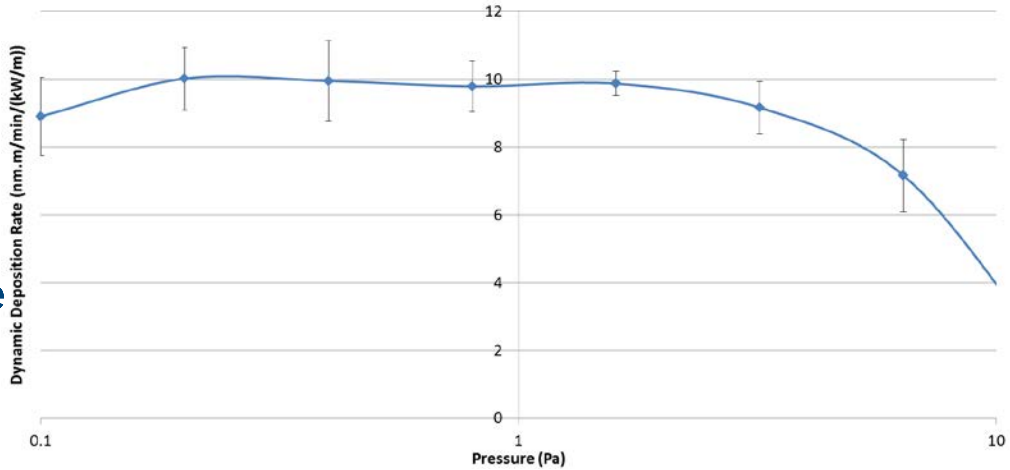
Dynamic Deposition Rate

- Deposition of Al in Ar on moving substrate from 0.05 to 10 Pa

- Almost constant deposition rate from 0.2 Pa to 1.6 Pa (for layers between 200 and 600 nm thick @ various power levels and transport speed)?

- Some observe a peak deposition rate at a given pressure point[1]

- Some describe a steady decline of deposition rate with[2]
  - Higher pressure p
  - Larger throw distance d
  - Lower particle energy E_s
  - Lower particle mass m_s

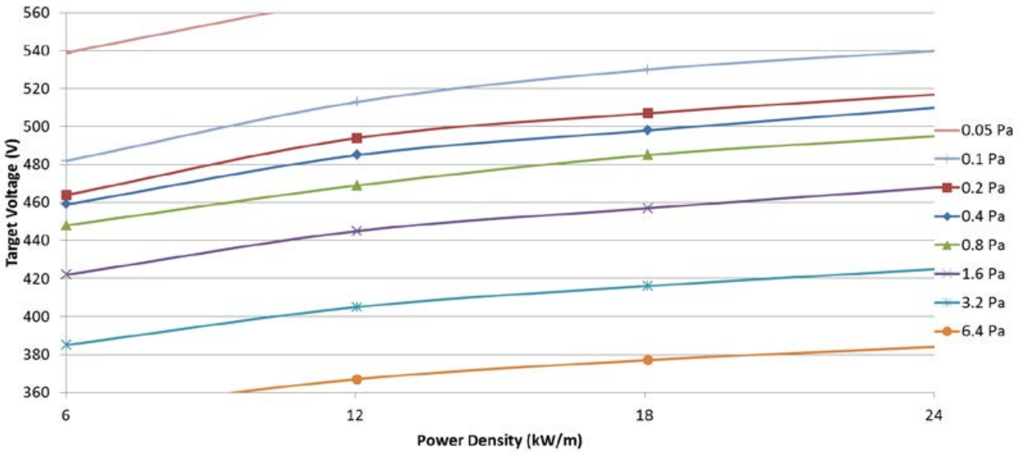


(1) L. Bing-Chi et al.
(2) T. Drüsedau

Results

I-V Characteristics

- Slight voltage increase at higher power density (constant pressure p)
- Important voltage decrease at higher pressure (constant power density P)
- Stable and same sputter regime from about 0.2 to below 3.2 Pa
- Does higher current provide higher sputter rate?
  - Higher current: more Ar^+ ion bombardment
  - Lower voltage: reduced sputter yield
  - Answer: No; mainly driven by power density



Current – Voltage relationship:

$$I = k \, . V^n$$

- n magnetic bottling efficiency (typically between 6 and 12)

Simulations

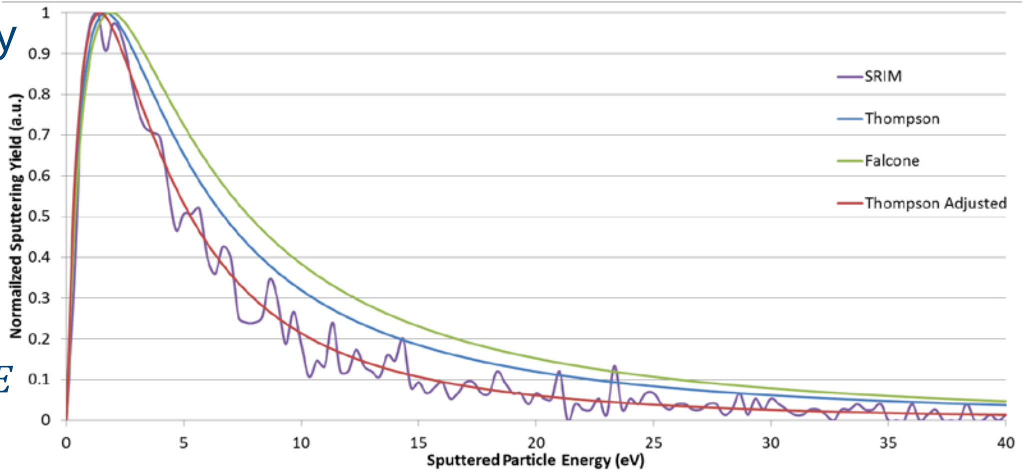
Ion Stopping and Interaction in Solid Matter

- Thompson sputtering yield energy distribution:

$$Y(E)dE \cong \frac{E}{(E+U_s)^3}dE$$

- Adjusted Thompson formula:

$$\cong \frac{E}{(E+U_s)^{3.3}}\left(1-\sqrt{\frac{(E+U_s)}{\gamma . U_t}}\right)dE$$



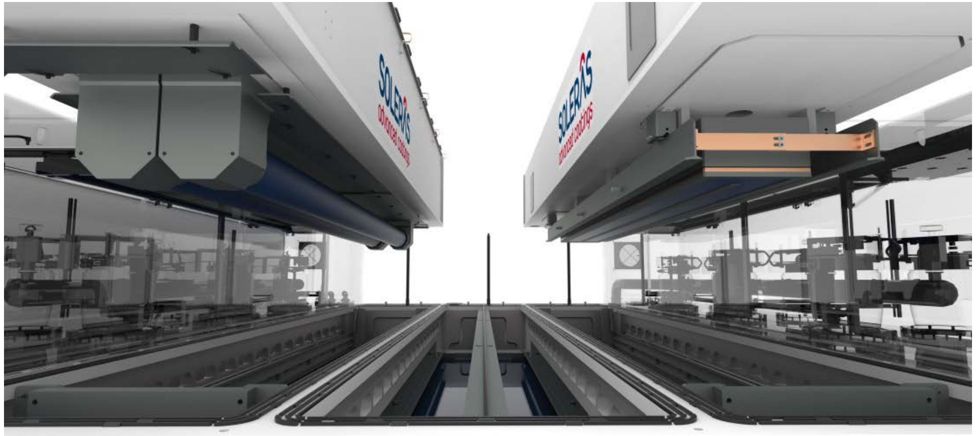
- U_s surface binding energy of target atoms
- E energy of sputtered particle
- U_t sputter target voltage
- γ energy transfer mass factor; $= \frac{4\, m_g\, m_s}{(m_g+m_s)^2}$

Simulations

Material Flux and Gas Interactions

- 3D Geometrical description of a large area glass coater rotatable sputter configuration

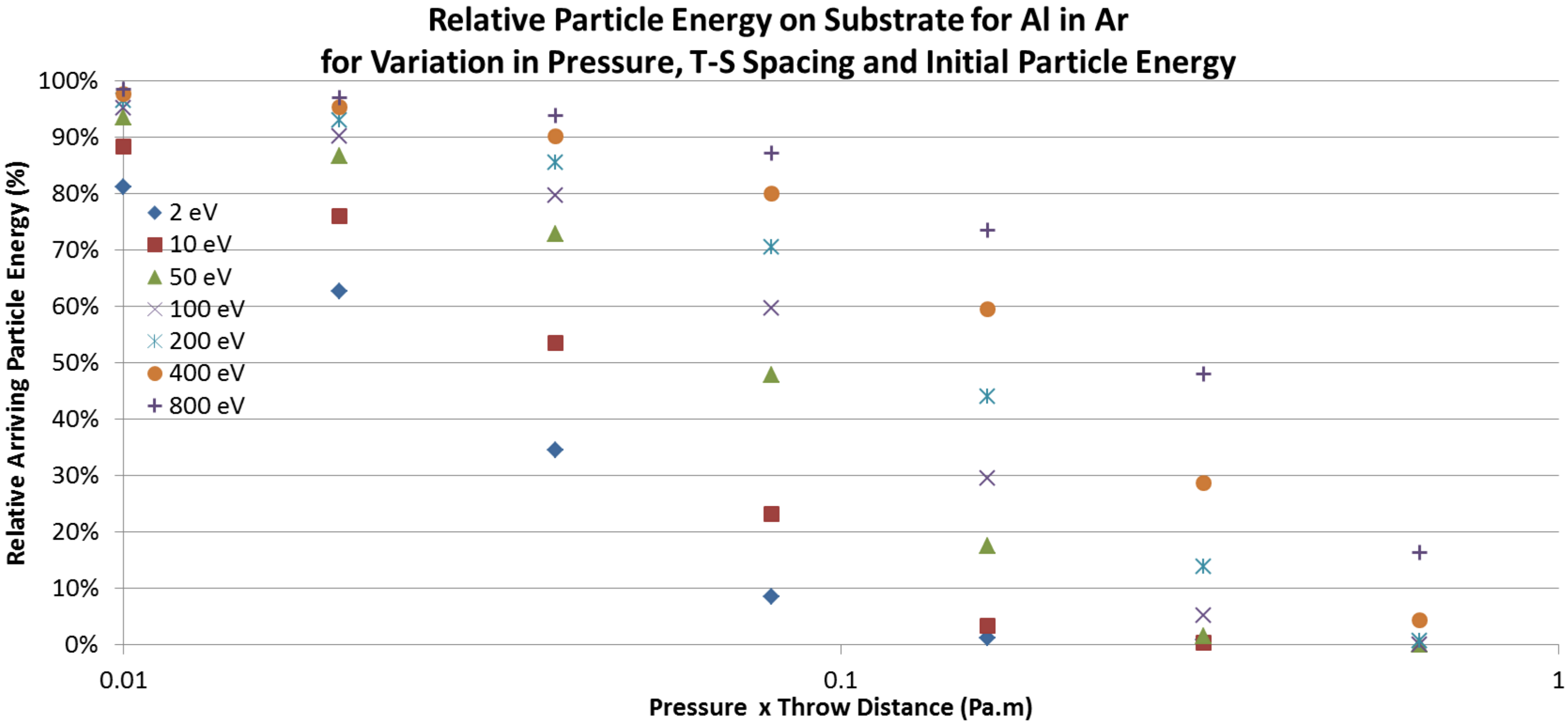
- Finite element Monte Carlo simulation for calculating the sputtered particles trajectories[1]:
  - Pressure: 0.05 to 12.8 Pa
  - Throw distance: 50 to 150 mm
  - Particle energy: 2 to 800 eV



(1) K. Van Aeken et al.

Simulations

Results from Monte Carlo Simulations



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Analytical Approximation

Introduction of the Scattering Factor ς

- Incorporating the effect of
  - Processing conditions: d, p, T
  - Material and energy considerations: m, E
  - $$\varsigma = \frac{d}{\lambda_m} \cdot \frac{m_g + m_s}{m_s} \cdot \sqrt{\frac{(1 + E_{ag})}{E_{as}}}$$
    - d throw distance (T-S spacing)
    - λ_m mean free path $= \frac{1}{n_g.\pi.(r_g+r_s)^2}$
    - n_g gas density = $\frac{p}{k.T}$
    - m mass of gas / sputtered atom
    - E_{ag} energy of activated gas
    - E_{as} average energy of sputtered atom

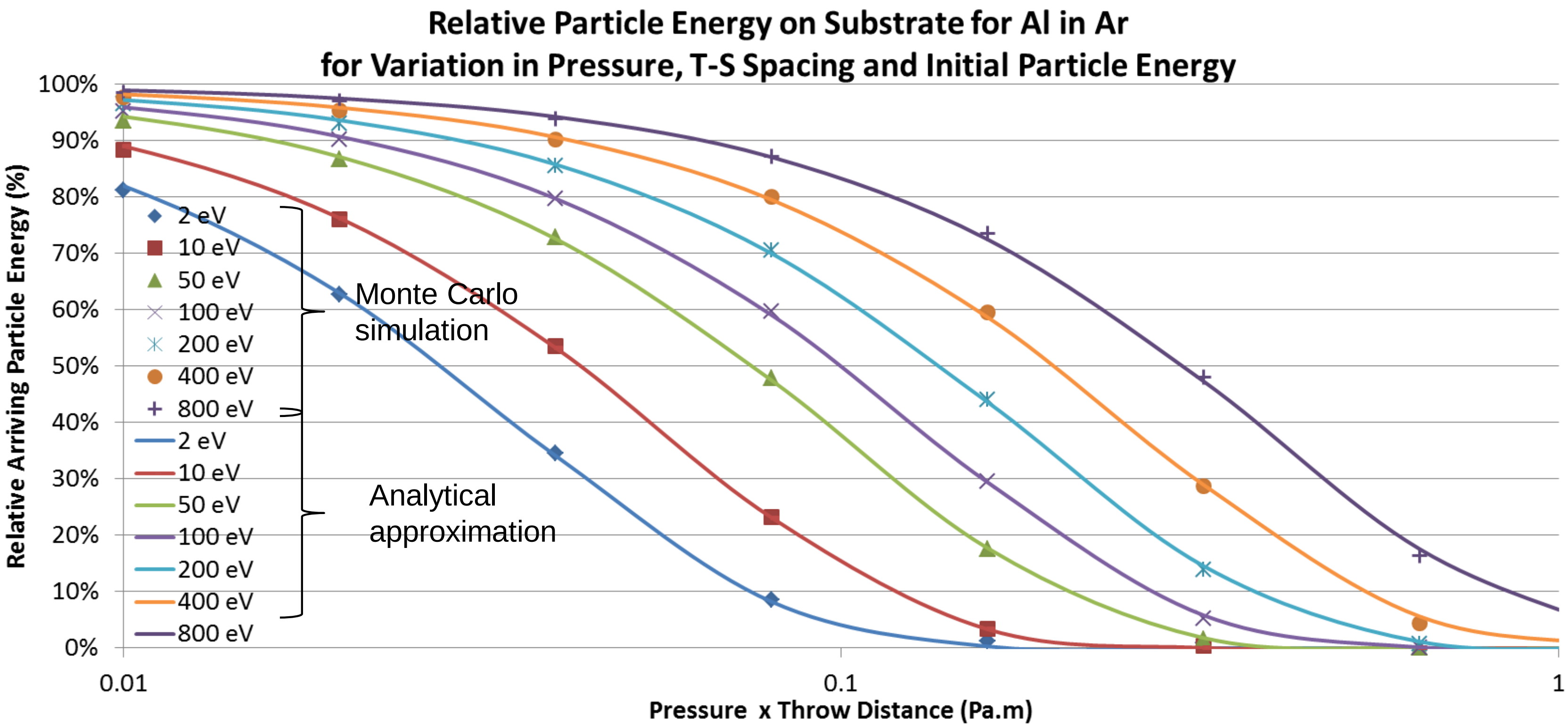
Analytical approximation of average energy E (d, p, T, m, E_{is}):

$$\mathrm{E} = E_{is} \,.\, e^{-\varsigma}$$

E_{is} initial energy of sputtered particle

- Where to find the p x d relationship?
  - $$\varsigma = \frac{d\,.p}{k.T} . \pi . (r_g + r_s)^2 . \frac{m_g + m_s}{m_s} . \sqrt{\frac{(1 + E_{ag})}{E_{as}}}$$

Bringing MC Results and Analytical Approach Together



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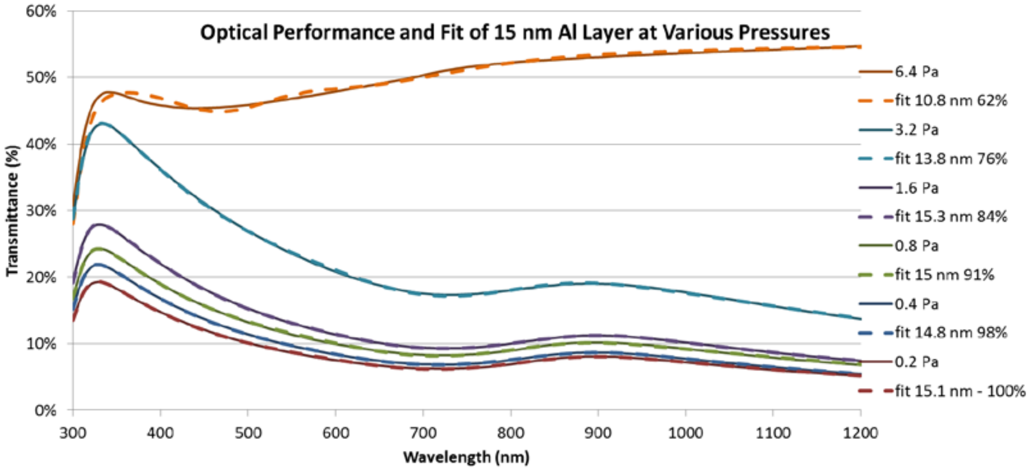
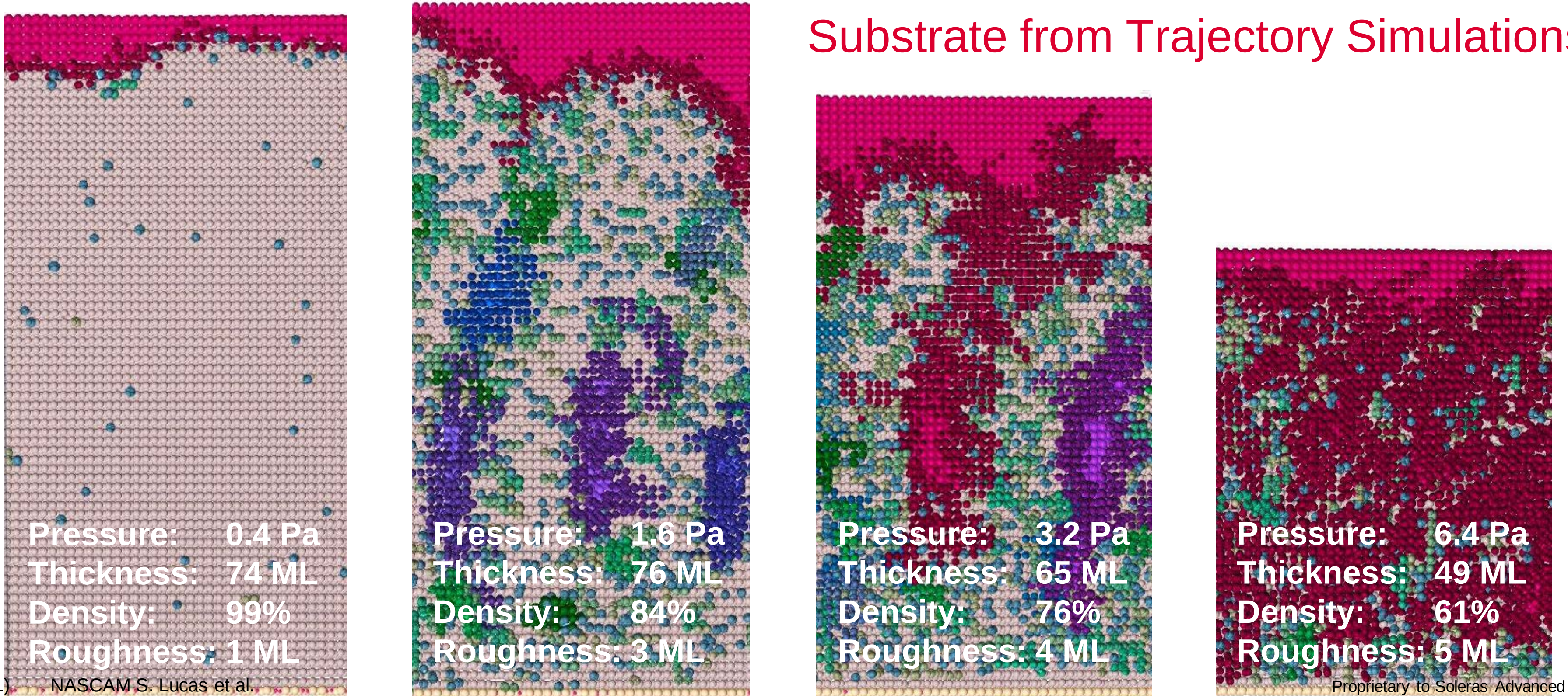
Optical Data
Measurements and Fitting

- Optical measurements are performed from 300 to 1200 nm
- Samples at 0.1 Pa are taken as a reference with nominal thickness and 100% density
- Fitting is performed based on
  - Optical thin film modelling
  - Al Palik library
  - Bruggeman effective medium approximation
- Extremely good fitting is obtained by adjusting layer thickness and density



Back to Simulations

Layer Growth Modelling[1]: Based on Energy and Angular Distributions at the Substrate from Trajectory Simulations

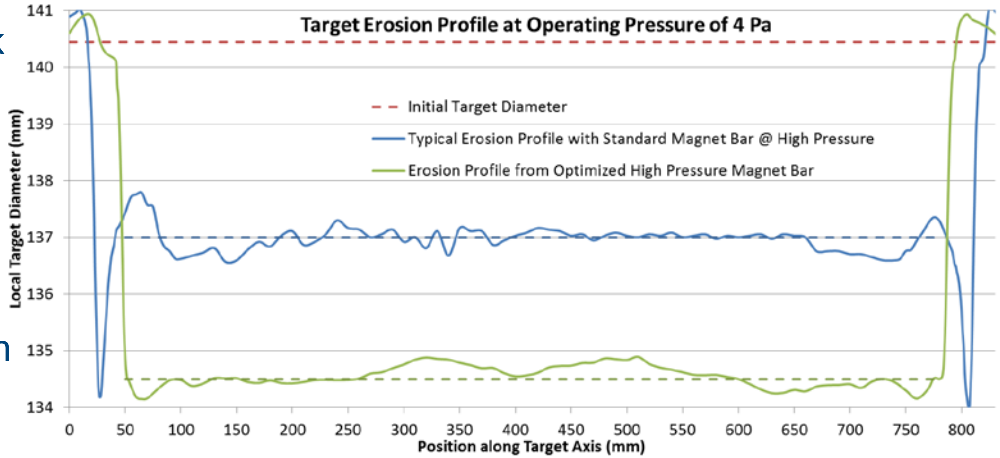


(1) NASCAM S. Lucas et al.

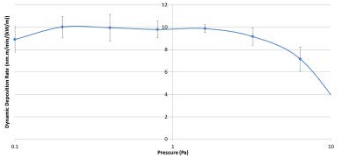
Particle Final Destination

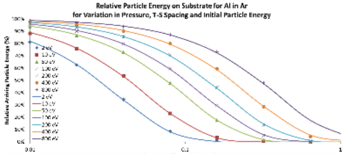
Effect on Target Erosion

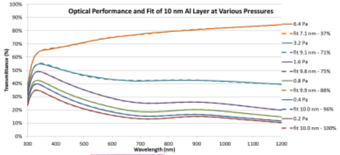
- Most particles do not reach the substrate at higher pressure, but return to the target
- Particles leave the target from the racetrack zone, but return evenly over the target surface:
  - More pronounced erosion groove formation
  - Reduced target utilization
- Standard magnetics perform poor on target utilization and will show pronounced erosion groove formation
- Optimized magnetics are required for sustaining long target life at higher pressure regimes

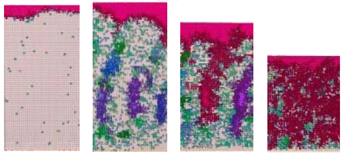


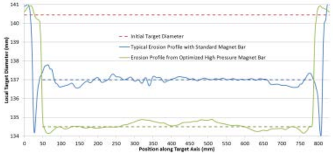
Conclusions











- Defined current – voltage behavior as a function of pressure
- Introduced scattering factor and analytical approximation for energy variation from Monte Carlo simulations
- Used transmittance measurements for calculating layer thickness and density and bringing measurement results on energy distribution and simulations into agreement
- Performed layer growth simulation, confirming layer thickness and density with optical performance, based on particle energy distribution
- Investigated effect on target erosion and proposing optimized magnetic configuration

Thank you for your attention!

Open for any Questions …

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