The impact of power supply arc response on production yield and field reliability

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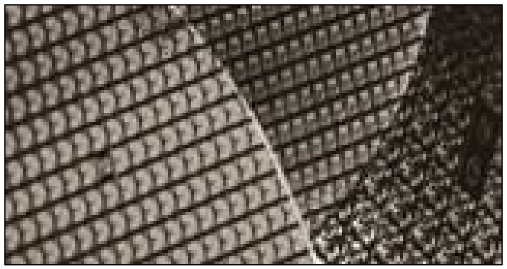
Agenda

- *Background*
- Arc formation and behavior
- Correlating arc energy, macro-particle size, defects due to macro-particle size, and field reliability
- Arc response time study: for reactive sputtering with modeling, implications for production yield

Motivation



Semiconductor

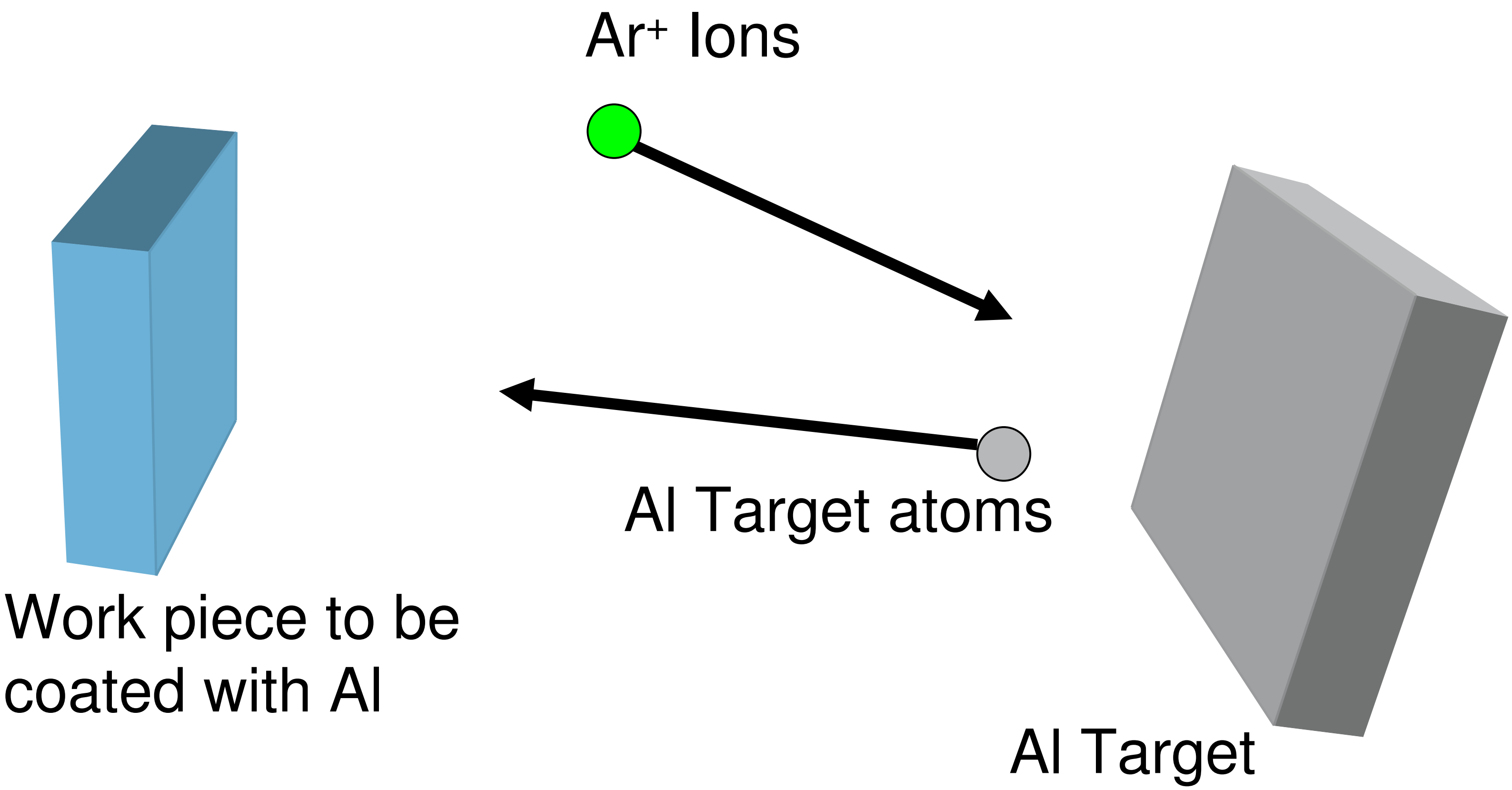
Architectural Glass

Solar Cells

Flat Panel

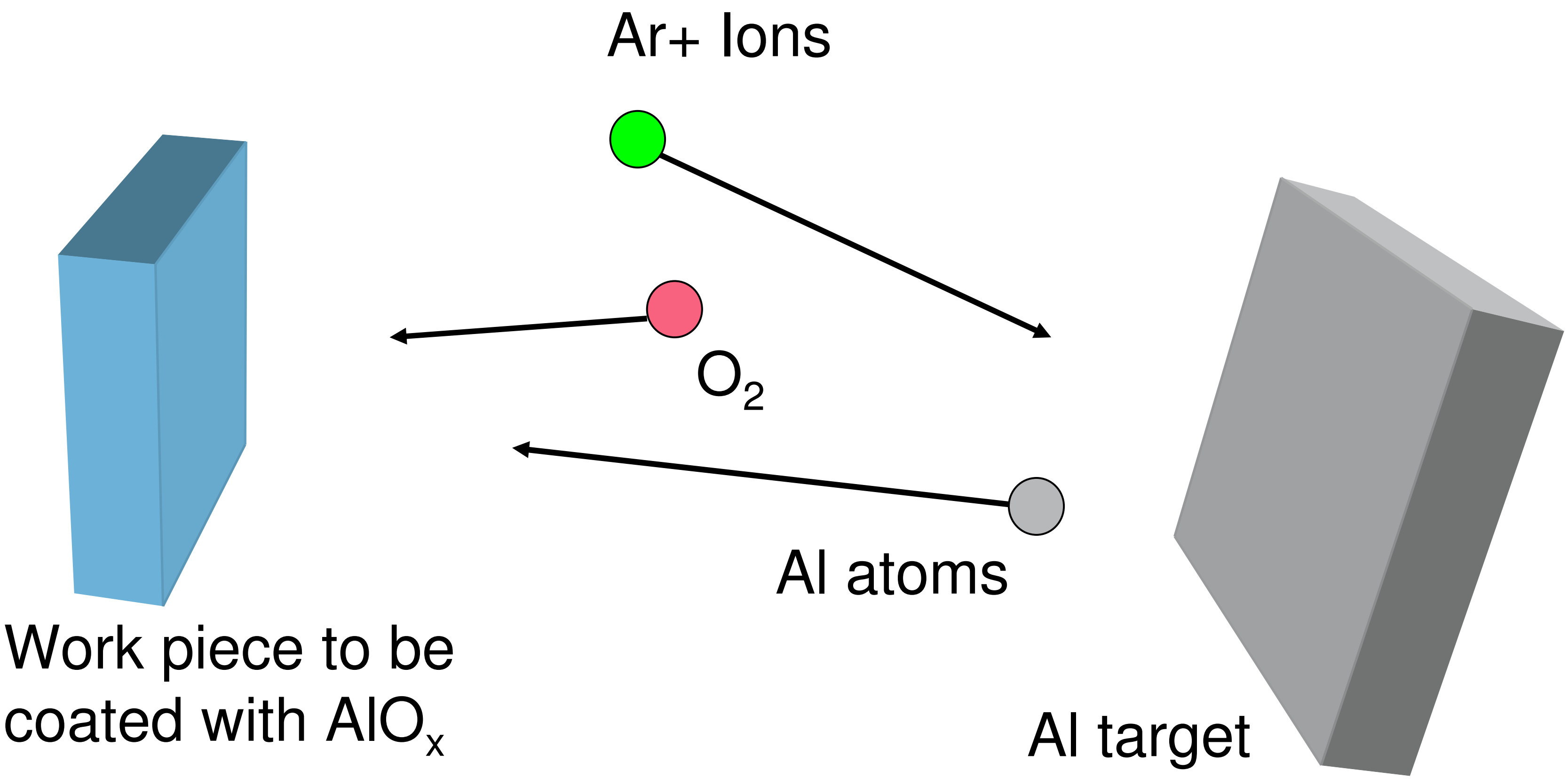
Data Storage

Al sputtering configuration



[1] W. D. Westwood, Sputter Deposition (AVS, New York, 2003).

AlO_x Reactive sputtering



Can be Si (SiO_x); Ti (TiO_x); Sn (SnO_x) or others

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Sputtering magnetrons: Two stable discharge modes

- Typical magnetron sputtering equipment will support two stable discharge modes
- The desired discharge mode is a glow or abnormal glow discharge, at low current density
- The undesired discharge mode is a cathodic arc discharge, at very high current density
- The cathodic arc mode causes damage to both target and workpiece, so must be detected and quenched

References:

1. A. Anders, Proc. 5th Intl. Conf. on Coatings on Glass, 59 (2004).
2. J. D. Cobine, Gaseous Conductors, (Dover, New York, 1958)
3. M. A. Lieberman, A. J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, (Wiley, New York, 1994)

Early work showed that oxide on the target surface is important to the transition from the glow to the cathodic arc mode

- When ultra pure noble gases were used, it was essentially impossible to sustain an arc
- Ar gas was purified *in situ* with the arc operating
- When a high level of purity was attained, the arc mode discharge ceased and only a glow discharge was possible
- Attributed to formation of oxides on the surface
- Suggests the importance of process gas and target material purity for sputtering
- An early suggestion that target arcing could develop when reactively sputtering oxides?

[1]G. M. Schrum, H. G. Wiest, Electrical Engineering 50, p. 827, 1931.

[2]G. E. Doan, J. L. Myer, Phys. Rev. 40, p. 36, 1932.

[3]G. E. Doan, A. M. Thorne, Phys. Rev. 46, p. 49, 1934.

[4]M. J. Druyvesteyn, Nature, p. 580, 1 April 1936.

[5]C. G. Suits, J. P. Hocker, Phys. Rev. 53, p. 670, 1938.

Characteristics of an arc

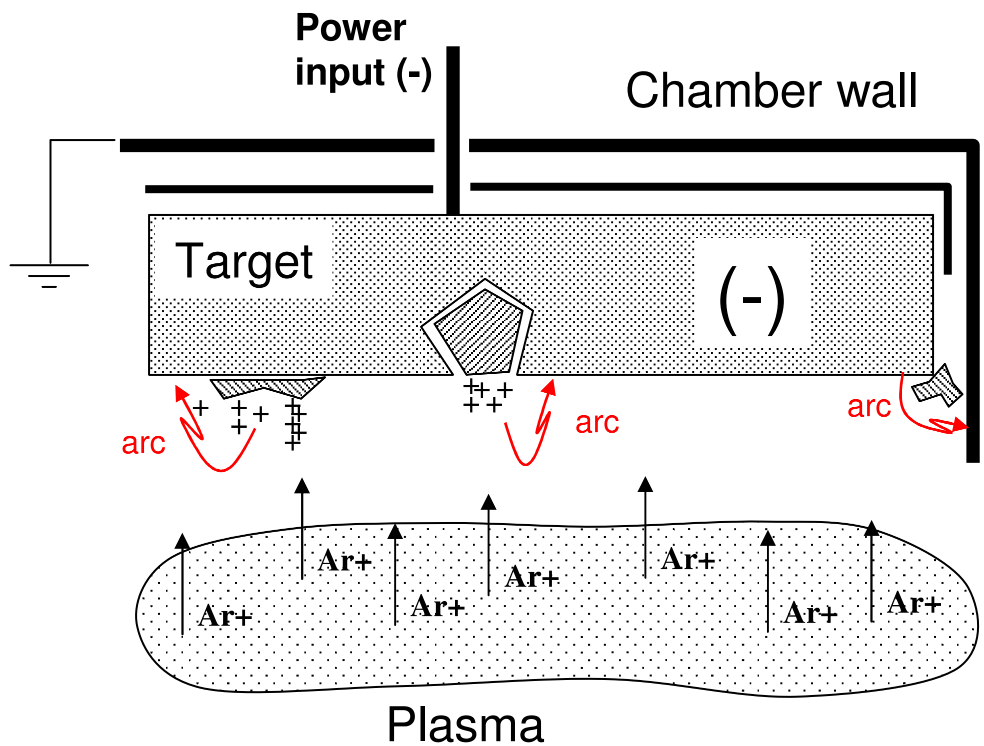
- Electrical breakdown of an insulating medium
- Forms intense, localized discharge
- Creates onset of a low impedance, high current condition
- Disrupts otherwise stable glow discharge
- Generates particles potentially lethal to delicate films and device structures

Formation of an arc

Flow of positive (Ar^+) ions to a sputtering cathode can cause charge buildup on any insulating region

- Surface particles, target defects/inclusions, reacted layers in reactive sputtering

Debris or other contamination bridging biased to grounded surfaces

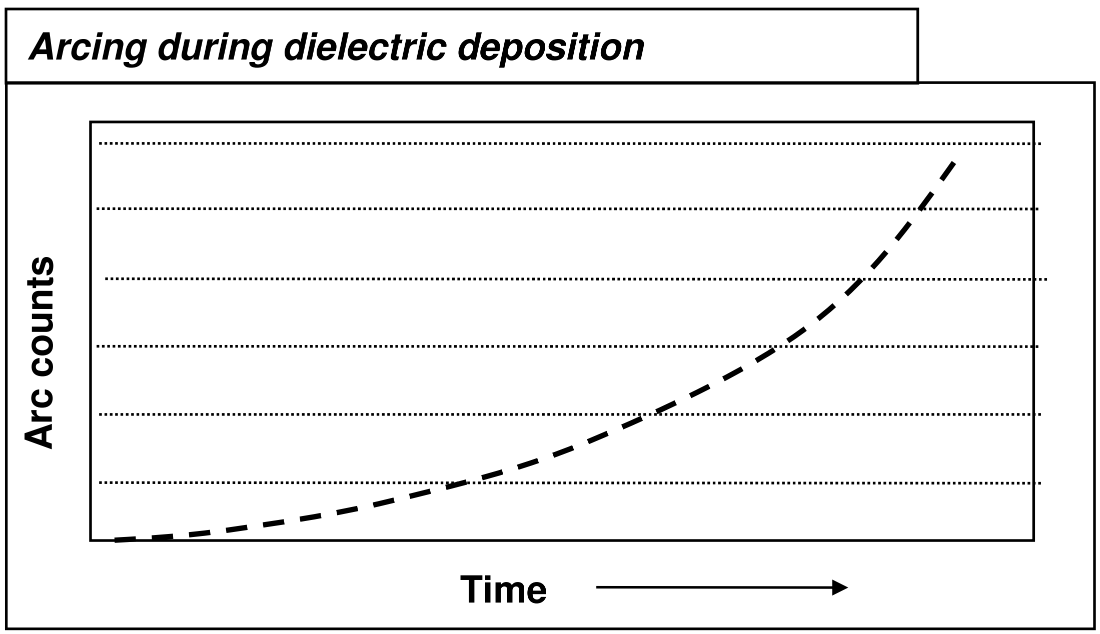


Left unchecked, arcs can propagate or proliferate to become quite disruptive

Reactive sputtering arcs

Arcing can be particularly problematic when reactively sputtering dielectrics

- Build-up of insulating layers on the cathode and chamber surfaces can lead to severe arcing issues



Arc Suppression - some history

- Pre 1983: SCR power supplies
  - No micro arc detection; over current protection only
  - Arc energy ~ 10 -100 Joules. Response ~ 2.8 msec
- 1983: 5/10 kW switch mode power supply with arc handling
  - Fast arc shut off; low stored energy: Arc energy ~ 100 mJ/kW
  - Arc information via analog and serial ports
- 1990: 2nd generation switch mode supplies 15/30 kW
  - Stored arc energy ~ 10mJ/kW
  - Arc detection <1 μsec; User parameters for optimized detection/control
- 1995: 3-phase resonant DC sputtering supply
  - Very fast arc detection; Stored arc energy < 2 mJ/kW
  - Multiple outputs: Arc counting, arc rate; multi-supply communication
- 2004: Technically evolved switch mode sputtering supply
  - Active arc switch with ultra fast reaction and arc diagnostics
  - Stored arc energy < 200 μJ/kW

Arc response in modern power supplies

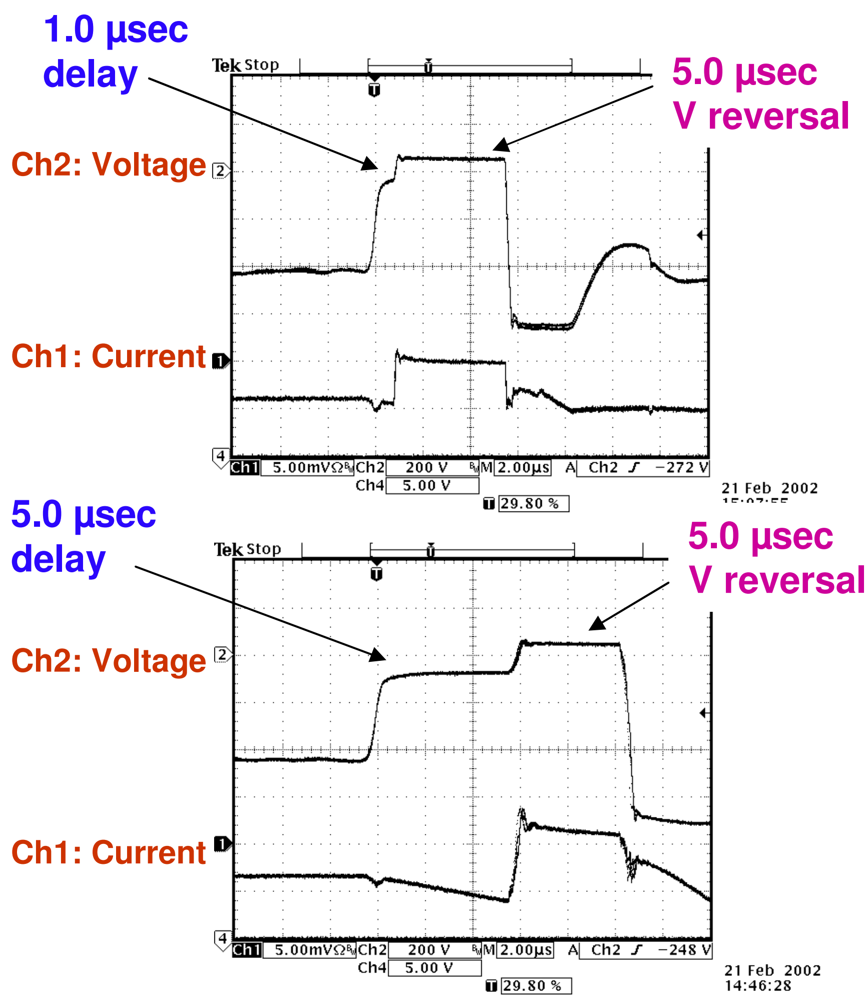
Arc detect
- ~ 100 nsec

Initiate response
- ~ 100's nsec
- User selectable delay

Response
- Single V reversal ~ µsecs
- Multiple reverse pulses
- Shutdown ~ msecs

"Micro-arcs" often clear in single reverse pulse
"Hard-arcs" require more aggressive response

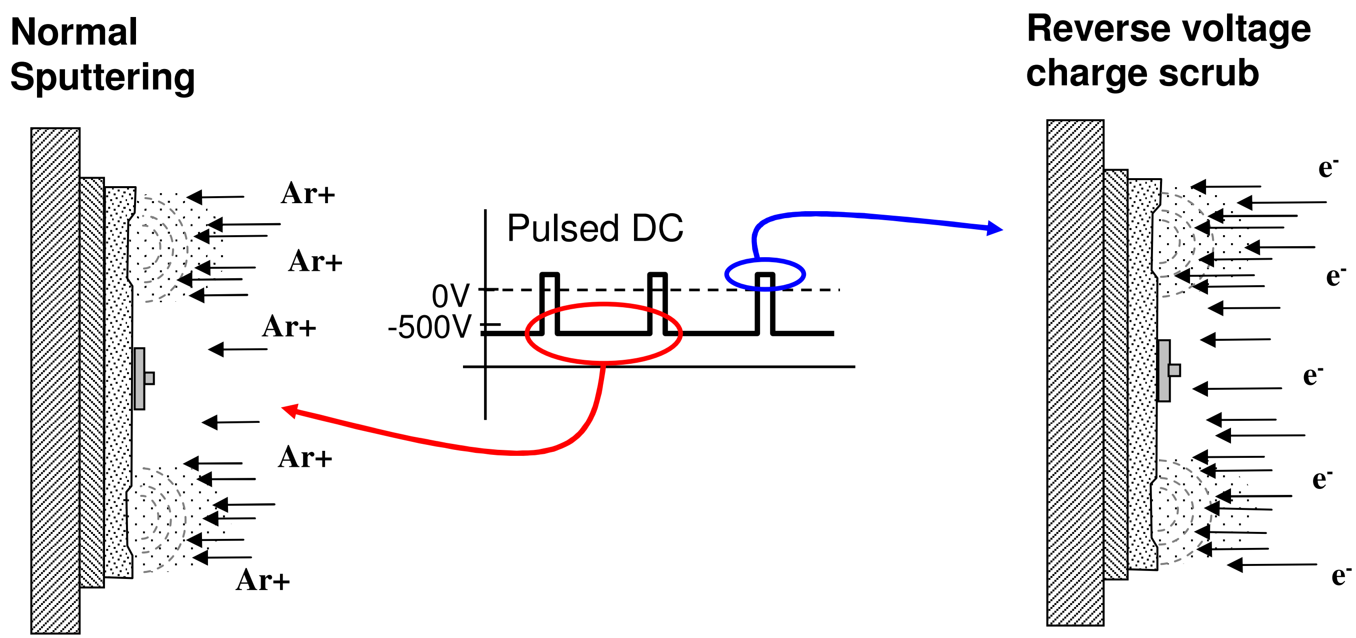
Voltage and current at cathode



Arc Prevention

Arc prevention can be accomplished when the target is periodically forced to a positive potential thereby "scrubbing" accumulated charge

- While positive, electrons are drawn to the target
- Pulsed-dc offers several parameters for optimizing charge scrubbing
- Further protection from damage comes via forced suppression upon detection of a arc should one occur



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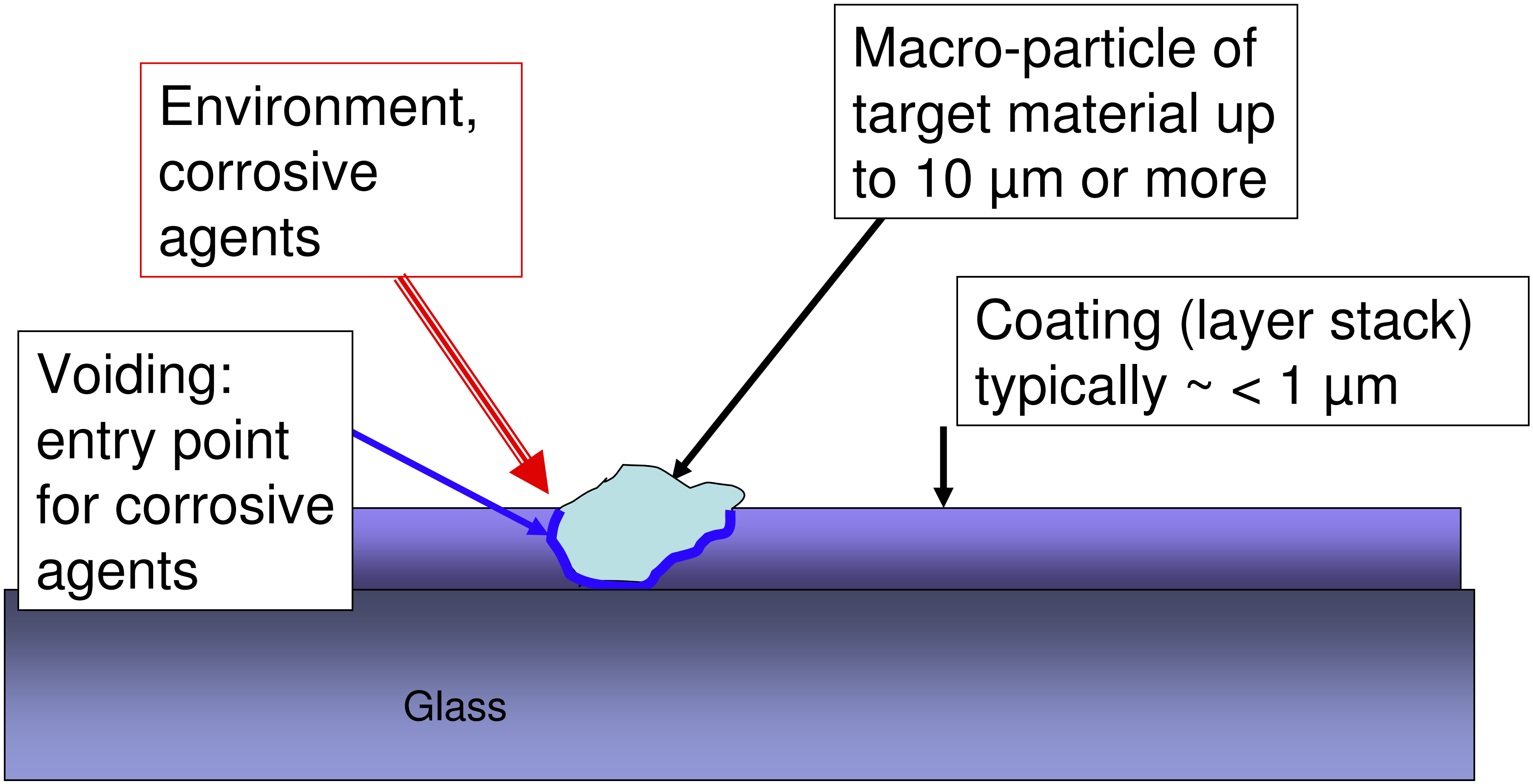
Macro-particle causes pathway for corrosive materials to get past dielectric layers – may impact field reliability

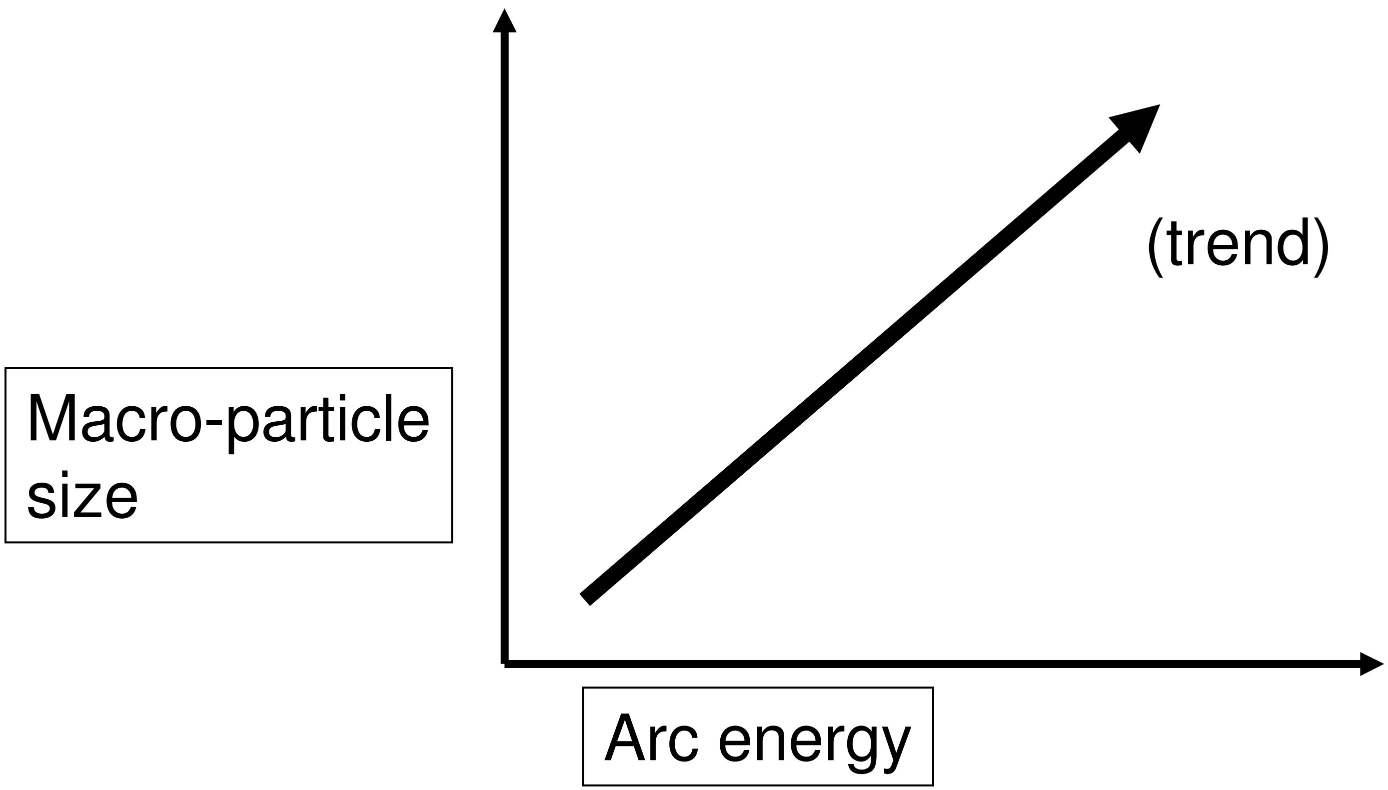


Some references…

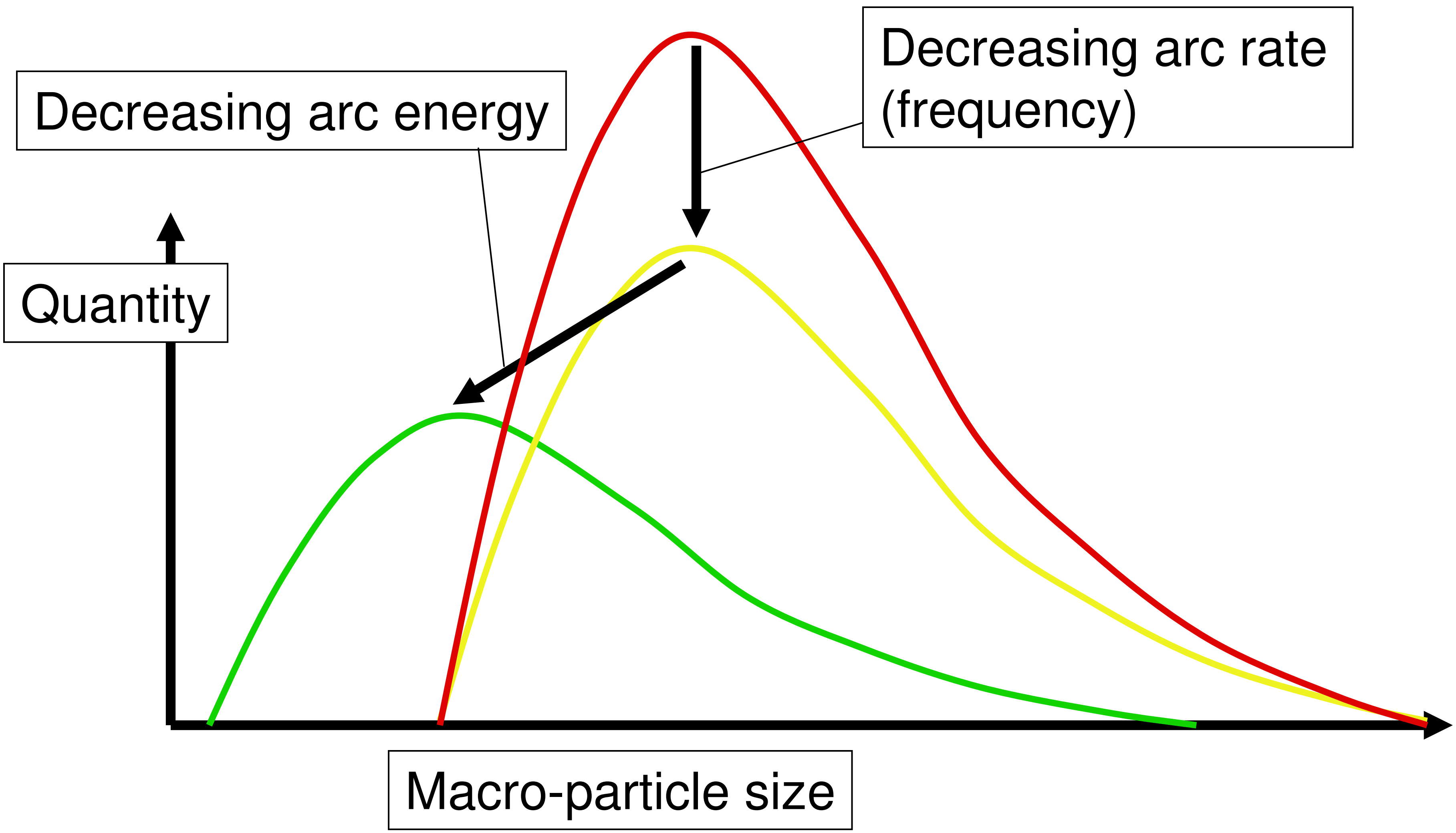
[1]C.E. Wickersham, Jr., J.E. Poole, J.S. Fan, L. Zhu, JVST A 19(6), 2741 (2001).
[2]C.E. Wickersham, Jr., J.E. Poole, A. Leybovich, L. Zhu, JVST A 19(6), 2767 (2001).
[3]C.E. Wickersham, Jr., J.E. Poole, J.S. Fan, JVST A 20(3), 833 (2002).
[4]K. Koski, J. Hölsä, P. Juliet, Surface and Coatings Technol. 115, 163 (1999).
[5]B. Jüttner, Physica 114C, 255 (1982).

Effect of arc energy on macro-particle size

⇒ Can have macro-particles larger than thin film layer stack thickness



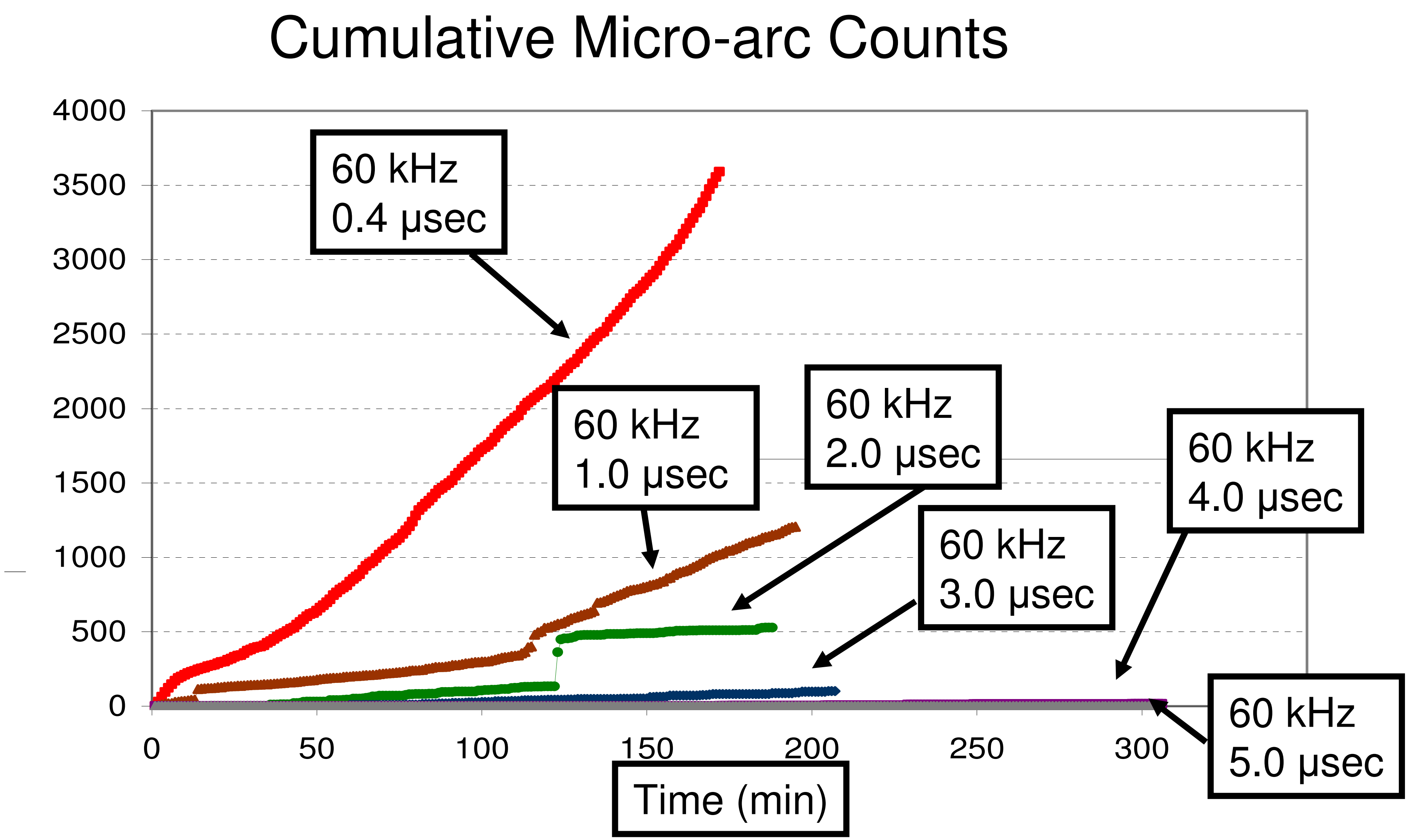
Arc induced macro-particle size distribution



Arc data collection

- Arc data can be viewed from front panel or collected by host computer through interface
- Data available includes arc density (rate) presented as a frequency arcs/sec (Hz) and total arc count for the recipe step
- Arc rate (arcs/second) and arc count (entire recipe step and intra recipe step) monitoring provide a useful process diagnostic tool

Arc rate reduction by pulsed DC setup



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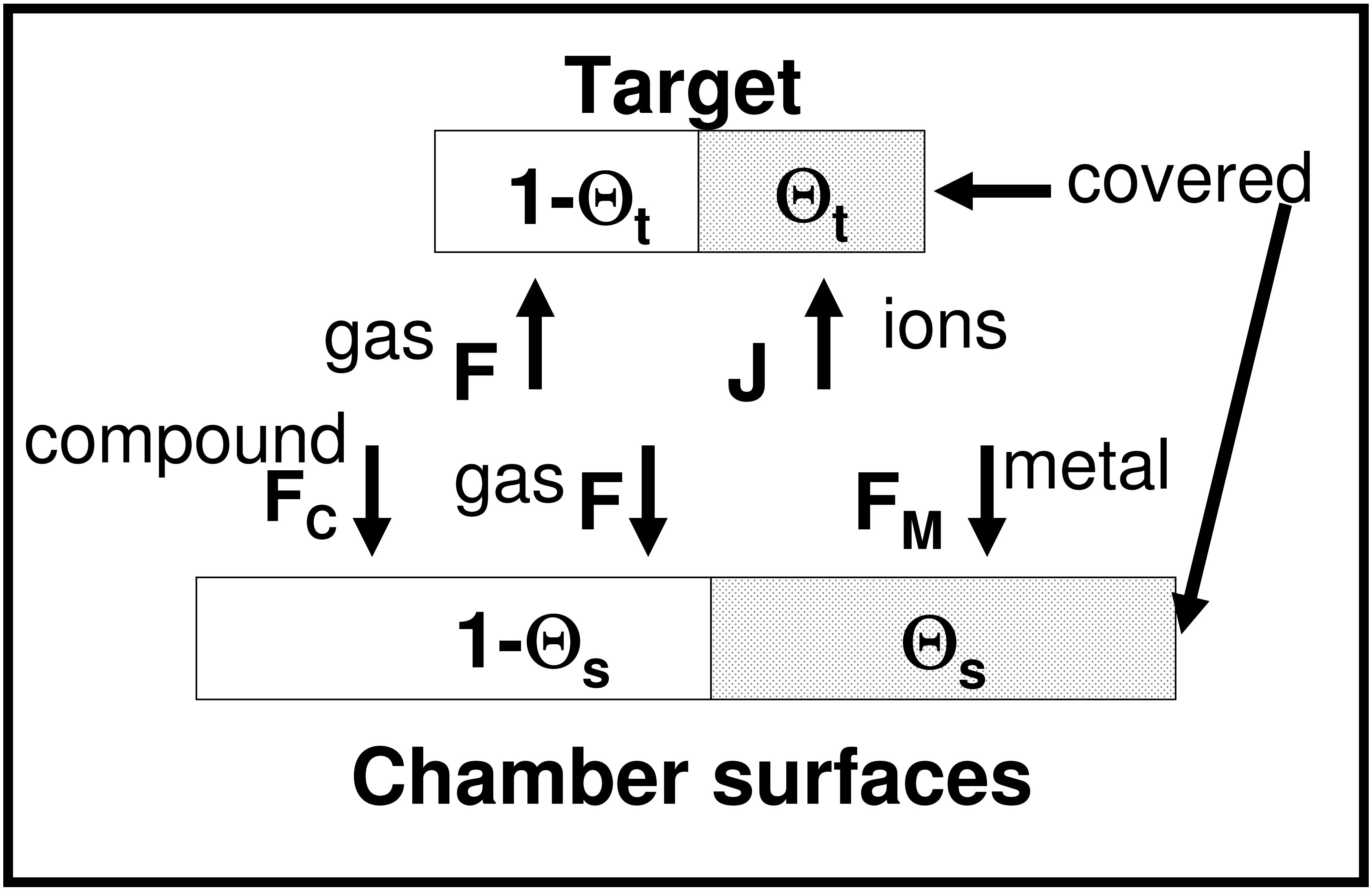
Arc response study

- Large area TiO_2 process
  - Greene, Dannenberg, SVC 1999
- Used MATLAB® and Simulink® (The Mathworks, Inc.)
- Feedback control design with MATLAB® Control System Toolbox

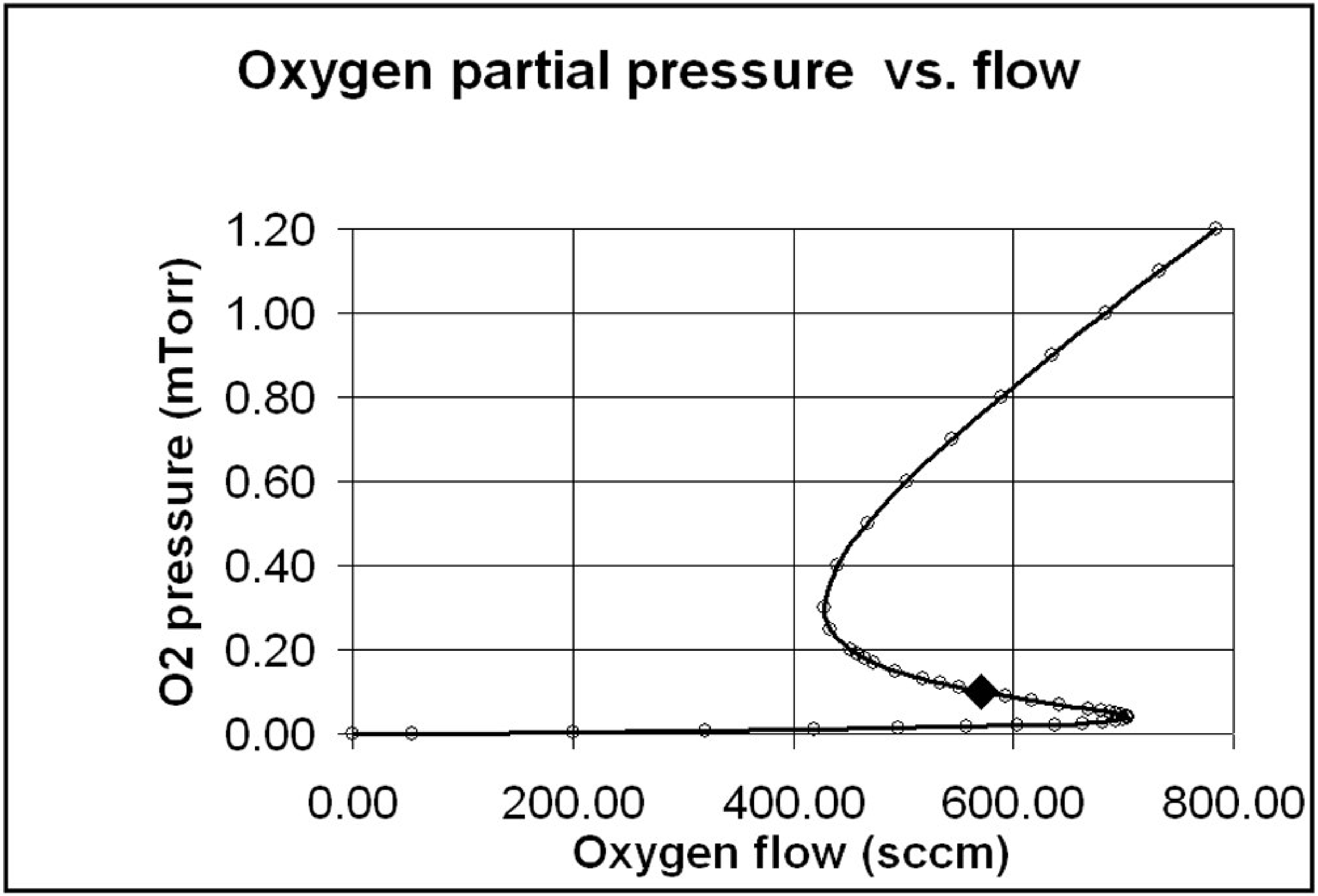
Berg model

- Three process states
  - partial pressure,
  - target coverage fraction,
  - chamber surface coverage fraction
- Rate taken as metal atom removal rate (from target): native target material and compound
- Based on continuity of flow and competing processes at target and chamber surfaces

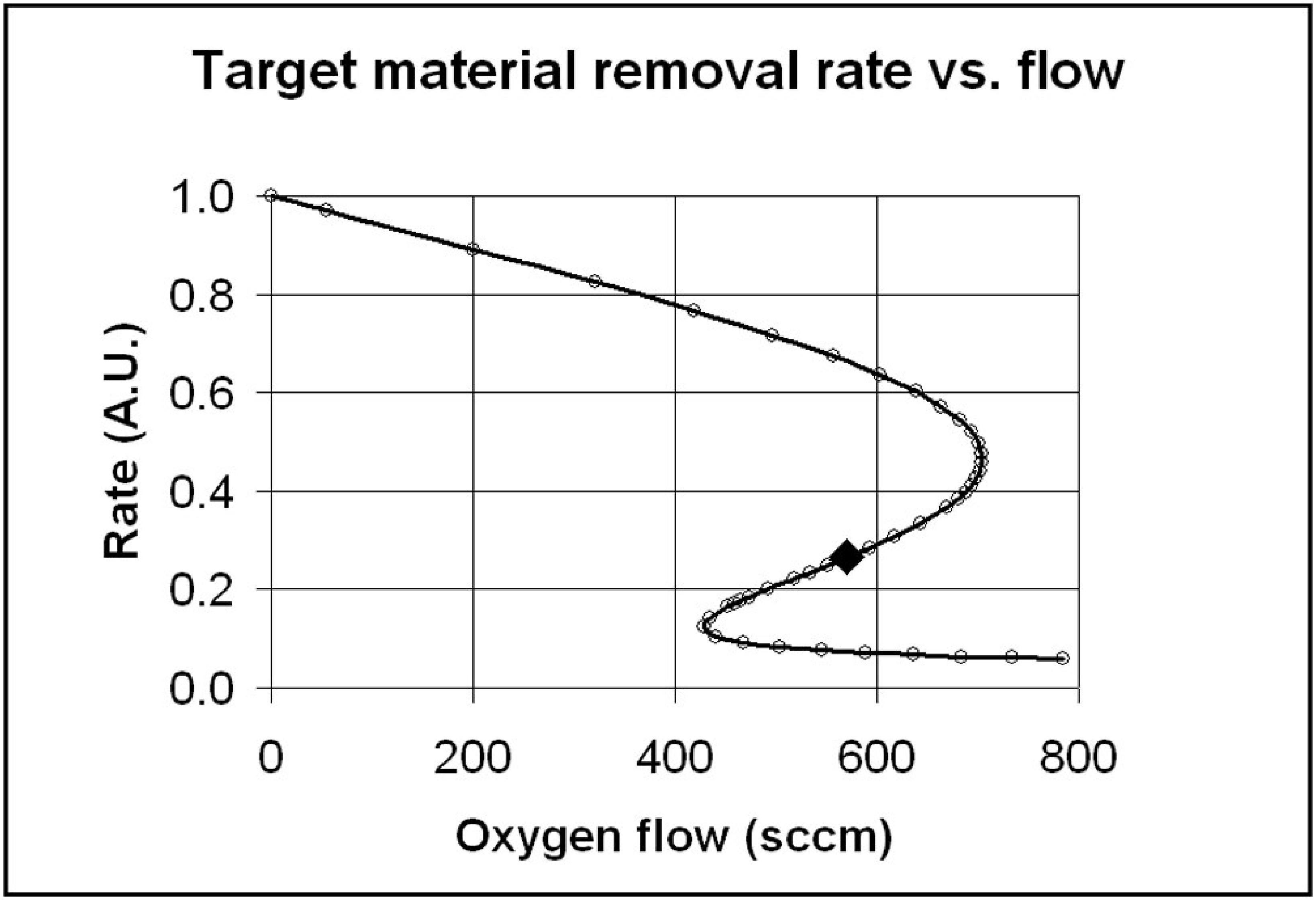
Berg model diagram



O_2 pressure versus flow



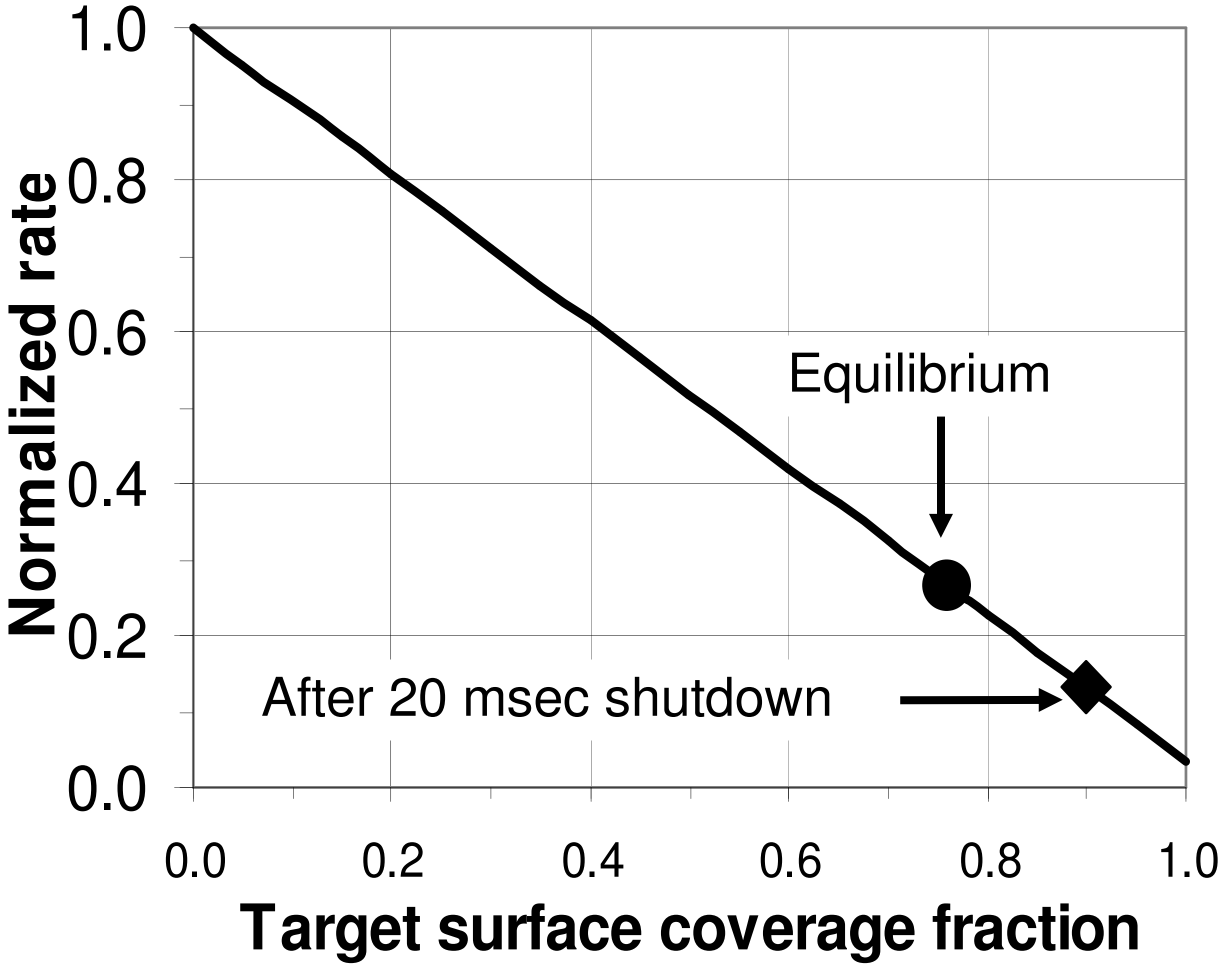
Rate (A.U.) versus O_2 flow



Arcing

- Power supply shuts off for arc handling
- Partial pressure increases
- Target coverage fraction (with compound) increases
- Sputtering rate decreased when power supply turns on
- Time required for rate to resume
- Process effect not just time off

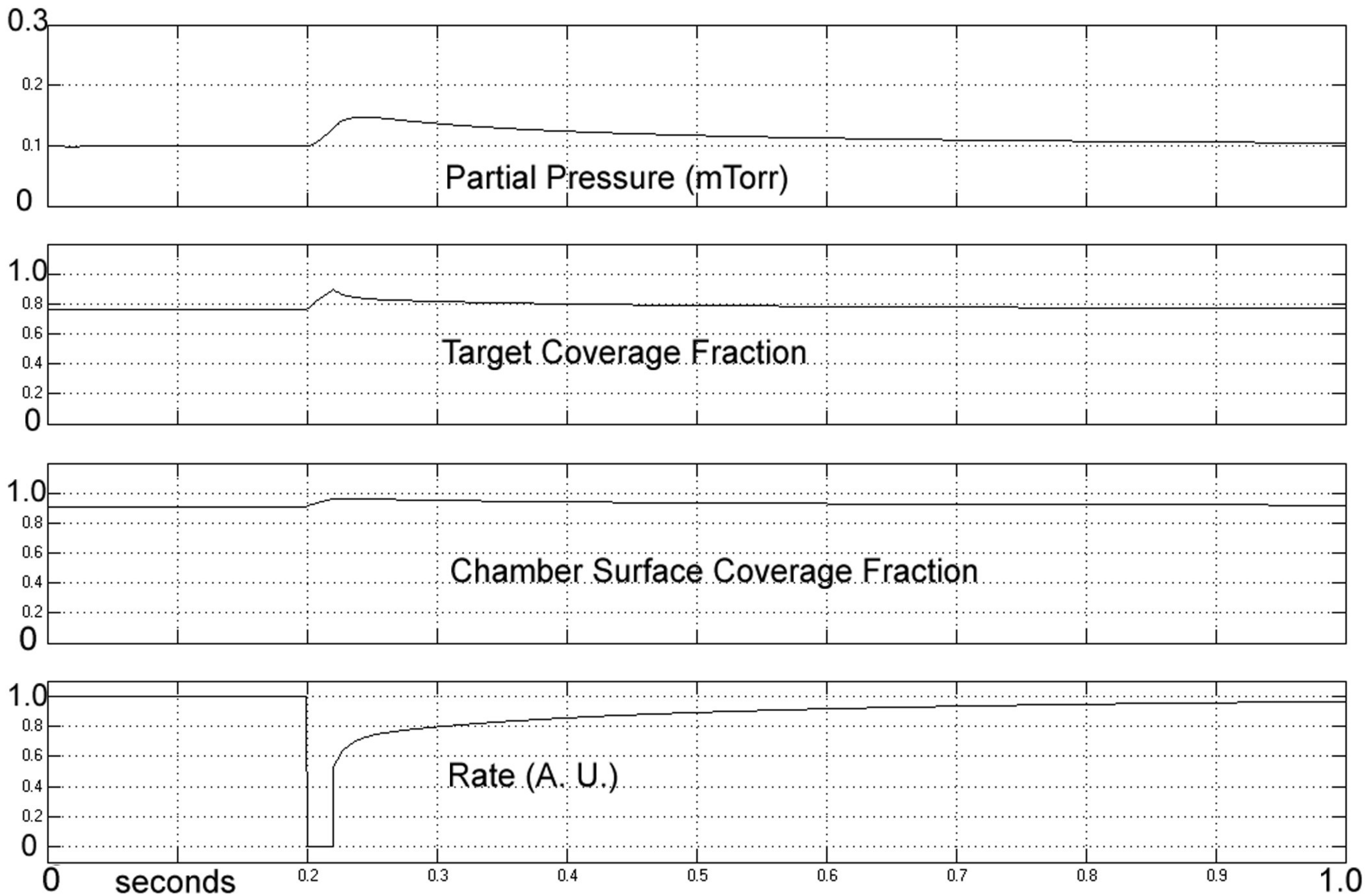
At high coverage fractions, a small increase in coverage fraction can cut rate in half



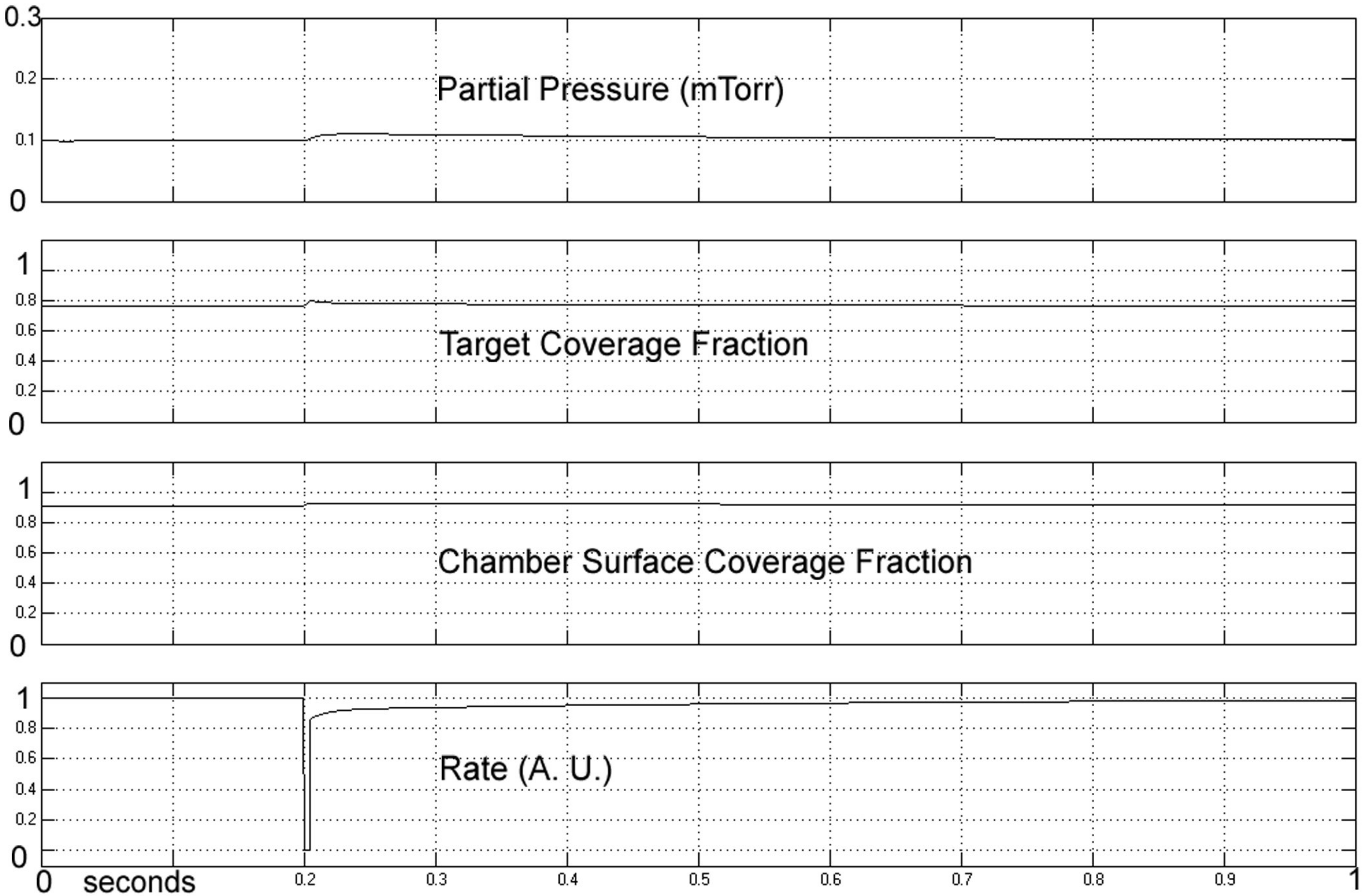
Dynamical model

- Used dynamical version of Berg model to simulate process response to power supply shutdown for arc handling
- Stabilized process in naturally unstable transition region for simulations
- Utilized knowledge across disciplines to simulate arc response dynamics (power conversion arc response routines, process models, dynamical modeling of non-linear systems, non-linear controls)

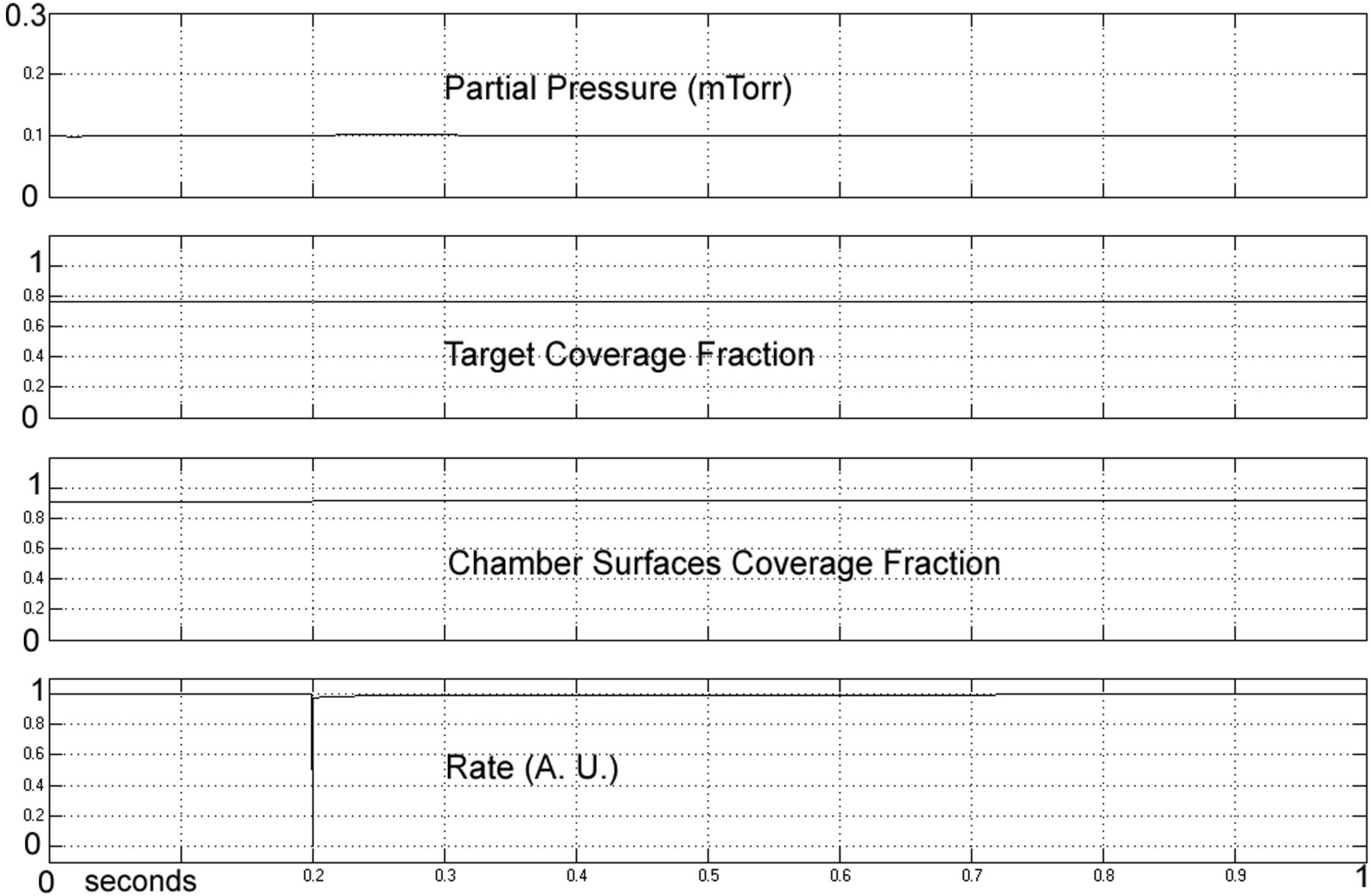
Arc response 20 msec



Arc response 5 msec



Arc response 1 msec



Key points

- Lose rate due to arcing
- Lost time when power supply off
- Process stabilization difficult with longer off time
- Reduced rate when power supply turns on again due to increased coverage fraction, takes time to achieve steady state rate
- Worst case: large differences in sputtering yield between target metal and compound
  - Example: $S_{Ti} \approx 0.7$, $S_{TiO2} \approx 0.03$

Closing comments

- Thin film coating presents special challenges for arc energy and arc rate control
- Arc energy should be reduced to minimize arc induced macro-particle size
- Arc frequency (rate) should be reduced to minimize arc-induced macro-particle quantity
- Fast arc response can minimize perturbation to the process
- Appropriate choice and setup of pulsed DC equipment can minimize arc energy and arc frequency (rate)

Thank you