UNIVERSITY OF MARYLAND

In-Situ Metrology: the Path to Real-Time Advanced Process Control

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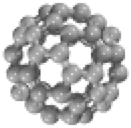


Department of Materials Science and Engineering

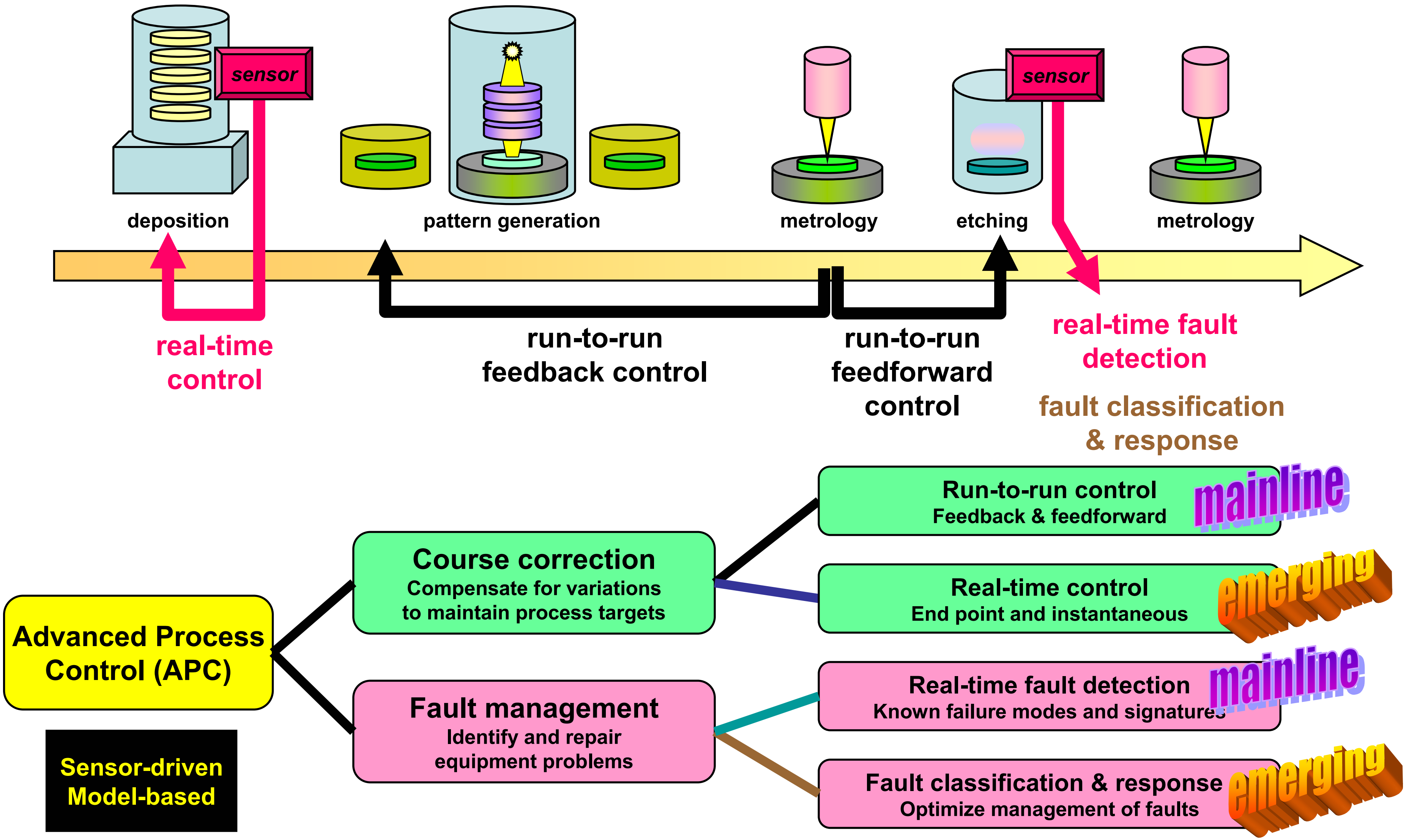
The Institute for Systems Research

Synopsis

- Advanced process control (APC) has become pervasive
- In-situ metrology is key to extending this to real-time APC
- In-situ chemical sensors provide viable quantitative real-time metrology
  - *Multiple sensors deliver <1% precision*
  - *Real-time end point control demonstrated*
  - *Course correction as well as fault detection*
  - *Application to CVD, PECVD, etch, spin-cast, …*

  } ready for tech transfer & evaluation in manufacturing environment
- New opportunities
  - *Uniformity control ➔ spatially programmable reactor design*
  - *Precursor delivery control ➔ solid & low p_{vapor} sources*

Advanced Process Control (APC)



APC Hierarchy

supervisory

Factory Control System

Course correction | *Fault management*

In-line & other metrology
Multi-step process control
Multi-scale time response

Run-to-run course correction
-feedback
-feedforward

Tool maintenance
- fault diagnosis
- PM scheduling

In-situ, real-time process sensors
Unit process control
Real-time response

Real-time course correction

Real-time fault detection

Real-Time APC

quantitative metrology
in-situ, real-time

Real-time equipment sensors
Equipment component control
Real-time response

Regulatory tool control
- equipment state

Tool Control System

regulatory

In-Situ Sensors for Quantitative Process Metrology

REQUIREMENTS

- In-situ, real-time
- Quantitative precision (~1%)
  - *Required for course correction*
- Process state
- Wafer state
- Preferably multi-use
  - *Indicators of process & wafer state*
  - *Simultaneous application for fault detection*
- Rich information
  - *Chemically specific*
- Robust, integratable

TECHNIQUES

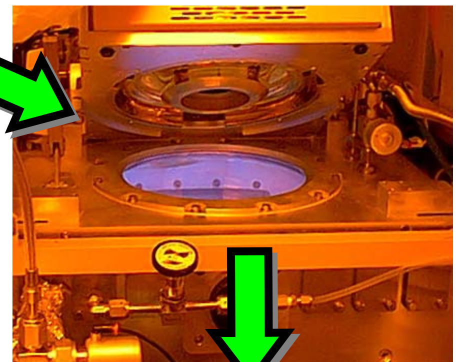
- Plasma optical emission spectroscopy (OES)
- Laser/optical interferometry
- Mass spectrometry
- Acoustic sensing
- Fourier transform infrared spectroscopy (FTIR)
- Plasma impedance
- Optical thermometry/pyrometry
- Ellipsometry
- Optical scatterometry
- …

Mass Spectrometry for Real-Time APC

Ulvac multi-chamber "cluster" tool

PROCESS CHAMBER

Chemical vapor deposition chamber for tungsten metal

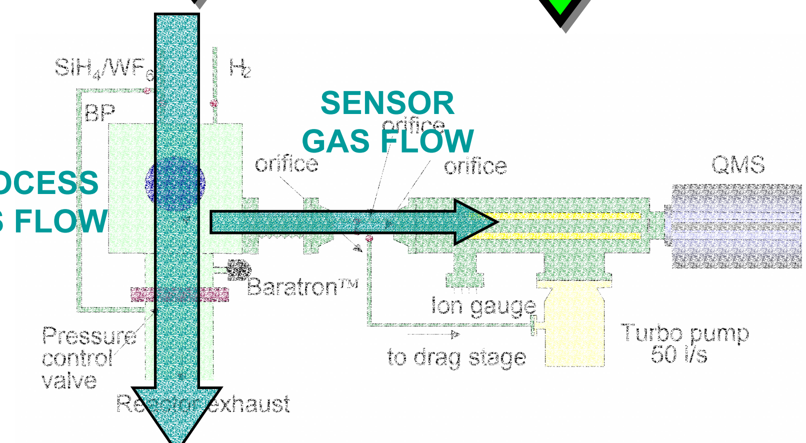


CHEMICAL SENSORS

Inficon Composer™ acoustic sensor

Inficon Transpector™ mass spec chemical sensor

Pressure transduction to low pressure



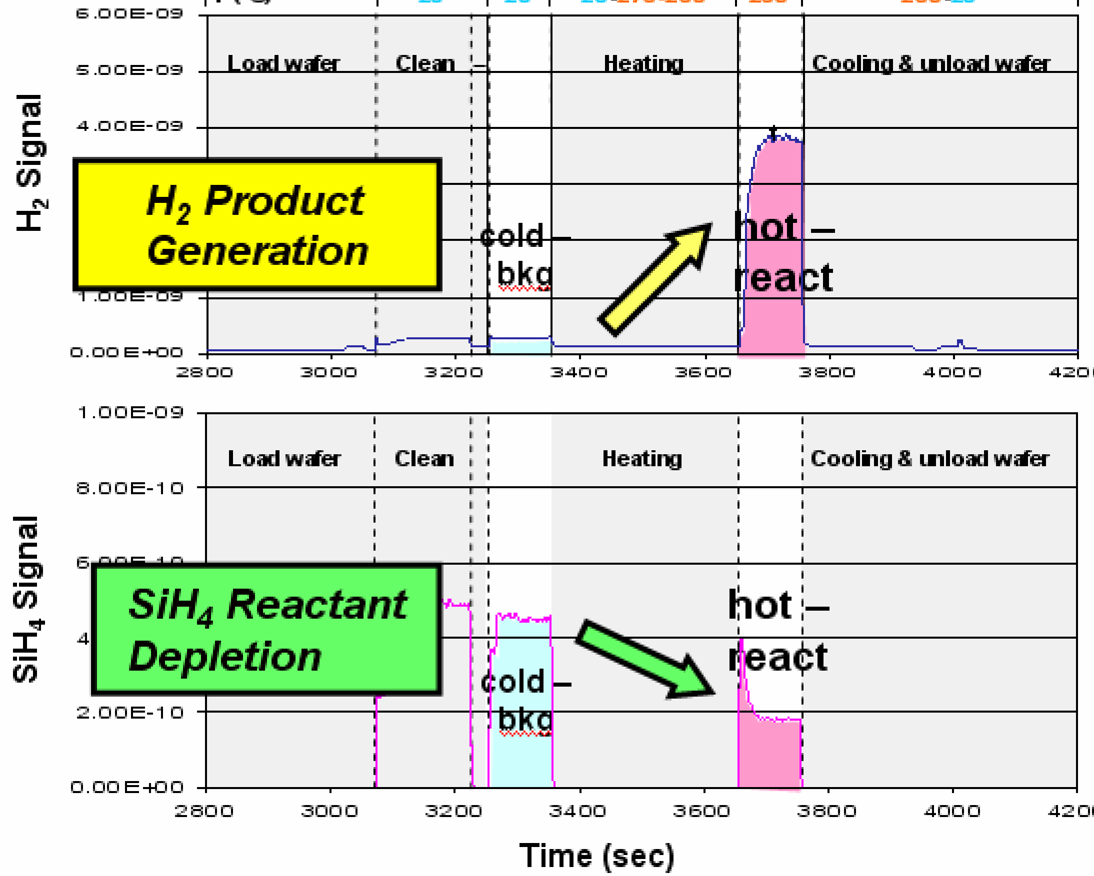
Real-Time Mass Spec in W CVD

- **W CVD by SiH_4 reduction of WF_6 in 0.5 torr thermal CVD**
- **Monitor process state as gas concentrations in reactor**
- **Product generation and reactant depletion reveal wafer state changes in real time**

$$2\ WF_6\ (g) + 3\ SiH_4\ (g) \rightarrow 2\ W\ (s) + 3\ SiF_4\ (g) + 6\ H_2\ (g)$$

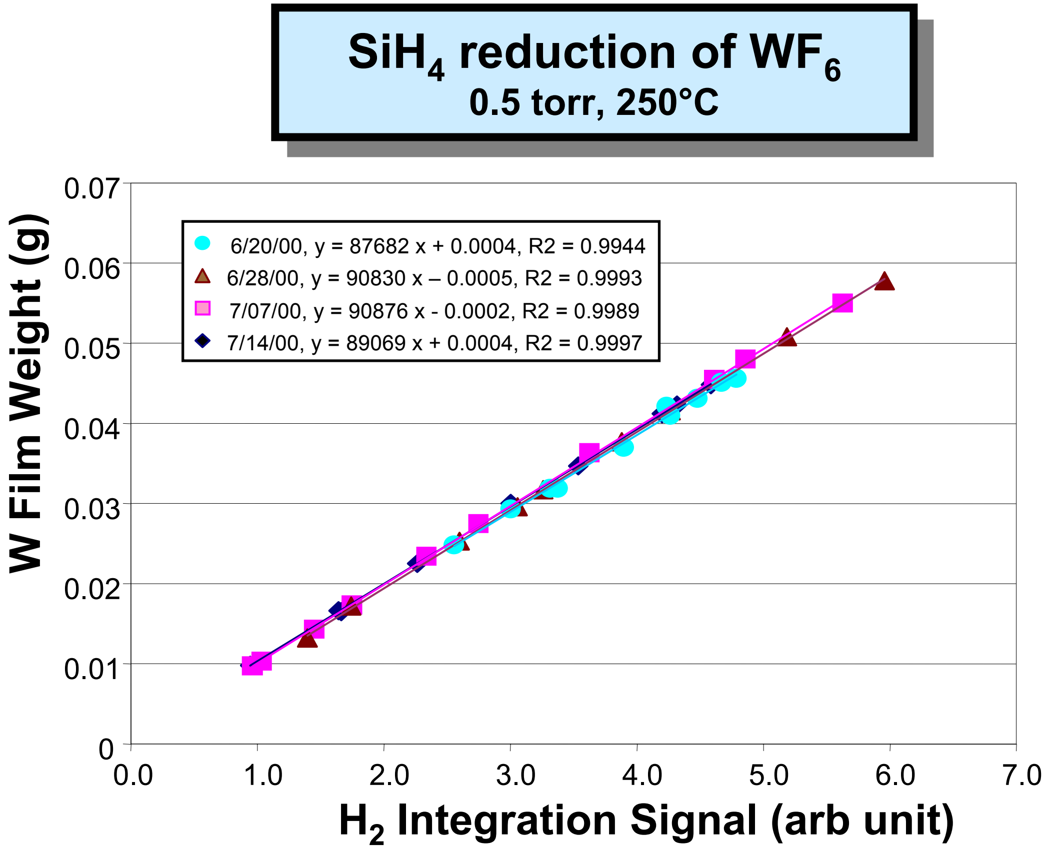
$$WF_6\ (g) + SiH_4\ (g) \rightarrow W\ (s) + 2\ SiHF_3\ (g) + 3\ H_2\ (g)$$

Step #	1 & 2	3	4	6	8
P (Mtorr)	100	100	100	100	100
Ar (Sccm)	180	180	180	180	198
SiH4 (Sccm)	8 & 0	8	0	8	0
WF6 (Sccm)	0	10	0	10	0
T (°C)	20	20	20-276-260	260	260-20

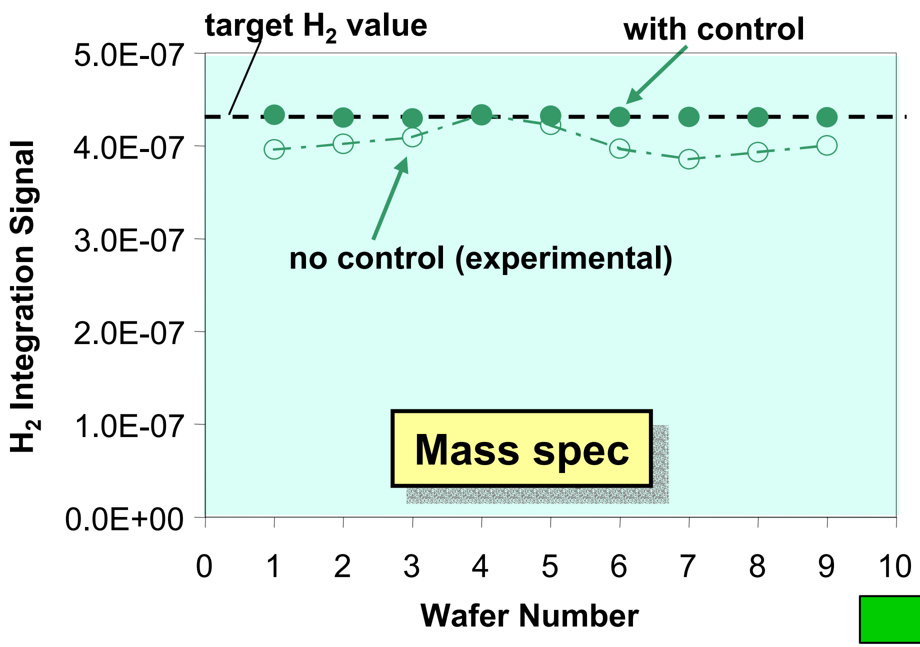


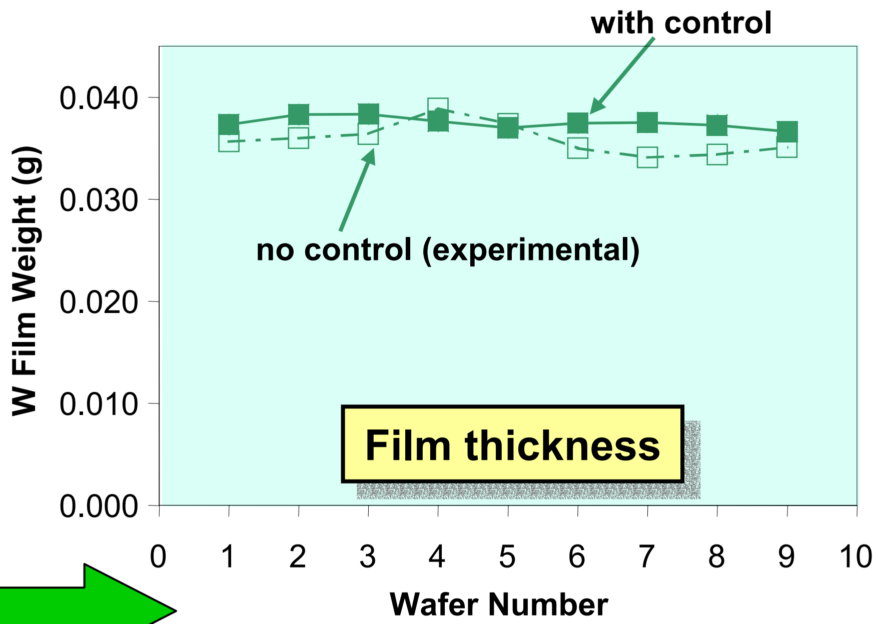
Real-Time Thickness Metrology

- **Reasonable Conversion Rate of WF_6 reactant (~20%)**
- **Metrology established from weight vs. integrated mass spec signal**
  - **Linear regression ➔ standard deviation 1.09%**
- **Viable for manufacturing process control**



Real-Time Thickness Control





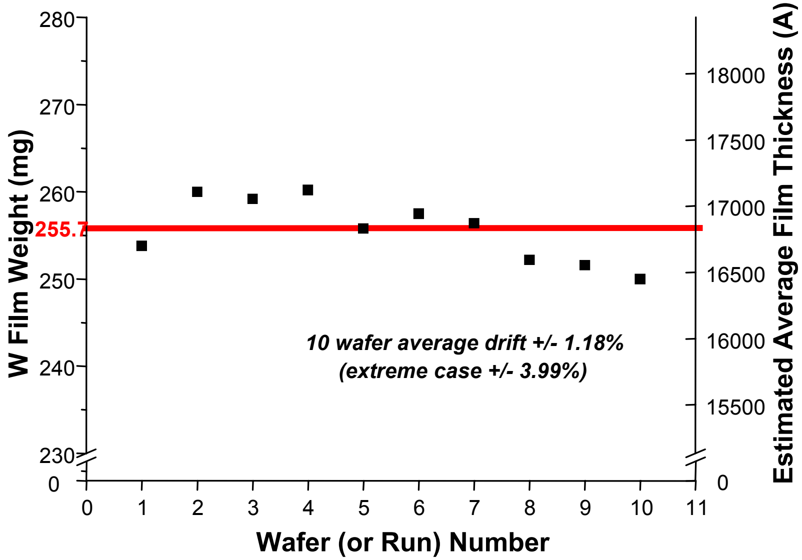
- *Open-loop wafer-to-wafer thickness variation ~ 10%*
- *Real-time end-point control of thickness to ~ 3%*
- *Real-time course correction to compensate for BOTH:*
  - *Random short-term variability*
  - *Systematic longer-term drift*

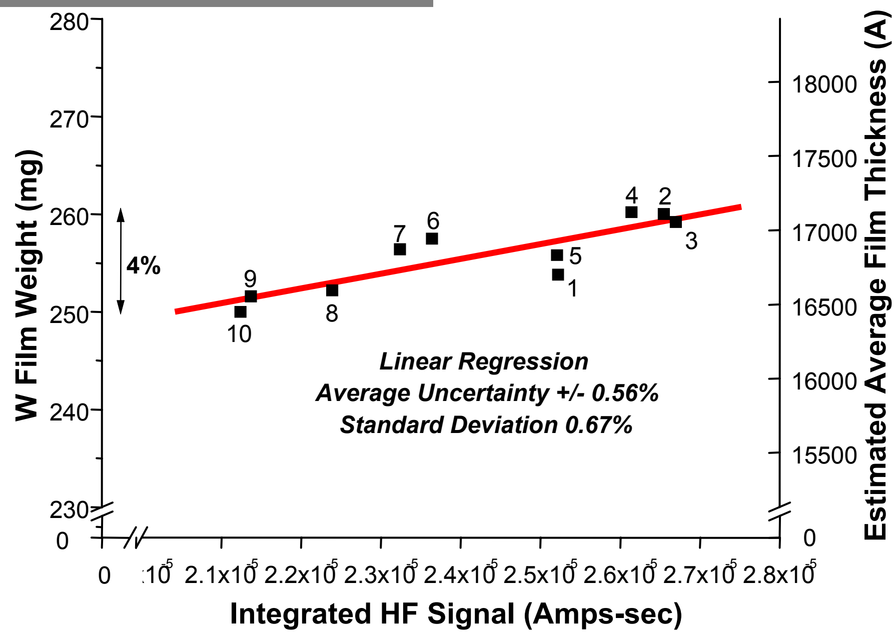
Mass Spec Thickness Metrology

H_2 reduction of WF_6

$WF_6(g) + 3\ H_2(g) \rightarrow W(s) + 6\ HF(g)$

Fixed process condition: 10 torr, 500°C, 640 sec





Run-to-run thickness drift

Average 1.18%

Extreme 3.99%

Mass spec thickness metrology

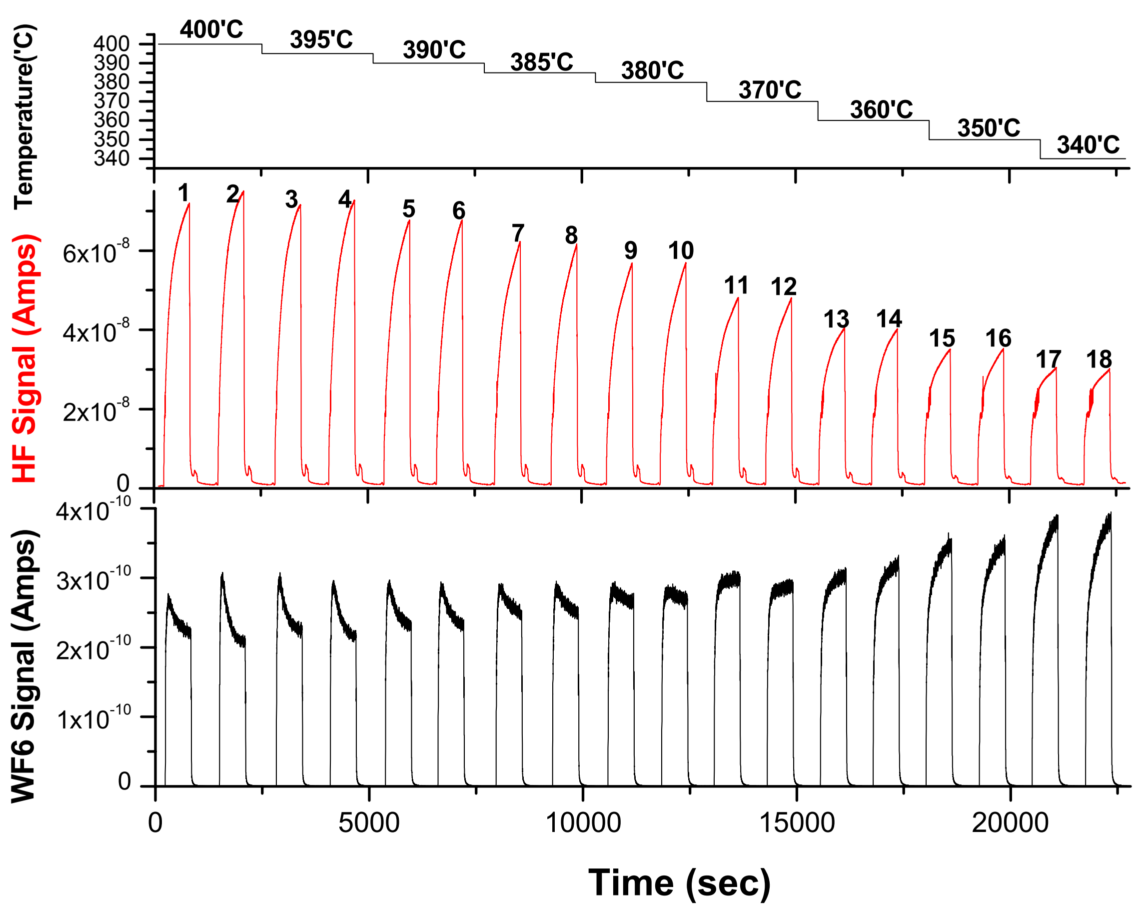
Average uncertainty 0.56%

Standard deviation 0.67%

Mass Spec Thickness Metrology: Intentional Temperature Drift

- **Introduce significant temperature drift to test robustness of metrology**
- **Substantial change in thickness (4X)**
  - ***Much larger than expected in manufacturing***

Intentional Run-to-Run Temperature Drift
Fixed Deposition Time 618 sec

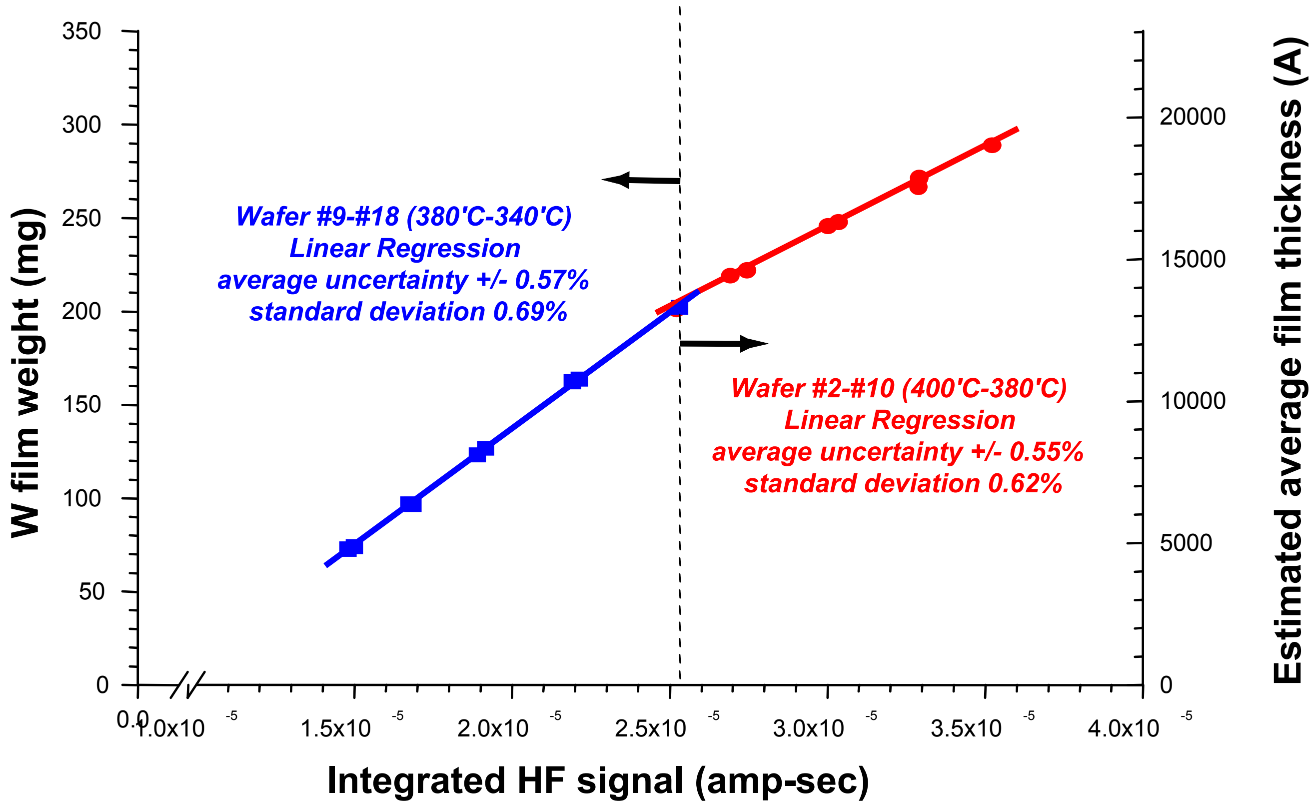


Mass Spec Thickness Metrology: Intentional Temperature Drift

Moderate non-linearity over broad temperature range

Deposition on showerhead, adsorption on chamber walls, …

***Metrology precision* ~ 0.6% near local process setpoint**



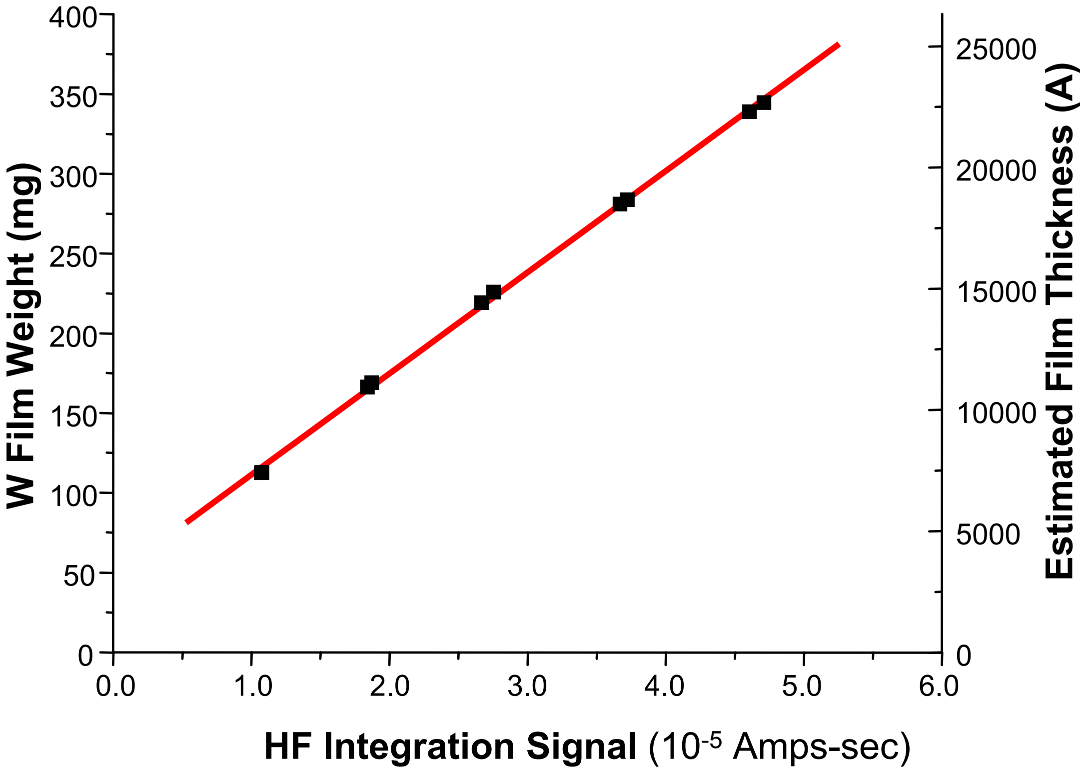
Mass Spec Thickness Metrology: Intentional Process Time Drift

- **Introduce significant process time drift to test robustness of metrology**
- **Substantial change in thickness (4X)**
  - *Much larger than expected in manufacturing*
- **Linear regression fit**
  - *Average uncertainty 1.19%*
  - *Standard deviation 1.59%*
- **Quadratic regression fit**
  - *Average uncertainty 0.48%*
  - *Standard deviation 0.57%*

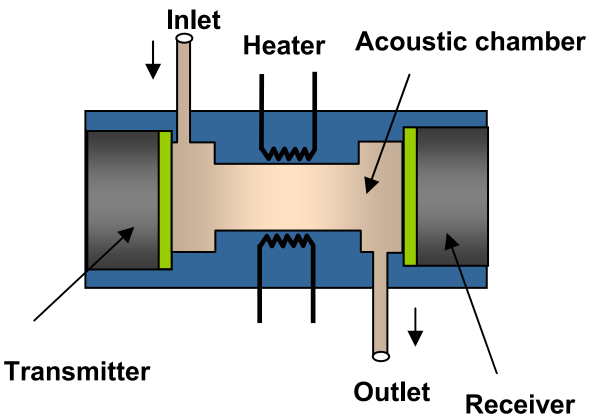
H_2 reduction of WF_6

$$WF_6(g) + 3\,H_2(g) \rightarrow W(s) + 6\,HF(g)$$

10 torr, 390°C



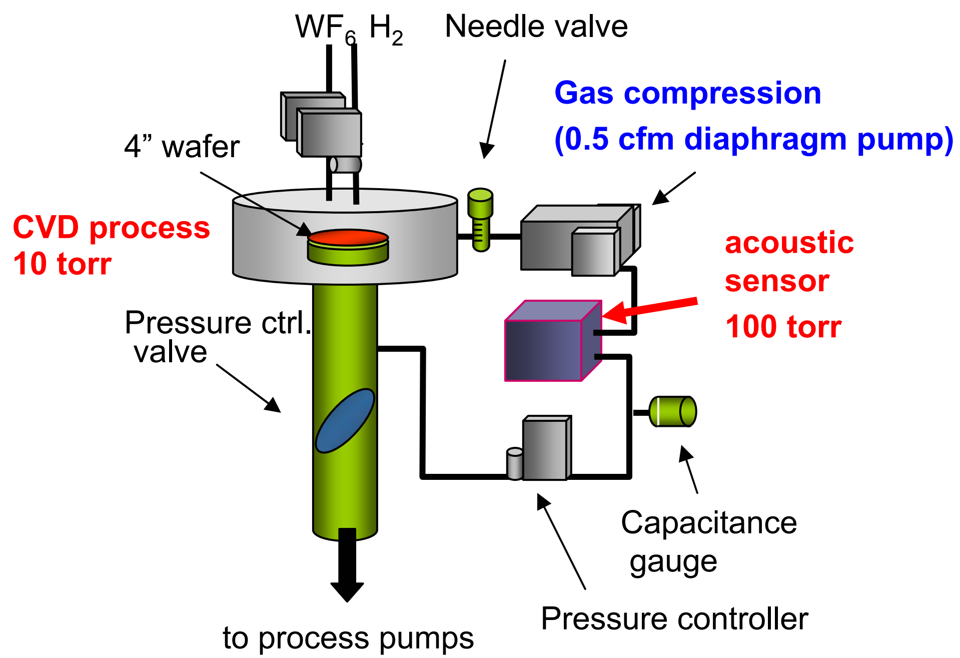
Acoustic Sensing for Real-Time APC



- **Acoustic wave propagation and resonance**
  P > 50 torr

- **Resonant frequency depends on average molecular weight, specific heat, and temperature of gas mixture**
  C = speed of sound

$$F = \frac{C}{2L} \quad \text{with} \quad C = \sqrt{\frac{\gamma_{avg} RT}{M_{avg}}}$$



Pressure transduction to higher pressure

Acoustic Sensor Thickness Metrology

Run-to-run thickness drift

Average 4% over 10 runs

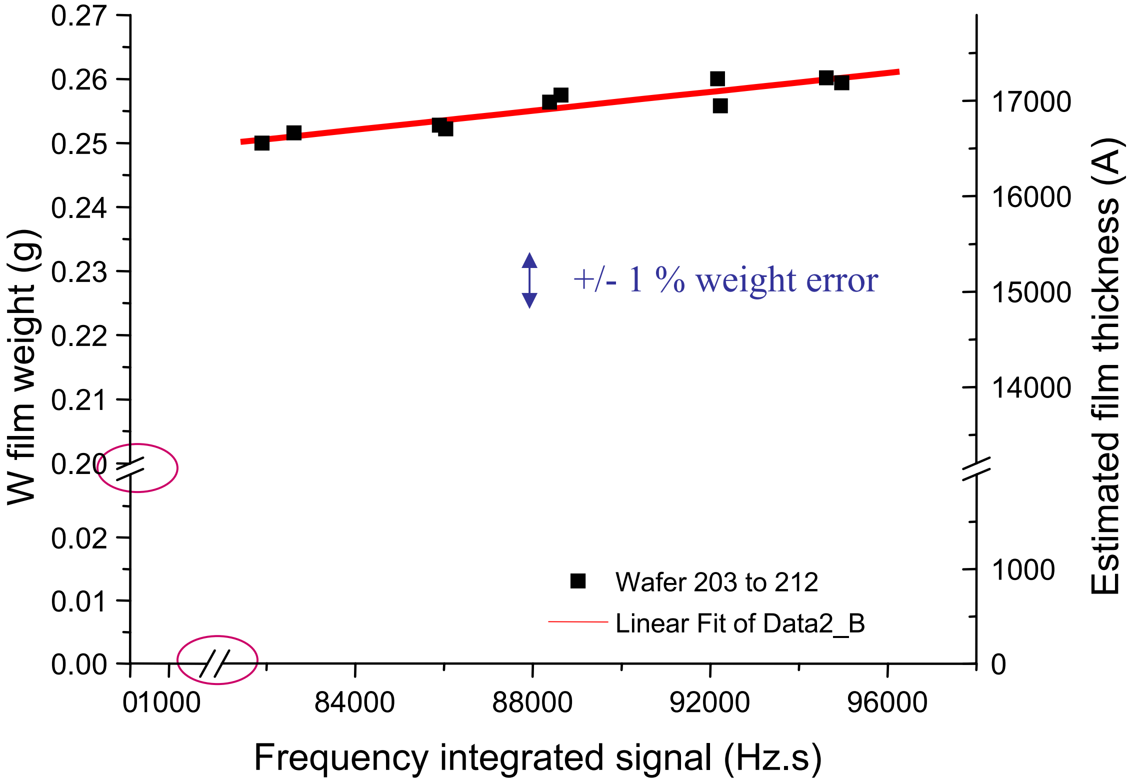
Acoustic sensor thickness metrology

0.5% average uncertainty from linear regression fit

H_2 reduction of WF_6

WF_6(g) + 3 H_2(g) ➔ W(s) + 6 HF(g)

Fixed process condition: 10 torr, 490°C, 640 sec



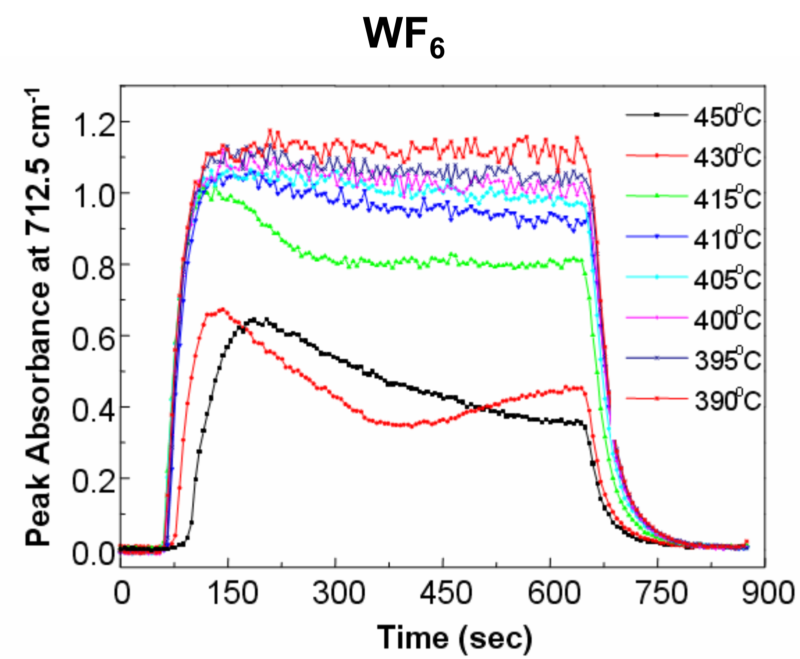
FTIR Sensing for Real-Time APC

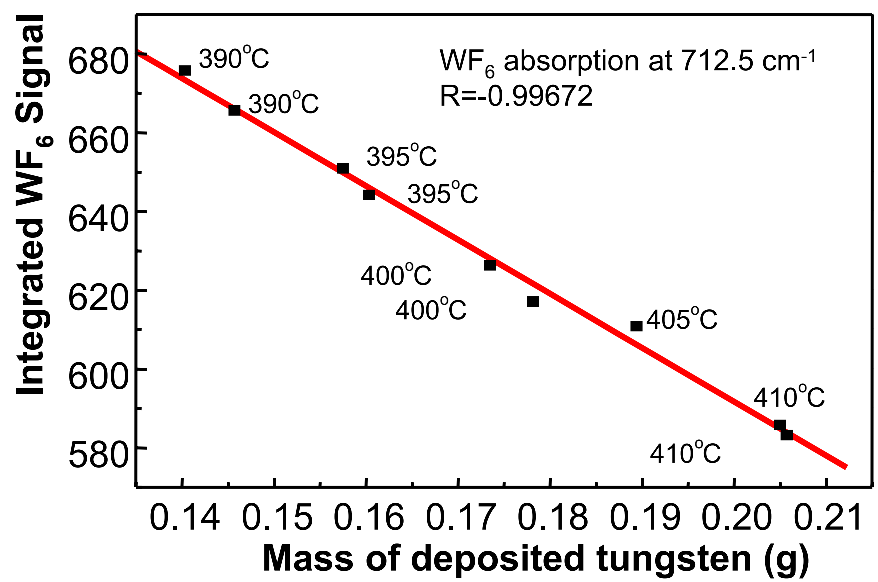
- **Implementation like acoustic sensor**
  P > 50 torr
- **Sense molecular vibrations (infrared) for product generation, reactant depletion**
- **WF_6 product depletion ➔ thickness metrology precision ~0.5%**

H_2 reduction of WF_6

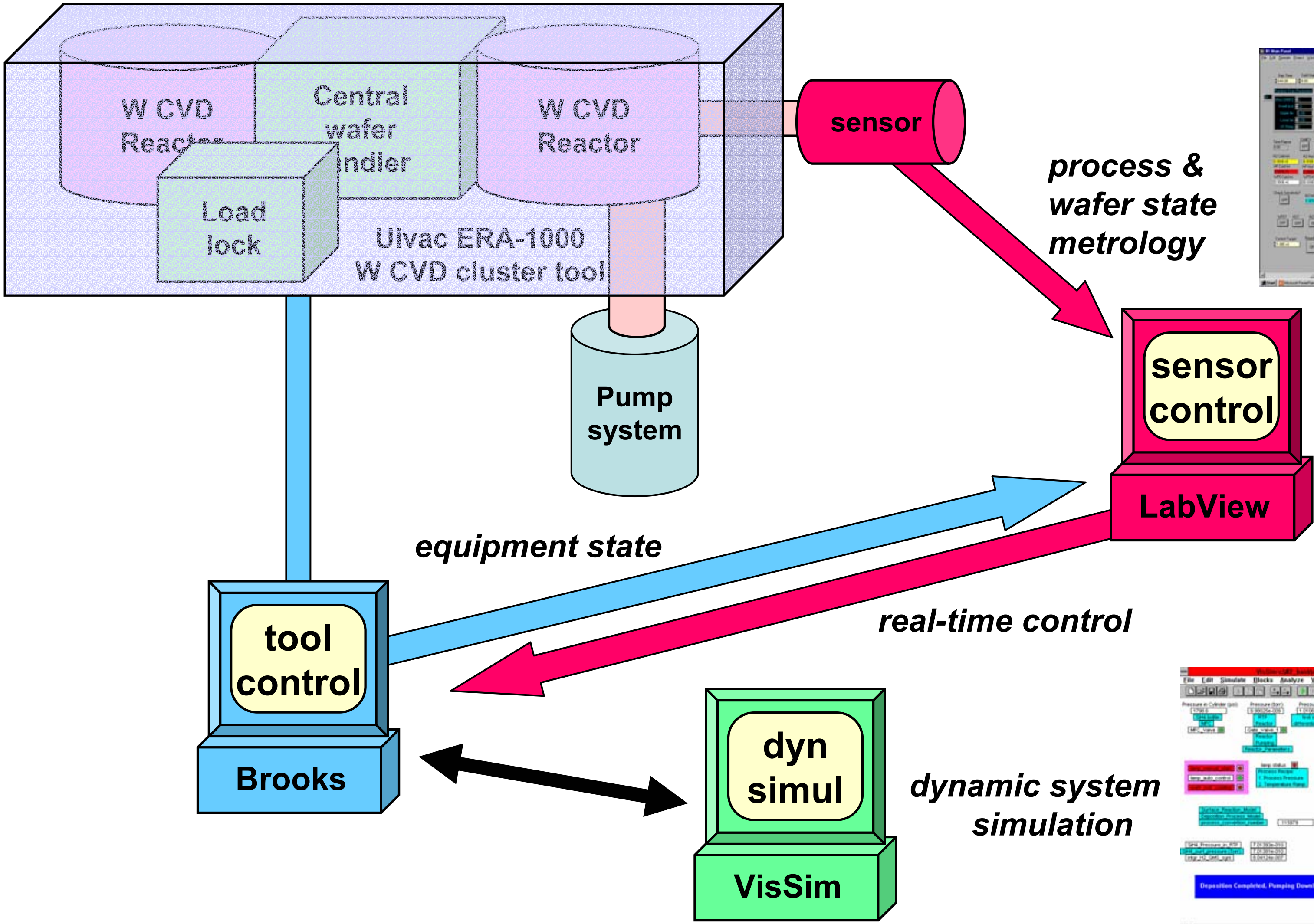
$WF_{6(g)} + 3 H_{2(g)} \rightarrow W_{(s)} + 6 HF_{(g)}$

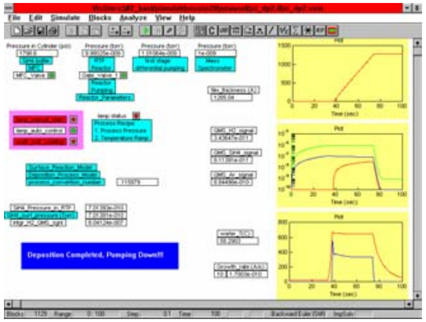
Intentional temperature drift: 10 torr, 390-450°C





Sensor Integration





Interface and Thin Layer Sensitivity

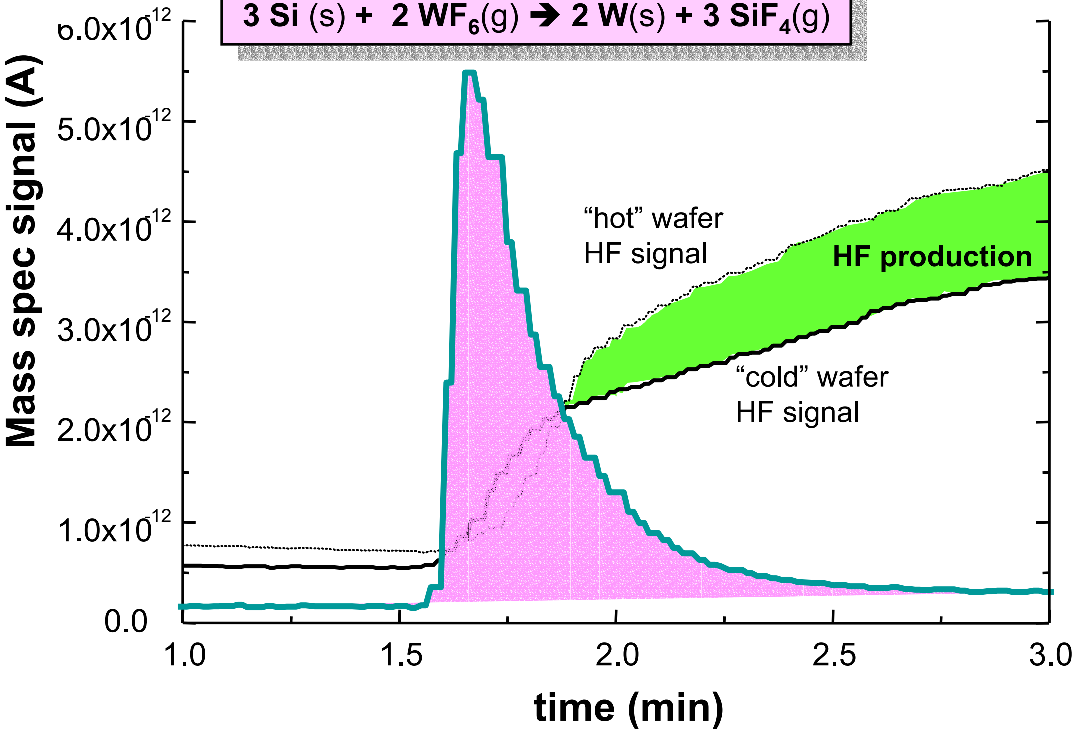
Initial reaction dominated by
WF_6 - Si nucleation

~30 nm W formed

Readily observed

H_2 reduction of WF_6:
$WF_{6(g)} + 3\ H_{2(g)} \rightarrow W_{(s)} + 6\ HF_{(g)}$

SiF_4 product of
Si reduction reaction
$3\ Si\ (s) + 2\ WF_6(g) \rightarrow 2\ W(s) + 3\ SiF_4(g)$



Implications:

Fault detection

assure oxide-free contacts)

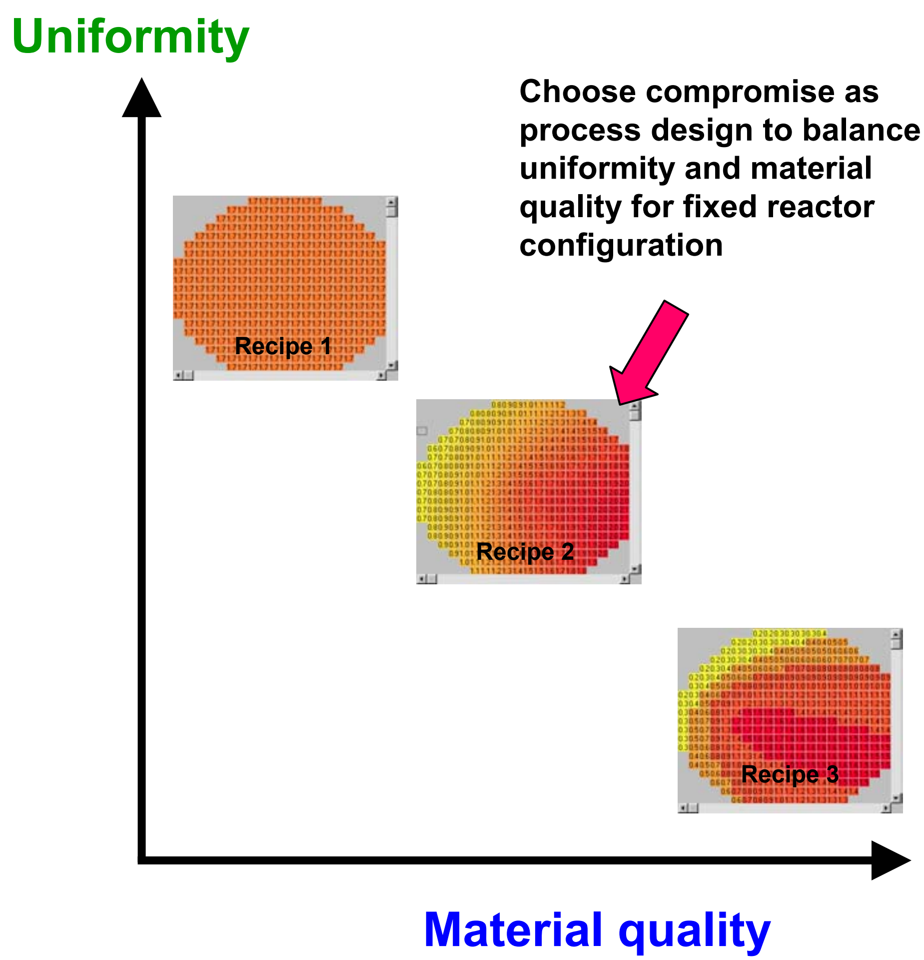
Metrology for ultrathin CVD layers

Ready for Technology Transfer

- **In-situ sensors deliver metrology for real-time APC**
  - *Quantitative precision for real-time course correction*
  - *Dual-use sensors to drive both course correction and fault management (e.g., mass spec)*
- **Research underpinnings in place**
  - *Multiple sensors with metrology at 1% or better*
  - *Real-time end point control demonstrated*
  - *Sensor-tool integration*
- **Ready for implementation in manufacturing environment**
  - *Compatible with existing/installed real-time sensors for fault detection*
  - *UMD anxious to assist, collaborate, …*
  - *Prediction: further improvement in metrology precision*
    - High throughput enhances sensor & tool conditioning

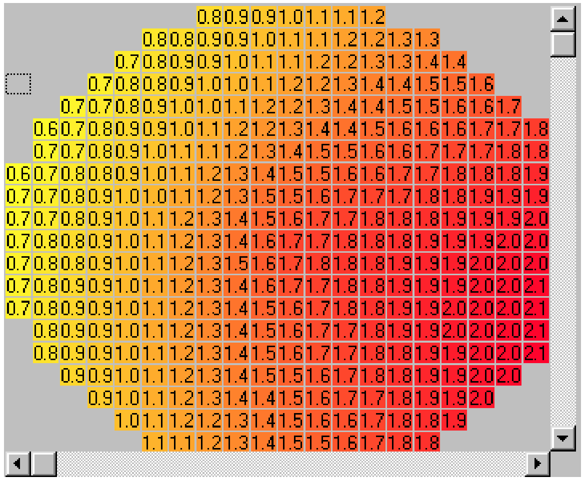
Across-Wafer Uniformity

- **Key manufacturing metric for yield**
- **In-situ sensor capability to date**
  - ***Spatially resolved optical (OES) – process state***
  - ***Full-wafer interferometry – wafer state***
- **No mechanism for real-time uniformity adjustment**
- **Currently, process optimization involves tradeoff between material quality metrics and uniformity**



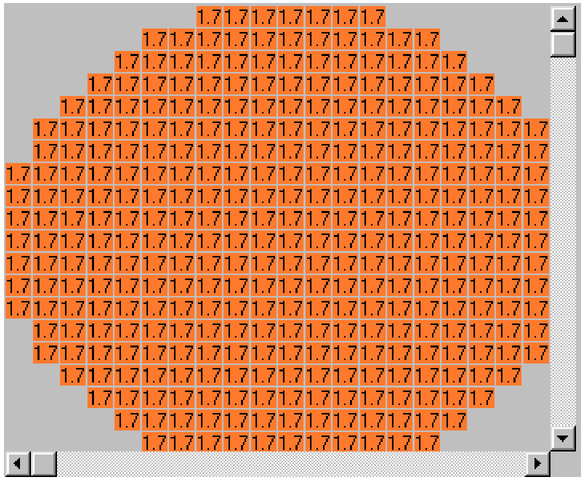
Programmable Uniformity
to Optimize Quality & Manufacturability

Choose process design point for optimal material and device performance



Uniformity unacceptable

Retune spatial conditions in programmable reactor



Produce high uniformity with optimal material and device performance

Spatially Programmable CVD Uniformity through a Smart Showerhead

Sensors - integrated into the showerhead

> ***Spatially resolved, multizone wafer and process state measurements***

Actuators - multizone, gas inlet

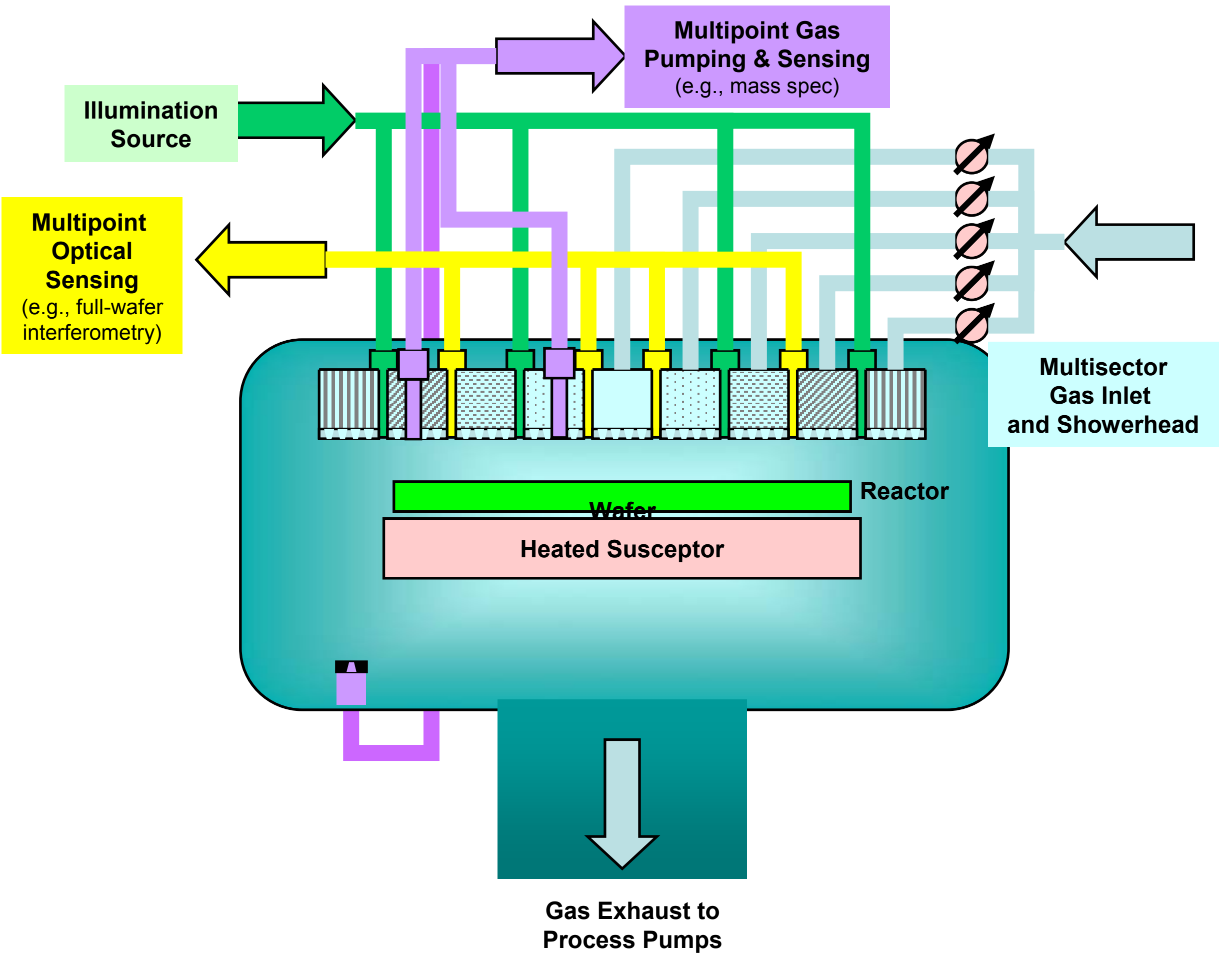
> ***Gas flow rates and compositions controlled within each showerhead segment***

Supplementary pumping through the showerhead

> ***Reduced inter-segment gas mixing, precise composition control, gas sampling for chemical sensing***

Simulation and reduced-order models

> ***Support for process equipment design and control***



Experimental Testbed:
Spatially Programmable CVD Showerhead

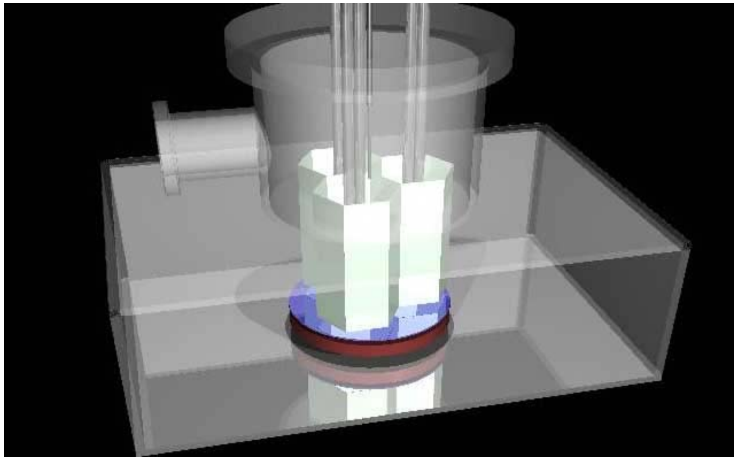
3-segment prototype

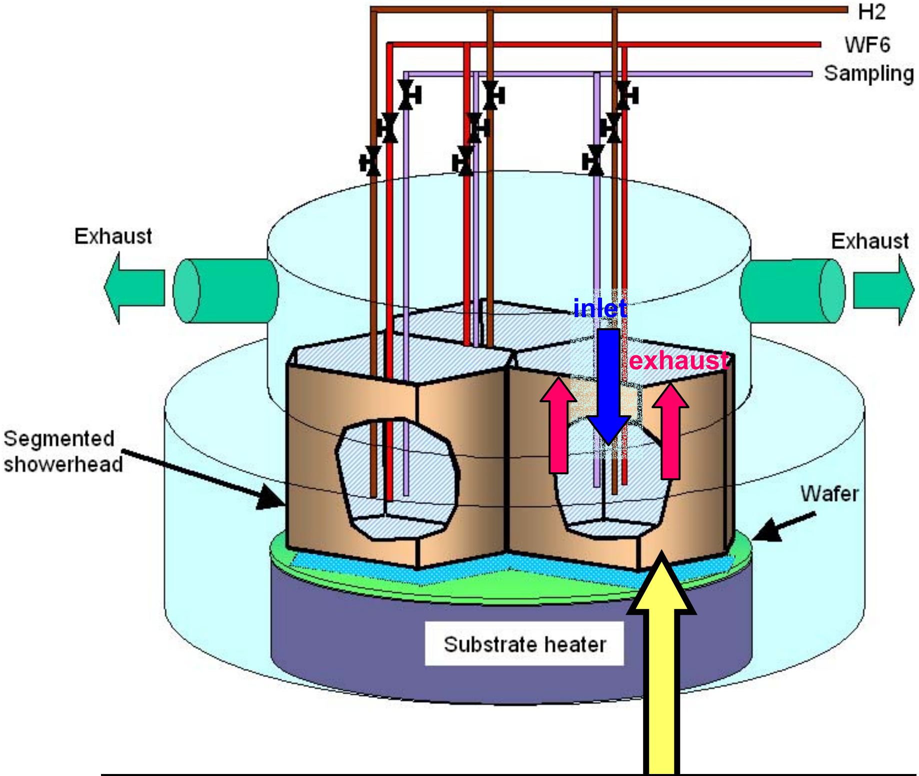
Exhaust and inlet in each segment

Adjustable spacings to wafer

intersegment vs. intrasegment mixing

Extensive coupling to modeling

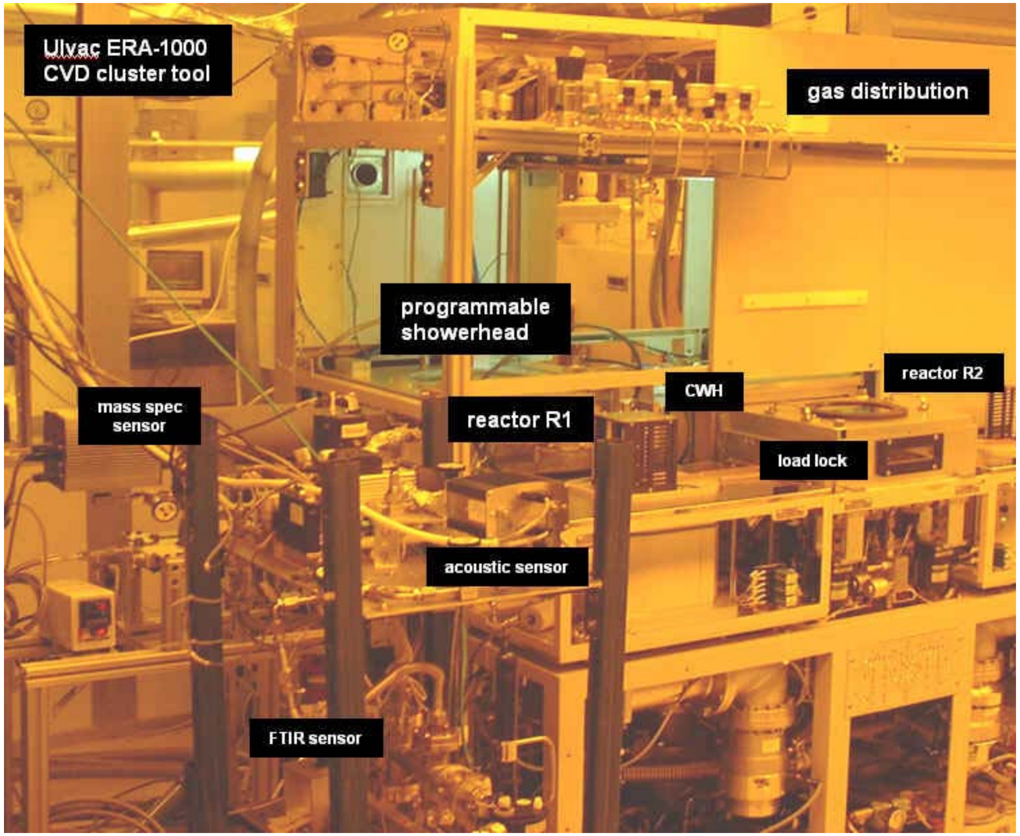


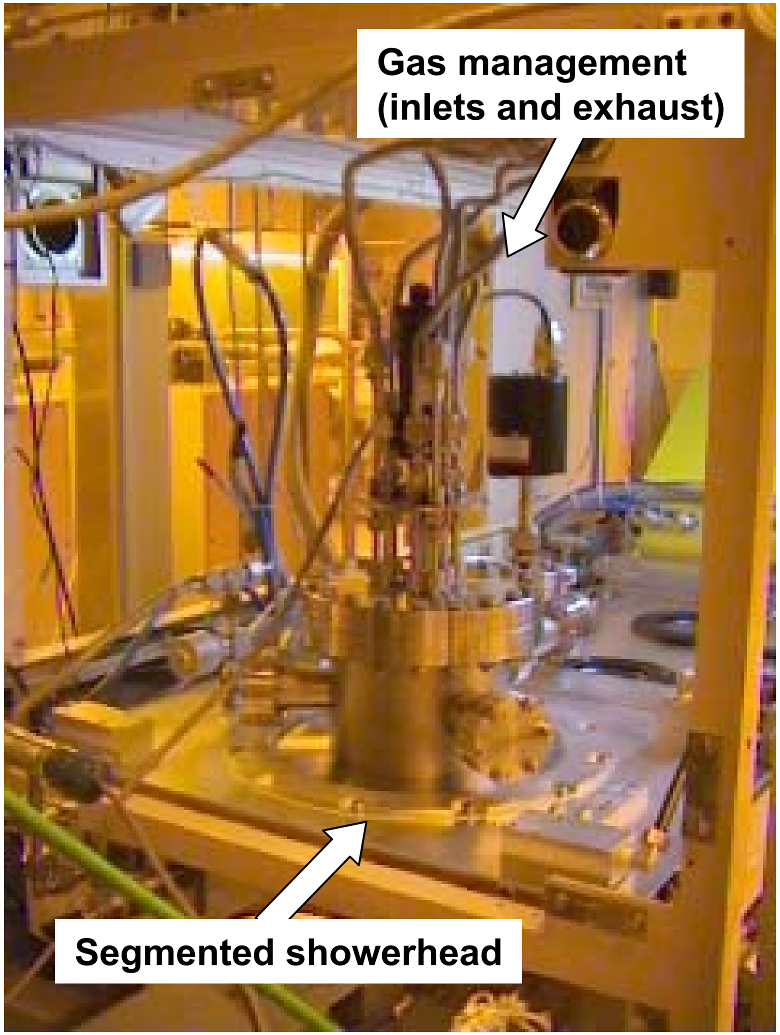


individual segment :
quasi-independent mini-showerhead incorporating gas inlet, exhaust, sensing, and model-based control of actuation

Experimental Testbed:
Spatially Programmable CVD Showerhead

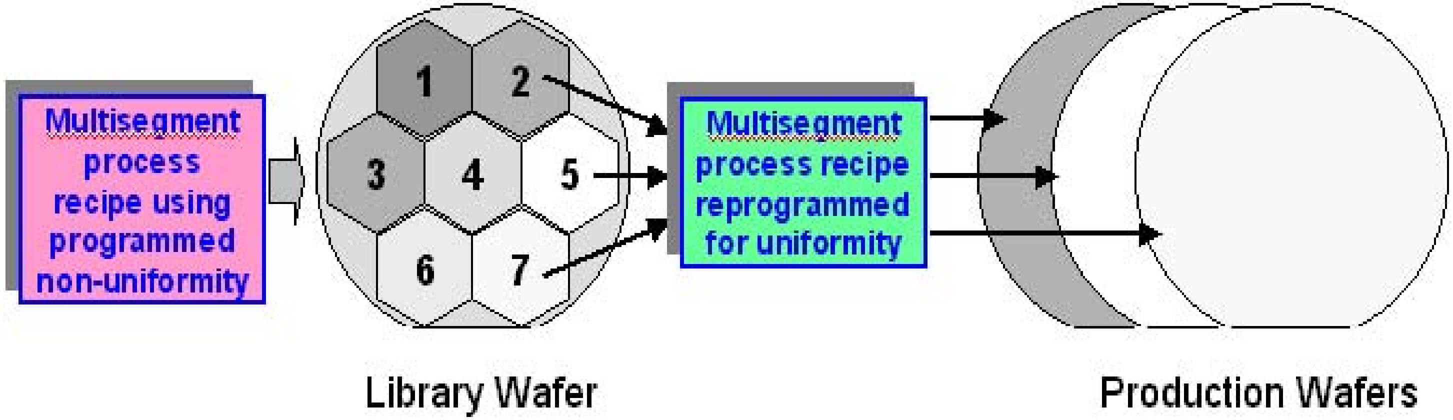
- **Ulvac ERA-1000 W CVD cluster tool**
- **W CVD process using $WF_6 + H_2$**



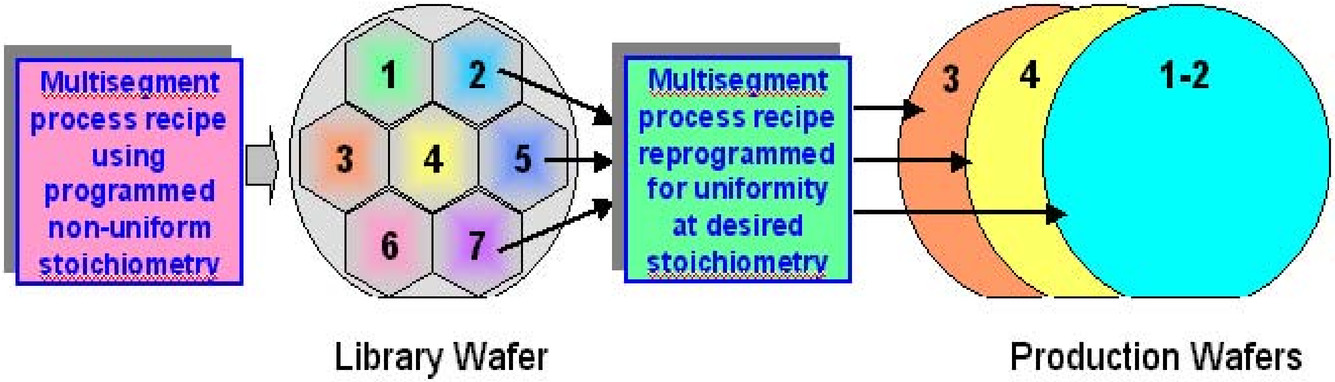


Programmable Nonuniformity
for Rapid Materials & Process Development

One-wafer DOE → process optimization

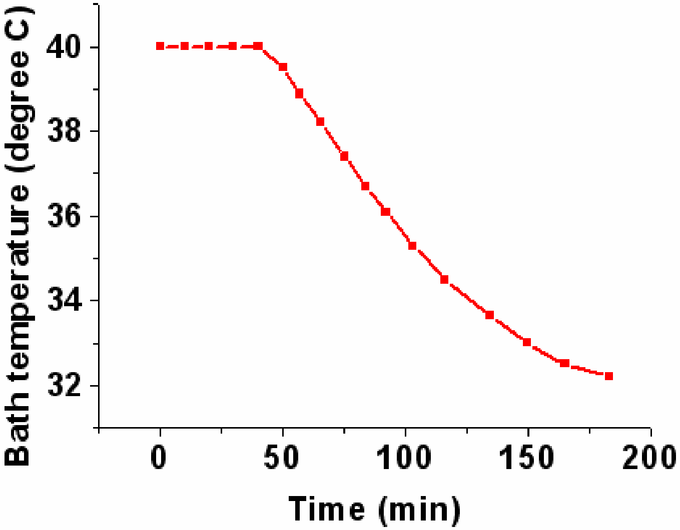


Combinatorial CVD → new materials discovery and development



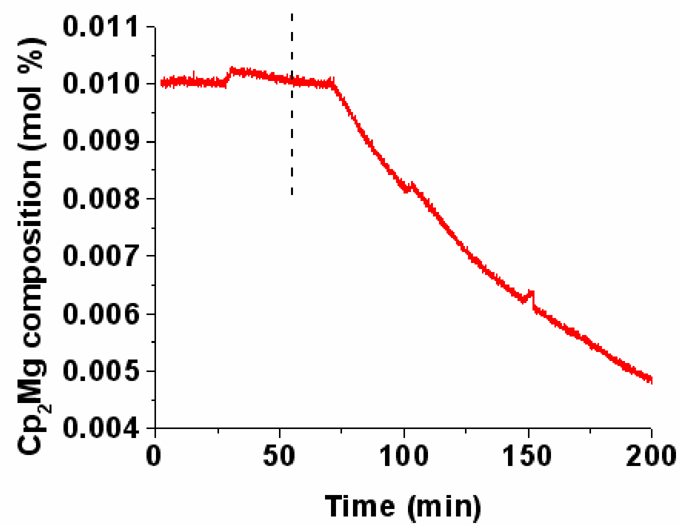
Precursor Delivery Challenges

- **Solid & low vapor pressure sources increasingly critical for new materials**
- **Precursor delivery control remains problematic**
  - ***Changing morphology with time and usage***
  - ***Adsorption on walls***
  - ***Complex chemical precursors***
- **Options limited for both chemical precursor and delivery system design**



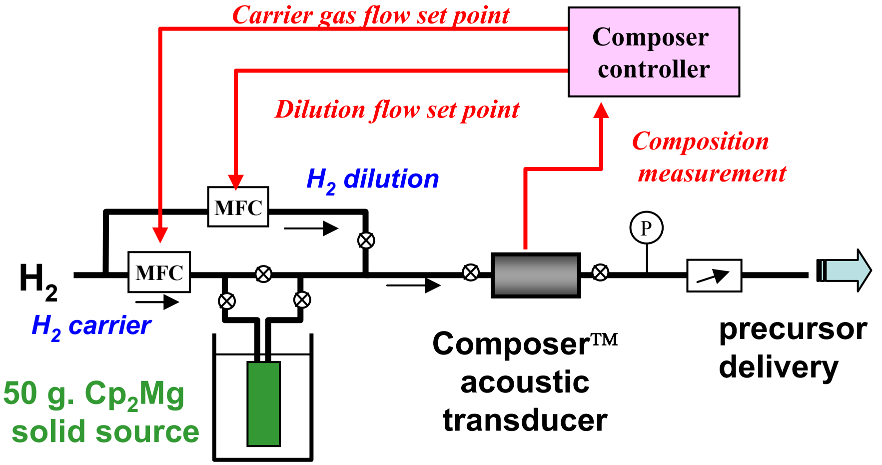
Example: Cp_2Mg temperature decrease 40→32°C reduces vapor pressure & composition 2X

Simulates "aging" effects



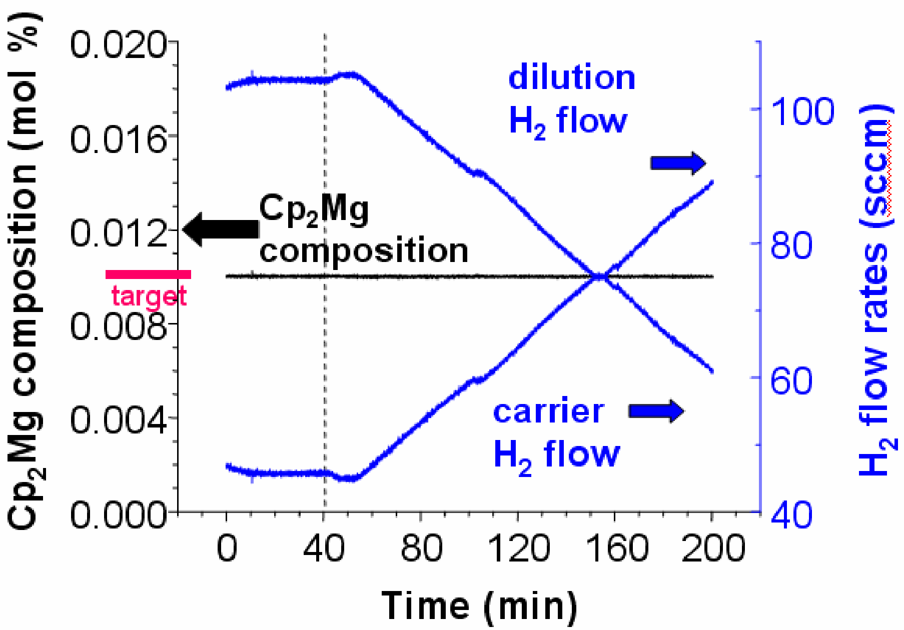
Real-Time Precursor Delivery Control

- Acoustic sensor for composition metrology
- Source and dilution gas flow control



Source temperature varied from 40→ 32°C
Σ (H_2 flows) = 150 sccm, P = 300 torr
Cp_2Mg target = 0.01 mol%

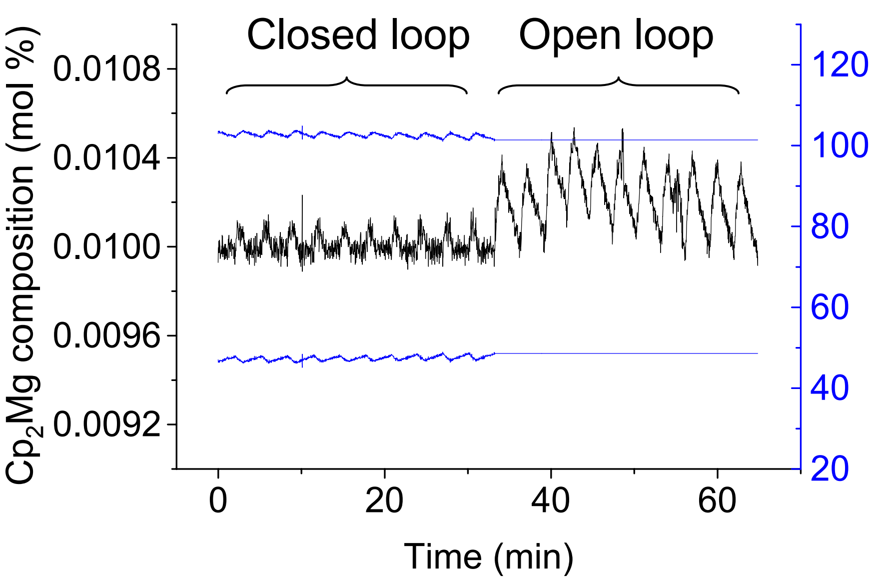
Cp_2Mg composition controlled to 1% of target (0.0001 mol %)

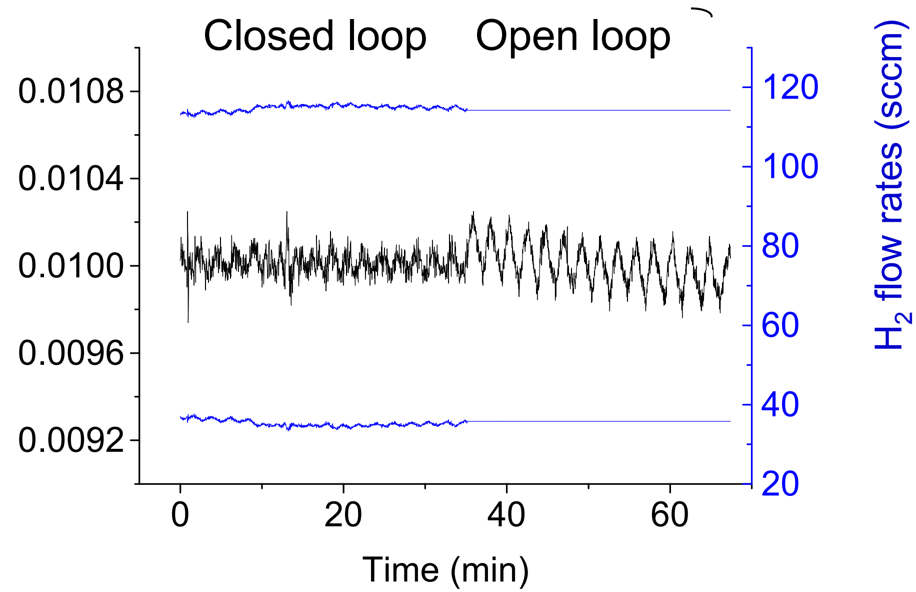


MOCVD Precursor Delivery Line Control

T(source) = 40°C

T (feed line) = 50 ± 1.5°C 60 ± 1.5°C





Acoustic sensor reveals wall adsorption fluctuations ➔ optimize wall temperature

Control system suppresses delivery fluctuations

Conclusions

- **In-situ metrology is key to achieving real-time APC**
  - *Benefits in rapid feedback at unit process (tool) level*
  - *Implementation within hierarchical control framework*
- **In-situ chemical sensors provide quantitative real-time metrology**
  - *Multiple sensors with <1% precision*
  - *Real-time end point control demonstrated*
  - *Course correction synergistic with fault detection*
  - *Broad applications - CVD, PECVD, etch, spin-cast, …*
- **Ready for tech transfer, evaluation in manufacturing environment**
- **New opportunities**
  - *Uniformity control*
  - *Precursor delivery control*

Acknowledgements

- **Research group**
  - *L. Henn-Lecordier, J. N. Kidder, T. Gougousi, Y. Xu, S. Cho, R. A. Adomaitis, J. Choo, Y. Liu, R. Sreenivasan, L. Tedder, G.-Q. Lu, A. Singhal*
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