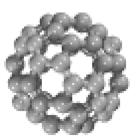
UNIVERSITY OF MARYLAND

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


## *Gary W. Rubloff*

Professor, Materials Science and Engineering, Institute for Systems Research,
and Electrical and Computer Engineering
University of Maryland
www.isr.umd.edu/gwrubloff, rubloff@isr.umd.edu



**Department of Materials Science and Engineering**

The Institute for Systems Research


NSF/SRC Center for Environmentally Benign Semiconductor Manufacturing
Teleseminar 7/31/03

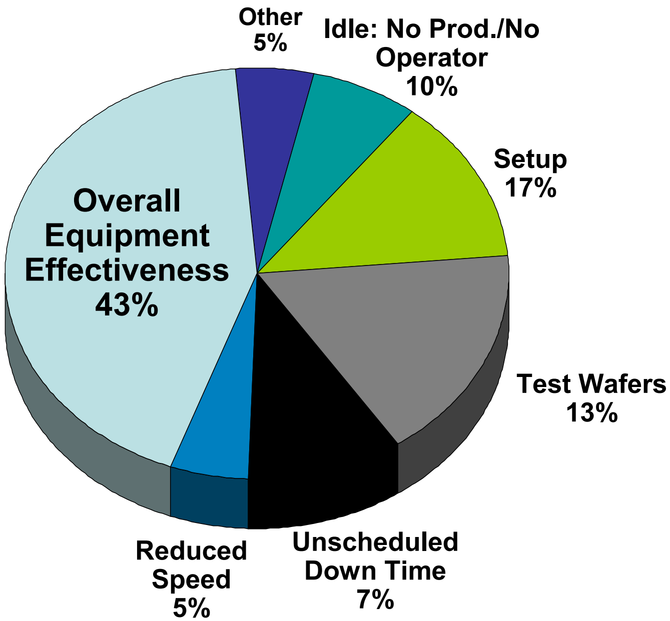
# Abstract

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

*Gary W. Rubloff*

While real-time and in-situ process sensors have been effectively applied to fault detection, process control through course correction has been mainly focused on in-line metrologies to drive run-to-run feedback and feedforward control. We have developed in-situ metrologies based on mass spectrometry, acoustic sensing, and FTIR techniques which enable real-time thickness metrology and control in CVD processes at a level of about 1% accuracy. These developments open the door to real-time sensors as the basis for both fault management and course correction, i.e., for real-time advanced process control. We have also employed in-situ metrology to develop robust control schemes for CVD precursor delivery from solid sources, and we are exploring a new spatially programmable reactor design paradigm for which real-time, in-situ sensing, metrology, and control of across-wafer uniformity is fundamental. These advances hold promise for more efficient manufacturing through advanced process control, and with it, improved environmental metrics from that manufacturing.

# Capital Equipment and Advanced Process Control




J. Hosch, Texas Instruments

- Factory cost dominated by huge investments in capital equipment
- But … equipment utilization <50%
- Pervasive concepts:
  - *Cost-of-Ownership (COO)*
  - *Overall Equipment Effectiveness (OEE)*

***Advanced Process Control***

*Sensor-driven*

*Model-based*

***Course Correction***

- Run-to-run control
- Real-time control

***Fault Management***

- Detection
- Classification
- Prognosis
- Response

# Manufacturing Productivity

## Solution – From Fabrication to Manufacturing

- Is
  - In-situ Sensors
  - Real-time Control
  - Single Wafer Interdiction
  - Feed Forward
  - Tool Idle Time Reduced by 2x per Node
  - Integration of Simulation, Modeling, & Factory Control Software
- Is Not
  - In-Line Metrology
  - Test Wafers
  - Scrapped Lots
  - Rework
  - Tool Idle Time
  - Tool Requals

**C.R. Helms**

# Benefits to ESH

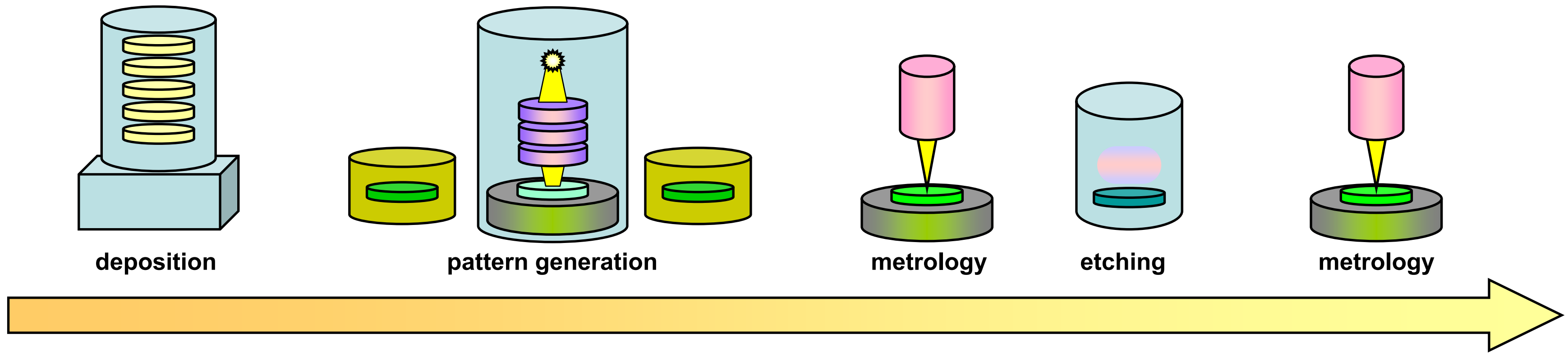
- ESH optimization must be consistent and/or synergistic with technology performance and manufacturing productivity.
- Materials and energy utilization (key ESH metrics) scale with number of wafers processed, not with yield.
- High equipment productivity minimizes ESH metrics.
- Advanced process control is the key to high equipment productivity.

# Synopsis

- **Advanced process control (APC) has become pervasive**
  - *In-situ metrology is key to achieving <u>real-time</u> 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)



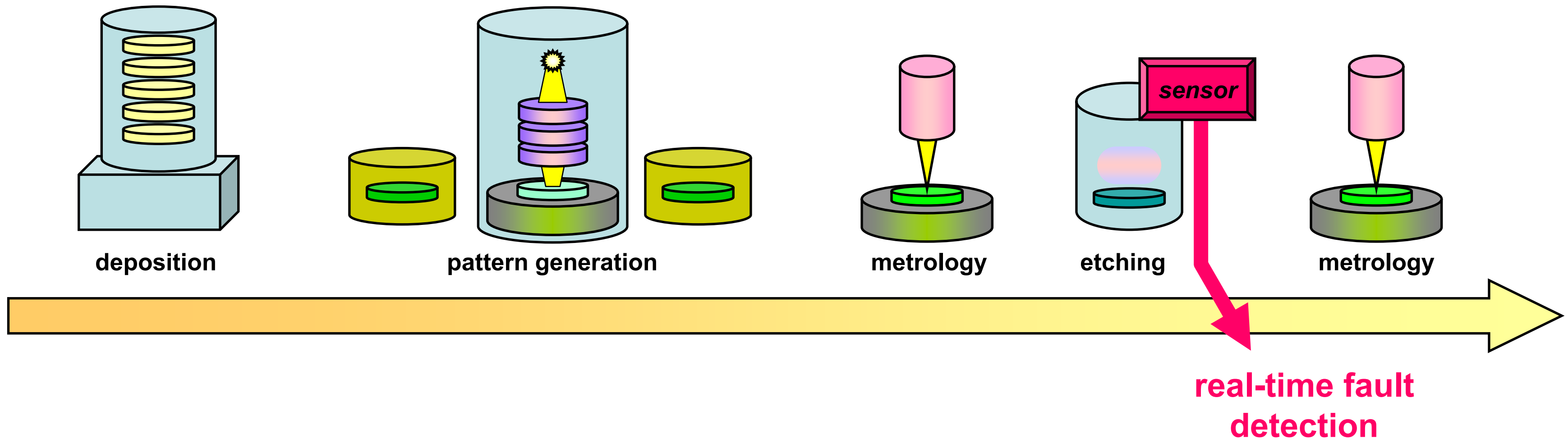

**Advanced Process Control (APC)**

**Course correction**
Compensate for variations to maintain process targets

**Fault management**
Identify and repair equipment problems

**Sensor-driven**
**Model-based**

# Advanced Process Control (APC)




**Advanced Process Control (APC)**

**Sensor-driven**
**Model-based**

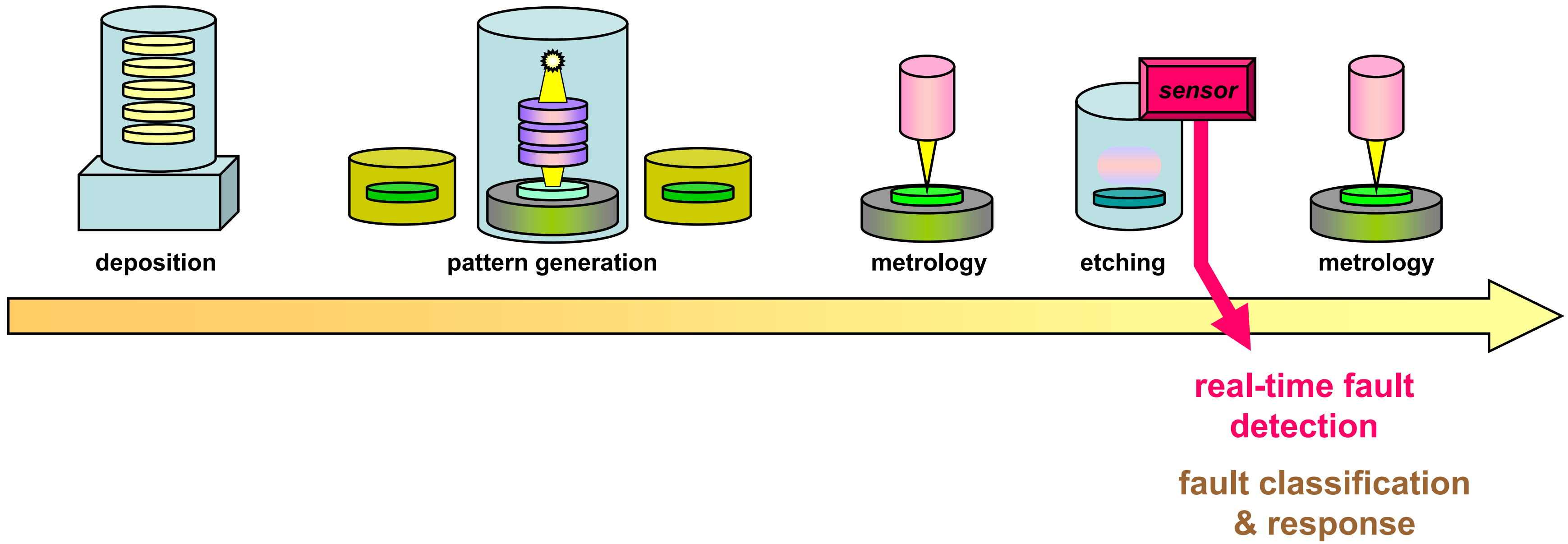
**Course correction**
Compensate for variations to maintain process targets

**Fault management**
Identify and repair equipment problems

**Real-time fault detection**
Known failure modes and signatures

mainline

# Advanced Process Control (APC)

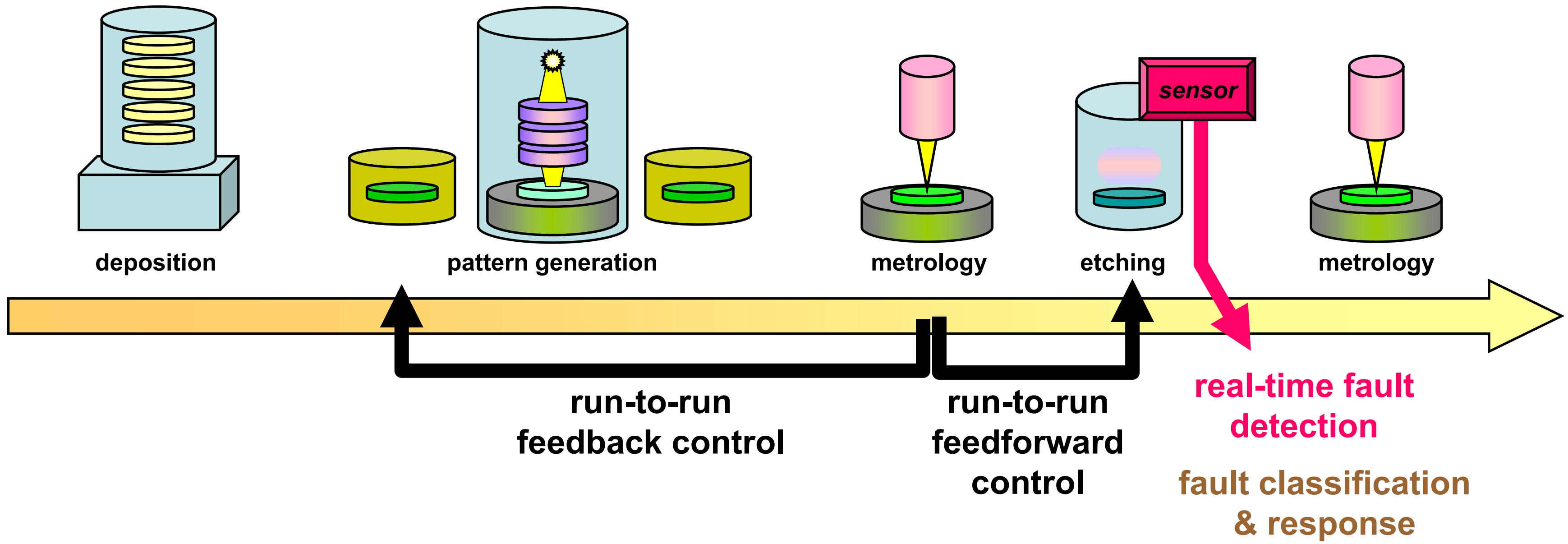


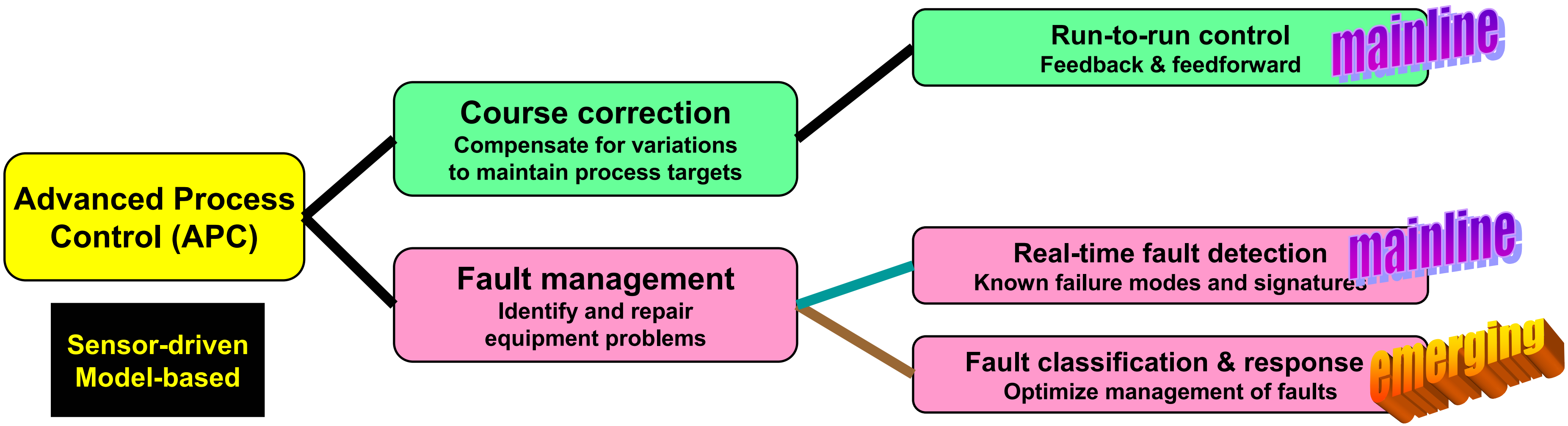

**Advanced Process Control (APC)**

**Sensor-driven**
**Model-based**

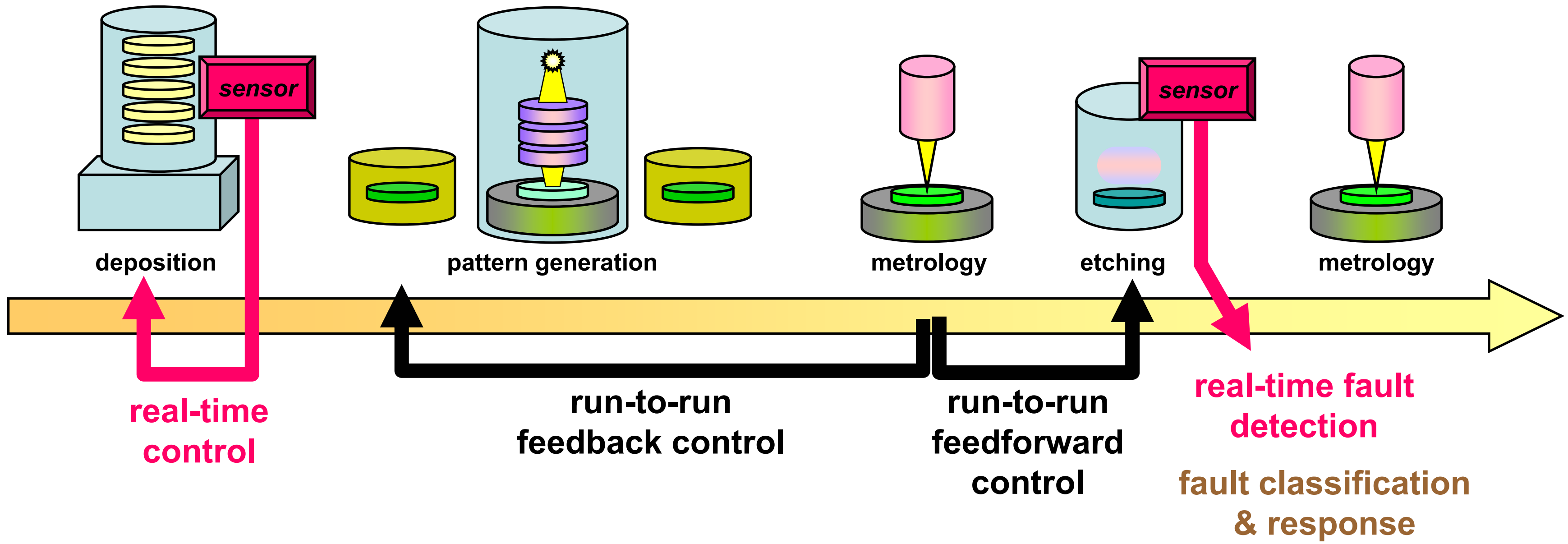
- **Course correction**
  Compensate for variations to maintain process targets
- **Fault management**
  Identify and repair equipment problems
  - **Real-time fault detection** — *mainline*
    Known failure modes and signatures
  - **Fault classification & response** — *emerging*
    Optimize management of faults

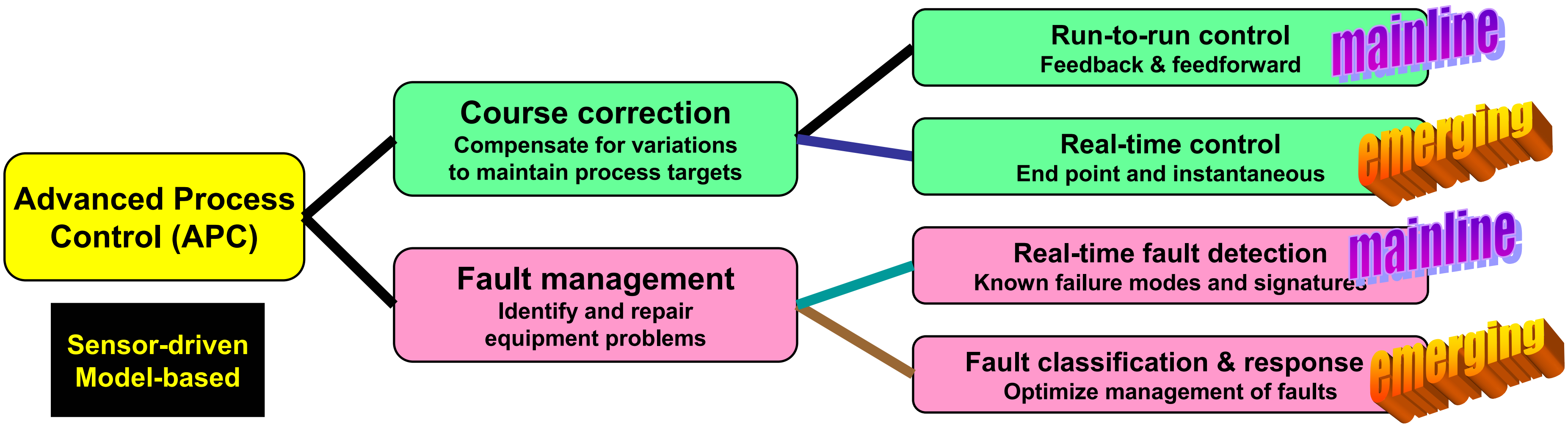
# Advanced Process Control (APC)



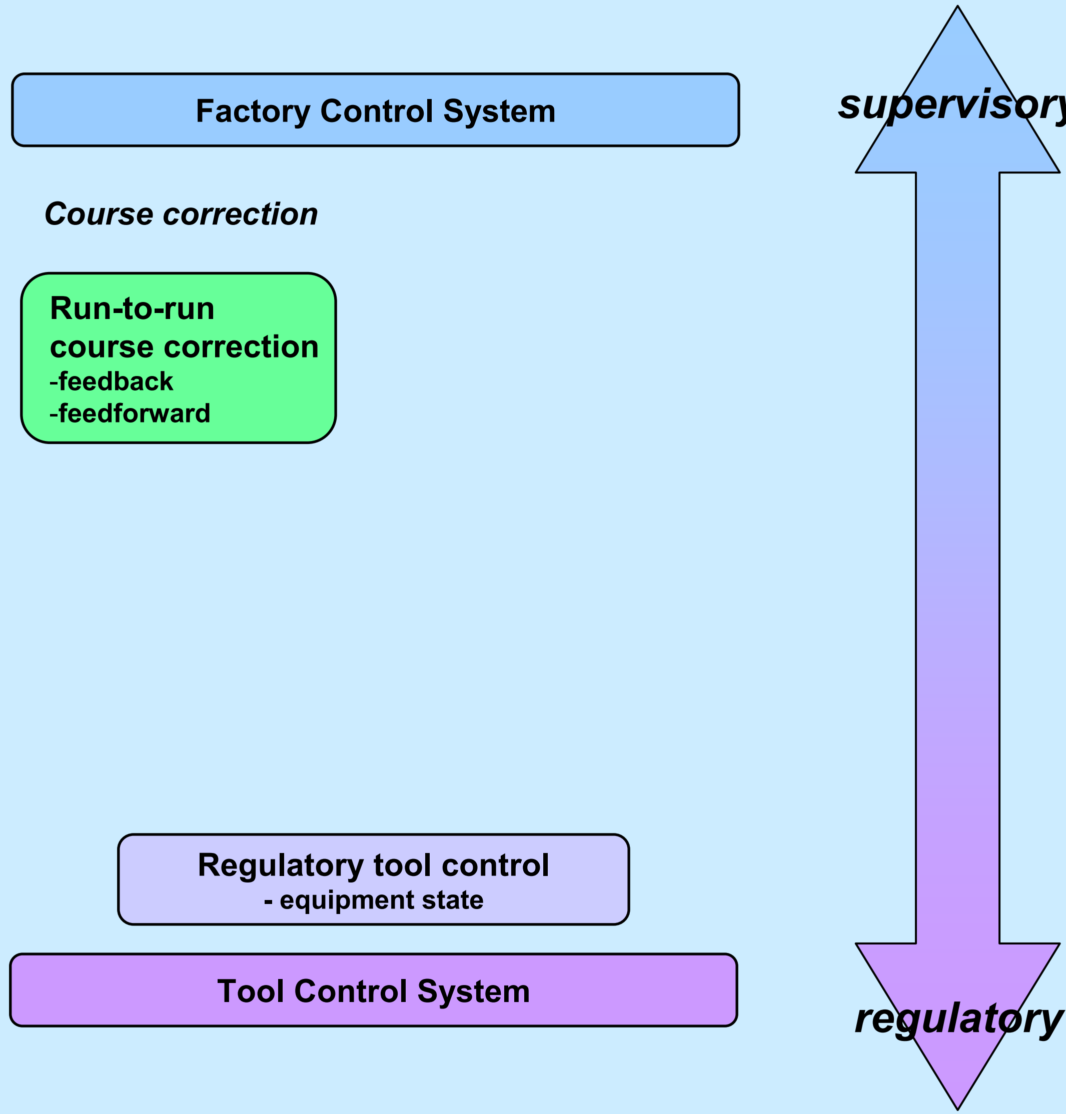



# Advanced Process Control (APC)



# APC Hierarchy

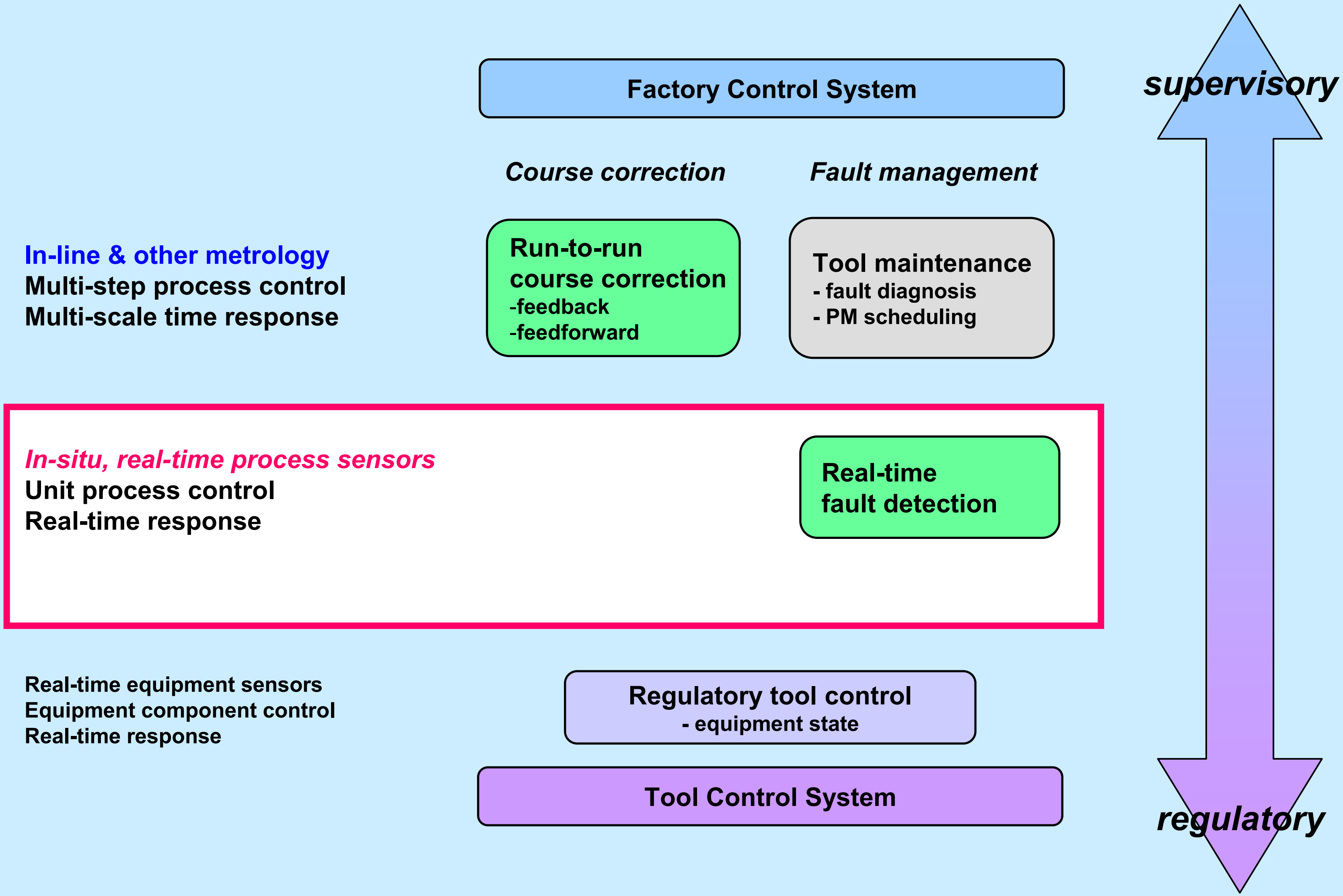



In-line & other metrology
Multi-step process control
Multi-scale time response

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

A. JAMES CLARK
SCHOOL OF ENGINEERING

# APC Hierarchy




A. JAMES CLARK SCHOOL OF ENGINEERING

# APC Hierarchy

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

*quantitative metrology in-situ, real-time*

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

Regulatory tool control
- equipment state

Tool Control System

*supervisory*

*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**

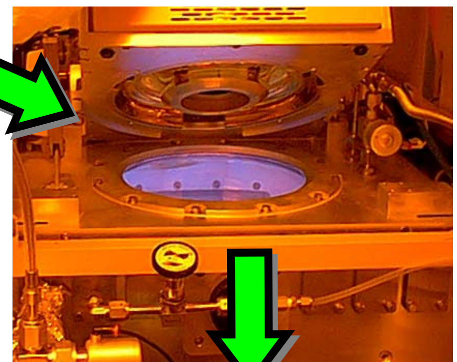
- Plasma optical emission spectroscopy (OES)
- Laser/optical interferometry
- Mass spectrometry
- Acoustic sensing
- Fourier transform infrared spectroscopy (FTIR)
- Plasma impedance
- Optical thermometry/pyrometry
- Ellipsometry
- Optical scatterometry
- …

# Mass Spectrometry for Real-Time APC

Ulvac multi-chamber "cluster" tool

**PROCESS CHAMBER**

Chemical vapor deposition chamber for tungsten metal

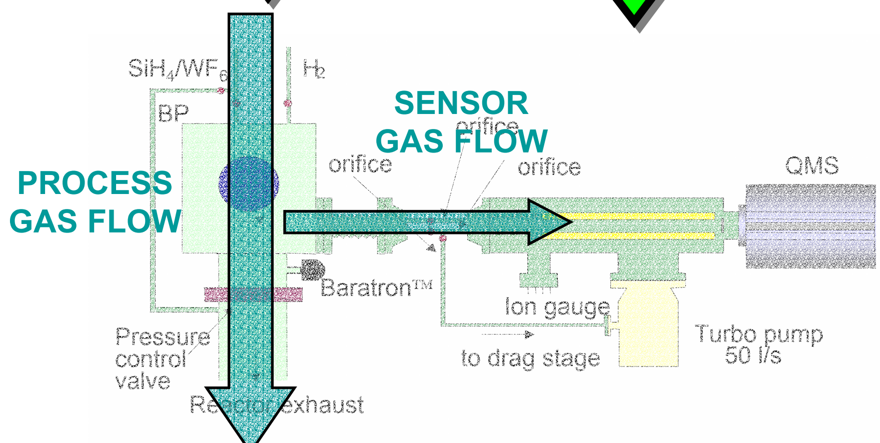


**CHEMICAL SENSORS**

Inficon Composer™ acoustic sensor

Inficon Transpector™ mass spec chemical sensor

***Pressure transduction to low pressure***

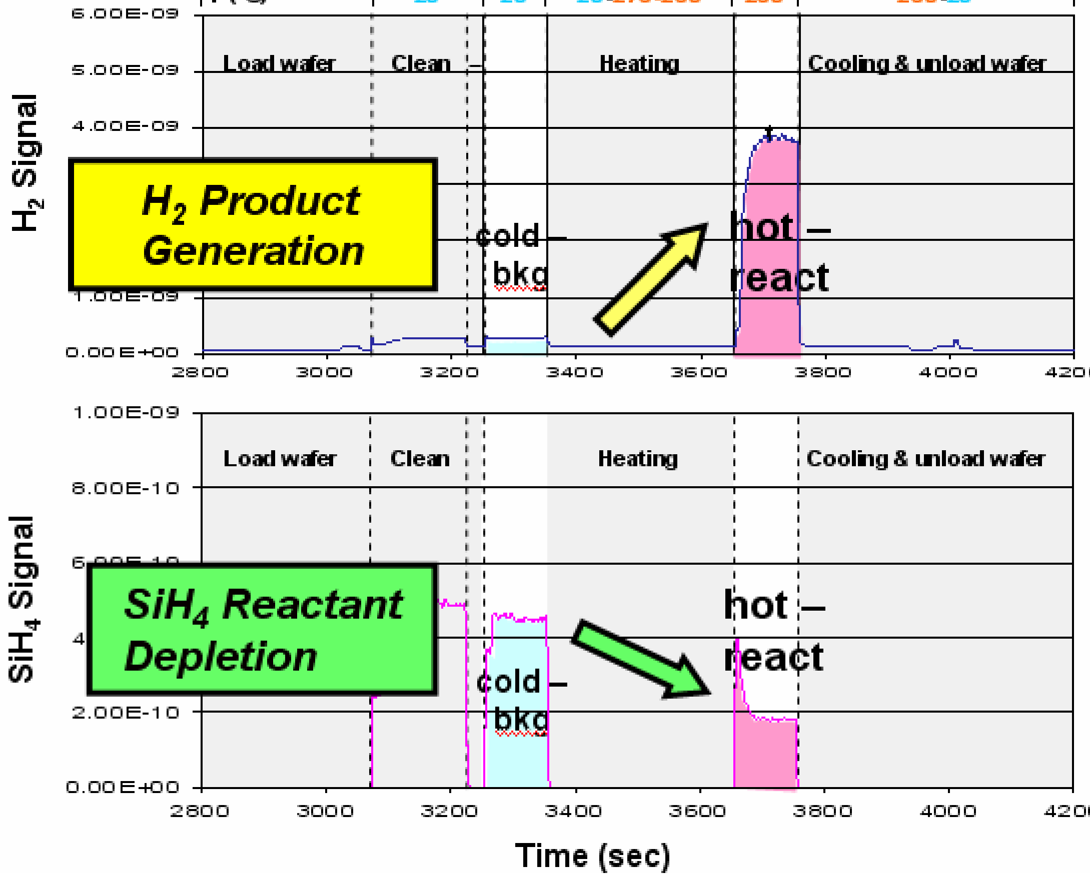


# Real-Time Mass Spec in W CVD

$$2\,WF_6\,(g) + 3\,SiH_4\,(g) \rightarrow 2\,W\,(s) + 3\,SiF_4\,(g) + 6\,H_2\,(g)$$
$$WF_6\,(g) + SiH_4\,(g) \rightarrow W\,(s) + 2\,SiHF_3\,(g) + 3\,H_2\,(g)$$

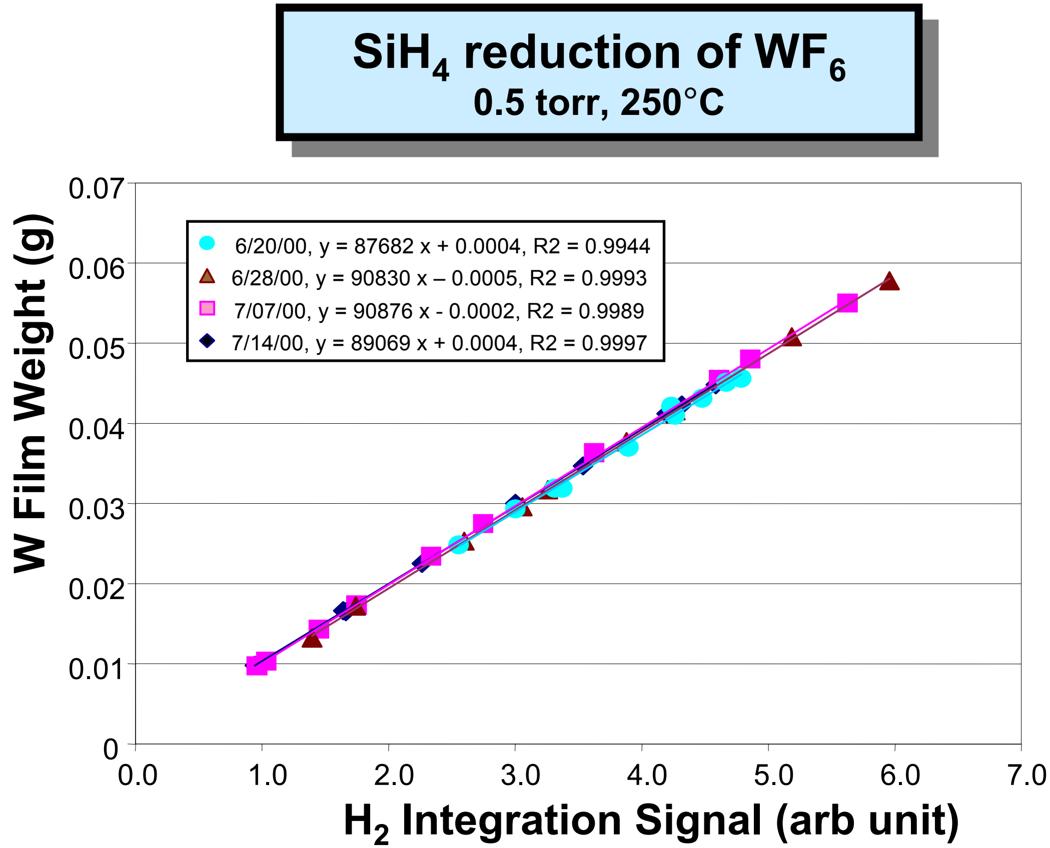
- W CVD by $SiH_4$ reduction of $WF_6$ in 0.5 torr thermal CVD
- Monitor process state as gas concentrations in reactor
- Product generation and reactant depletion reveal wafer state changes in real time

| Step # | 1 & 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|
| 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 |

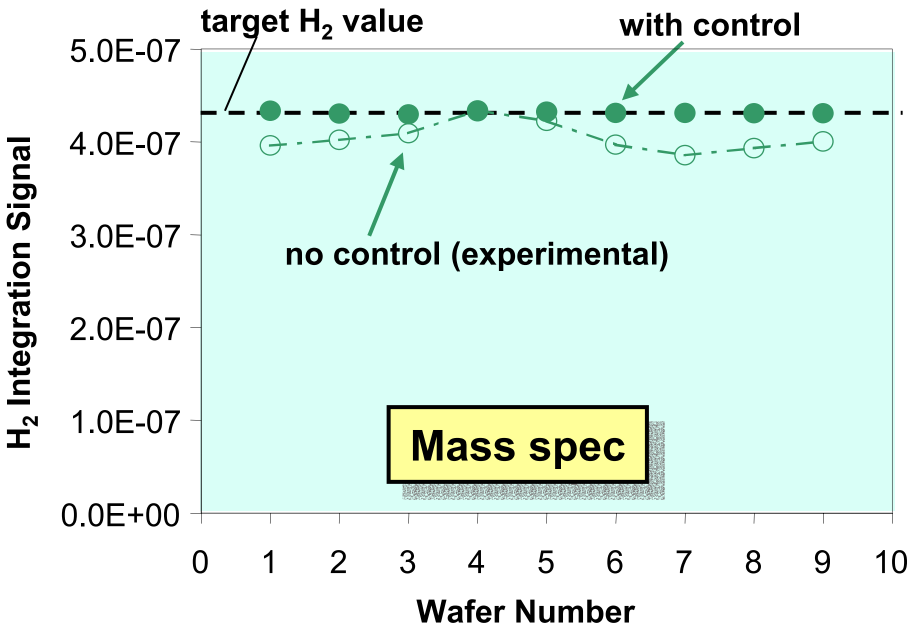


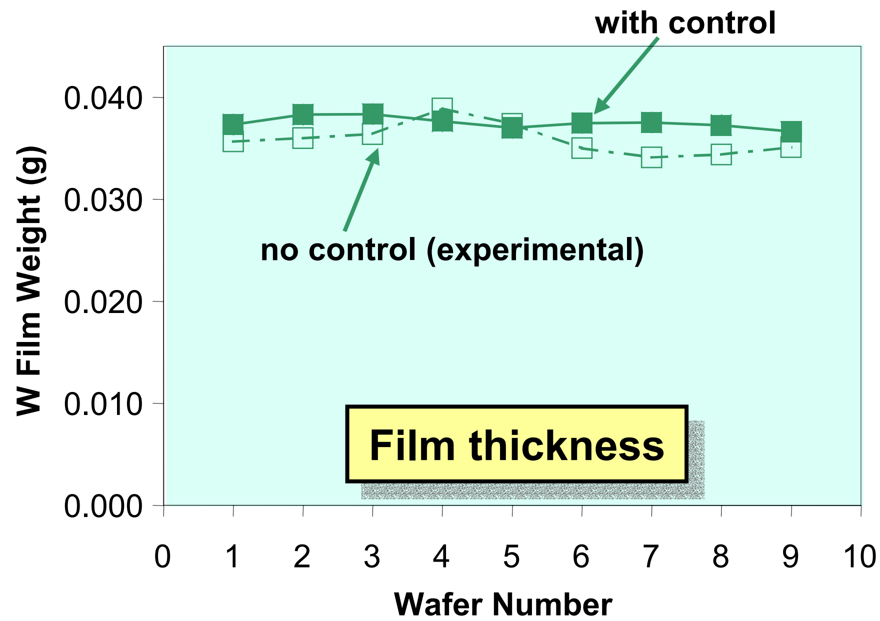
# Real-Time Thickness Metrology

- **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



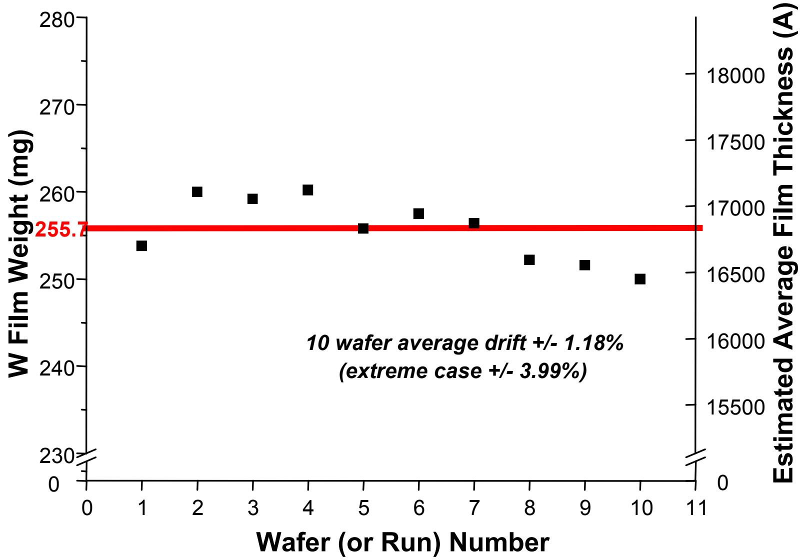

- *Open-loop wafer-to-wafer thickness variation ~ 10%*
- *Real-time end-point control to ~ 3%*
- *Real-time course correction to compensate for BOTH:*
  - *Random short-term variability*
  - *Systematic longer-term drift*

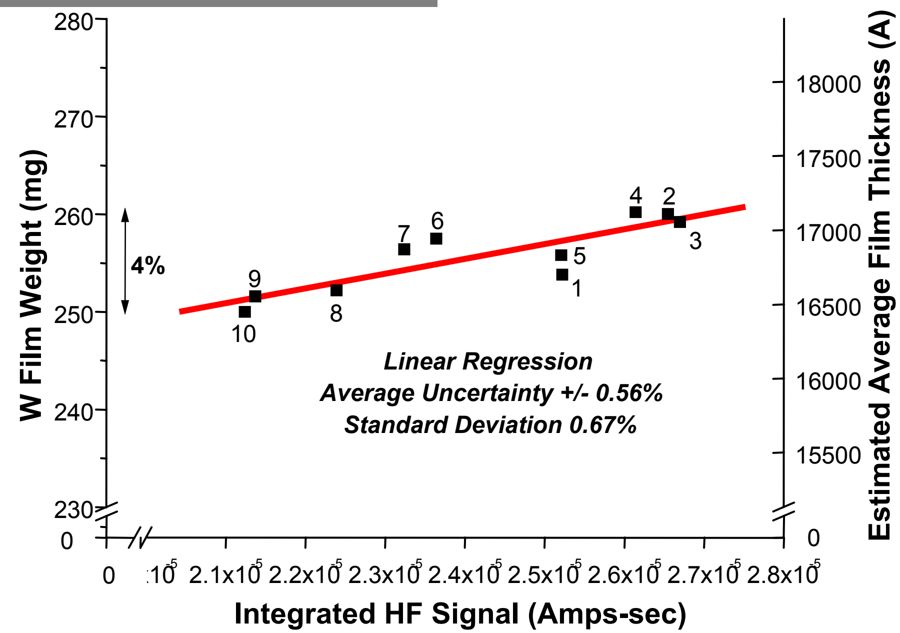
# Mass Spec Thickness Metrology

**$H_2$ 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***

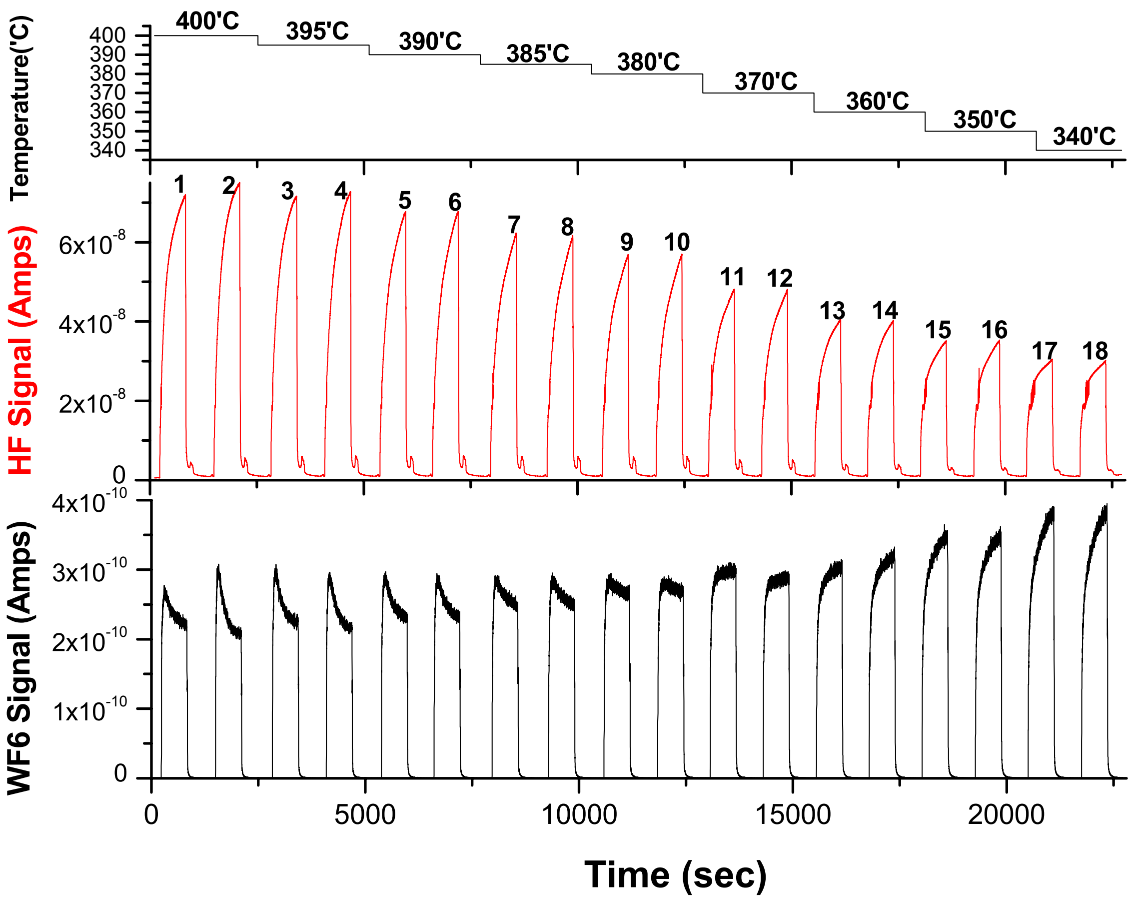
**Average uncertainty 0.56%**

**Standard deviation 0.72%**

# 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**

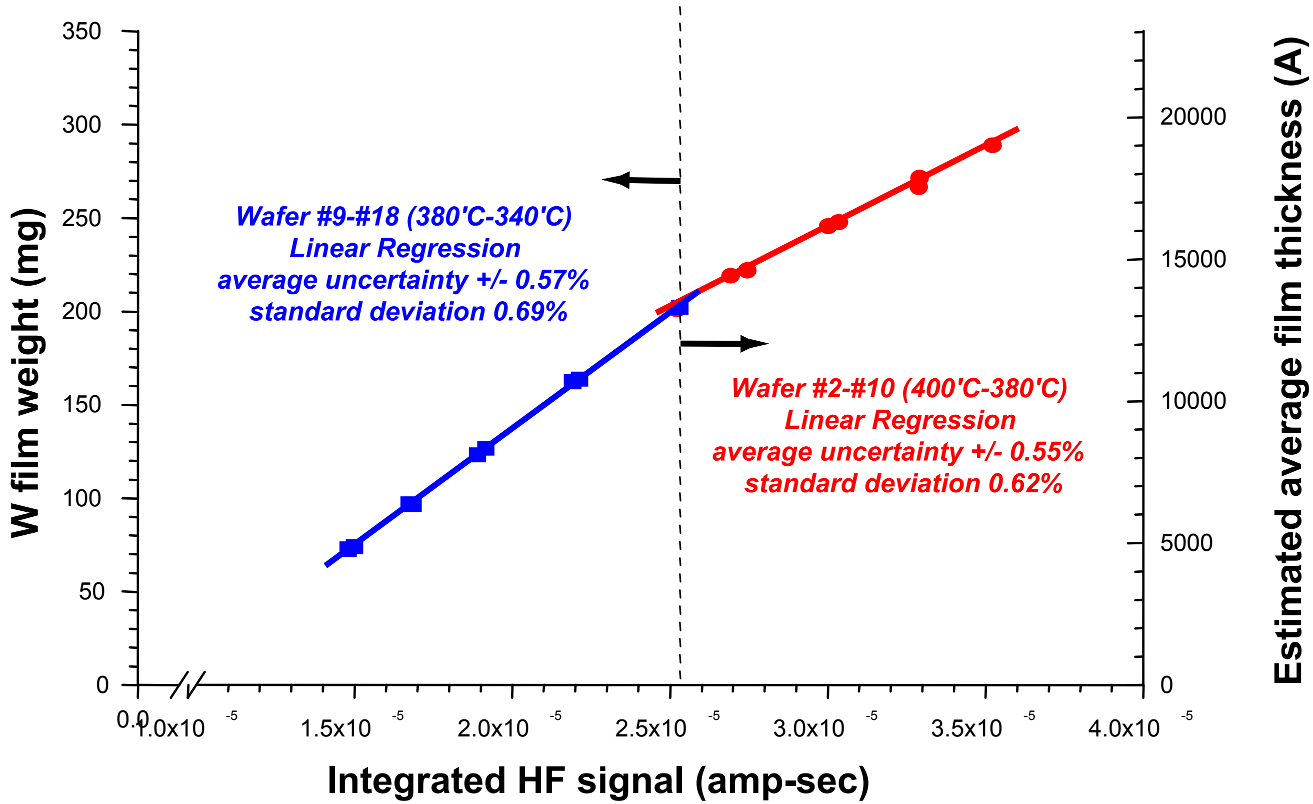


# Mass Spec Thickness Metrology: Intentional Temperature Drift

***Moderate non-linearity over broad temperature range***

**Deposition on showerhead, adsorption on chamber walls, …**

***Metrology precision* ~ 0.5% near local process setpoint**



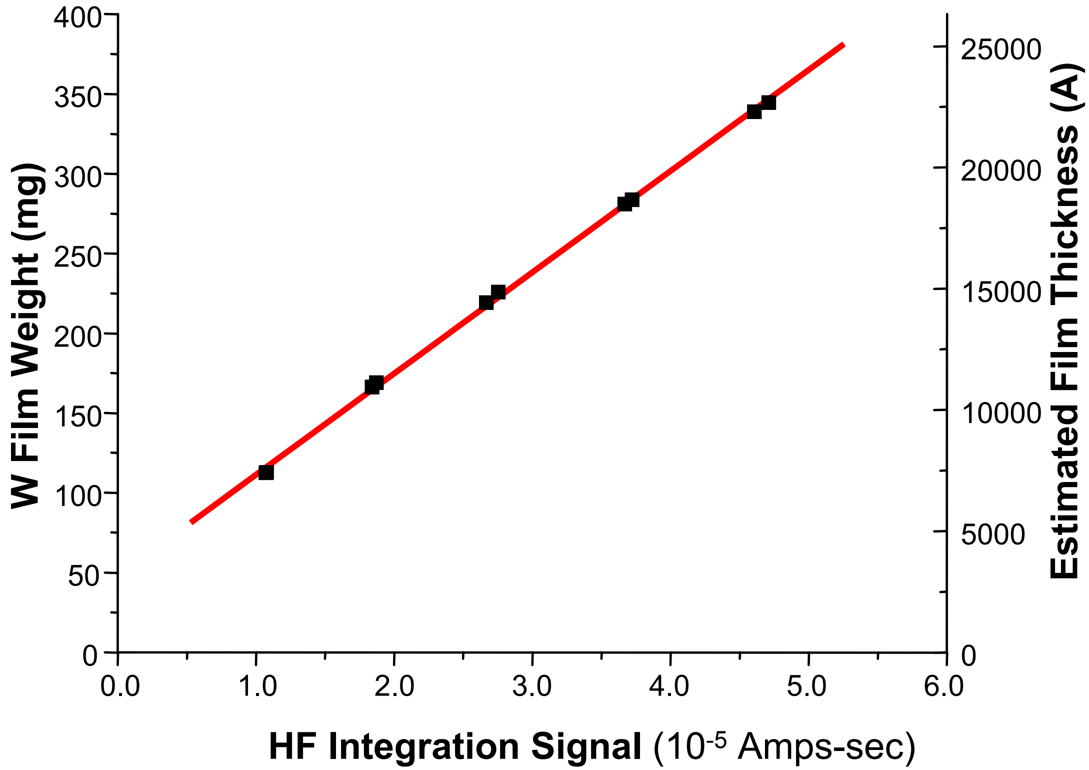
# Mass Spec Thickness Metrology: Intentional Process Time Drift

- **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**



# Seed (Nucleation) Layer Growth

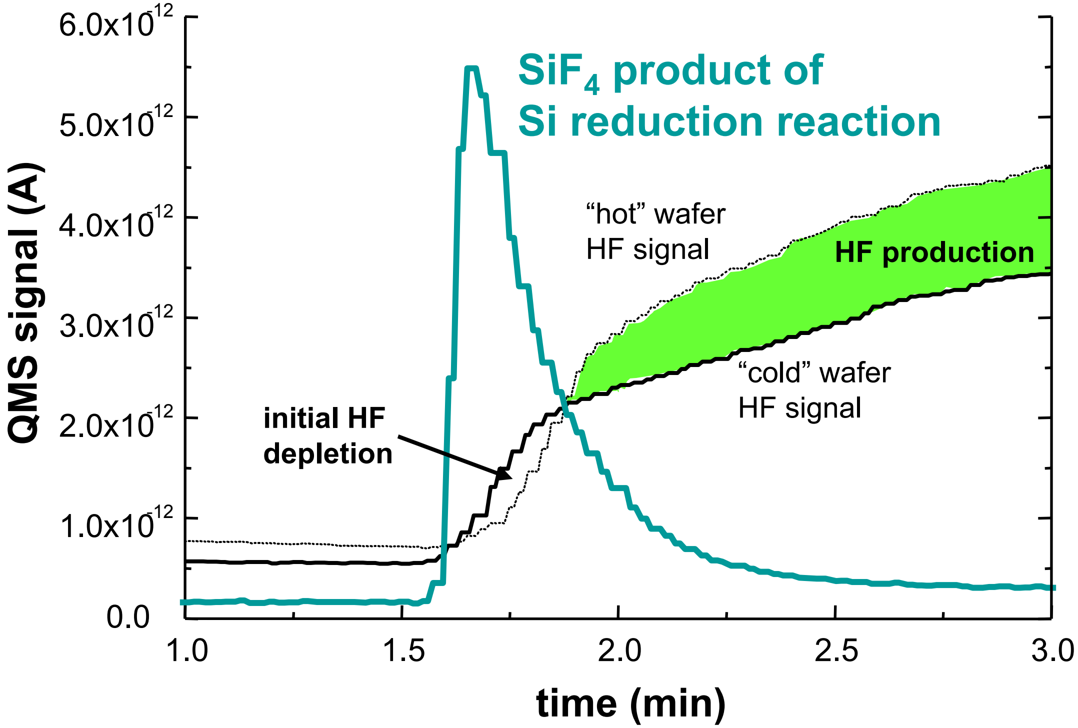
Initial nucleation dominated by $WF_6$ - Si reaction in presence of $H_2/WF_6$ CVD reactants

Forms ~30 nm thick W film

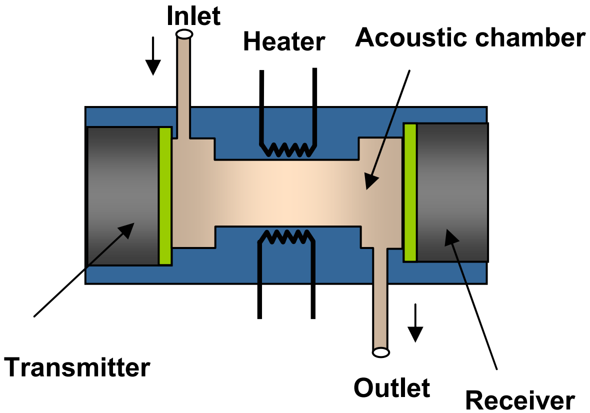
Reduced HF production during nucleation stage

Possible fault detection application (assure oxide-free contacts)

Sensitivity for ultrathin barrier layer CVD processes



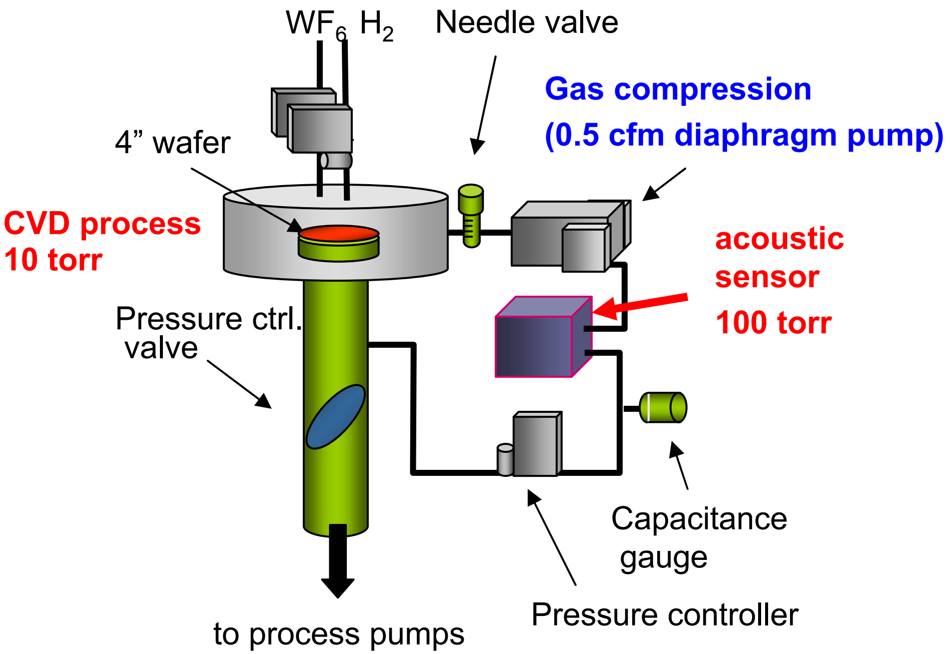
# Acoustic Sensing for Real-Time APC




- **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**

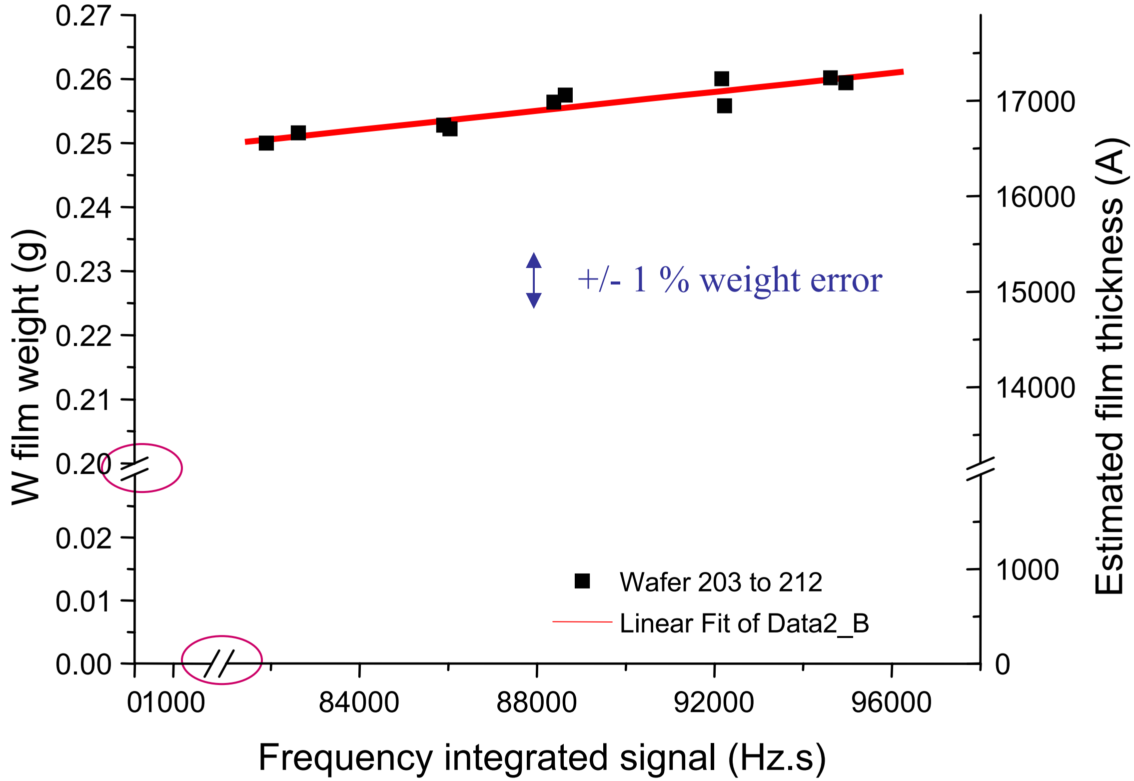
***Acoustic sensor thickness metrology***

**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**



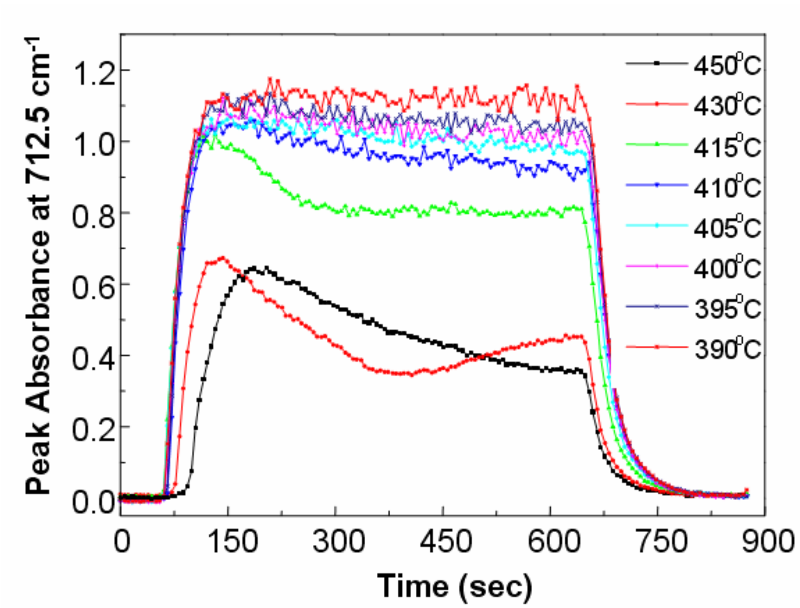
# FTIR Sensing for Real-Time APC

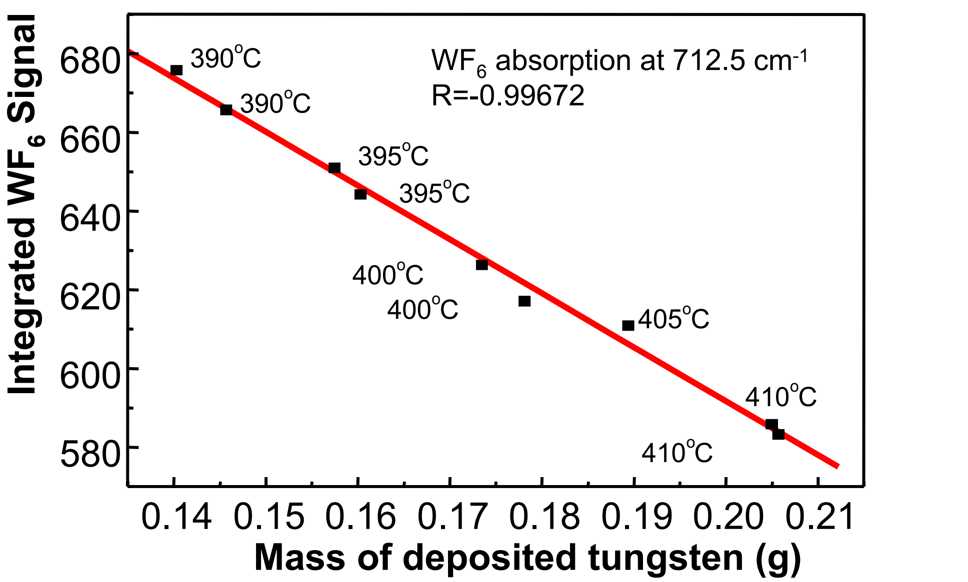
- **Implementation like acoustic sensor**
  ***P > 50 torr***
- **Sense molecular vibrations (infrared) for product generation, reactant depletion**
- **$WF_6$ product depletion ➔ thickness metrology precision ~0.5%**

**$H_2$ reduction of $WF_6$**

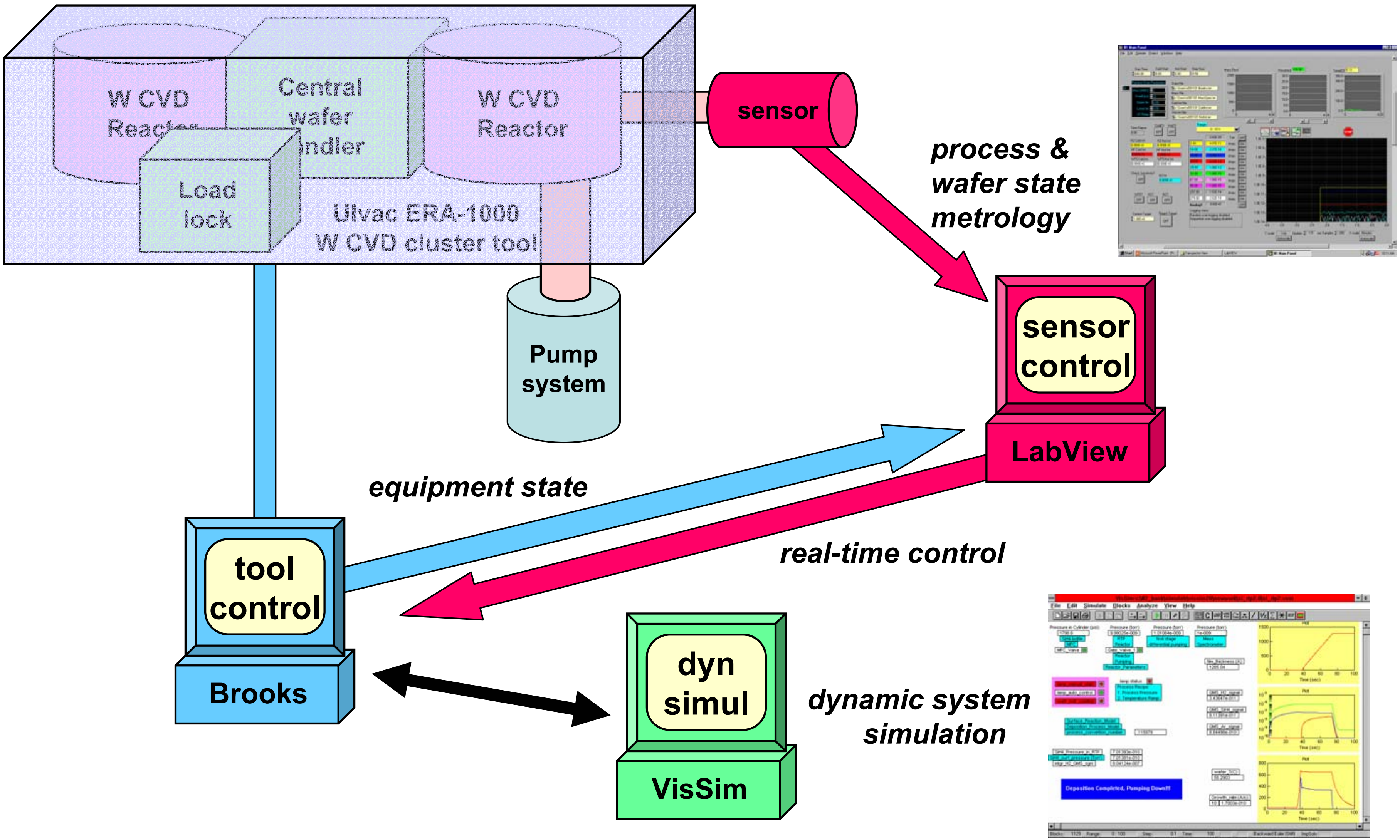
**$WF_{6(g)} + 3\ H_{2(g)} \rightarrow W_{(s)} + 6\ HF_{(g)}$**

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



# Sensor Integration

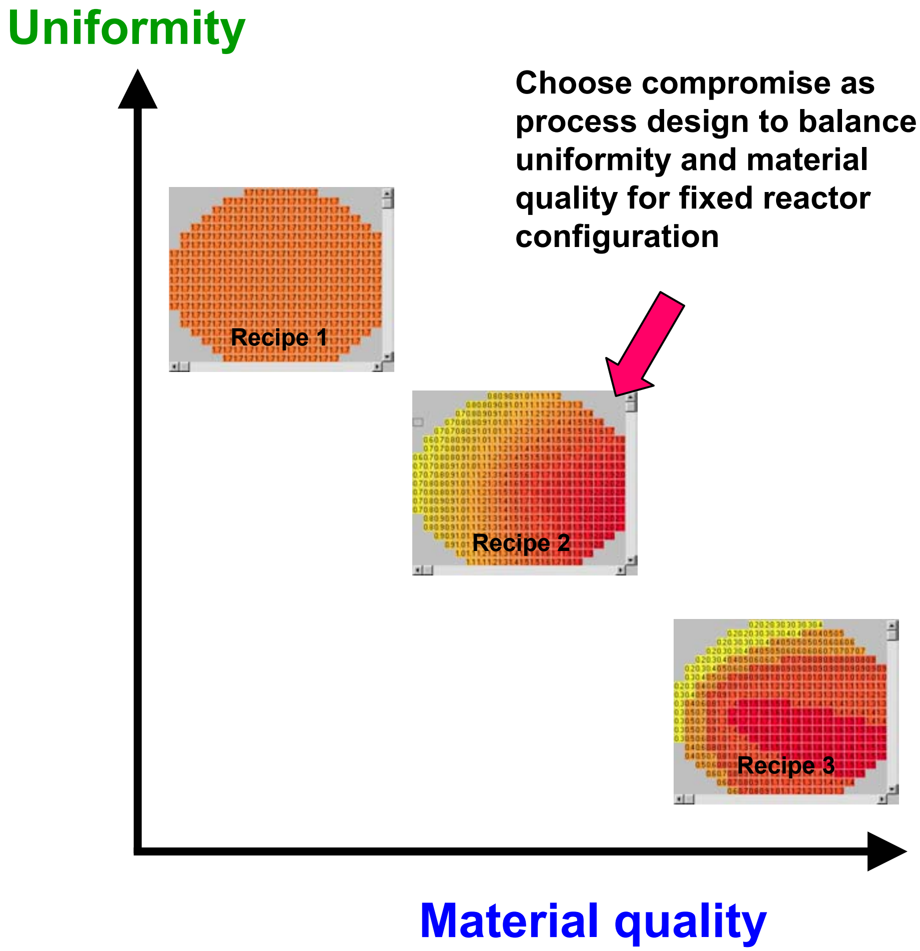


# Ready for Technology Transfer

- **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
- Limited in-situ sensor capability to date
  - *Full-wafer interferometry – wafer state*
  - *Spatially resolved optical (OES) – process state*
- No mechanism for real-time uniformity adjustment
- Process optimization involves tradeoff between material quality metrics and uniformity



# 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***

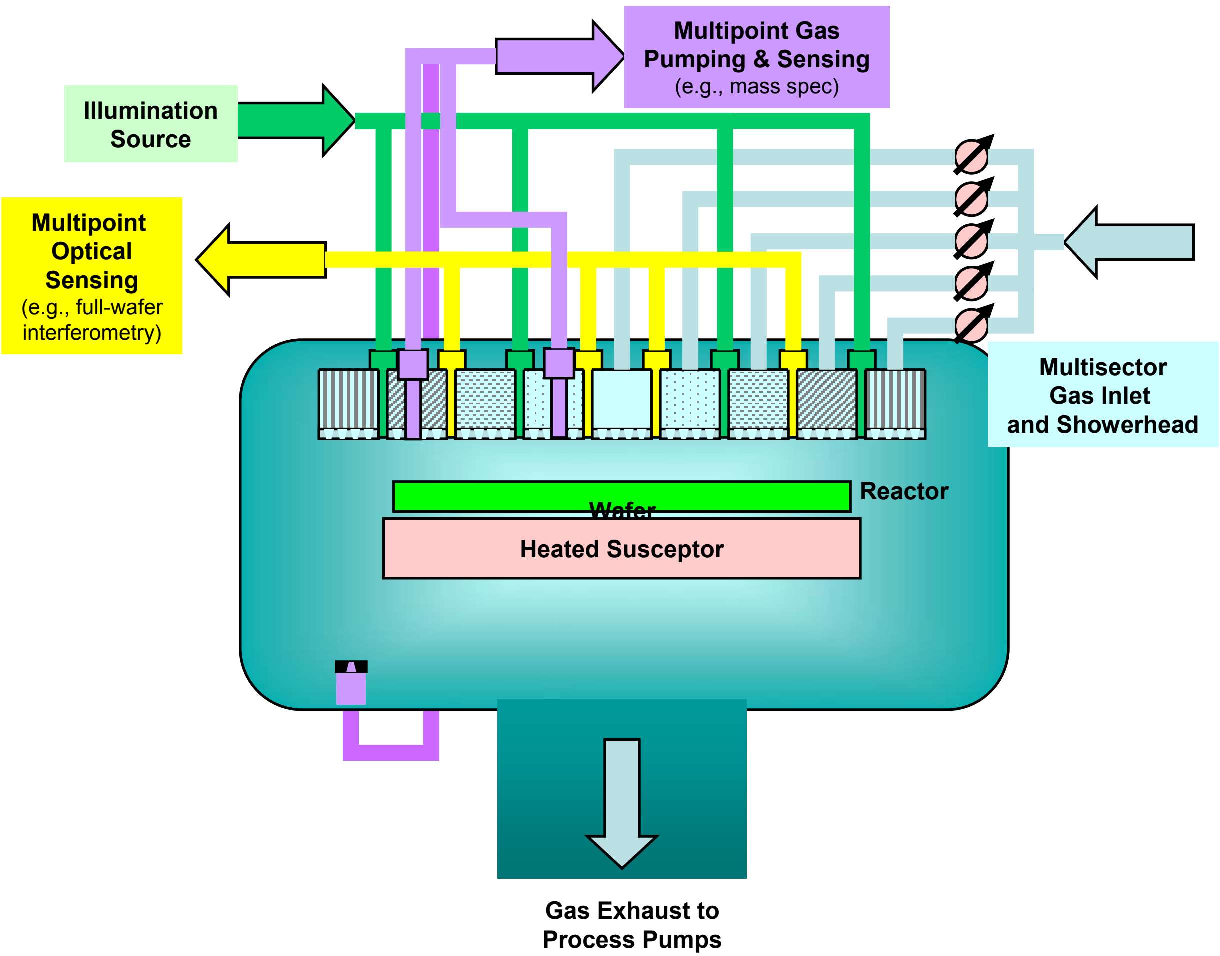
*Gas flow rates and compositions controlled within each showerhead segment*

***Supplementary pumping through the showerhead***

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

***Simulation and reduced-order models***

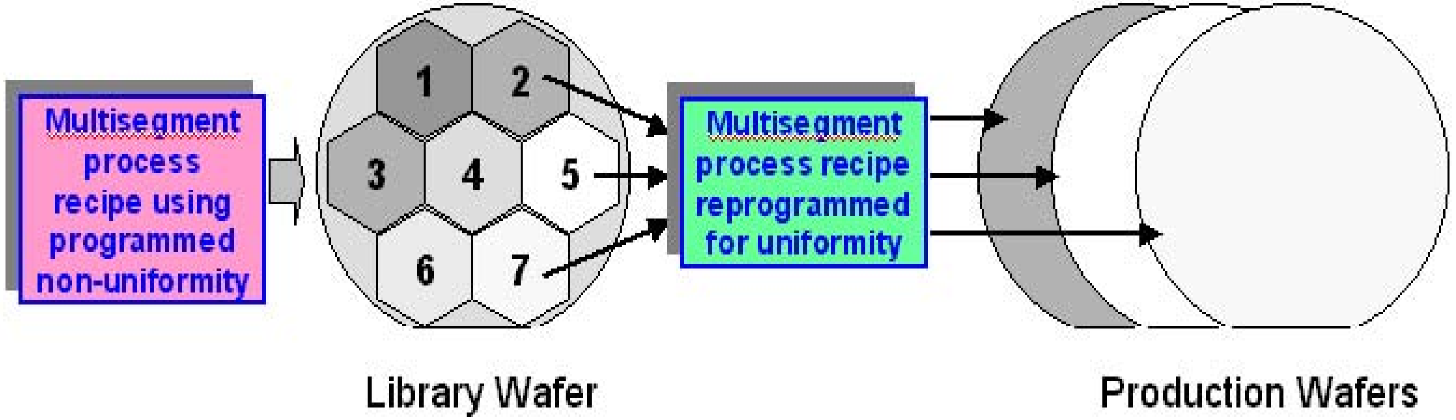
*Support for process equipment design and control*



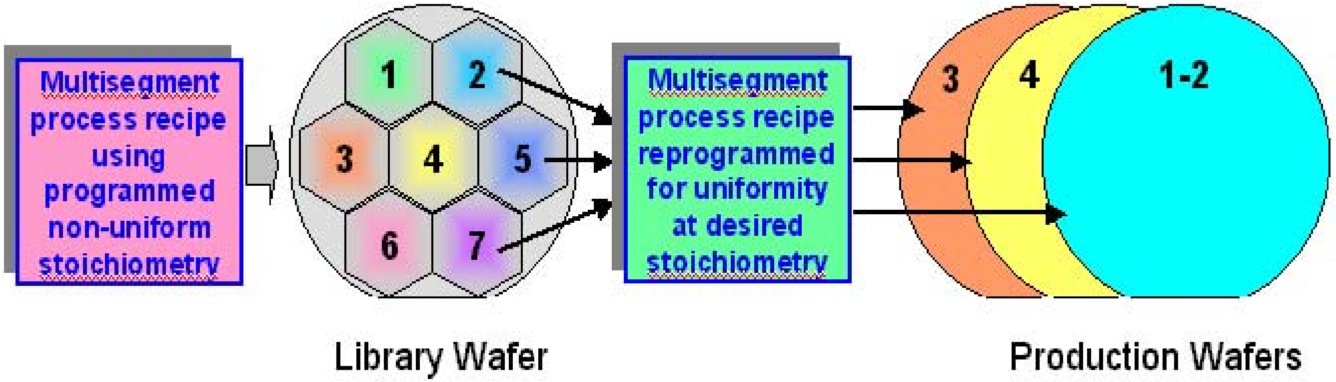

***Programmable Uniformity for Enhanced Manufacturing***

# Programmable Nonuniformity
## for Rapid Materials & Process Development

**One-wafer DOE → process optimization**

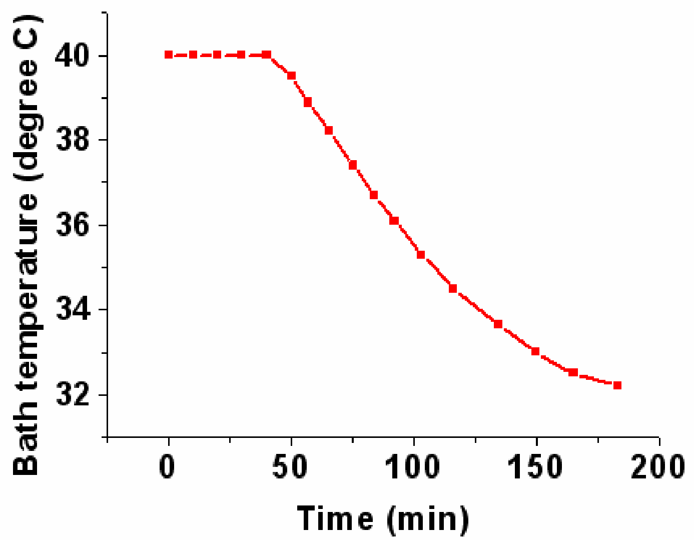



**Combinatorial CVD → new materials discovery and development**



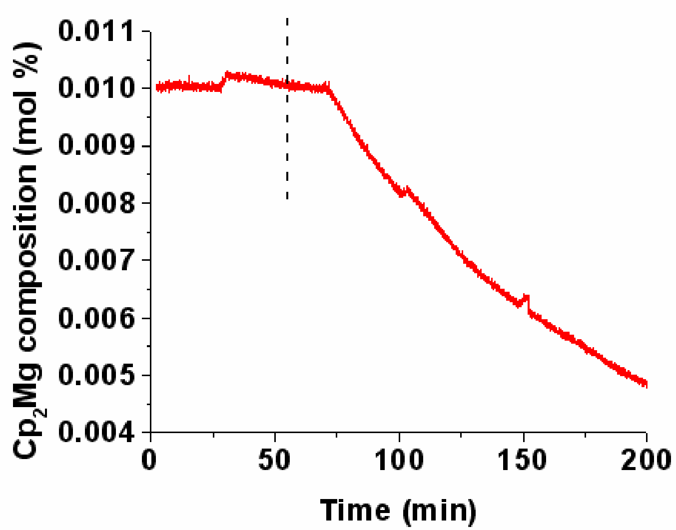
# Precursor Delivery Challenges

- **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**



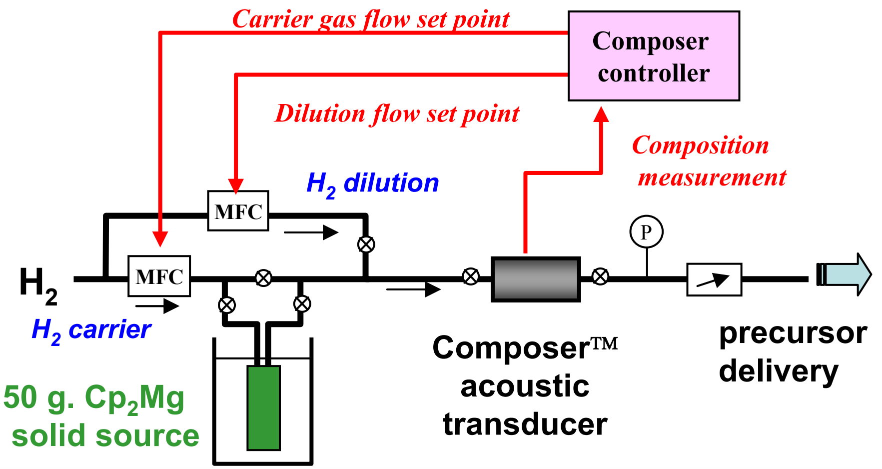

Example: $Cp_2Mg$ temperature decrease 40➔32°C reduces vapor pressure & composition 2X

*Simulates "aging" effects*



# Real-Time Precursor Delivery Control

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

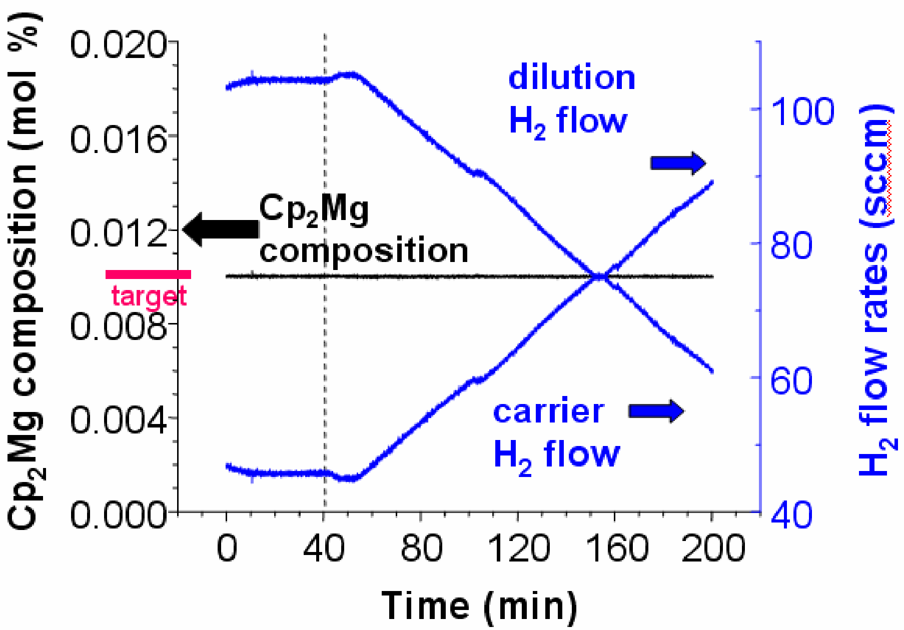



Source temperature varied from 40→ 32°C

$\Sigma$ ($H_2$ flows) = 150 sccm, P = 300 torr

$Cp_2Mg$ target = 0.01 mol%

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



# 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*
- **Advanced process control promises benefit to both manufacturing and environment**

# 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*
- NIST
  - *J. Whetstone, A. Lee, C. Tilford*
- Inficon
  - *R. Ellefson, L. Frees, C. Gogol, A. Wajid, J. Kushneir*
- Other colleagues
  - *Metrology TWG, AEC/APC, AVS MSTG*
- Support