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

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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, …

- New opportunities
  - Uniformity control ➔ spatially programmable reactor design
  - Precursor delivery control ➔ solid & low $p_{vapor}$ sources

ready for tech transfer & evaluation in manufacturing environment
Advanced Process Control (APC)

- **Course correction**: Compensate for variations to maintain process targets.
- **Fault management**: Identify and repair equipment problems.
- **Fault classification & response**: Optimize management of faults.
- **Run-to-run control**: Feedback & feedforward.
- **Real-time control**: End point and instantaneous.
- **Real-time fault detection**: Known failure modes and signatures.

**Mainline**

- **Sensor-driven**
- **Model-based**
APC Hierarchy

Factory Control System

Course correction
- Run-to-run course correction
  - feedback
  - feedforward
- Fault management
  - Tool maintenance
    - fault diagnosis
    - PM scheduling

Fault management

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

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

Real-time APC
- Real-time course correction
- Real-time fault detection
- Real-time fault management

Regulatory tool control
- equipment state

Tool Control System

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

Run-to-run course correction
- feedback
- feedforward

Tool maintenance
- fault diagnosis
- PM scheduling

APC Hierarchy

supervisory

regulatory

Real-Time APC

in-situ, real-time

quantitative metrology

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A. JAMES CLARK
SCHOOL OF ENGINEERING
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

**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**

**Process Chamber Details**

- Ultrasonic waveguide
- Inficon Transpector™ mass spec chemical sensor
- Turbo pump 50 l/s
- Ion gauge
- Pressure control valve
- Baratron™
- QMS

**Chemical Flow**

- SiH₄/WF₆
- H₂

**Ulvac multi-chamber “cluster” tool**
Real-Time Mass Spec in W CVD

- W CVD by SiH₄ reduction of WF₆ 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
Real-Time Thickness Metrology

• Reasonable Conversion Rate of WF$_6$ reactant (~20%)

• Metrology established from weight vs. integrated mass spec signal
  – Linear regression $\rightarrow$ standard deviation 1.09%

• Viable for manufacturing process control

![Graph showing SiH$_4$ reduction of WF$_6$](image)

0.5 torr, 250°C

$y = \begin{cases} 
7/14/00, & 89069 x + 0.0004, \text{R}^2 = 0.9997 \\
7/07/00, & 90876 x - 0.0002, \text{R}^2 = 0.9989 \\
6/28/00, & 90830 x - 0.0005, \text{R}^2 = 0.9993 \\
6/20/00, & 87682 x + 0.0004, \text{R}^2 = 0.9944 \\
\end{cases}$
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

\[ \text{H}_2 \text{ reduction of } \text{WF}_6 \]

\[ \text{WF}_6(g) + 3 \text{H}_2(g) \rightarrow \text{W}(s) + 6 \text{HF}(g) \]

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%

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**Figure:**
- Graph showing the relationship between Wafer (or Run) Number and Estimated Average Film Thickness (Å).
- Graph showing the relationship between Integrated HF Signal (Amps-sec) and Estimated Average Film Thickness (Å).
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

![Graph showing temperature and signal changes](image)

**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

![Graph showing linear regression with data points and error bars]

- **Wafer #9-#18 (380°C-340°C)**
  - Linear Regression
  - Average uncertainty +/- 0.57%
  - Standard deviation 0.69%

- **Wafer #2-#10 (400°C-380°C)**
  - Linear Regression
  - Average uncertainty +/- 0.55%
  - Standard deviation 0.62%
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
  $C = \text{speed of sound}$

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

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

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

- Run-to-run thickness drift: Average 4% over 10 runs
- Acoustic sensor thickness metrology: 0.5% average uncertainty from linear regression fit

**Graph**

- **X-axis:** Frequency integrated signal (Hz.s)
- **Y-axis:** Frequency integrated signal (Hz.s)
- **Legend:**
  - **Black squares** (Wafer 203 to 212)
  - **Red line** (Linear Fit of Data2_B)

- +/- 1% weight error

**Estimated film thickness (Å)**
FTIR Sensing for Real-Time APC

- Implementation like acoustic sensor
  \[ P > 50 \text{ torr} \]
- Sense molecular vibrations (infrared) for product generation, reactant depletion
- \( \text{WF}_6 \) product depletion \( \rightarrow \) thickness metrology precision \( \sim 0.5\% \)

\[ \text{H}_2 \text{ reduction of } \text{WF}_6 \]
\[ \text{WF}_6(g) + 3 \text{H}_2(g) \rightarrow \text{W}(s) + 6 \text{HF}(g) \]
Intentional temperature drift: 10 torr, 390-450°C

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

WF\(_6\)

- Peak Absorbance at 712.5 cm\(^{-1}\)
- Integrated \( \text{WF}_6 \) Signal

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Mass of deposited tungsten (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>390°C</td>
<td>0.14</td>
</tr>
<tr>
<td>390°C</td>
<td>0.15</td>
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<tr>
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<tr>
<td>390°C</td>
<td>0.21</td>
</tr>
</tbody>
</table>

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

WF\(_6\) absorption at 712.5 cm\(^{-1}\)

R = 0.99672
Sensor Integration

- Real-time control
- Equipment state
- Sensor
- Process & wafer state metrology
- LabView
- Tool control
- Brooks
- Dynamic system simulation
- VisSim
- Pump system

- W CVD Reactor
- Central wafer handler
- Uvvac ERA-1000
- W CVD cluster tool
- W CVD Reactor
- Load lock
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) → W(s) + 6 HF(g)

SiF$_4$ product of Si reduction reaction
3 Si (s) + 2 WF$_6$(g) → 2 W(s) + 3 SiF$_4$(g)

Implications:
Fault detection
assure oxide-free contacts)
Metrology for ultrathin CVD layers

Mass spec signal (A)

“hot” wafer HF signal
“cold” wafer HF signal

HF production

Mass spec signal (A)

Time (min)

1.0 1.5 2.0 2.5 3.0
0.0 1.0x10$^{12}$ 2.0x10$^{12}$ 3.0x10$^{12}$ 4.0x10$^{12}$ 5.0x10$^{12}$ 6.0x10$^{12}$
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

Choose compromise as process design to balance uniformity and material quality for fixed reactor configuration

Material quality

Uniformity

Recipe 1
Recipe 2
Recipe 3

Choose compromise as process design to balance uniformity and material quality for fixed reactor configuration
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: \( \text{Cp}_2\text{Mg} \) temperature decrease 40°C to 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 (H₂ flows) = 150 sccm, P = 300 torr
Cp₂Mg target = 0.01 mol%

Cp₂Mg composition controlled to 1% of target (0.0001 mol %)
MOCVD Precursor Delivery Line Control

\[
T(\text{source}) = 40^\circ \text{C}
\]

\[
T(\text{feed line}) = 50 \pm 1.5^\circ \text{C}
\]

Acoustic sensor reveals wall adsorption fluctuations \(\Rightarrow\) 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

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