Thickness Metrology and Real-Time End-Point Control in W CVD using in-situ Mass Spectrometry

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OUTLINE

**FIRST HALF**

Low – Press Selective W CVD: 
Metrology & Control

- Pressures < 1 Torr
- Lamp Heating
- $H_2/WF_6 \& SiH_4/WF_6$
- Conversion Rate 5-20%

~ 1.5% Metrology
~ 3% End-Point Control

**SECOND HALF**

High – Press Blanket W CVD: 
Metrology & Control

- Pressures upto 100 Torr
- Substrate Heating
- $SiH_4/WF_6$ Seed & $H_2/WF_6$ Fill
- Conversion Rate 20-30%

~ 0.5% Metrology
End-Point Control TBD

**FIRST HALF**

200 AMU Mass Spec chemical sensor

**SECOND HALF**

300 AMU Mass Spec Sampling System from Inficon

Ulvac ERA-1000 CVD Cluster Tool

W CVD Reactor
Process, Equipment & Sensor Signals Integration for Real-Time Process Control

ULVAC ERA-1000 Cluster Tool

BROOKS Control System

In-situ Mass Spec Sampling System

LabView™-based program for Real-Time Data Acquisition & Process Control

Integrated Sensor Signals
In-Situ RGA Sensing & Metrology in Low-Press W CVD Process

- **Significant Chemical Complexity**
  - **Chamber Wall Effects, both Adsorption and Reaction**
    - must stabilize process, sample downstream but closer to wafer
  - **Ionization and Background Reaction in Mass Spec**
  - **Reactant Conversion Rate Effects**
    - Very Low (< 5%) for Selective H₂/WF₆ ➔ Large Background
    - Reasonable (~ 20%) for Selective SiH₄/WF₆ ➔ Small Background
Metrology Development in 0.5 Torr SiH₄/WF₆ Process

Reasonable Conversion Rate (~20%)
No apparent need for calibration against unheated-wafer Background

Readily observe & measure Product Generation and Reactant Depletion
H₂ Product Generation
SiH₄ Reactant Depletion

Use Product Generation and/or Reactant Depletion Time-Integrated Signals for Film Thickness Metrology

\[2 \text{WF}_6 (g) + 3 \text{SiH}_4 (g) \rightarrow 2 \text{W} (s) + 3 \text{SiF}_4 (g) + 6 \text{H}_2 (g)\]
\[\text{WF}_6 (g) + \text{SiH}_4 (g) \rightarrow \text{W} (s) + 2 \text{SiHF}_3 (g) + 3 \text{H}_2 (g)\]

<table>
<thead>
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<th>Step #</th>
<th>1 &amp; 2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
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<tbody>
<tr>
<td>P (Mtorr)</td>
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<td>100</td>
<td>100</td>
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<td>Ar (Sccm)</td>
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<td>SiH₄ (Sccm)</td>
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<tr>
<td>WF₆ (Sccm)</td>
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<td>0</td>
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<td>T (°C)</td>
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<td>20</td>
<td>20-275-250</td>
<td>250</td>
<td>250-20</td>
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</tbody>
</table>

Load wafer  Clean  Heating  Cooling & unload wafer

Hot – react  Cold – bkg

Product Generation

Load wafer  Clean  Heating  Cooling & unload wafer

Hot – react  Cold – bkg

Reactant Depletion
In-situ Film Thickness Metrology in 0.5 Torr SiH\(_4/\)WF\(_6\) Process

Reasonable Conversion Rate (~20%)

- Improved Metrology
  - Average Uncertainty 1.25%
  - Standard Deviation 1.09%

Viable for Manufacturing

Process Control for Film Thickness

- Run-to-Run
- Real-Time End-Point

![Graph showing SiH\(_4\) reduction of WF\(_6\)](graph.png)

- 7/14/00, \(y = 89069 x + 0.0004, R^2 = 0.9997\)
- 7/07/00, \(y = 90876 x - 0.0002, R^2 = 0.9989\)
- 6/28/00, \(y = 90830 x - 0.0005, R^2 = 0.9993\)
- 6/20/00, \(y = 87682 x + 0.0004, R^2 = 0.9944\)
Real-Time Film Thickness Control in 0.5 Torr SiH$_4$/WF$_6$ Process

in-situ Deposition Metrology ➔ Real-Time End-Point Control

- Monitor and Integrate H$_2$ Product Signal
- When target value is reached, terminate process
Real-Time End-Point Control of W Film Thickness in SiH₄/WF₆ Process

Systematic & Random Variation Control

- Real-Time End-Point Control is capable of handling BOTH: RANDOM VARIATION AS WELL AS SYSTEMATIC PROCESS DRIFTS (Run-to-Run)
- Open-loop wafer-to-wafer thickness variation ~ 10%
- Real-Time End-Point Control to ~ 3%
In-Situ RGA Sensing & Metrology in HIGH-PRESS W CVD Process

- Blanket W CVD conditions – modified equipment design
  - Pressure at 10 Torr (capable of up to 100)
  - Substrate Heating
  - $H_2 / WF_6$
- Exploit new Inficon CIS300 Gas Sampling System (R. Ellefson and L. Frees)
High Conversion Rate (20 - 30%)

Species
- HF Product Generation
- \( H_2/WF_6 \) Reactant Depletion

Parasitic Reactions
- \( SiO_2 + 4HF \leftrightarrow SiF_4 + 2H_2O \) (showerhead)
- \( H_2O + WF_6 \rightarrow WOF_4 + 2HF \) (chamber wall, mass spec)

Chamber cleaning & conditioning critical for metrology
Watch for stability and magnitude of \( WOF_4, WF_6, SiF_4, H_2O \) signals

\[ WF_6(g) + 3 H_2(g) \rightarrow W(s) + 6 HF(g) \]
Metrology Development in 10 Torr H₂/WF₆ Process

Sensor Response during Process Cycle

WF₆ 150 - 10 sccm
H₂ 900 - 60 sccm
RAW PROCESS TIME

Press
WF6MFC
H2MFC
N2MFC

Equipment State (arb unit)

10 sccm
60 sccm

HF Product Generation

Time (sec)

Press
WF6MFC
H2MFC
N2MFC

Equipment State (arb unit)

0
10
-10
-20
-30
-40
-50

10.30.2001
Soon Cho - AVS01 MS-TuA8
Run-to-Run Process Drift is a Concern

Run-to-Run Process Drift can be significant for Manufacturing

Run-to-Run Film Thickness Drift due to process drift
- Extreme Case 3.99%
- Average Drift 1.18%

Metrology in the range of process drift (linear regression fit)
- Average Uncertainty 0.56%
- Standard Deviation 0.72%

Fixed Process Condition
- Nominal Temp 500°C
- Deposition Time 640sec

Average Film Weight 255.7mg

Average Uncertainty 0.56%

Estimated Film Thickness (Å)
Intentionally Introduced
Run-to-Run Temp Drift

**Graph Description:**
- **Y-axis:** HF Signal (Amps)
- **X-axis:** Time (sec)
- **Red Line:** HF Product Generation
- **Blue Line:** WF₆ Reactant Depletion

**Data Points:**
- Times: 260000, 265000, 270000, 275000, 280000
- HF Signal Values: 1x10⁻¹⁰, 2x10⁻¹⁰, 3x10⁻¹⁰, 4x10⁻¹⁰, 5x10⁻¹⁰, 6x10⁻¹⁰, 7x10⁻¹⁰, 8x10⁻¹⁰
- WF₆ Signal Values: -1x10⁻¹⁰, 0, 1x10⁻¹⁰, 2x10⁻¹⁰, 3x10⁻¹⁰, 4x10⁻¹⁰, 5x10⁻¹⁰, 6x10⁻¹⁰
Global Range Metrology

2\textsuperscript{nd} order polynomial regression fit yields average uncertainty of 1.61%

Effect of deposition on non-wafer surfaces becomes more significant at higher temps (e.g. heater surface, showerhead, chamber walls, etc.)

Local Range Metrology

Low-Temp & High-Temp regions:
Both regions yield similar metrology accuracy

Average Uncertainty \sim 0.5%

Local range metrology more likely and viable for manufacturing application
Film Thickness Metrology w/ Run-to-Run Time Variation

Test case for our metrology
Large film weight range ~230mg

Reasonable metrology from linear regression fit
Average Uncertainty 1.19%
Standard Deviation 1.59%

2nd-order Polynomial fit
Average Uncertainty 0.48%
Standard Deviation 0.57%

Local range metrology more likely and viable for manufacturing application
CONCLUSIONS

Successful implementation of in-situ RGA sensing for W film thickness metrology
- 0.5Torr SiH\textsubscript{4} reduction process
  - 1-1.5\% average uncertainty
- 10Torr H\textsubscript{2} reduction process
  - <1\% average uncertainty

Successful demonstration of real-time end-point control for film thickness in SiH\textsubscript{4} reduction process ~ 3\%
  - Control both Random Variation & Systematic Process Drift

Good prognosis for real-time end-point control in high-pressure H\textsubscript{2} reduction process

Viable for Manufacturing application to achieve Real-Time APC

R. Ellefson & L. Frees