Run by Run Control Methods

Outline

- Run by Run Control
  - Equipment Cell Control
  - Basic EWMA Algorithm
  - Additional Algorithmic Issues

- Applications
  - Example 1 -- Univariate Time-Based Control & Sputter Deposition
  - Example 2 -- Multivariate Control & Chemical Mechanical Polishing
  - Example 3 -- Spatial Uniformity Control & Plasma Etch

Run by Run Control Methodology

- Off-line experiments to build empirical response surface model of the process
- Select initial "optimal" recipe
- Processing: single wafer or batch
- Adapt model based on product/process measurements
- Generate new recipe using updated model to
  - achieve closest match to targets
  - achieve targets with smallest change in recipe
Run by Run Control Context - Cell Control

- System Architecture
  - Equipment and Sensor Modules
  - Run by Run Control
  - Fault Detection/Monitoring Module
  - Diagnosis Modules
  - Infrastructure
  - Module Coordination

- Testbed System
  - AME5000 at MIT's Microsystems Technology Lab.

EWMA Run by Run Control Approach

- Affine model of process: $y[n] = Ax[n] + b[n]$

- Exponentially Weighted Moving Average (EWMA) update of model based on current run: $b[n+1] = W(y[n] - Ax[n]) + (I - W)b[n]$

- Use model to generate a new recipe for next run
  - Linear solver uses model equations to find
Model Adaptation and Recipe Generation

Key Idea: Equipment changes (approximately) cause models to shift (drift), but not change in shape.

Recipe Generation

- Constrained problem cases:

\[
\begin{align*}
\min & \quad \| x[n] - x[n-1] \| \\
& \quad x[n] \\
\text{such that} & \quad x_{\max} > x[n] > x_{\min} \\
\text{and} & \quad T = Ax[n] + b[n] \\
\end{align*}
\]

\[
\begin{align*}
\min & \quad \| T - (Ax[n] + b[n]) \| \\
& \quad x[n] \\
\text{such that} & \quad x_{\max} > x[n] > x_{\min} \\
\end{align*}
\]

⇒ Minimize Recipe Change  ⇒ Minimize Error from Target

- In the unconstrained case the above solutions are simple
  - E.g. for a multivariate linear model - simple matrix inversion

- With current hardware and reasonable problem sizes, constrained solution can be accomplished in short time (i.e. time between runs)
**Additional Algorithmic Issues**

- Controller robustness and stability
  - Understand bounds for well-behaved control

- Controller tuning
  - Appropriate selection of controller EWMA weights

- Extended EWMA controllers:
  - Predictor-Corrector Control (PCC) - appropriate for strongly (linear) drifting processes
  - Nonlinear control models -
  - Full model adaptation (in addition to model offset term)

- Control of Spatial Uniformity
  - Correct construction of process-dependent uniformity models
    - "Multiple" vs. "Single" response surface approaches
  - Appropriate formulation of control problem to handle uniformity

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**Example 1: Univariate Time-Based Control of Sputter Deposition (MIT/TI)**

![Diagram of sputter deposition process]

- The goal is to maintain a desired metal deposition thickness from wafer to wafer and lot to lot.
Process Behavior for Metal Sputter Deposition

- Metal sputter deposition processes are characterized by a decrease in deposition rate as the sputter target degrades and material builds up in the collimator.
- The process drift rates vary from target to target.
- The drift rate may change over the life of a single target.
- The starting deposition rate may differ from target to target.

Control Approach: Rate Model & Time Adjustment

- RbR MBPC, based on the exponentially-weighted moving-average filter, provides the ability to track and compensate for process drifts without a priori assumptions on their magnitude or consistency.
- A simple model for sputter deposition is:
  \[ \text{filmThickness}[n] = \text{depRate}[n] \times \text{depTime}[n] \]
- An open loop estimate of the deposition rate can account for the drift dynamics in metal sputter deposition:
  \[ \text{depRate}_{\text{est}}[n] = w \cdot \frac{\text{filmThickness}[n]}{\text{depTime}[n]} + (1 - w) \cdot \text{depRate}_{\text{est}}[n-1] \]
- Given the revised deposition rate model, a new deposition time is simply found:
  \[ \text{depTime}[n+1] = \frac{\text{filmThickness}_{\text{desired}}}{\text{depRate}_{\text{est}}[n]} \]
State Estimation Results for EWMA Control (Aluminum Sputter Deposition)

Performance Results - TiN/Al/TiN

- $C_{pk}$, the process capability, improved by 44% with the EWMA controller. With RbR MBPC, control of aluminum thickness was to within 3% of the goal, compared to approximately 5% without MBPC.

- Increased processing efficiency:
  - Monitor wafers reduced from 1 every lot to 1 in 3 lots
  - Look-ahead wafers were eliminated

- Simplified processing for technicians
Example 2: Multivariate Control of Chemical Mechanical Polishing

- CMP is critical to advanced IC interconnect technologies
- Key capability: “global” planarization of surface topography
- Active research in process, equipment, and sensor development

Problem: CMP Limitations and Control Challenges

- Limited understanding of the process
- Substantial drifts in equipment operation
- Limited in-situ sensors

Blanket oxide wafer:
- 6 mm edge exclusion

Targets:
- Removal Rate
- Nonuniformity
CMP Control Model Experiments

- Initial screening in seven factors to determine key control parameters
- Central composite DOE in four factors performed:

<table>
<thead>
<tr>
<th>Factor</th>
<th>Lower Bound</th>
<th>Upper Bound</th>
</tr>
</thead>
<tbody>
<tr>
<td>speed (rpm)</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td>pressure (psi)</td>
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<td>7</td>
</tr>
<tr>
<td>force (lb)</td>
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<td>10</td>
</tr>
<tr>
<td>profile</td>
<td>-0.9</td>
<td>0.9</td>
</tr>
</tbody>
</table>

- Second order polynomial regression models fitted:
  - Removal rate -- $R^2$ of 89.7%
  - Nonuniformity -- $R^2$ of 76.9%

CMP Control Model Development

- Response surfaces are nearly linear and well-behaved over operating region:

Removal Rate

Nonuniformity

- Models Linearized for Control:

$$ y = Ax + b $$

$$ \begin{bmatrix} \text{removal rate} \\ \text{non-uniformity} \end{bmatrix} = A \begin{bmatrix} \text{speed} \\ \text{pressure} \\ \text{force} \\ \text{profile} \end{bmatrix} + b $$
CMP Control Experiment: Inputs

- Control Inputs:

  ![Graphs showing control inputs](image)

- Controller produces increasingly aggressive control to compensate for drift

CMP Control Experiment: Outputs

- Output Results:

  ![Graphs showing output results](image)

- Controller successfully compensates for drift in the process, and maintains adequate uniformity
Example 3: Spatial Uniformity Control on a Dual Coil Plasma Etch Tool (Lam TCP)

Modified TCP for polysilicon etch:
Dual-Coil Antennae
Full Wafer Interferometry

- Dual-Coil TCP antennae allows shaping of the plasma etching profile
  - Independent RF Generators allow control of power to inner and outer coils
  - More power to inner coil increases the etch rate in the middle of wafer
  - Concentric coils can control radial uniformity
  - **There is an optimal power setting that will maximize etching uniformity**

ANN-EWMA Run-to-Run Control Approach

ANN-EWMA Controller

Artificial Neural Network model was built from Full Wafer Interferometry data obtained through a 2 variable 3 level full factorial experiment:
12 wafers for model development
Full Wafer Interferometry

- Modulation is observed as a thin film is etched
  - Periodicity of the modulation can provide information about etching rate

- CCD array allows resolution of spatial variation in the etching rate
  - We measure etch rates at 81 different sites on the wafer

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An Artificial Neural Network EWMA Controller

- Use a multilayer perceptron neural network to capture nonlinear process model
  \[ y[n] = f(x[n]) + b[n] \]

- Adapt the bias weights in the NN output layer based on EWMA update
  \[ b[n] = W(\hat{b}[n]) + (I - W)b[n - 1] \text{ where } W = diag\left[ w_1 \ldots w_m \right] \]

- Generate recipe from nonlinear model via optimization
ANN model based EWMA controller

Key Idea: Artificial neural network provides functional approximation to site models.

Etch Process Control - Results:

- Objective: Minimize etch nonuniformity and recipe change from setpoint
  \[ \min \left( \beta \cdot \frac{\text{std}(\tilde{y}[n])}{\text{mean}(\tilde{y}[n])} + (1 - \beta) \cdot \| u[n] - u[0] \| \right) \]

- Process shift introduced at wafer #6
  - ANN-EWMA controller responds to disturbance and brings the wafer uniformity and etch rate back within specifications
Etching rate profile is improved

Disturbance introduced
Etching uniformity is poor

System has responded to process shift

Wafer 6

Wafer 17

- Full Wafer Interferometry can yield spatial etching rate information in-situ
  - This information is utilized by the Run-to-Run controller to maintain wafer specifications by suggesting minor recipe perturbations

- The Dual-Coil TCP allows for recipe adjustments that can correct for etching uniformity variation within less than 3 wafers