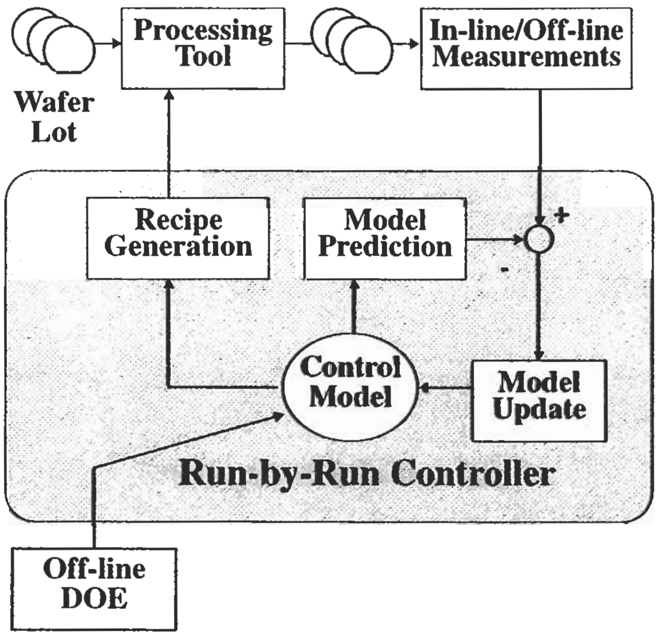
Run by Run Control Methods

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

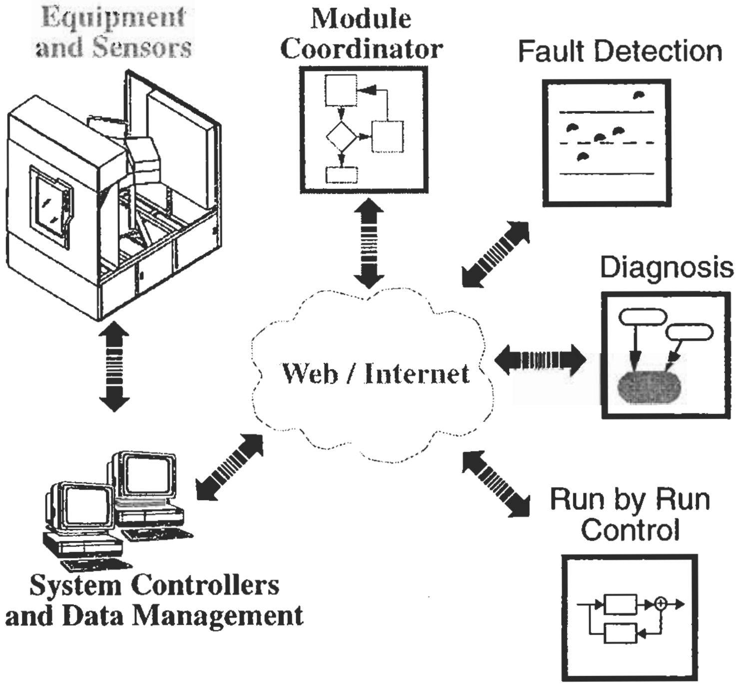
Run by Run Control Methodology



- 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.



Equipment and Sensors

Module Coordinator

Fault Detection

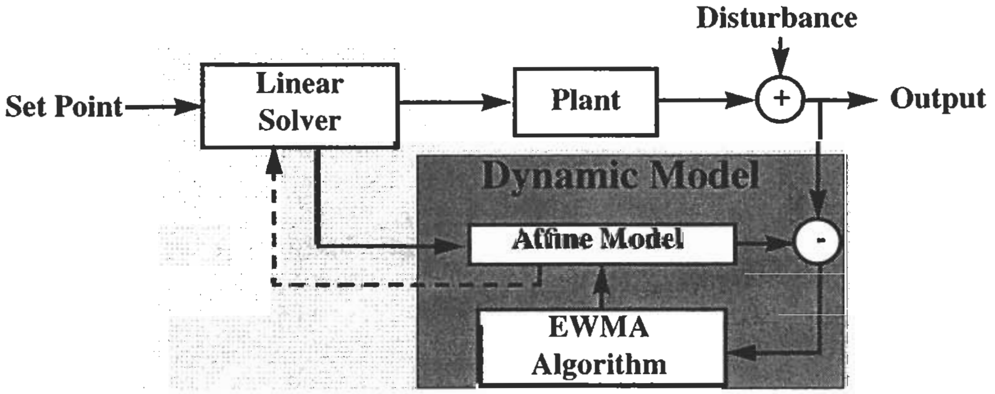
Diagnosis

Web / Internet

Run by Run Control

System Controllers and Data Management

EWMA Run by Run Control Approach



Disturbance

Set Point

Linear Solver

Plant

Output

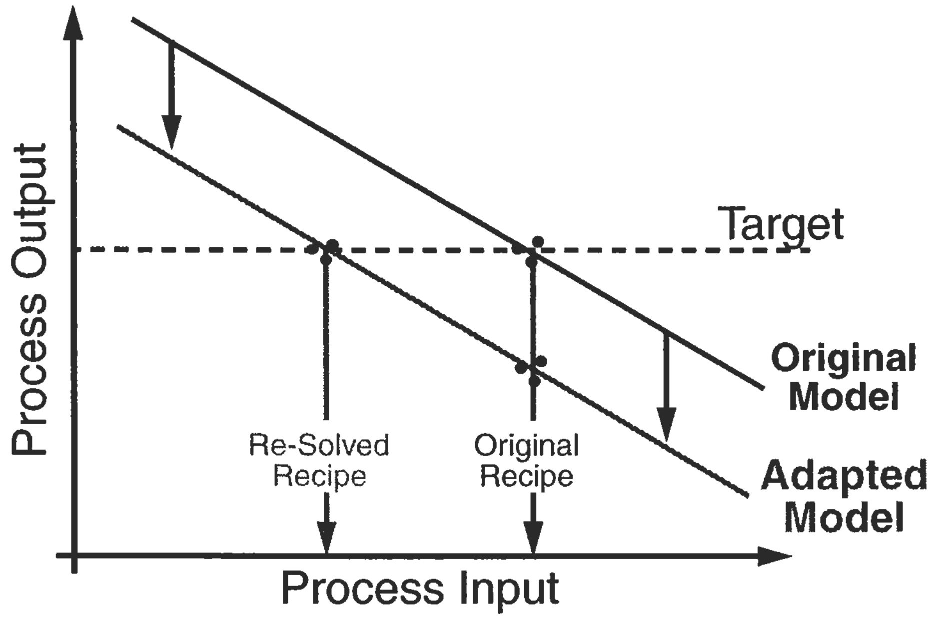
Dynamic Model

Affine Model

EWMA Algorithm

- 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:

$$\min_{x[n]} \|x[n] - x[n-1]\|$$

$$\text{such that} \quad x_{max} > x[n] > x_{min}$$

$$\text{and} \quad T = Ax[n] + b[n]$$

➠ Minimize Recipe Change

$$\min_{x[n]} \|T - (Ax[n] + b[n])\|$$

$$\text{such that} \quad x_{max} > x[n] > x_{min}$$

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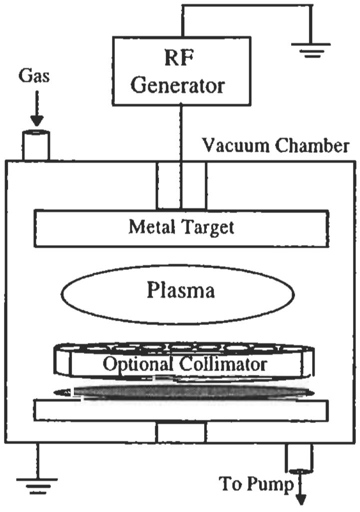
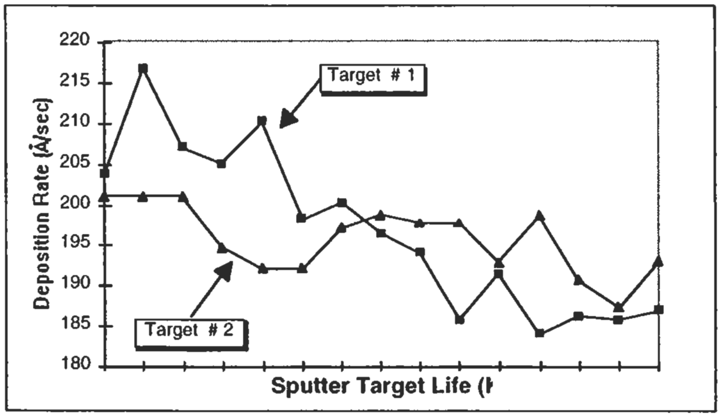
Example 1: Univariate Time-Based Control of Sputter Deposition (MIT/TI)



- 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:

$$filmThickness[n] = depRate[n] \times depTime[n]$$

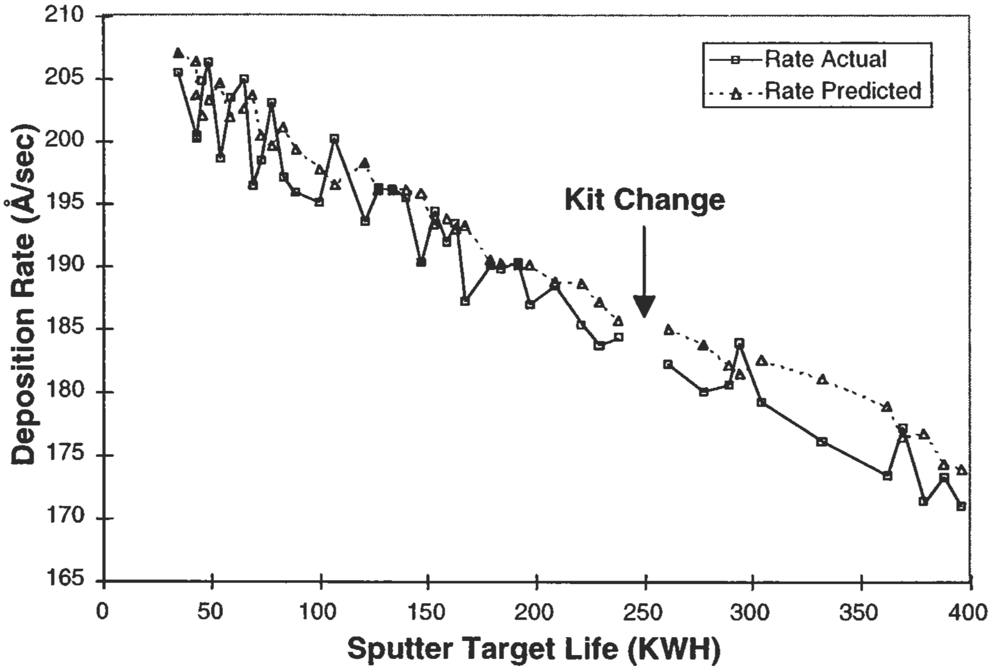
- An open loop estimate of the deposition rate can account for the drift dynamics in metal sputter deposition:

$$depRate_{est}[n] = w \cdot \frac{filmThickness[n]}{depTime[n]} + (1 - w) \cdot depRate_{est}[n-1]$$

- Given the revised deposition rate model, a new deposition time is simply found:

$$depTime[n+1] = \frac{filmThickness_{desired}}{depRate_{est}[n]}$$

State Estimation Results for EWMA Control (Aluminum Sputter Deposition)

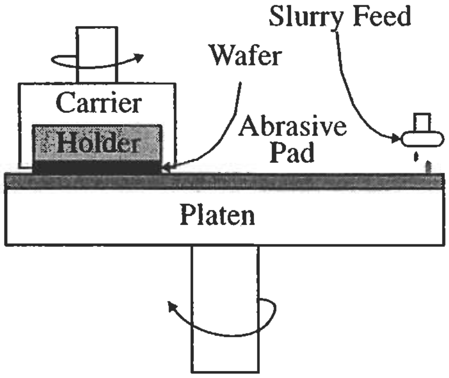


Performance Results - TiN/Al/TiN

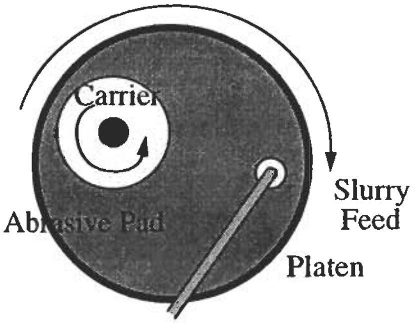
- C_{pk}, the process capability, improved by 44% with the EWMA controller. With RbR MBPC, control of aluminum thickness was to within 3% of the goal, compared to approximately 5% without MBPC.
- Increased processing efficiency:
  - Monitor wafers reduced from 1 every lot to 1 in 3 lots
  - Look-ahead wafers were eliminated
- Simplified processing for technicians

Example 2: Multivariate Control of Chemical Mechanical Polishing

Side View



Top View



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

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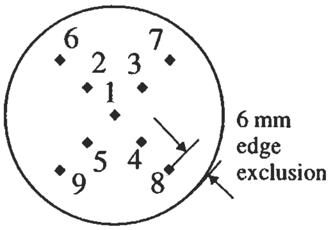
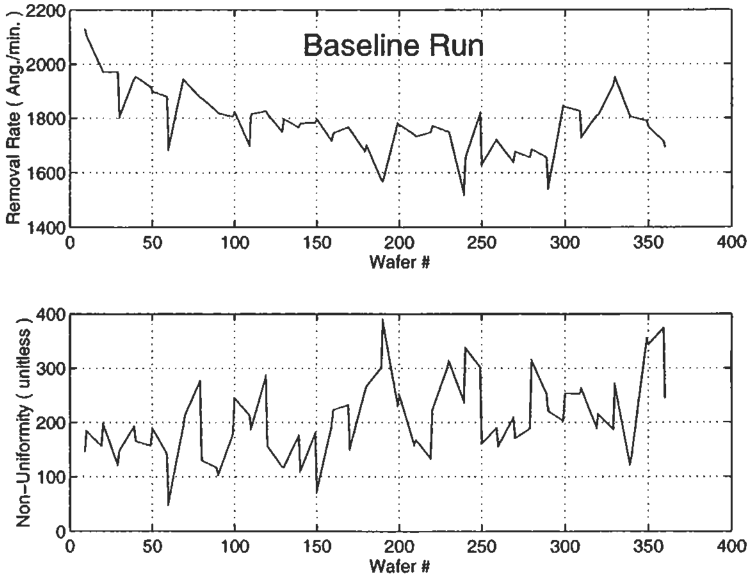
Problem: CMP Limitations and Control Challenges

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

Blanket oxide wafer:



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:

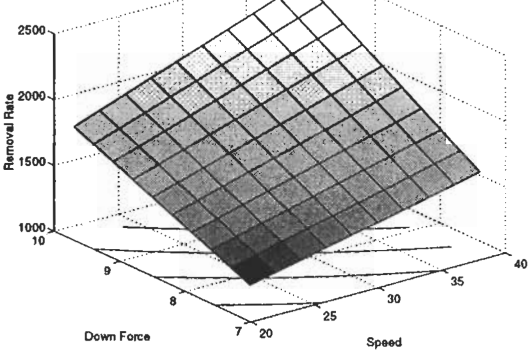
Factor	Lower Bound	Upper Bound
speed (rpm)	20	40
pressure (psi)	0	7
force (lb)	8	10
profile	-0.9	0.9

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

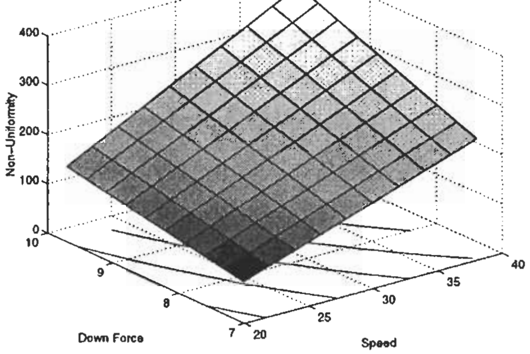
CMP Control Model Development

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

Removal Rate



Nonuniformity



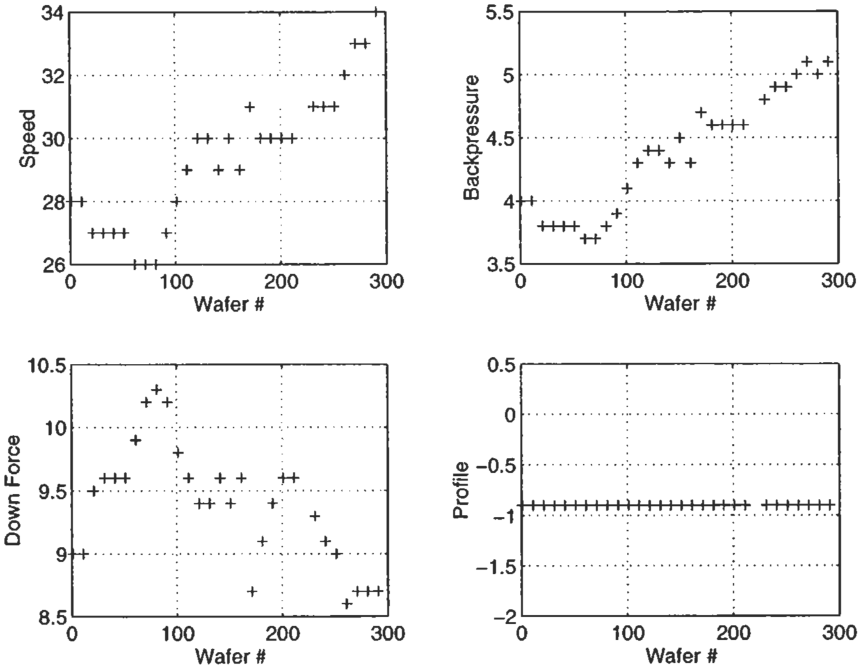
- Models Linearized for Control:

$$y = Ax + b$$

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

CMP Control Experiment: Inputs

- Control Inputs:



- Controller produces increasingly aggressive control to compensate for drift

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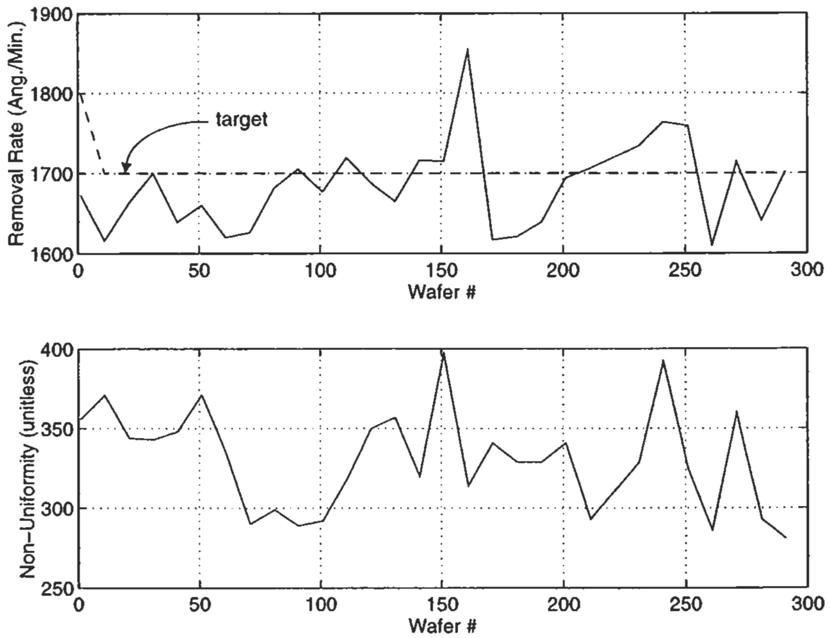
CMP Control Experiment: Outputs

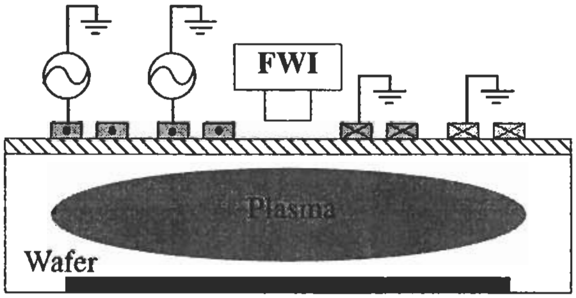
- Output Results:



- Controller successfully compensates for drift in the process, and maintains adequate uniformity

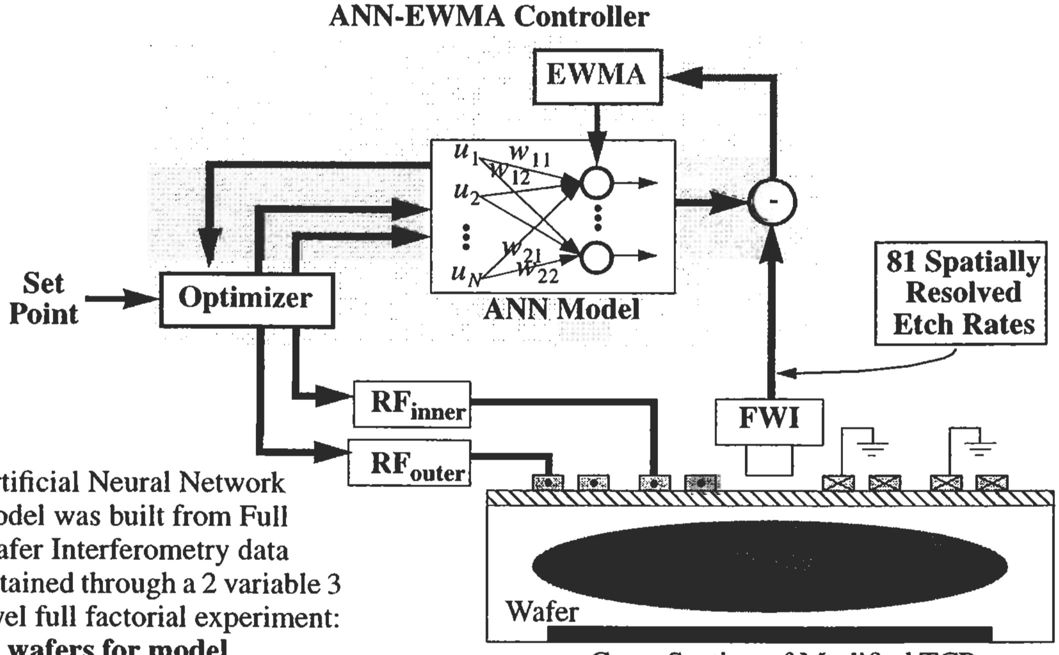
Example 3: Spatial Uniformity Control on a Dual Coil Plasma Etch Tool (Lam TCP)

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**

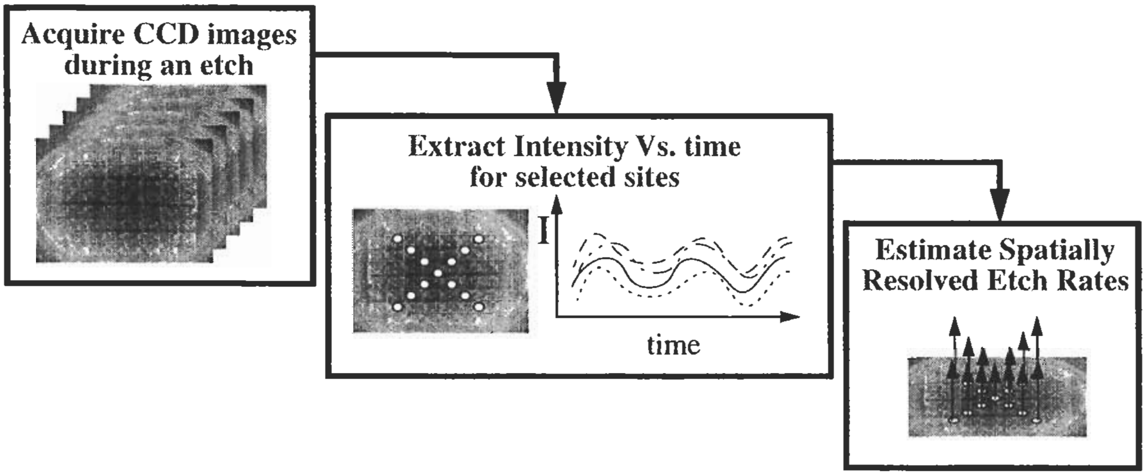
ANN-EWMA Run-to-Run Control Approach



Cross Section of Modified TCP

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



Acquire CCD images during an etch

Extract Intensity Vs. time for selected sites

Estimate Spatially Resolved Etch Rates

- 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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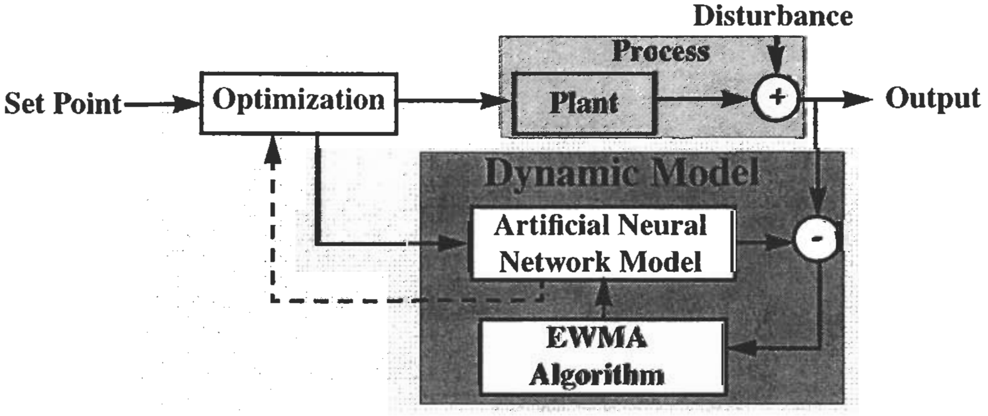
An Artificial Neural Network EWMA Controller



Disturbance

Process

Set Point

Optimization

Plant

Output

Dynamic Model

Artificial Neural Network Model

EWMA Algorithm

- Use a multilayer perceptron neural network to capture nonlinear process model

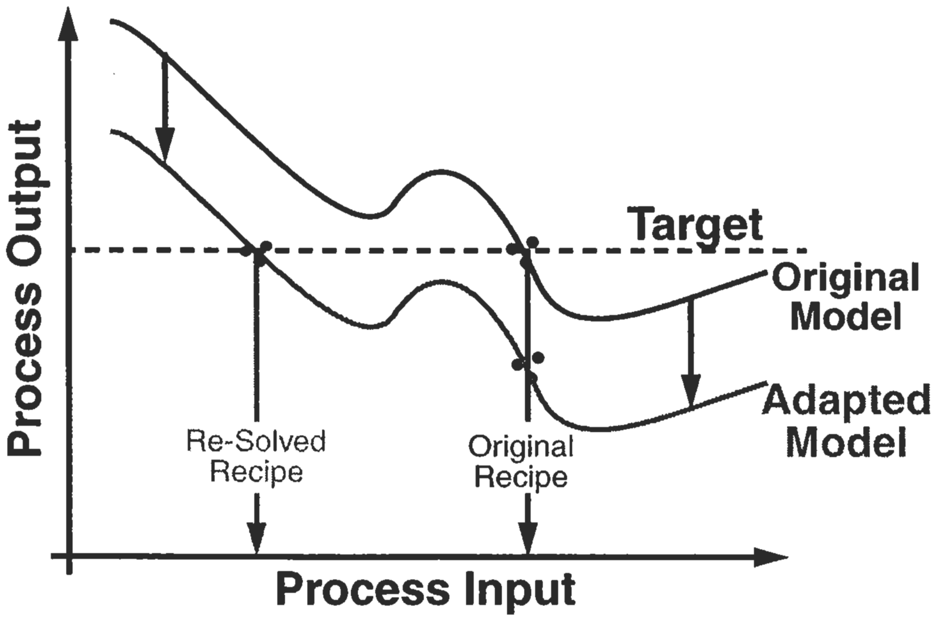
$$y[n] = f(x[n]) + b[n]$$

- Adapt the bias weights in the NN output layer based on EWMA update

$$b[n] = W(\hat{b}[n]) + (I - W)b[n-1] \text{ where } W = diag(\begin{bmatrix} w_1 & \ldots & w_m \end{bmatrix})$$

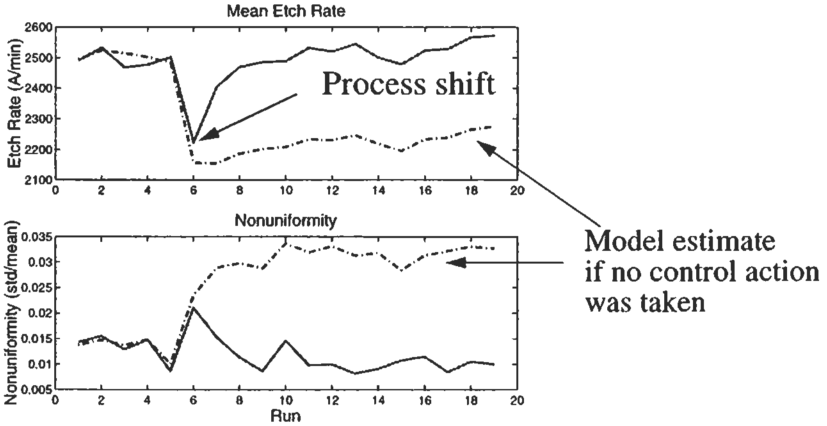
- Generate recipe from nonlinear model via optimization

ANN model based EWMA controller



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

Etch Process Control - Results:



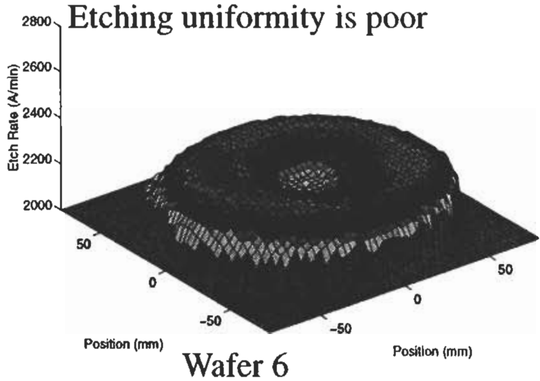
- Objective: Minimize etch nonuniformity and recipe change from setpoint

$$min\left(\beta \cdot \frac{std(\hat{y}[n])}{mean(\hat{y}[n])} + (1-\beta) \cdot \|u[n] - u[0]\|\right)$$

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

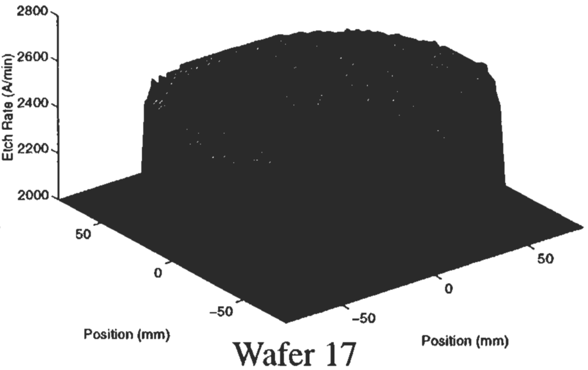
Etching rate profile is improved

Disturbance introduced
Etching uniformity is poor



Wafer 6

System has responded to process shift



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**