Estimation and Control for Plasma Processes

Presentation at the DARPA/NSF Crosscutting Workshop on Virtual Integrated Prototyping

Pramod P. Khargonekar
Dept. of Electrical Engineering and Computer Science
University of Michigan
Ann Arbor, MI 48109-2122
Email pramod@umich.edu Tel (313) 764-4328 Fax (313) 763-1503

PRESENTATION OUTLINE

- Introduction, Overview, and Background
- Plasma Etching
- Nonlinear Estimation of Etch Depth
- Experimental Results
- New Nonlinear Estimation Theory
- Conclusions

SEMICONDUCTOR MANUFACTURING

- Sequence of unit process steps
  - Deposition, Patterning, Etching
- Key unit processes
  - Photolithography Physical and Chemical Vapor Deposition
  - Thermal Processing *Plasma Etching*
  - Ion implantation
- Expensive Manufacturing Equipment
  - A high end machine can cost $5 M
  - Large fraction of technology advancements come from equipment and process advances
- A modern megafab can cost as much as $2.5 B
  - 70% of the cost is the equipment

UNIT PROCESS CONTROL - CURRENT STATE

- PID Controllers on machine inputs
  - » Gas flows into machines - Mass flow controllers
  - » Pressure Controllers
  - » Matching networks for RF Power delivery
- Statistical Process Control
  - » Detection of “out of control” status based on prespecified upper and lower limits
  - » Root cause analysis
- Run-to-run control is still not widely accepted and practiced
- No real-time multivariable control

WHY IS PROCESS CONTROL DIFFICULT?

- It is difficult to build in-situ wafer sensors
  - » Wafer is inaccessible - lack of ports
  - » Deducing key wafer parameters from optical measurements is a challenging and difficult problem
  - » Process variables can sometimes be sensed
- Processes are very complex
  - » Lack of good first principles models
  - » Empirical models have limited utility
- Equipment is not designed for real-time control
  - » Lack of actuators
  - » Computing hardware and software is “closed architecture”

RESEARCH OBJECTIVES

- RESEARCH GOAL:

  Significant improvements in the robustness and performance of processes used in the manufacture of integrated circuits and flat panel displays

- **Focus on plasma deposition and etching**
- Approach - Synergistic Combination of
  - **Modeling and Simulation** - First Principles, Phenomenological, Response Surface and System Identification
  - **Sensors** - In-Situ Process and Substrate Sensors
  - **Control** - Real-Time, Run-to-Run, Supervisory, SPC, Diagnostics
  - **Laboratory and Industrial Demonstrations**

RESEARCH GROUP

Faculty

- J. S. Freudenberg
- J. W. Grizzle
- E. Gulari
- P. Kabamba
- J. Kanicki
- P. P. Khargonekar
- D. Koditschek
- M. Kushner (Illinois)
- V. Nair
- F. L. Terry, Jr.
- C. F. J. Wu

Research Staff

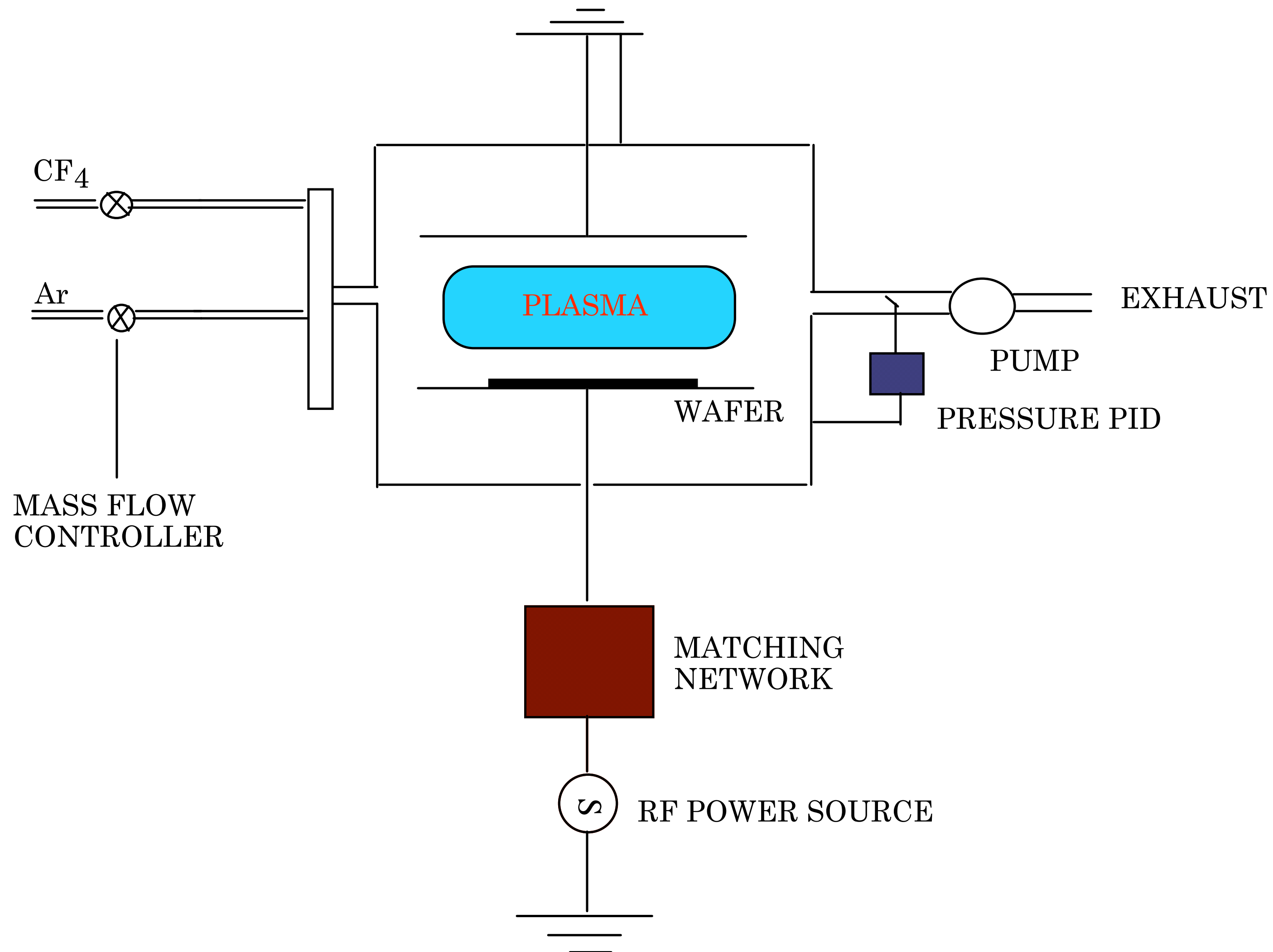
- M. Elta
- D. Grimard
- P. Klimecky
- J. Moyne
- S. Rauf (Illinois)
- W. Sun

+ Lab Staff

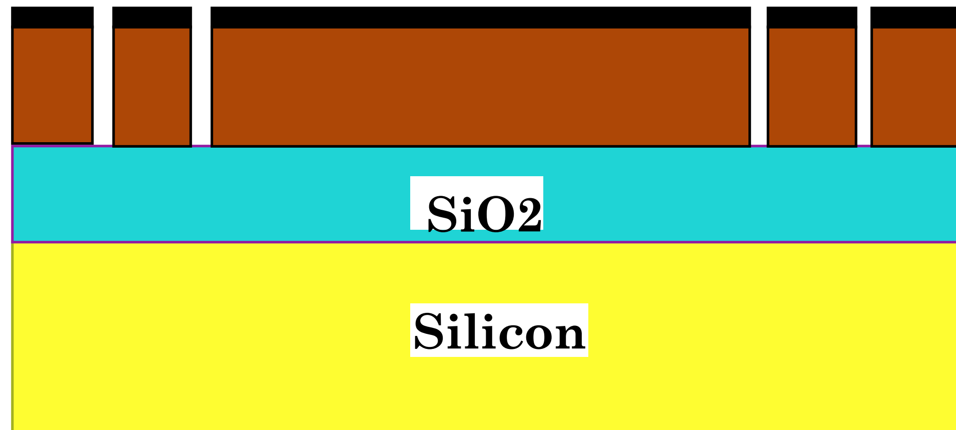
Graduate Students:

N. Chaudhry, C. Galarza, L. Dong, X. Dong, C. Garvin, E. Hamby, M. Hankinson, W. Kong, H. Kim, Z. Ning, H. Park, O. Patterson, A. Ramamoorthy, S. Ruegsegger, J. Shah, S. Shannon, B. Stutzman, T. Vincent

SCHEMATIC OF A PLASMA ETCHER



CONTROL OBJECTIVES

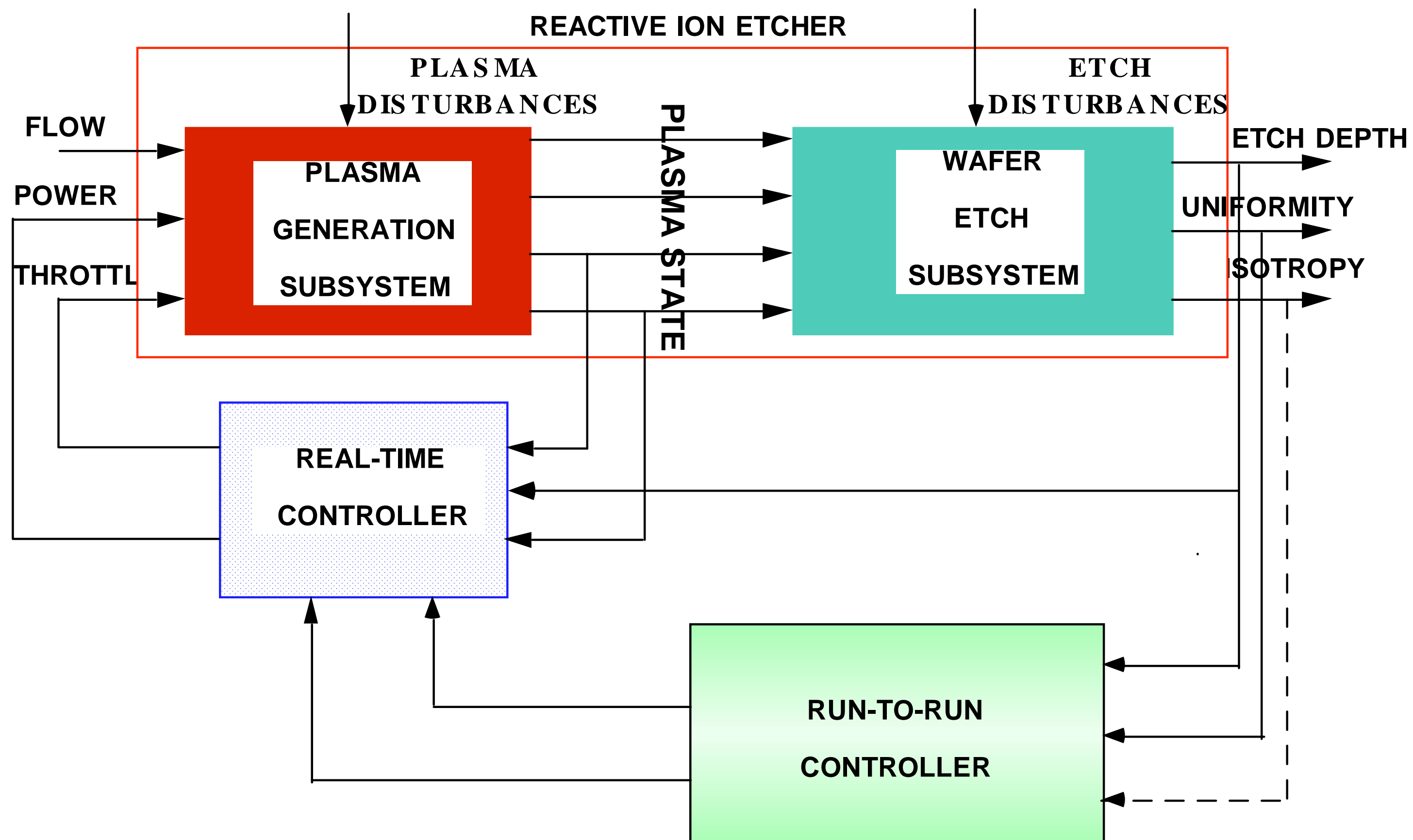


- Etch depth
- Selectivity - Etch only polysilicon but not the photoresist or SiO2
- Anisotropy - vertical walls
- Spatial uniformity

CONTROL STRATEGY

- Process Sensors based Control
  - » Select key process parameters which can be measured
    - – Concentration of fluorine, bias voltage, ion energy flux
  - » Devise controllers to use the process information with the aim of controlling the wafer etch
  - » Experiments are necessary to check the efficacy of the control strategy
- Product Sensors based Control
  - » Estimation of product parameters based on indirect measurements
- Combined use of Process and Product Sensors

CONTROL OF REACTIVE ION ETCHING



REAL-TIME CONTROL OF RIE

- We have designed and implemented several real-time controllers
  - Controlled Variables: Fluorine concentration, Bias Voltage or Ion Energy Flux, Pressure
  - RF Power, Throttle angle, %O2 as actuators
- Controller designs have been performed using both system identification as well as phenomenological models
- We have done many tests to evaluate the robustness of the closed loop system
  - The closed loop system shows much greater robustness to matching network variations, flow rate variations, gas leaks, ...

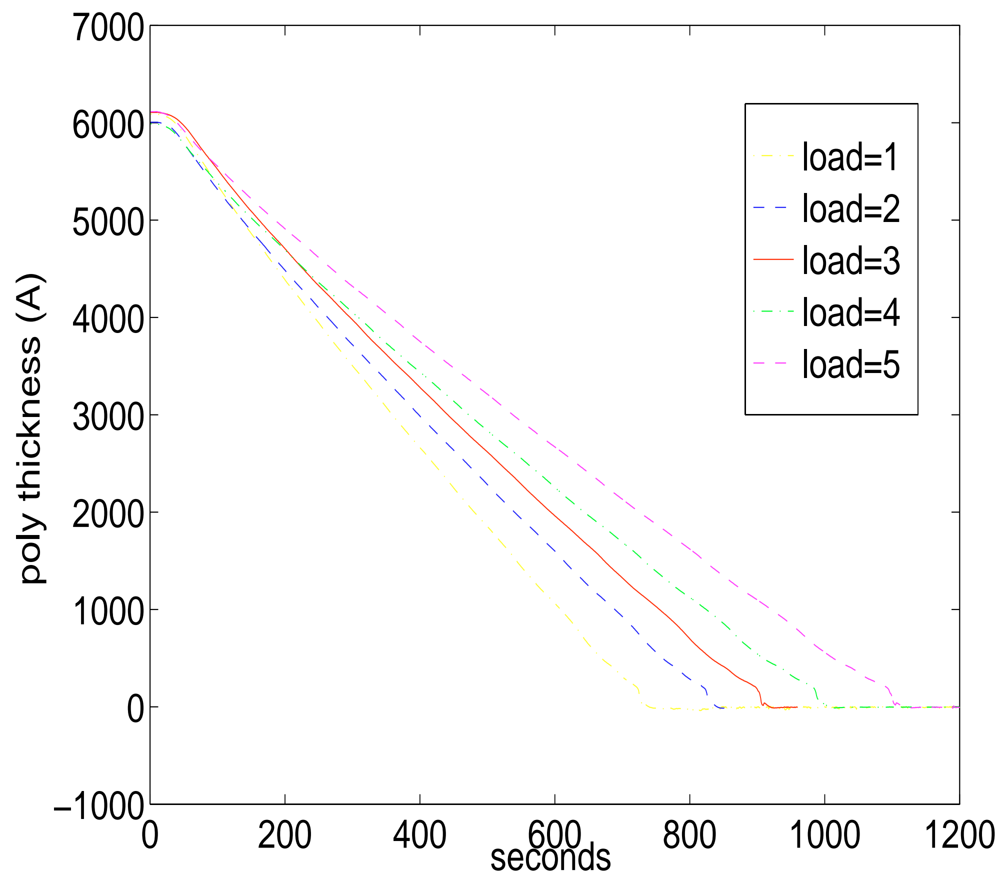
A LOADING EFFECT STUDY

- Loading effect: etch rate decreases as the amount of exposed area of silicon increases
  - » Greater consumption of reactant as area increases
  - » Becomes more pronounced towards the end of the etch run as some areas are etched before some others due to spatial nonuniformity
  - » Known to be a significant problem in etching of silicon using fluorine chemistry
- Inverse of etch rate is linearly proportional to the exposed area - Mogab, Flamm
- We did a systematic study to evaluate the improvement against loading effect offered by real-time closed loop control

Patterson and Khargonekar

LOADING EFFECT UNDER CONVENTIONAL CONTROL

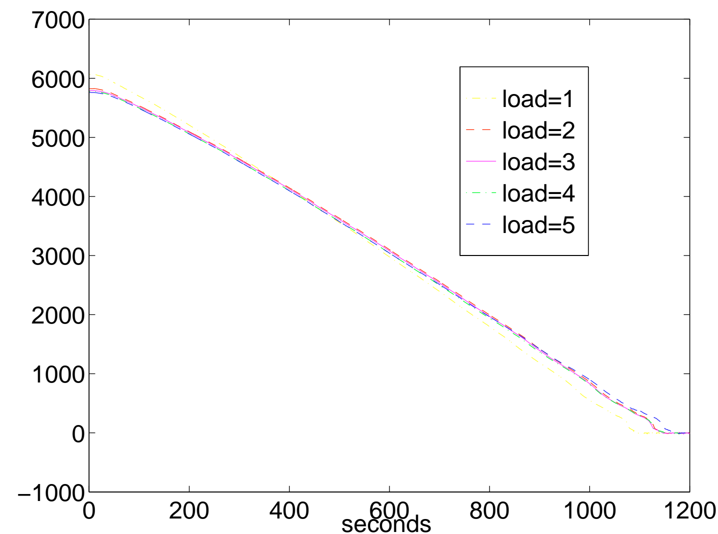
- The plots show thickness of remaining silicon as a function of time for various loads
- As the load increases, the etch rate decreases
- These results are for a multiwafer reactor but similar phenomenon occurs in single wafer reactors as the exposed area varies



Thickness of Si vs Time as a function of load

THICKNESS VS TIME UNDER REAL-TIME CLOSED LOOP CONTROL

- These plots show the thickness of silicon as a function of time under real-time closed loop control



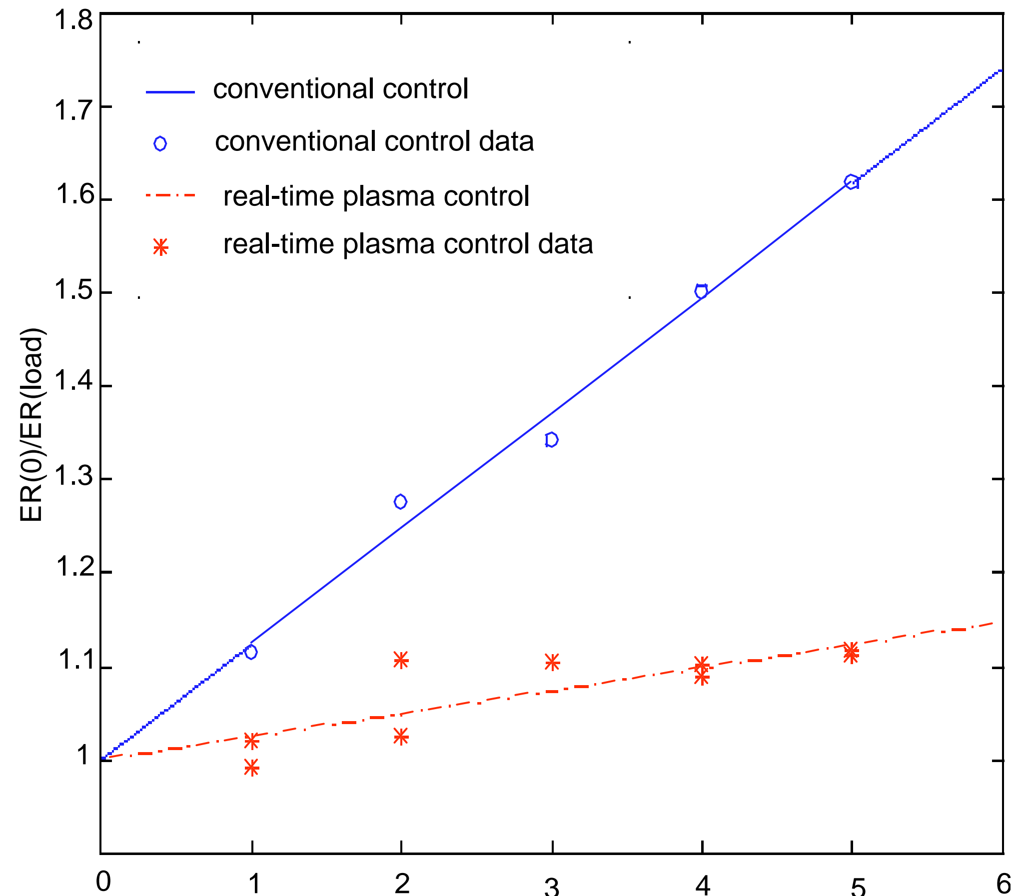
- As one can see, the etch rate is virtually independent of the loading conditions

REDUCTION IN LOADING EFFECT

- The plot shows that the inverse of etch rate is, indeed, linearly proportional to the load. This verifies the Mogab-Flamm model for our case.

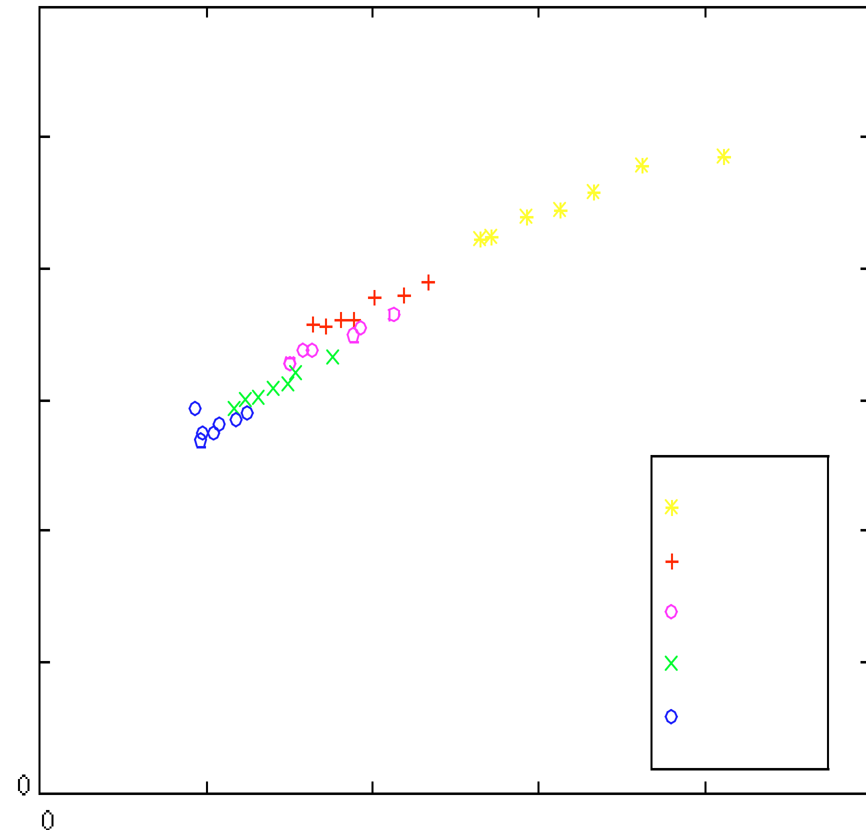
- Under real-time closed loop control, the slope of the line is much smaller than under conventional control.

- **80% reduction in loading effect**



CORRELATION BETWEEN [F] AND ETCH RATE

- This graph shows the correlation between etch rate and fluorine concentration under conventional control
- The data shows that there is a linear relationship between etch rate and fluorine concentration
- This explains why by keeping fluorine concentration constant under real-time closed loop control, we can reduce the loading effect



INTEGRATED REAL-TIME AND RUN-TO-RUN CONTROL

- We have also designed, implemented and test integrated real-time and run-to-run controllers.
  - » Most of wafer level parameters can only be measured after the process run
- The real-time controller maintains [F] and Vbias at desired set points. The run-to-run controller provides set points on [F] and Vbias to the real-time controller on the basis of etch depth and uniformity measurements.
- Both real-time and run-to-run controllers are multivariable.
- Several experiments have been done to evaluate the robustness of performance of the closed loop system.
- *Joint project with the SRC Center*

Hankinson, Vincent, Irani, and Khargonekar

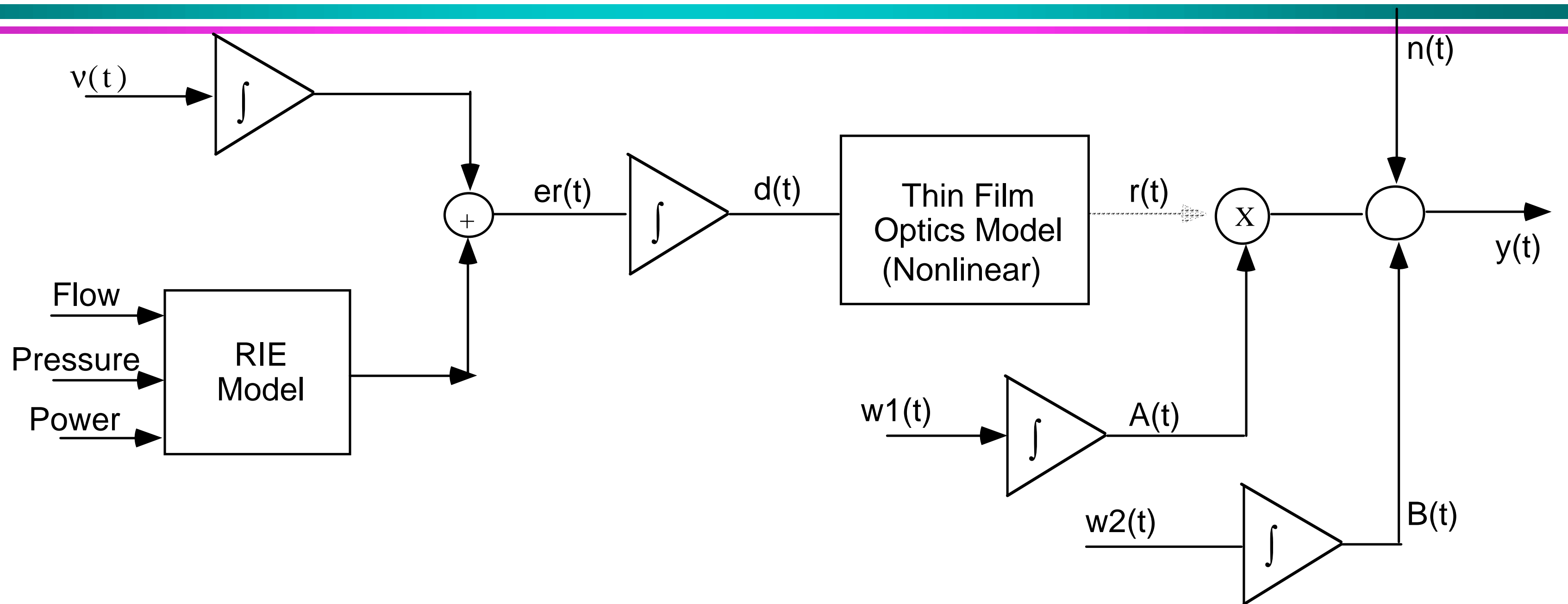
THE DUAL WAVELENGTH LASER SET UP

Beam Splitter
Optic Fiber
Lock-In Amplifier #1
Beam Combiner
Red HeNe
Photo Diode
Chamber
Choppers
Lock-In Amplifier #2
Green HeNe

KEY ISSUES

- High signal to noise ratio as a result of using lasers
  - Can get high data rates
- Fairly inexpensive
  - Cheap commercial lasers
- The technical problem is to extract the etch rate and depth from the photodiode voltage signals
  - Changes in gain and offset in the optical system
  - Sensor noise, window coating
  - An inverse problem where the physical model is nonlinear with moderate complexity
- Our solution uses advanced techniques from nonlinear estimation theory - Extended Kalman filtering

NONLINEAR DYNAMIC MODEL



- Dynamics due to etching + Nonlinearity due to the optical model
- Time varying gain A(t) and offset B(t)
- We have not incorporated an RIE model so far. Results will only improve when we incorporate the RIE model.

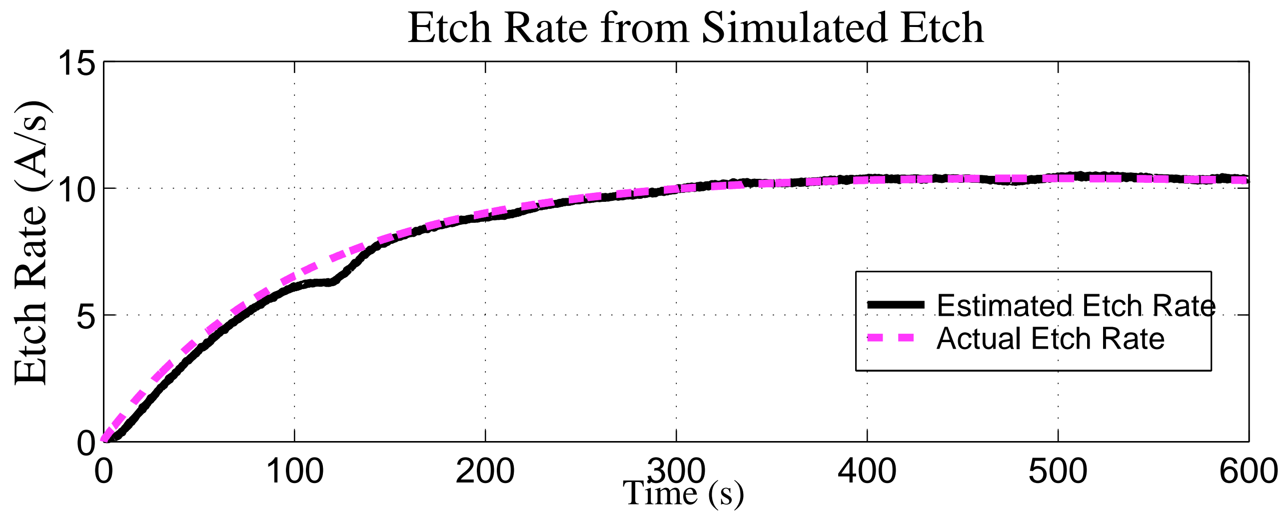
ESTIMATION PROBLEM

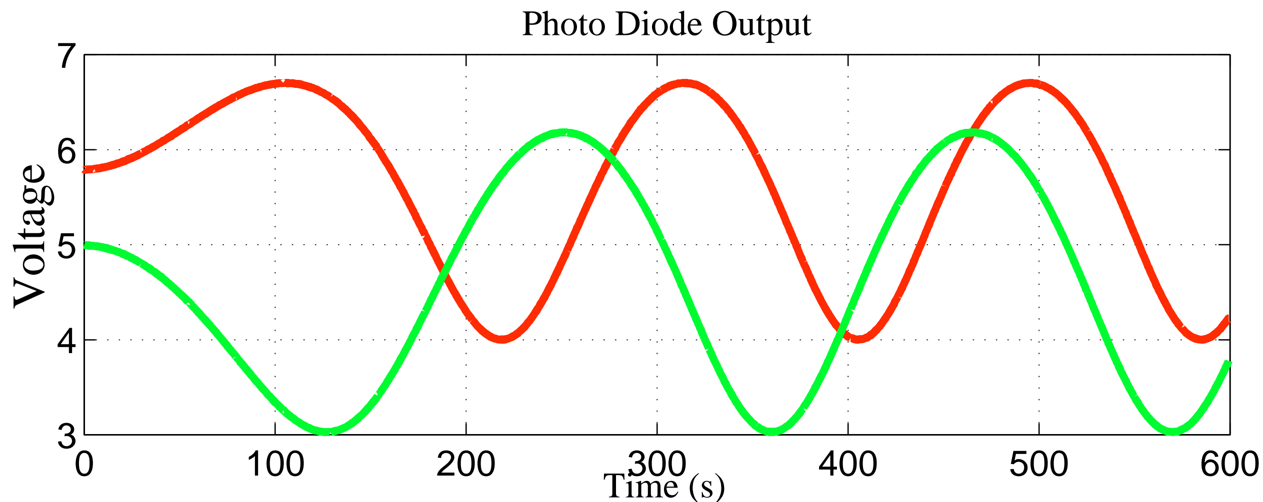
- The problem is to estimate the etch rate and depth in real-time given the photo-diode voltage measurements in real-time
- We can write a dynamic model of the form

$$\frac{dx}{dt} = f(x(t), v(t), w_1(t), w_2(t))$$
$$y(t) = h(x(t)) + n(t)$$

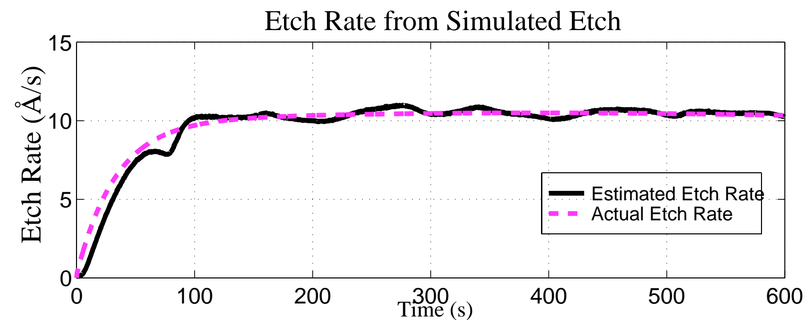
- As a matter of fact, f is linear but h is highly nonlinear.
- The problem is to estimate x(t) given the noisy signal y and the model above.
- SOLUTION: Extended Kalman Filter. In the linear model with Gaussian noise case, it is known to be the optimal estimator.
- We have designed and implemented this filter.

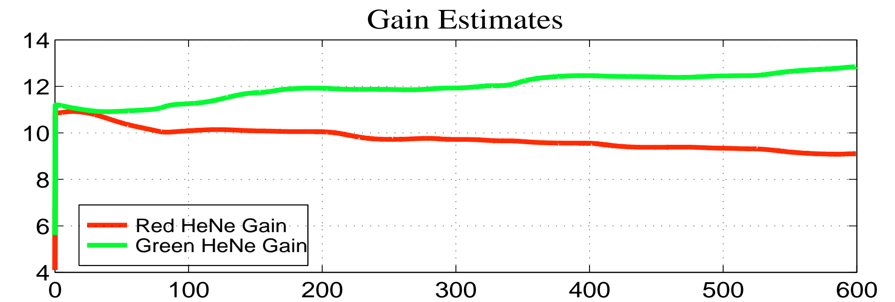
SIMULATION RESULTS

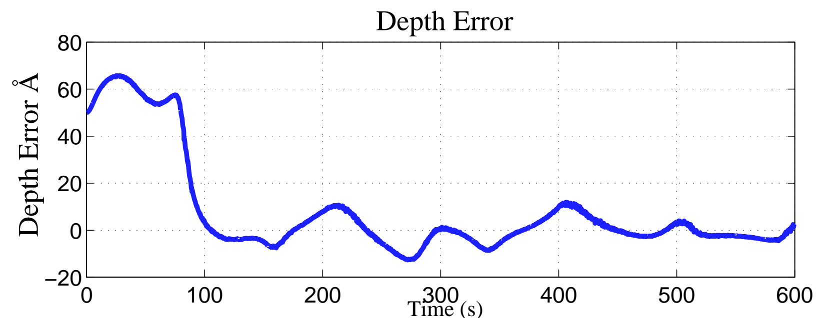


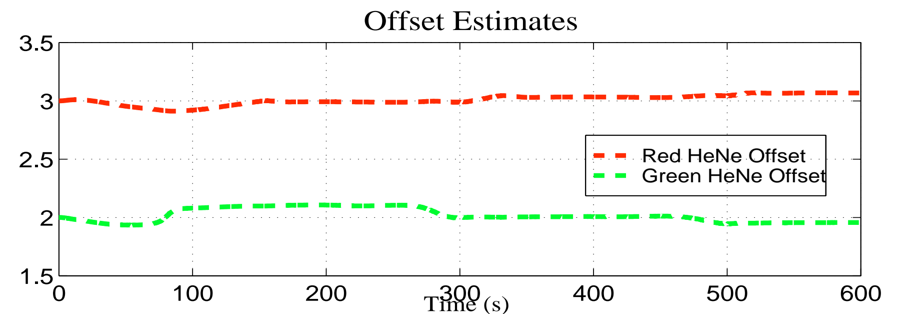


SIMULATIONS WITH GAIN AND OFFSET DRIFTS



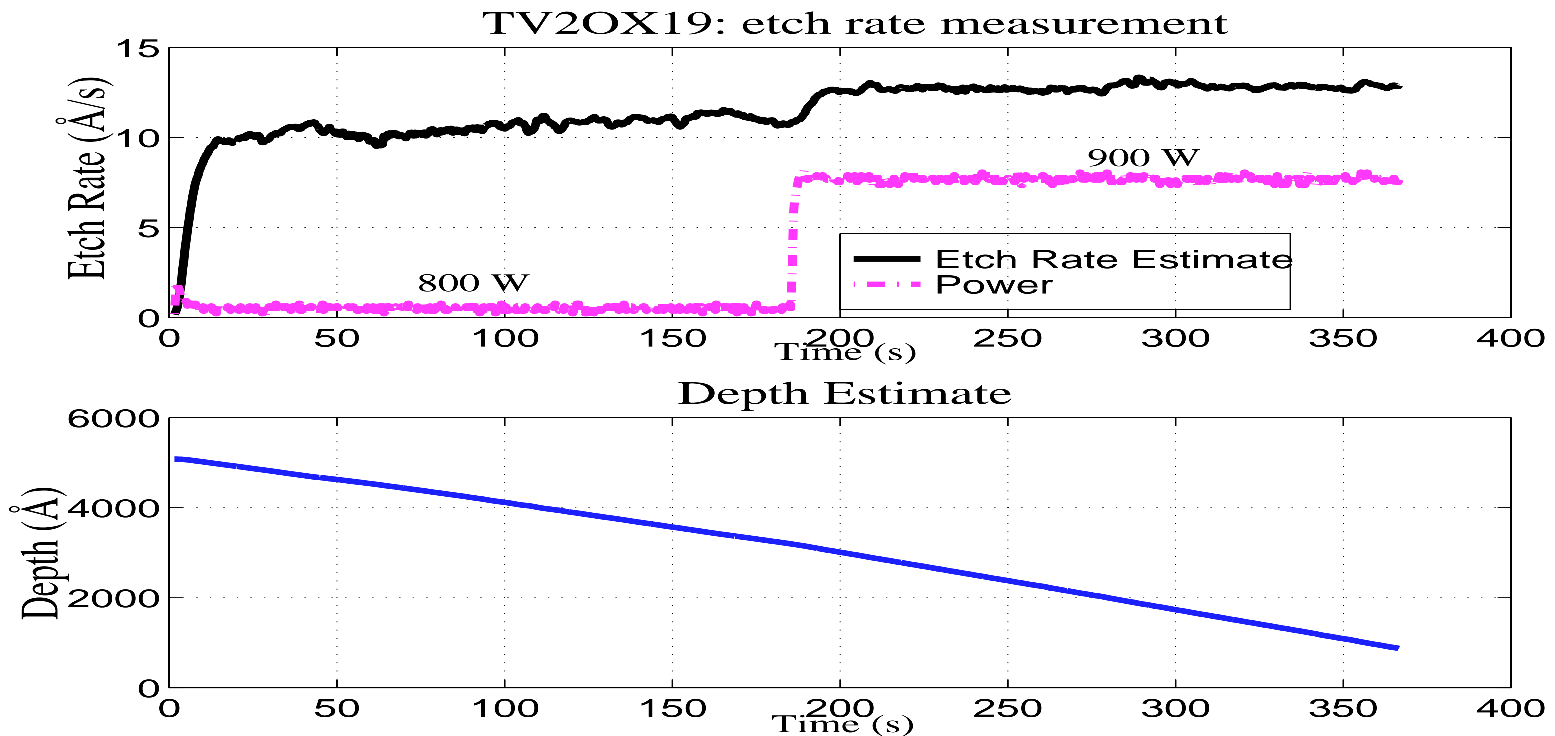






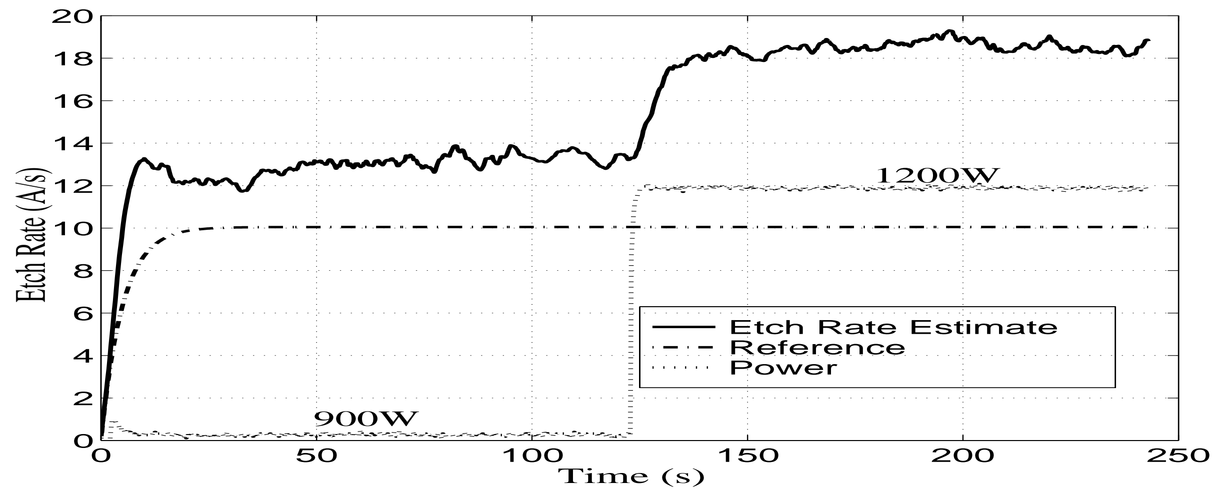
- Red HeNe Gain from 12 to 13 Green HeNe Gain from 10 to 9
- Red HeNe Offset from 3 to 3.1 Green HeNe Offset from 2 to 1.9
- Error in initial depth by 50 A

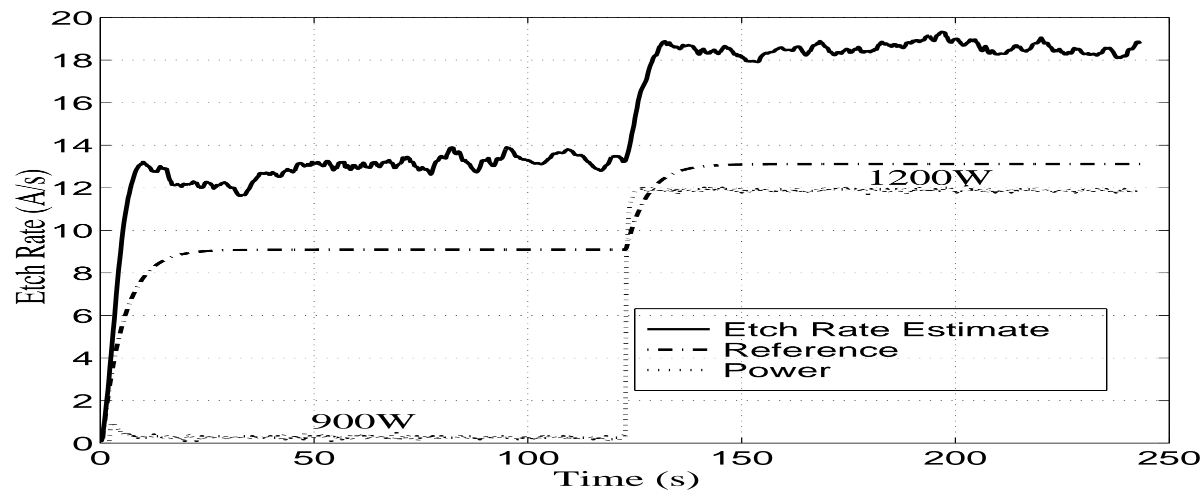
REAL-TIME ETCH RATE AND DEPTH ESTIMATES



- SiO2 Etch for 360 seconds
- Power step at 180 seconds
- Rapid dynamic response of the etch rate and depth estimators

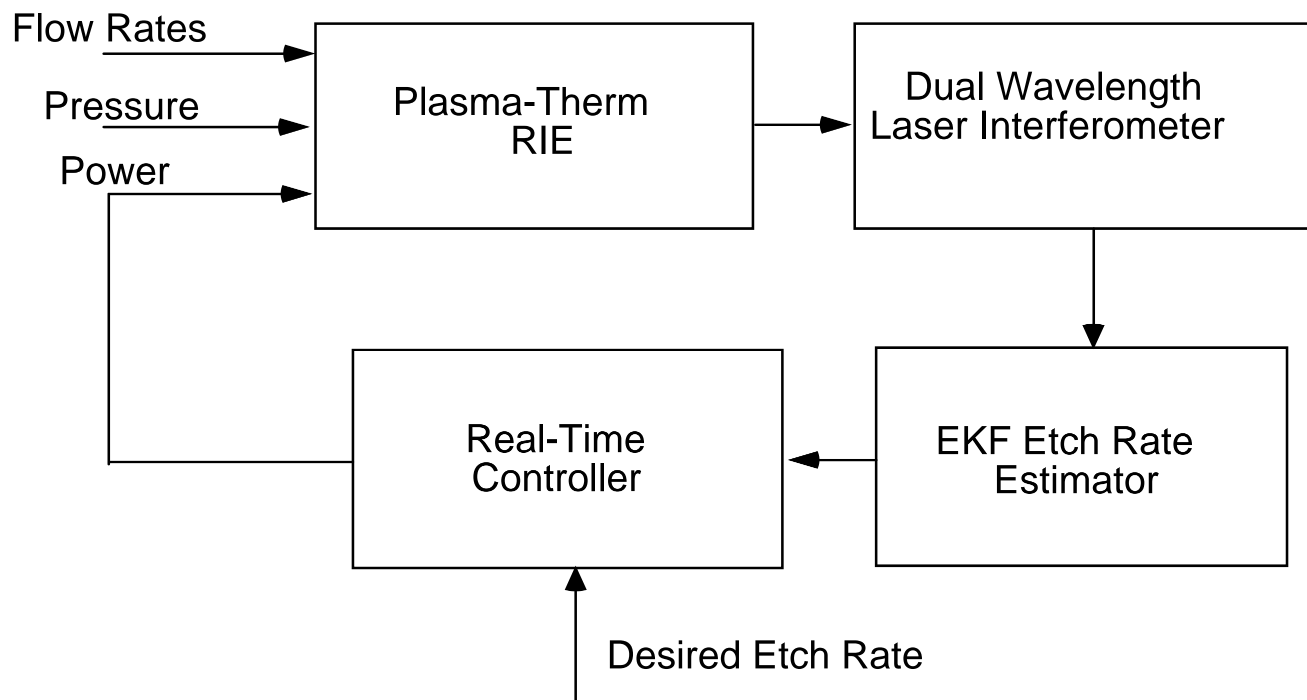
INCORPORATING A RIE MODEL



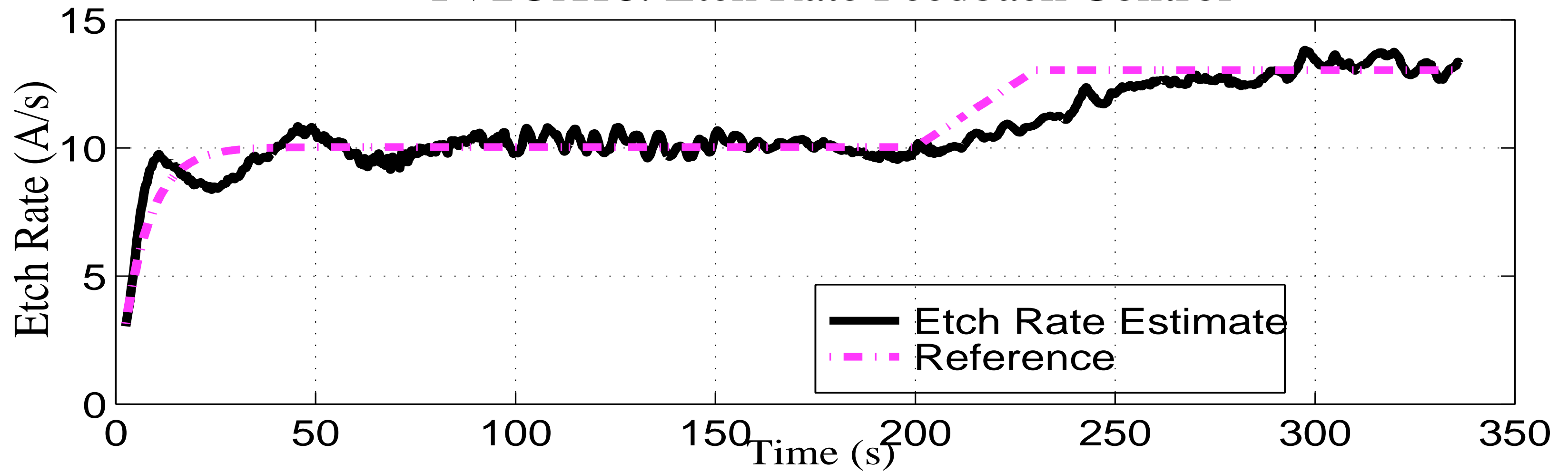


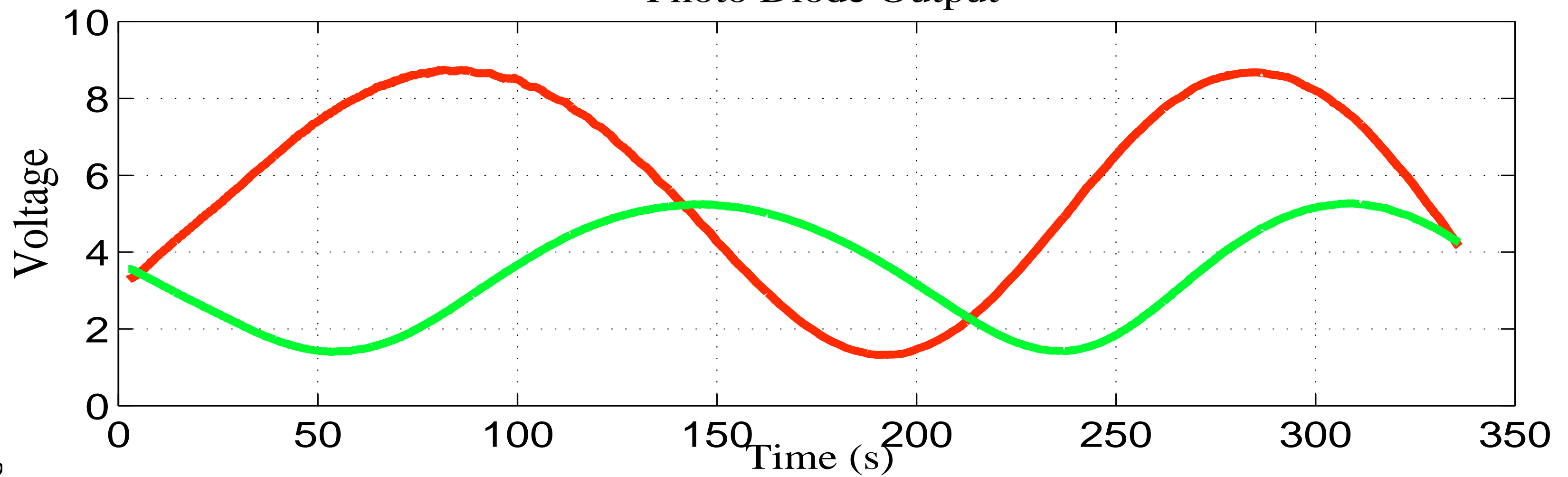
REAL-TIME FEEDBACK CONTROL OF ETCH RATE

- We have designed, implemented, and tested a real-time feedback controller to maintain etch rate at a desired level or follow a desired trajectory.
- Estimation/control code running at 20 Hz - could be made faster
- Single loop feedback design



EXPERIMENTAL RESULTS





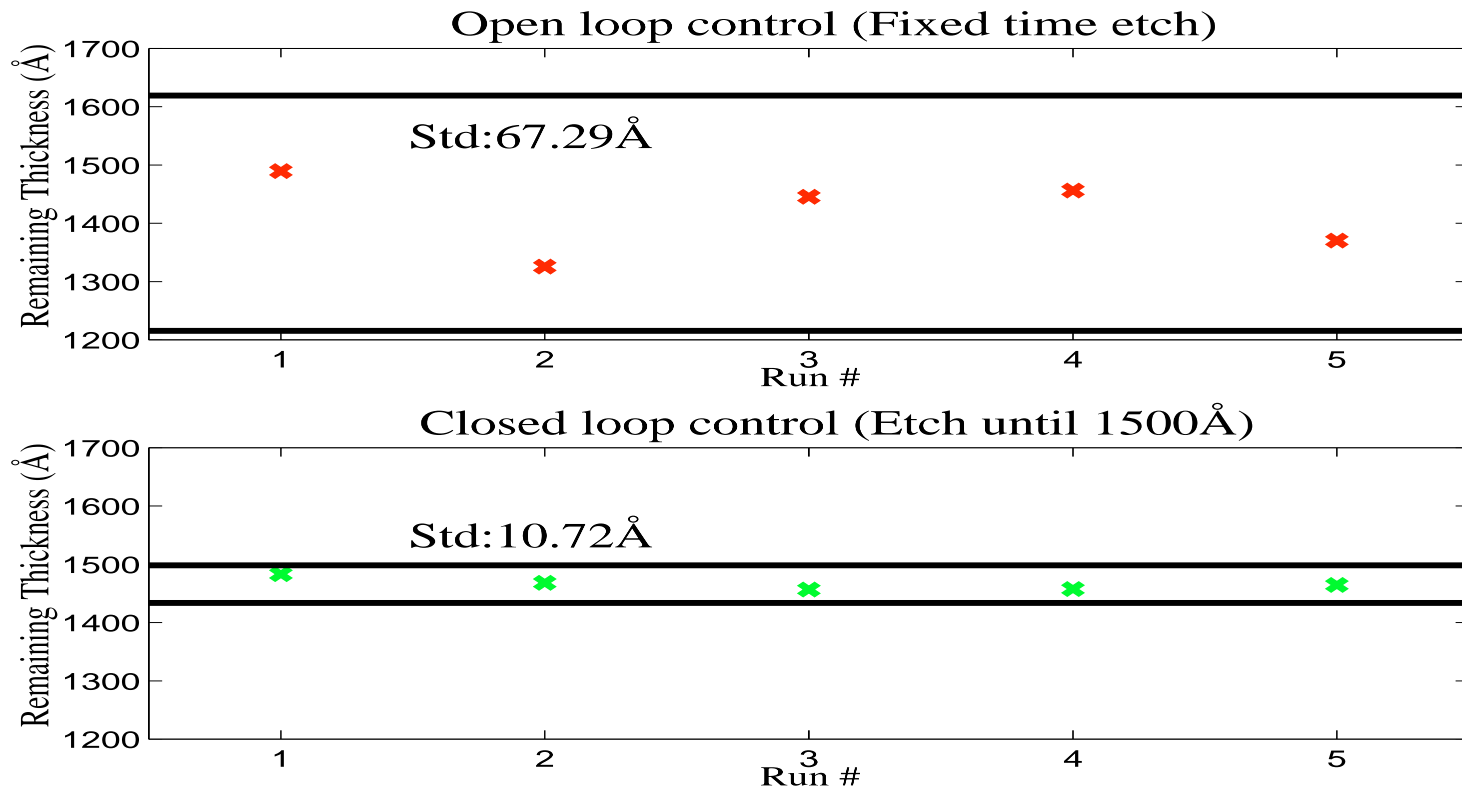
END POINTING USING DUAL WAVELENGTH INTERFEROMETER/EKF ETCH DEPTH SENSOR

- The combination of the dual wavelength interferometer and the EKF based estimator gives not only an estimate of etch rate but also of etch depth.
- The depth estimator can be used to end point an etching process
  - » The end point need not be at an interface as is common in OES methods of end point detection
  - » Motivated by etching problems in AMLCDs. Need to selectively etch n+doped a-Si:H on intrinsic a-Si:H. Etches are not selective.
- We devised a set of experiments to compare the end point accuracy achievable using our technique over timed etches.

SiO2 ETCH EXPERIMENT

- Experiment:
  - 5 times etches and 5 closed loop etches - alternated
  - Power = 800 W, Flow = 100 sccm, Pressure = 50 mTorr
  - In closed loop etches, the real-time controller was used to stabilize the etch rate. This is not, however, essential to the results.
- Performance Metric
  - Initial and final depth measured using Leitz SP - a completely independent tool for measurement
  - Closed Loop Metric - Variance of SiO2 remaining
  - Open Loop Metric - Variance of SiO2 remaining
  - In the open loop case, proper adjustments were made to account for variations in initial thickness. This makes sure that the timed etches are not unfairly penalized due to the variability of the incoming material. No such adjustments were made in the closed loop case.

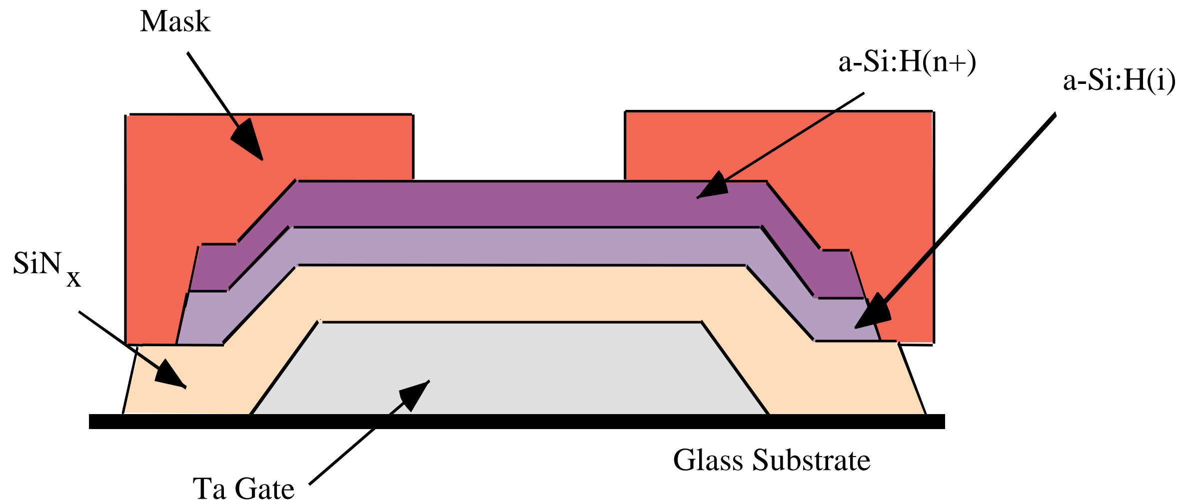
END POINT ACCURACY EXPERIMENTS



Etching of SiO2 on Si

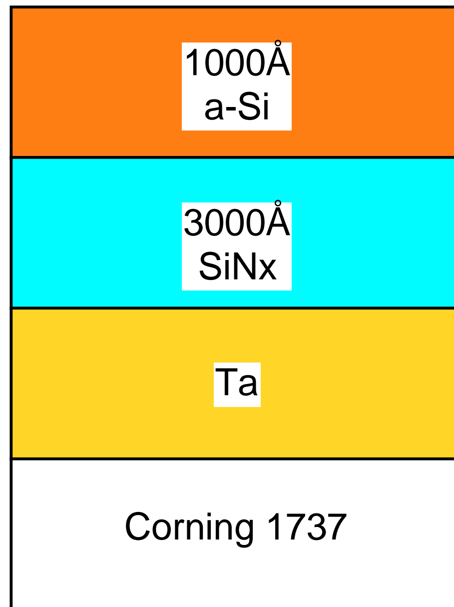
83% reduction in etch depth standard deviation

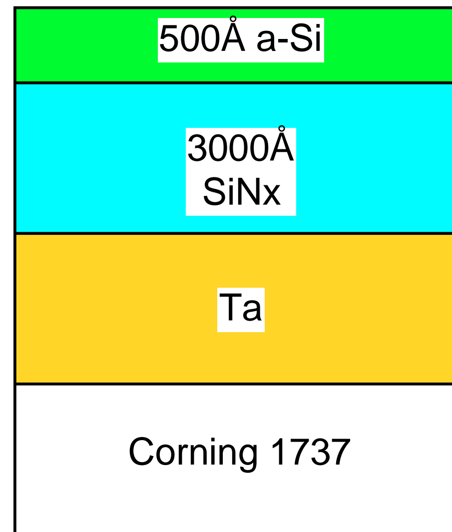
TFT BACKCHANNEL RECESS ETCH



- Desired result: Etch through a-Si:H(n+) and endpoint at a-Si:H(n+)/a-Si:H(i) interface
  - » Can not use OES to solve this endpoint problem.
- a-Si:H(i) thickness impacts device performance

ETCH EXPERIMENT TEST STACK

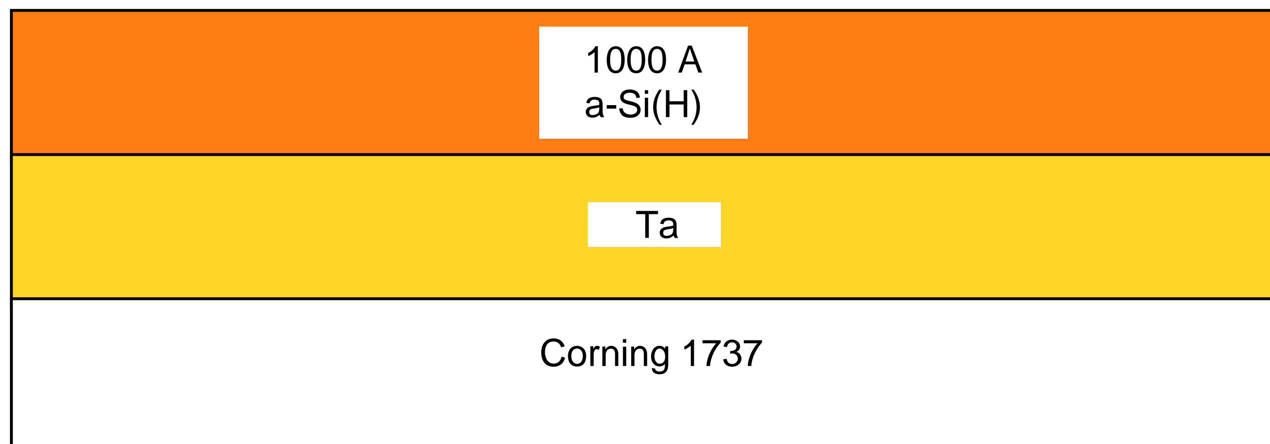




Vincent, Klimecky, Sun, Khargonekar, and Terry

ENDPOINT EXPERIMENT

- 20 Etch Experiments
  - » 10 timed etches (standard practice.) Etch time 100 seconds
  - » 10 endpointed using estima from EKF-R



Experimental Stack

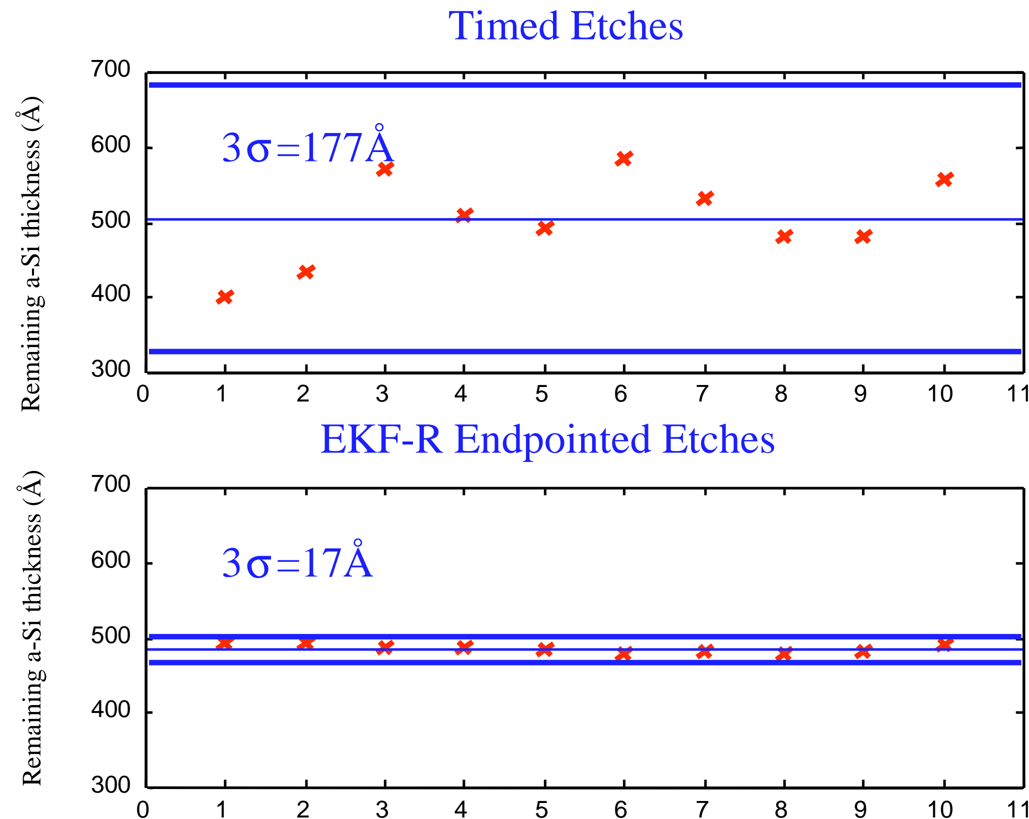
- Goal: Etch 500 Å of 1000 Å a-Si film

EXPERIMENTAL METHOD

- EKF setup
  - » Noise covariances tuned using simulated and actual data. Held fixed throughout experiment.
  - » Initial guess for a-Si thickness: 1000 Å
- Independent Verification:
  - » Pre-etch thickness measured using a Spectral Photometer
    - – Accuracy +/- 20 Å
    - – Information **not** supplied to EKF
    - – Pre-etch a-Si thickness 3σ: 128 Å
  - » Post-etch thickness measured using a Spectroscopic Ellipsometer
    - – Accuracy +/- 5 Å

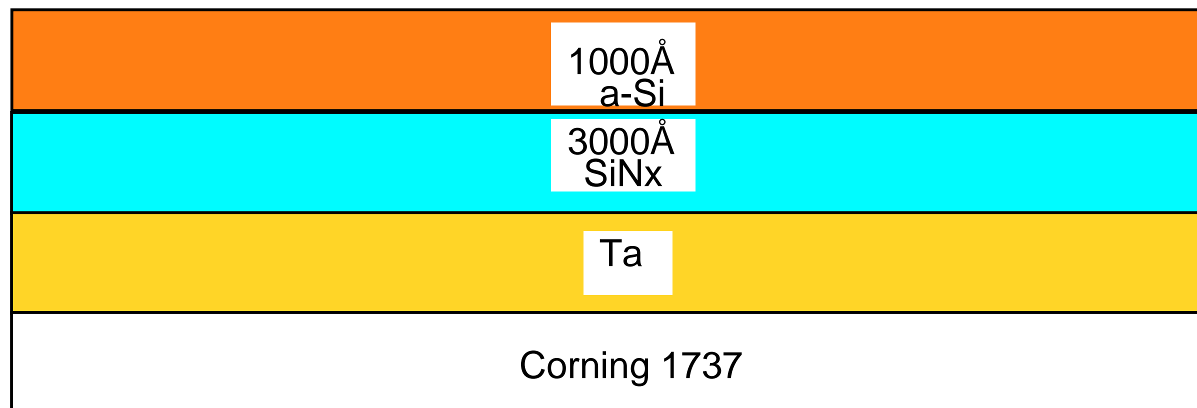
ENDPOINT RESULT

- Result: 90% reduction in standard deviation of remaining film thickness by using EKF-R endpoint.



ENDPOINT EXPERIMENT - II

- 10 Etch Experiments
  - 5 timed etches (standard practice.) Etch time 100 seconds
  - 5 endpointed using estimated etch depth from EKF-R

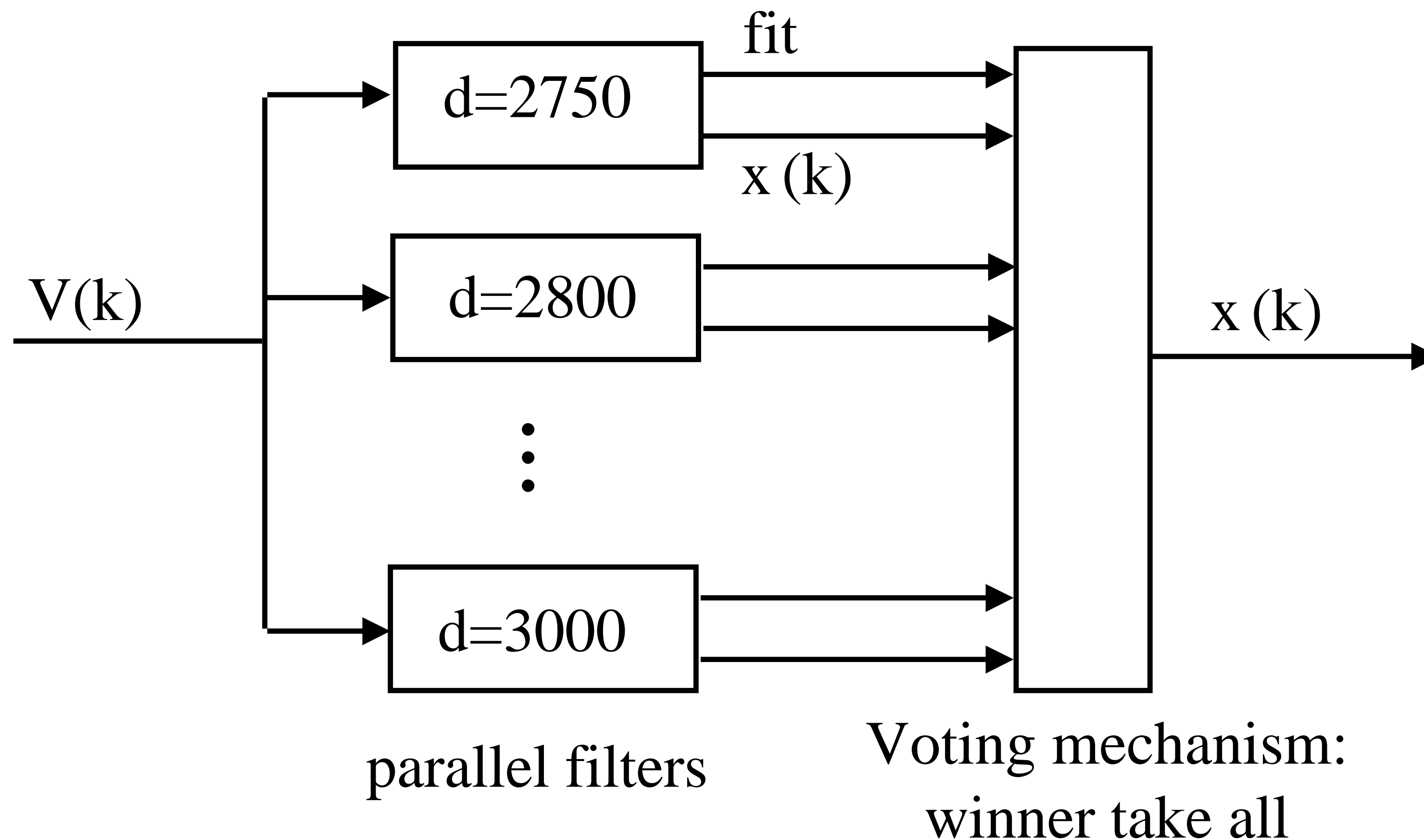


Experimental Stack

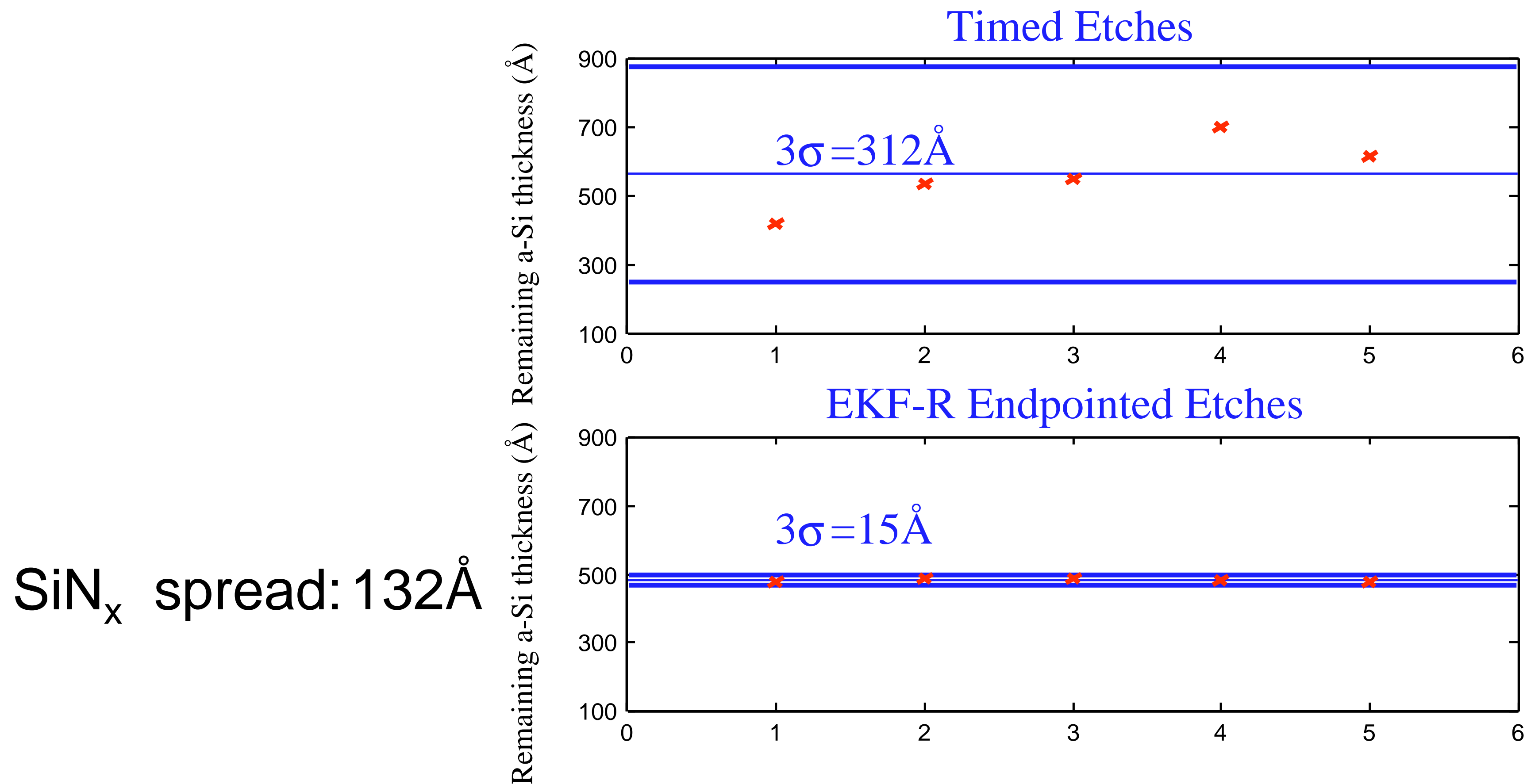
- Goal: Etch 500 Å of 1000 Å a-Si film

ADAPTIVE ESTIMATION STRATEGY

- Finite set of possible models - Magill (1965)



EXPERIMENTAL RESULTS

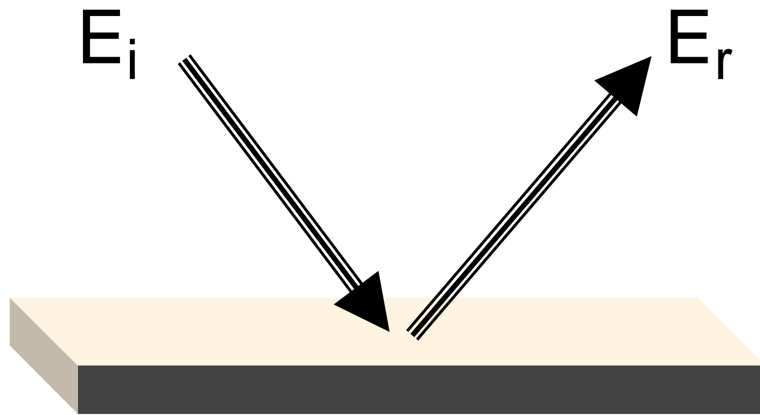


95% reduction in standard deviation

RESULTS - SiNx THICKNESS

Final a-Si Thickness (Å)	EKF SiN_x estimate (Å)	SE SiN_x (measured) (Å)
475	2950	2966
489	2950	2911
485	2950	2929
484	2850	2834
479	2900	2917

EXTENSION TO ELLIPSOMETRY



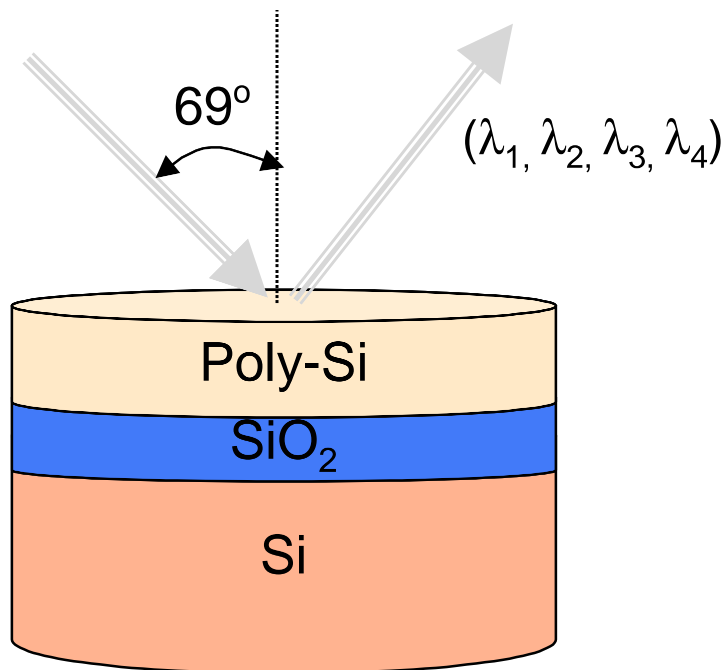
$$E_r = r\,E_i \qquad r = r_p \ \text{ or } \ r_s$$

$$\rho = \frac{r_p}{r_s} = \tan(\Psi)e^{j\Delta}$$

$$\begin{bmatrix}\Psi\\ \Delta\end{bmatrix} = \mathbf{f}(\lambda, \phi_0, \mathbf{N}, \mathbf{d})$$

λ : wavelength of incident light
ϕ_0 : angle of incidence
$\mathbf{N}$: vector of refractive indices
$\mathbf{d}$: thickness vector

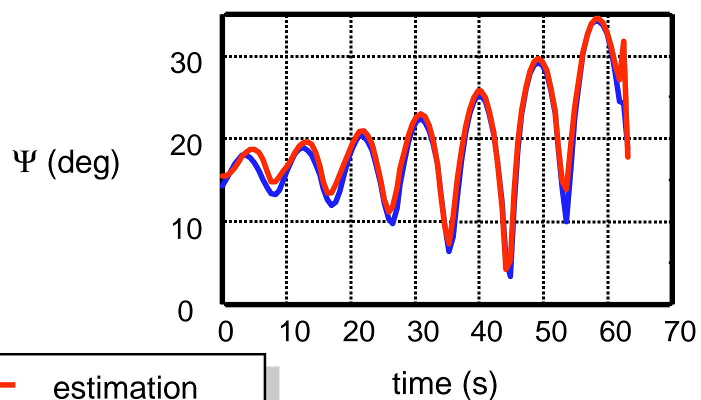
DESCRIPTION OF THE EXPERIMENT

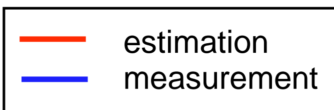


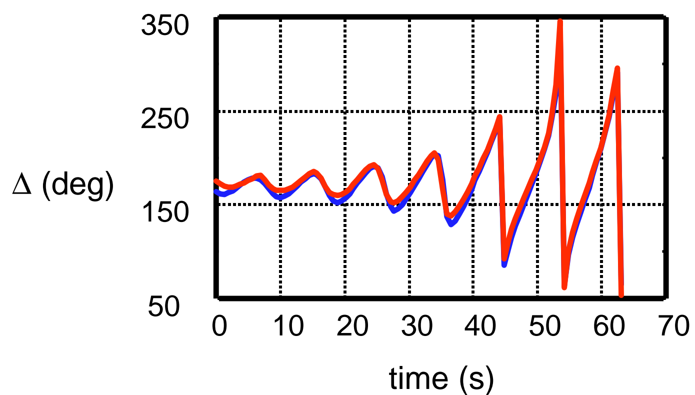
- In-Situ measurement of Ψ and Δ
- Four incident wavelengths (UV and visible ranges)
- Poly-Si/SiO_2/Si
- All the experiments were done at Bell Labs-Lucent Technologies
  - Galarza *et al.*

EXPERIMENTAL RESULTS

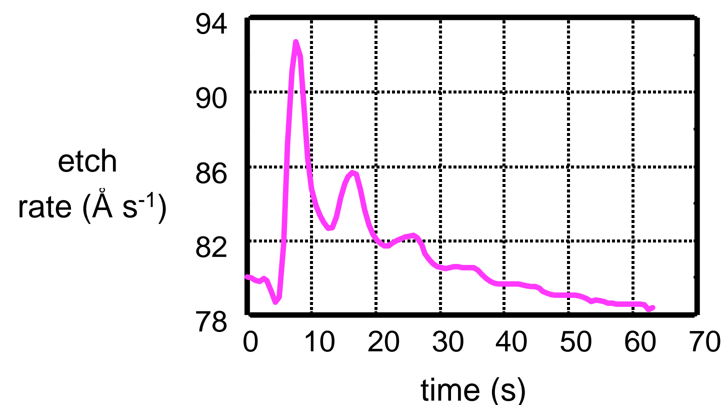
Output Estimation

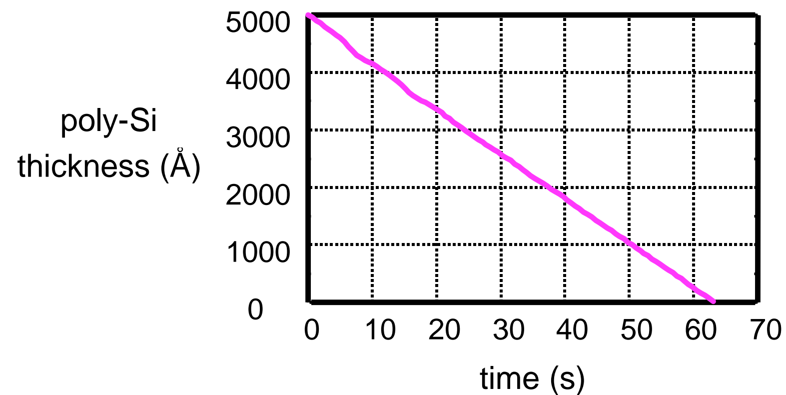






State Estimation





A NONLINEAR ESTIMATION PROBLEM

- Consider the system

$$\frac{dx}{dt} = Ax + Bu + Ew$$

$$\frac{dz}{dt} = Fz + Gu + Hw$$

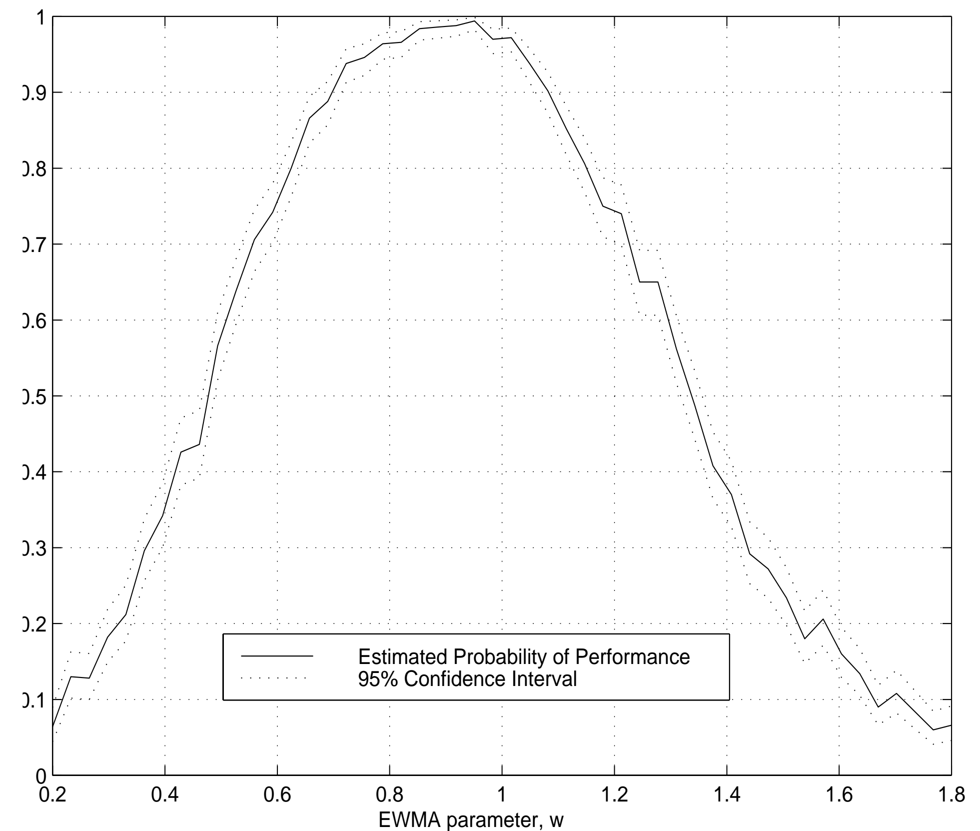
$$y = (I + diag(z))Cx + v$$

- z - slow sensor drift, u - known input, w, v noise
- Problem: estimate x (and z) given y
- A nonlinear filtering problem which captures a key part of the etch depth estimation problem
- A family of estimators for this problem that include EKF, IKF, etc. as special cases
  - » Also, a general stability result

Vincent & Khargonekar

STOCHASTIC APPROACH TO ROBUSTNESS OF RUN-TO-RUN CONTROL

- Regard the model parameters as random variables
  - Consistent with statistical I/ modeling
- Analytic formula for probability of stability for EWMA R-t-R controller
- General results on analys and design of R-t-R controllers
  - Hamby, Kabamba, and Khargonekar
- Ex: Kushner simulation a the controlled plant



CONCLUSIONS

- Advanced control and estimation problems for semiconductor manufacturing processes present many challenges
- Nonlinear estimation and filtering can be very useful in getting more out of existing sensors
  - Good physical models are crucial
- Need effective techniques for dealing with indirect process variables based control