Control of Spatial Uniformity in Microelectronics Manufacturing: An Integrated Approach

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Real-Time Feedback Control of Spatial Uniformity: Limitations

- Spatial uniformity sensors
- Plasma sensors
- Models
- Feedback control on-line computations

Objectives

- Overall
  - – Develop and experimentally implement an integrated methodology to *model*, *measure*, and *control* spatial uniformity in semiconductor processing
- This presentation
  - – Simulation study on real-time feedback control of plasma etching uniformity

Modeling

- Use Modular Plasma Reactor Simulator (MPRES)
- Develop control-oriented reduced-order models

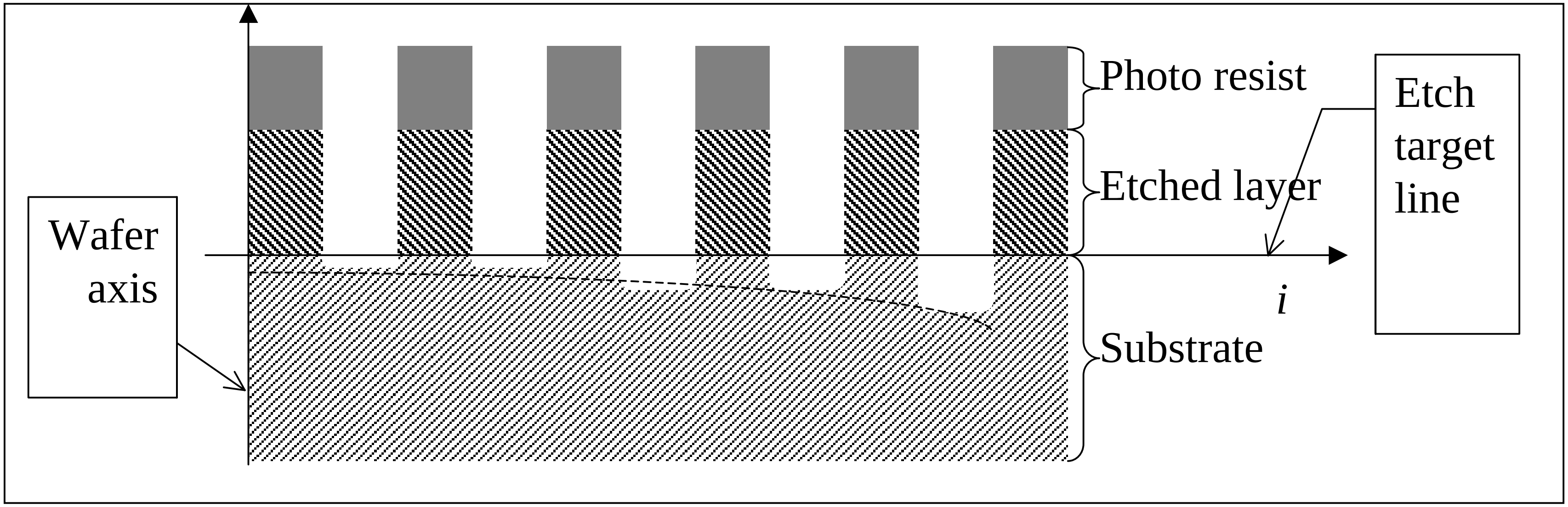
Sensors

- CCD interferometry camera (Leybold-Inficon, LES 1200)
- Need
  - Time resolution
  - Spatial resolution

Feedback Control

- Control strategy:
  - completion of the task within finite time
  - precise arrival at a final target
  - satisfaction of intermediate constraints
- Analogs:
  - Aircraft landing
  - Batch chemical reactor control

Feedback Control (Cont'd)



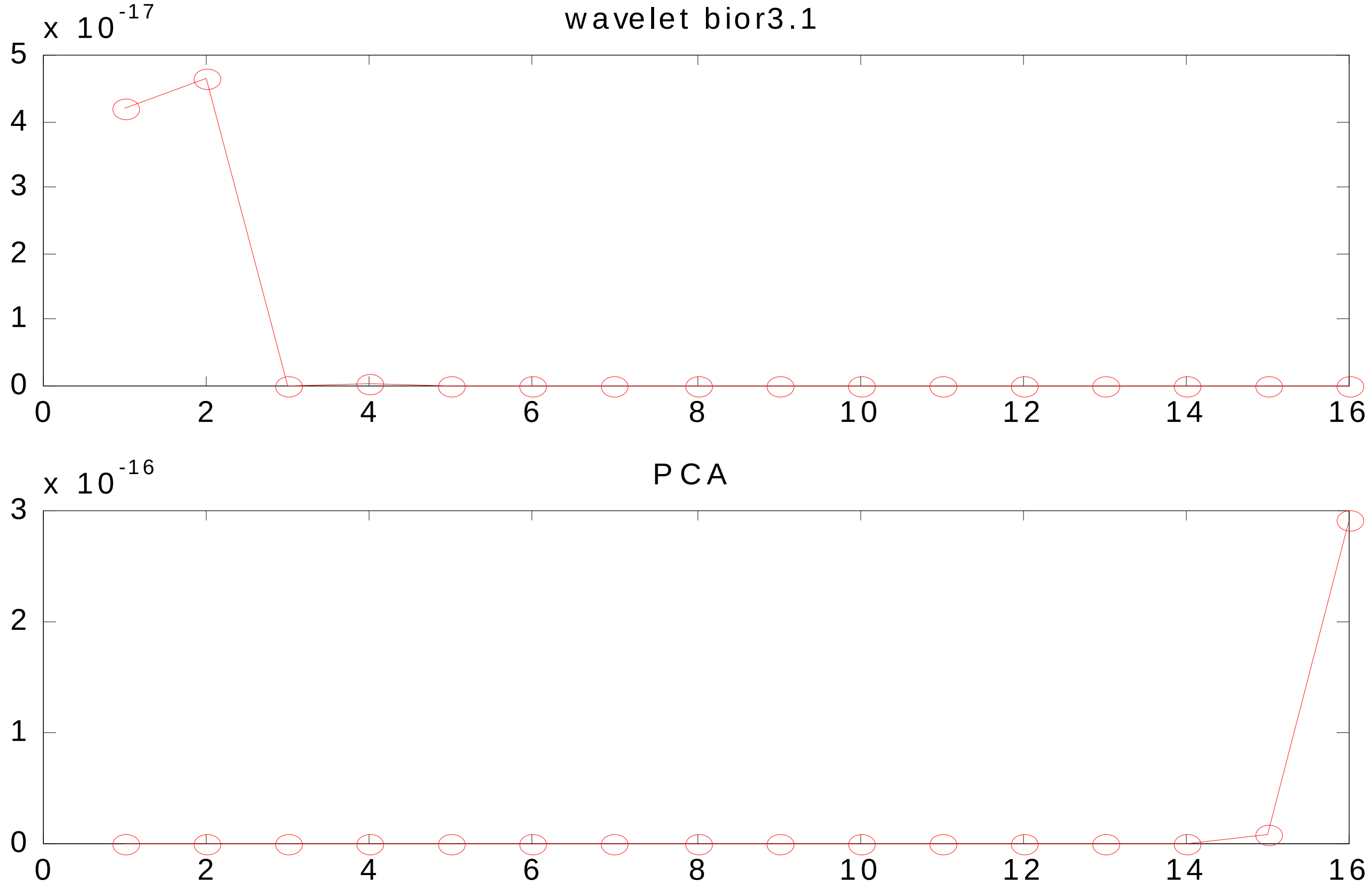
Case Study

- Chlorine etching of polysilicon
- Empirical model: $\text{output}_k = f(\text{input}_{k-1})$

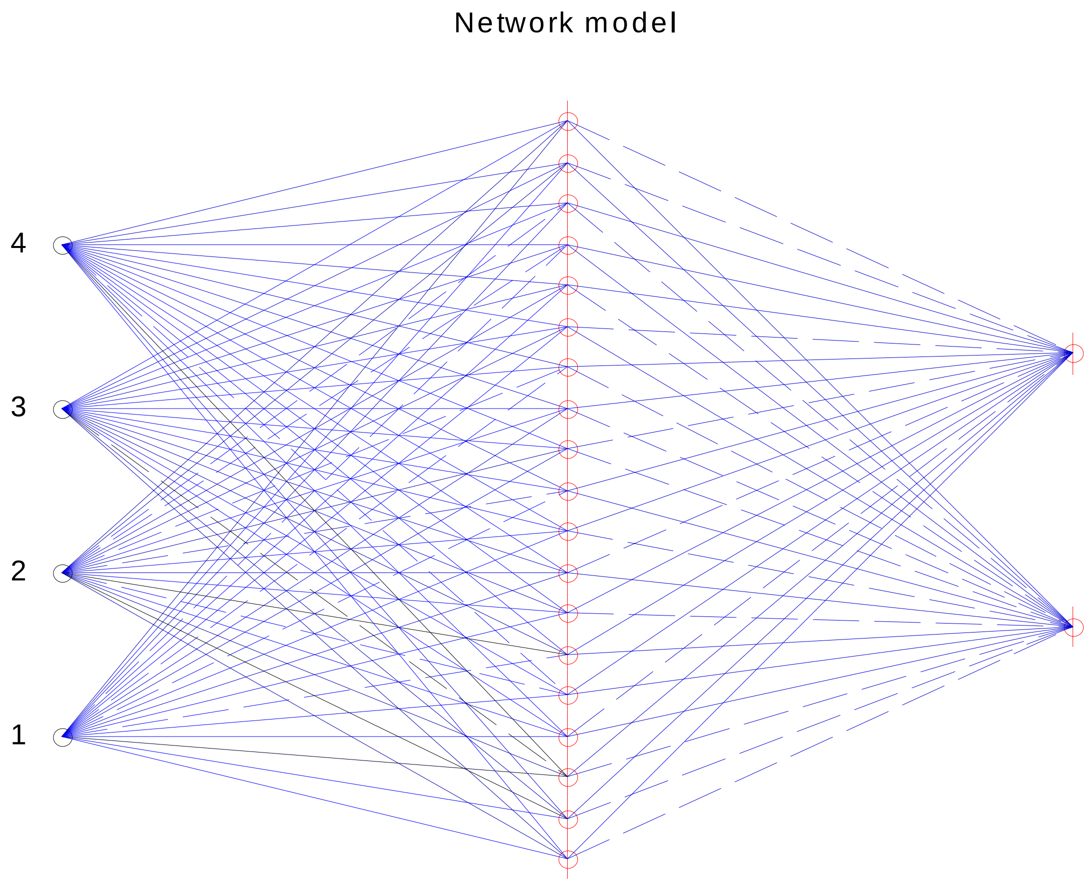
Model Reduction

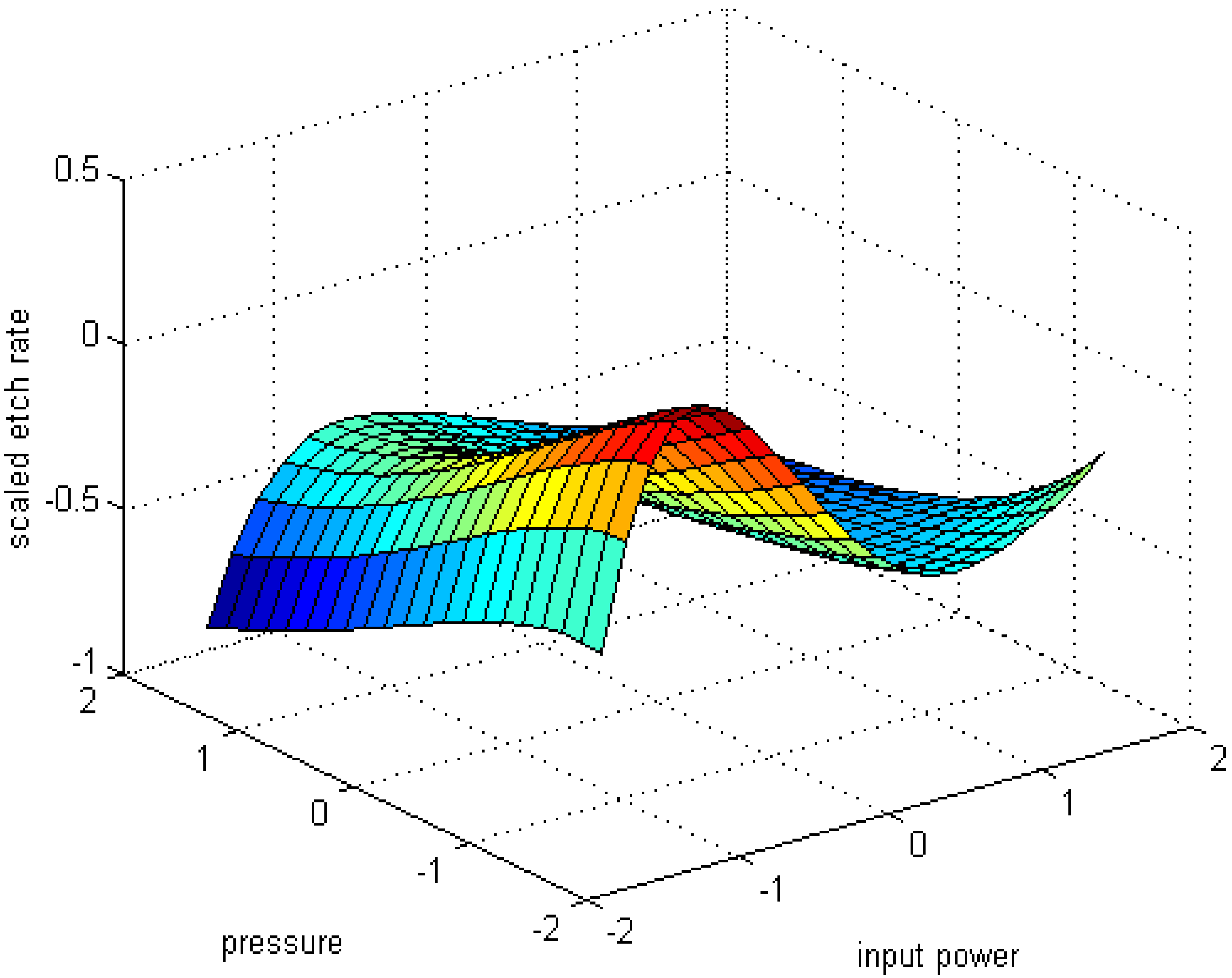
- The basic idea: $y=Mz\approx Mz_c$
- Examples:
  - Principal component regression
  - Wavelet compression

Model Reduction (Cont'd)

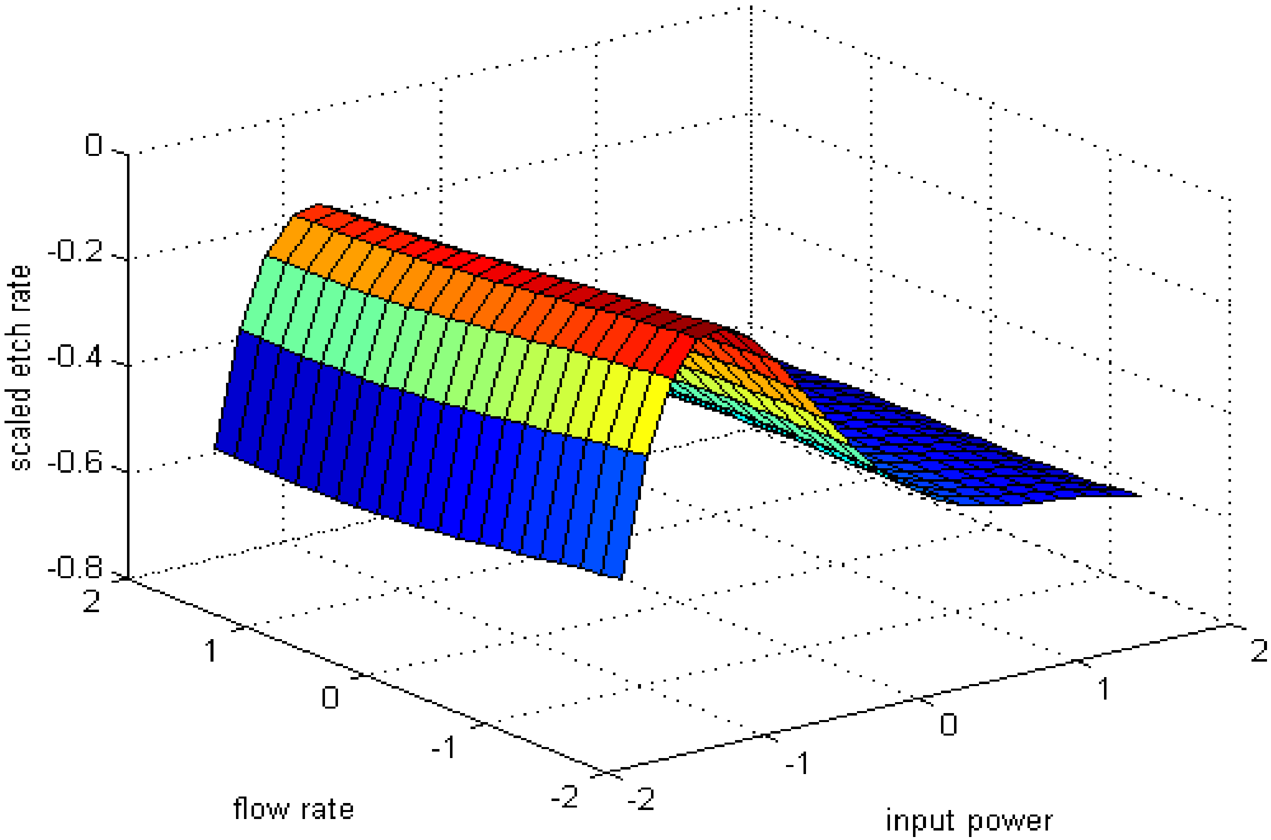


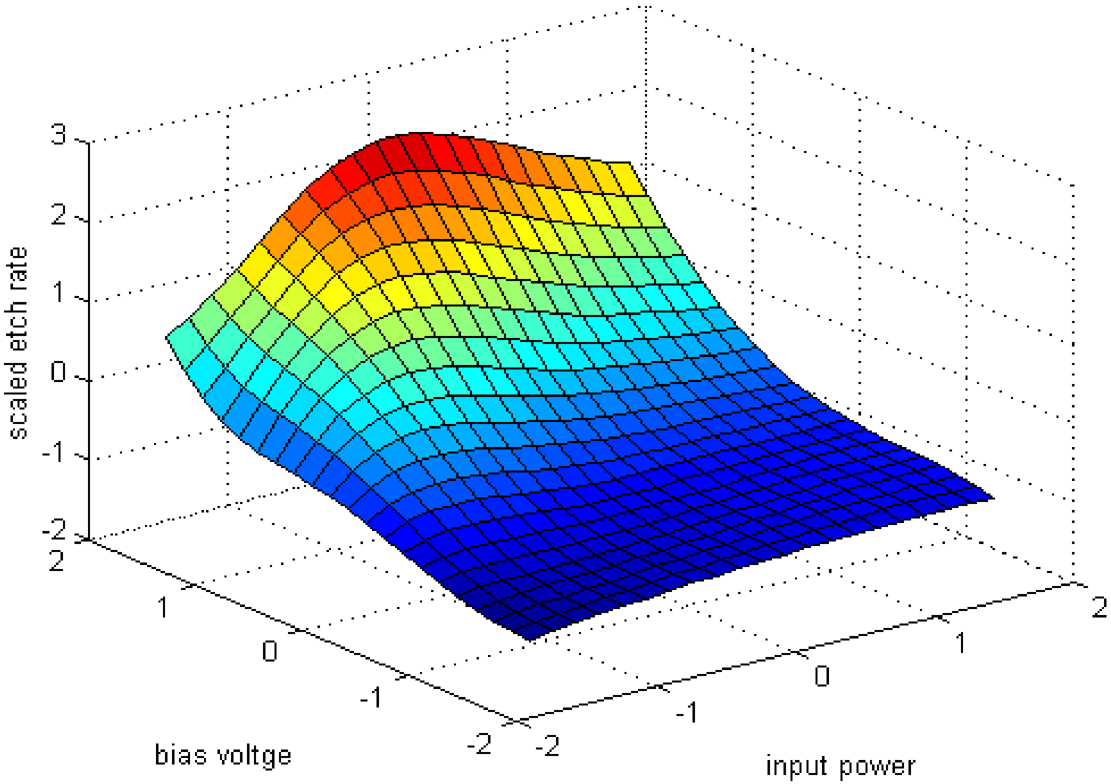
Reduced Model from First-Principles Model



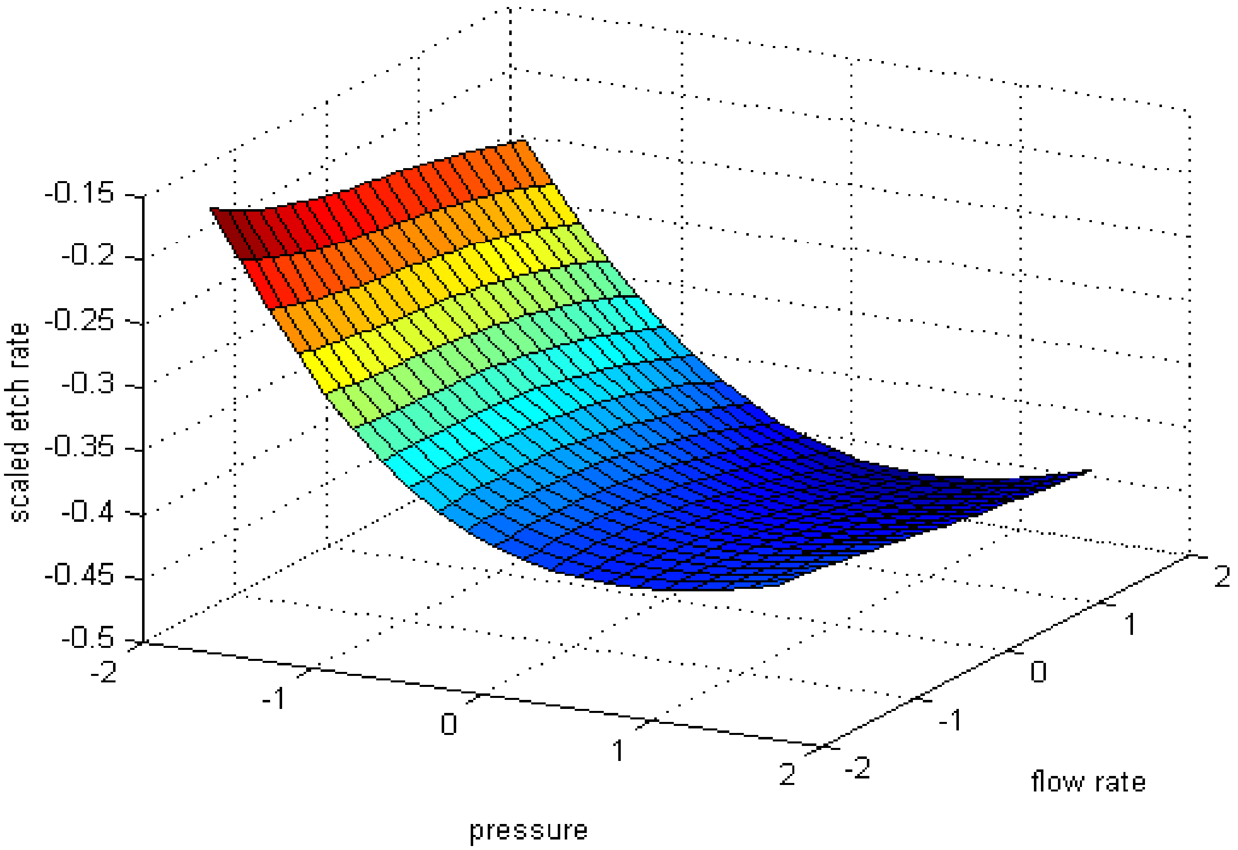


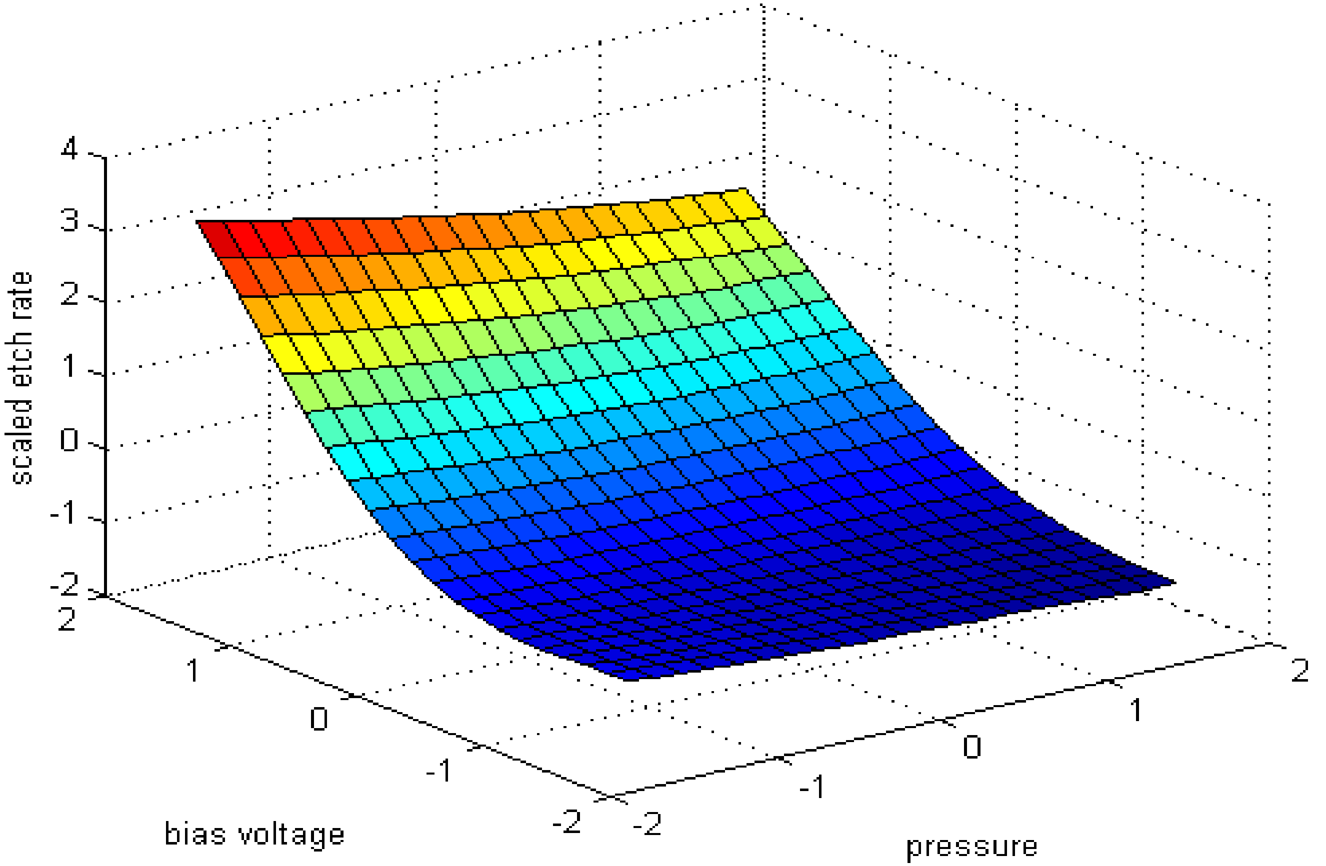
scaled etch rate
0.5
0
-0.5
-1
2
1
0
-1
-2
pressure
-2
-1
0
1
2
input power


0
-0.2
-0.4
-0.6
-0.8
scaled etch rate
2
1
0
-1
-2
flow rate
-2
-1
0
1
2
input power



3
2
1
0
-1
-2
scaled etch rate
2
1
0
-1
-2
bias voltge
-2
-1
0
1
2
input power


-0.15
-0.2
-0.25
-0.3
-0.35
-0.4
-0.45
-0.5
scaled etch rate
-2
-1
0
1
2
pressure
-2
-1
0
1
2
flow rate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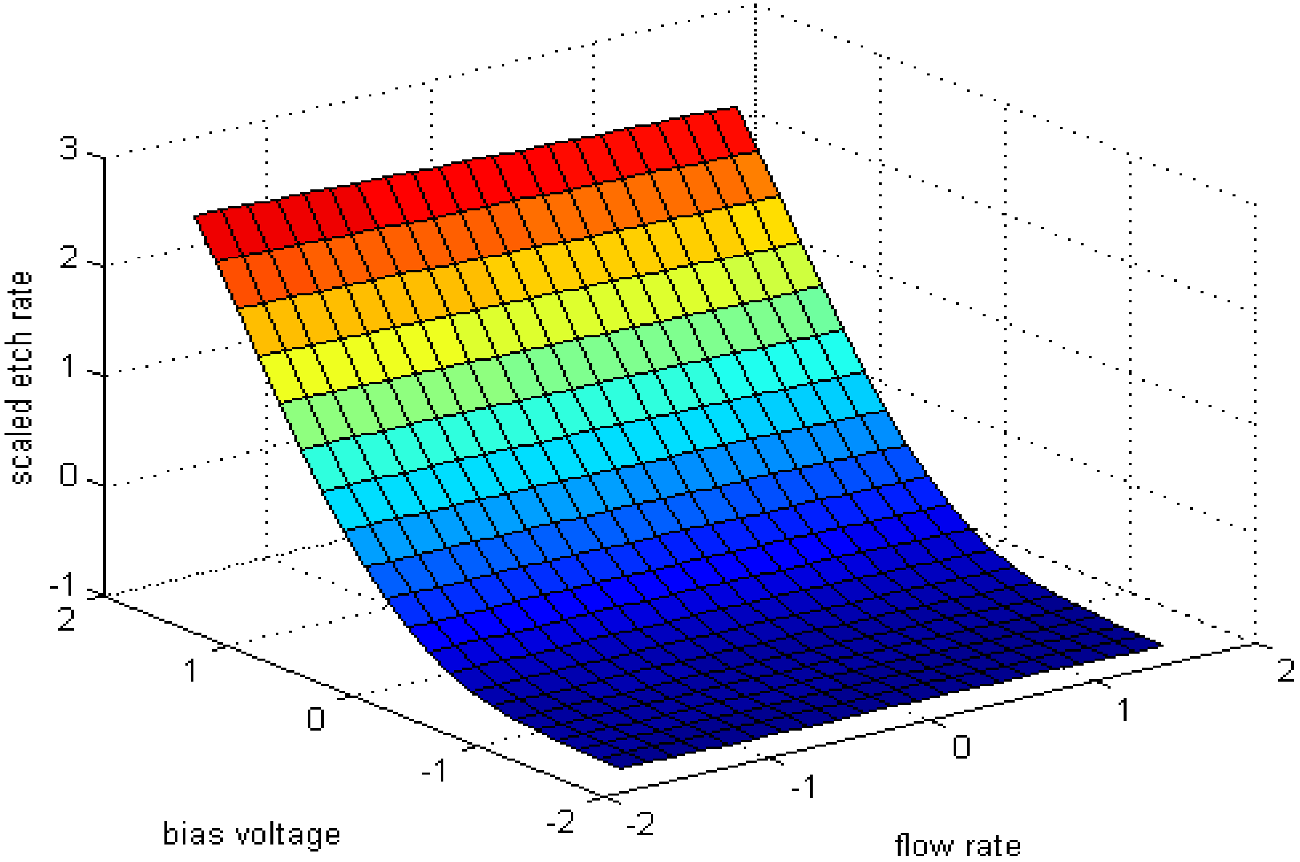
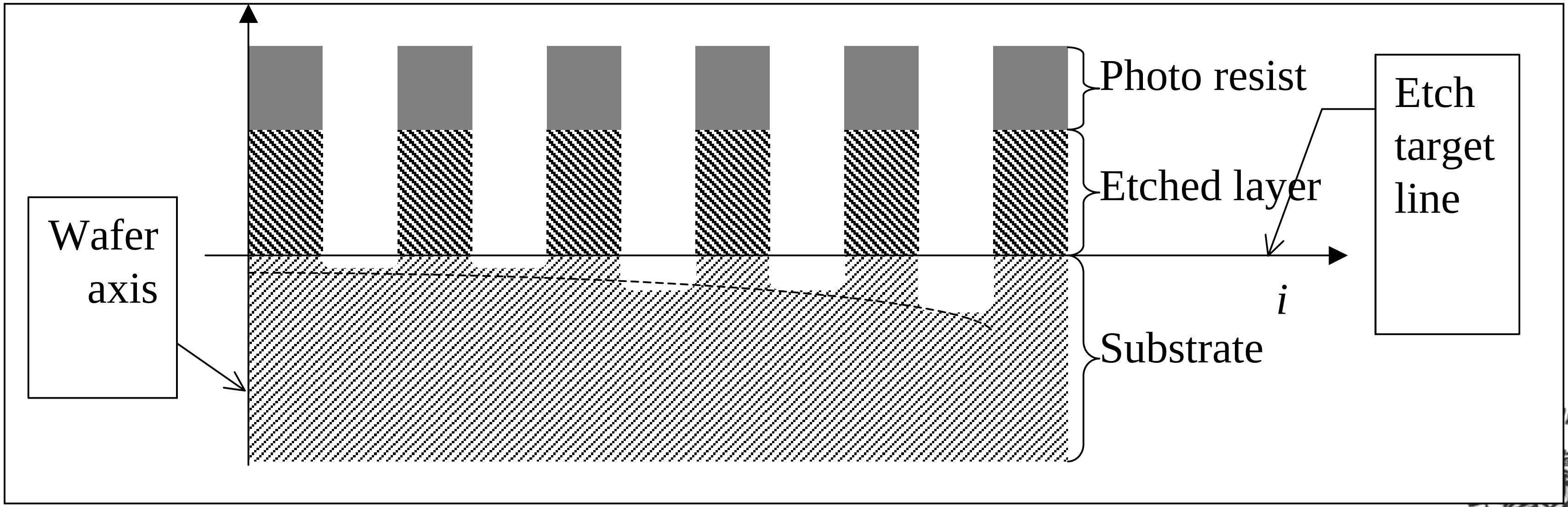
4
3
2
1
0
-1
-2
2
1
0
-1
-2
bias voltage
-2
-1
0
1
2
pressure


scaled etch rate
3
2
1
0
-1
2
1
0
-1
-2
bias voltage
-2
-1
0
1
2
flow rate

Control Objective

- At end of run, t_K
  - – Etch wafer completely: $y_i \leq 0$
  - – Minimize non-uniformity: $y_i \approx 0$



Feedback Strategy

- At each time step, t_k :

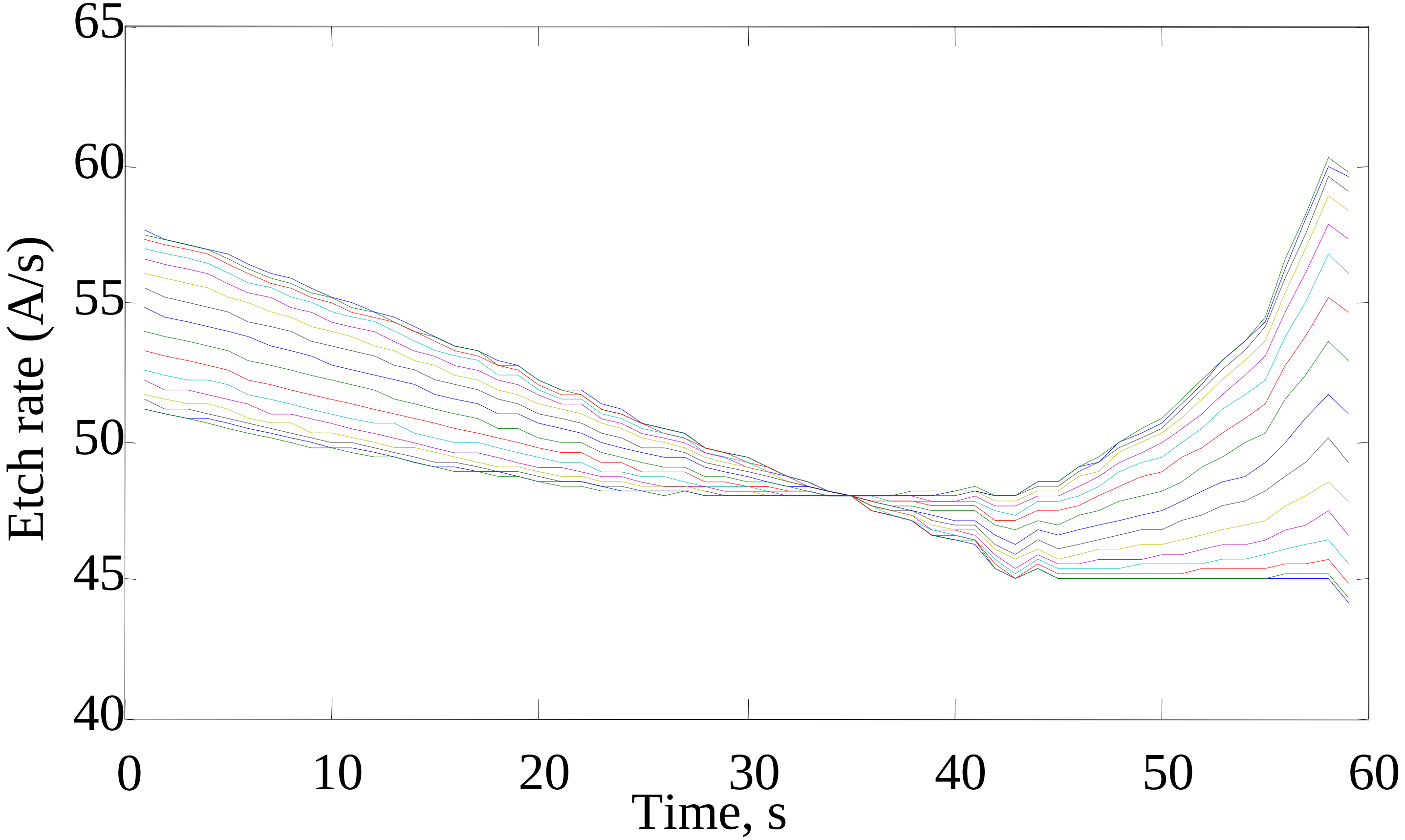
$$\underset{v(t_k),\cdots,v(t_{K-1}),t_K}{\text{minimize}} E\left[\sum_{i=1}^{N} |\hat{y}_i(t_K \mid t_k)|^p\right.^{1/p}$$

subject to

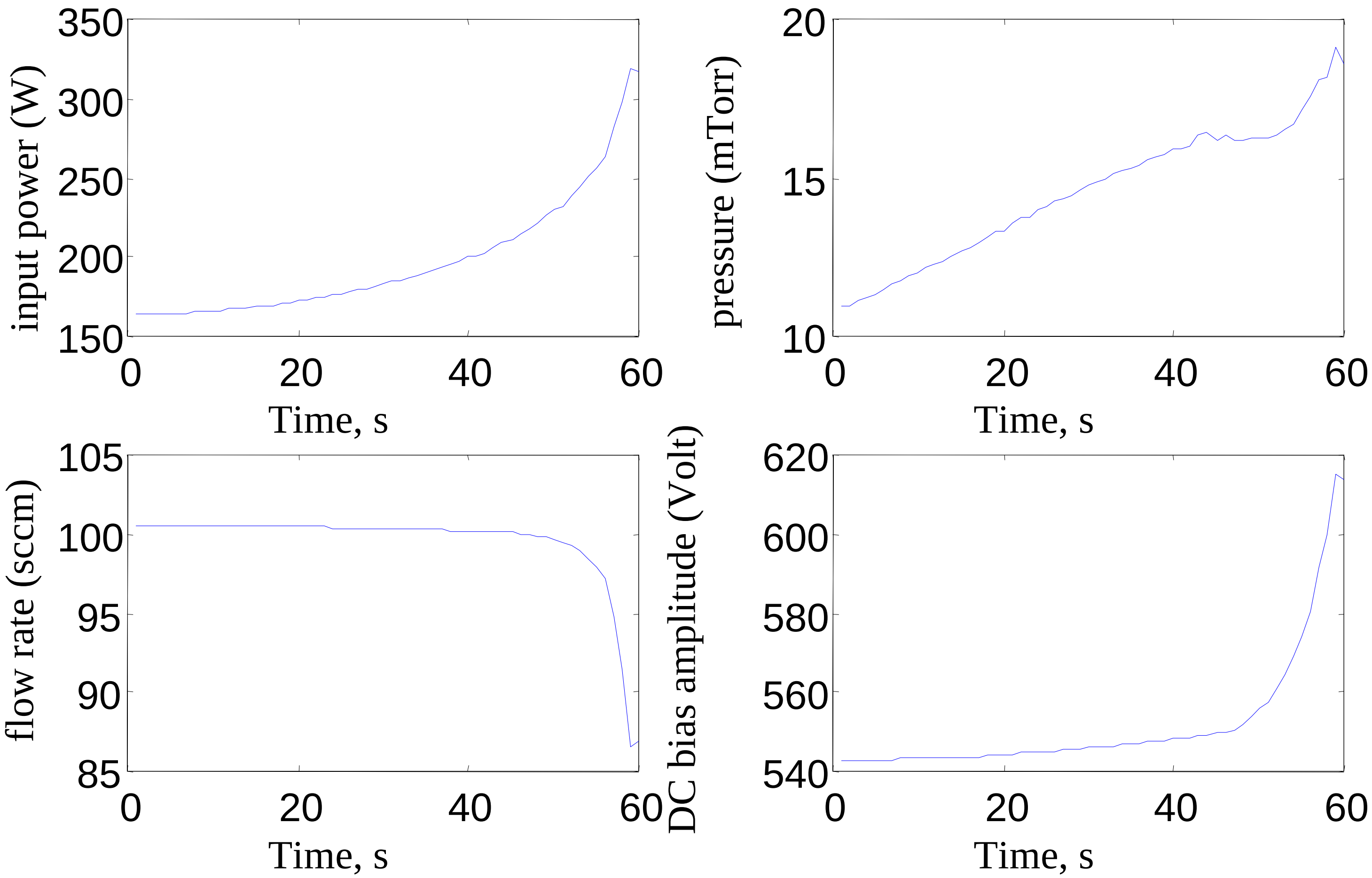
$$P[\hat{y}_i(t_K \mid t_k) \le 0] \ge 1-\alpha \qquad t_{K_{\min}} \le t_K \le t_{K_{\max}}$$

$$u_{\min} \le v(t_j) \le u_{\max} \qquad i = 1,2,\ldots,N$$

Results

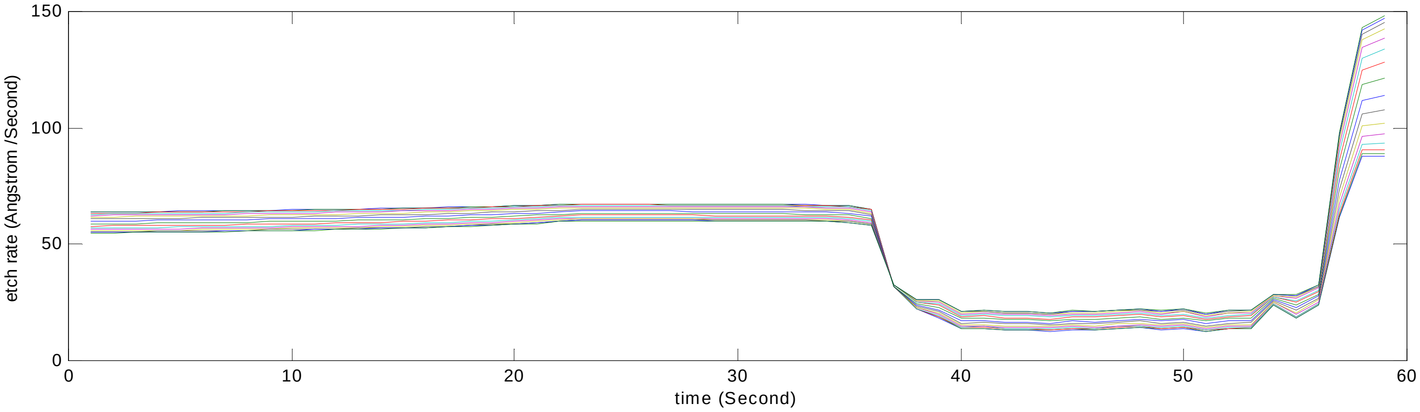


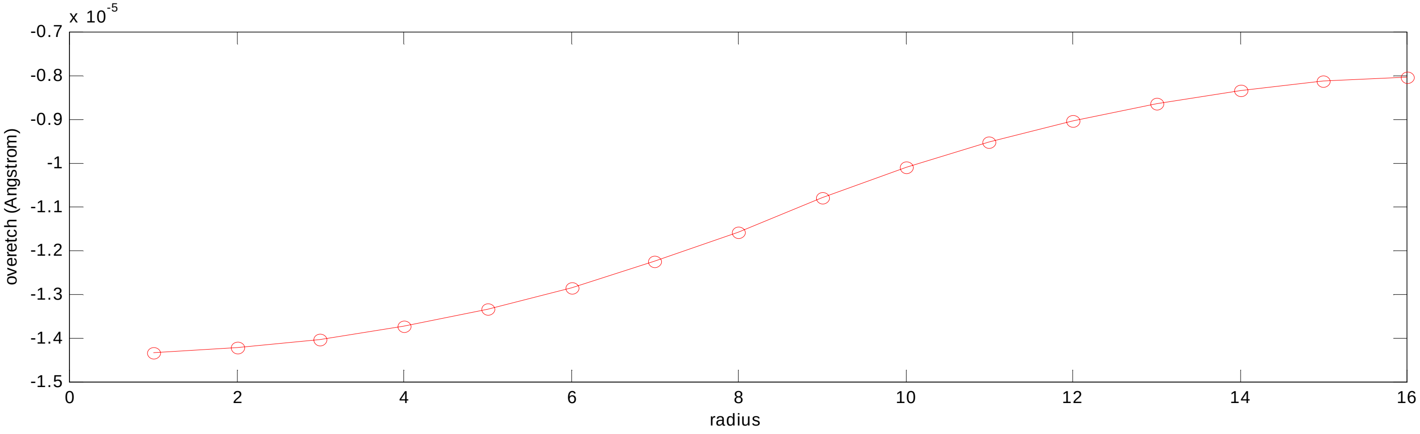
Results (Cont'd)



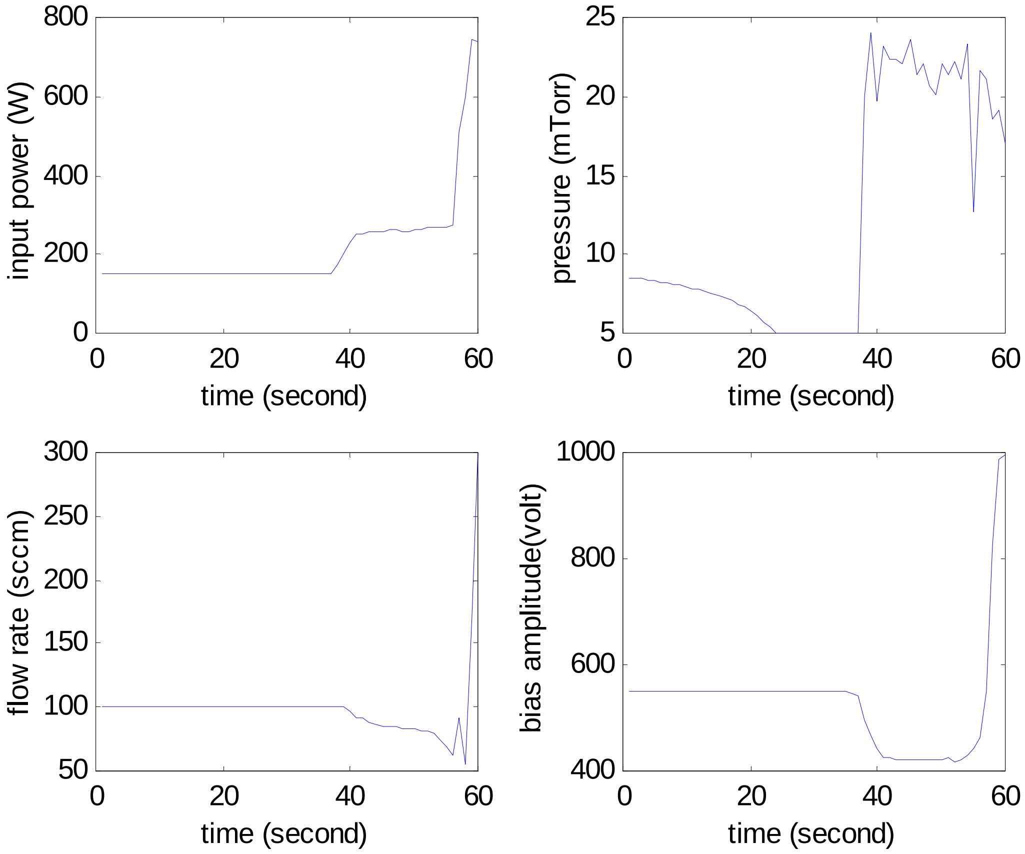
Results (Cont'd)

No noise and no input move/output constraints

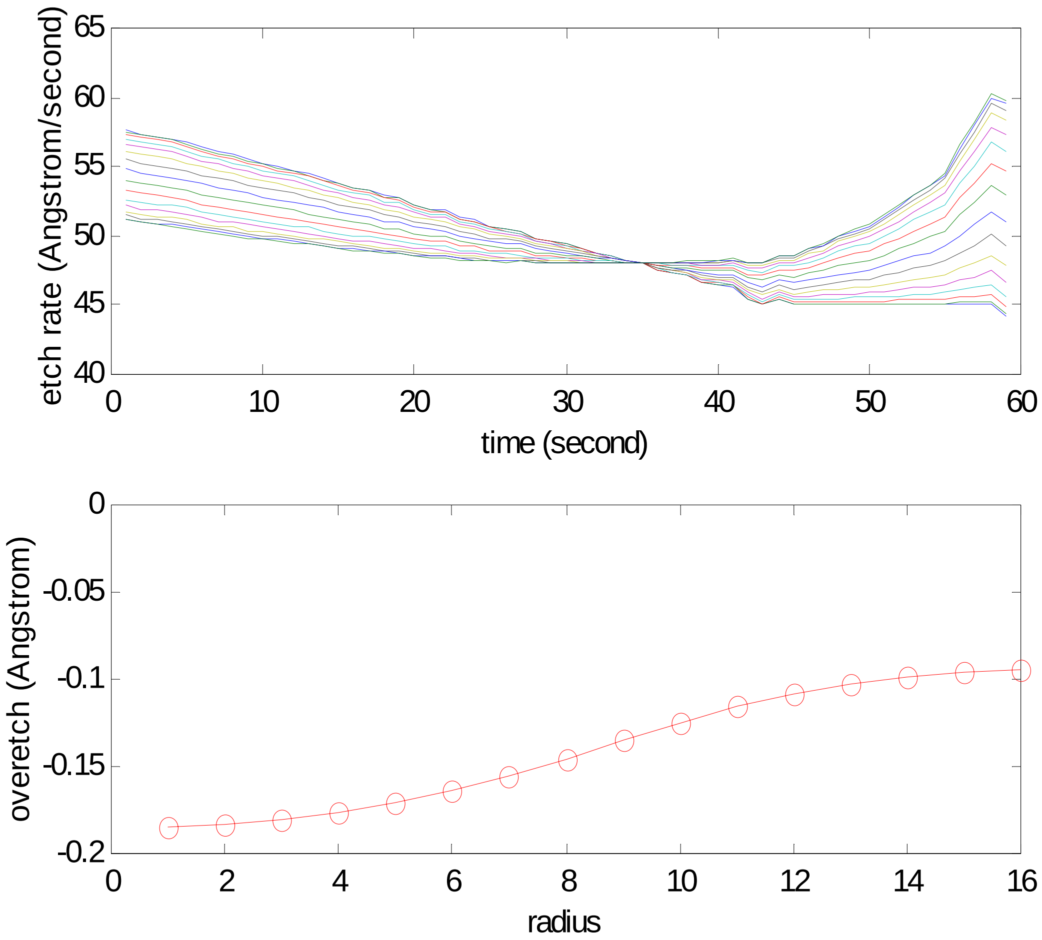




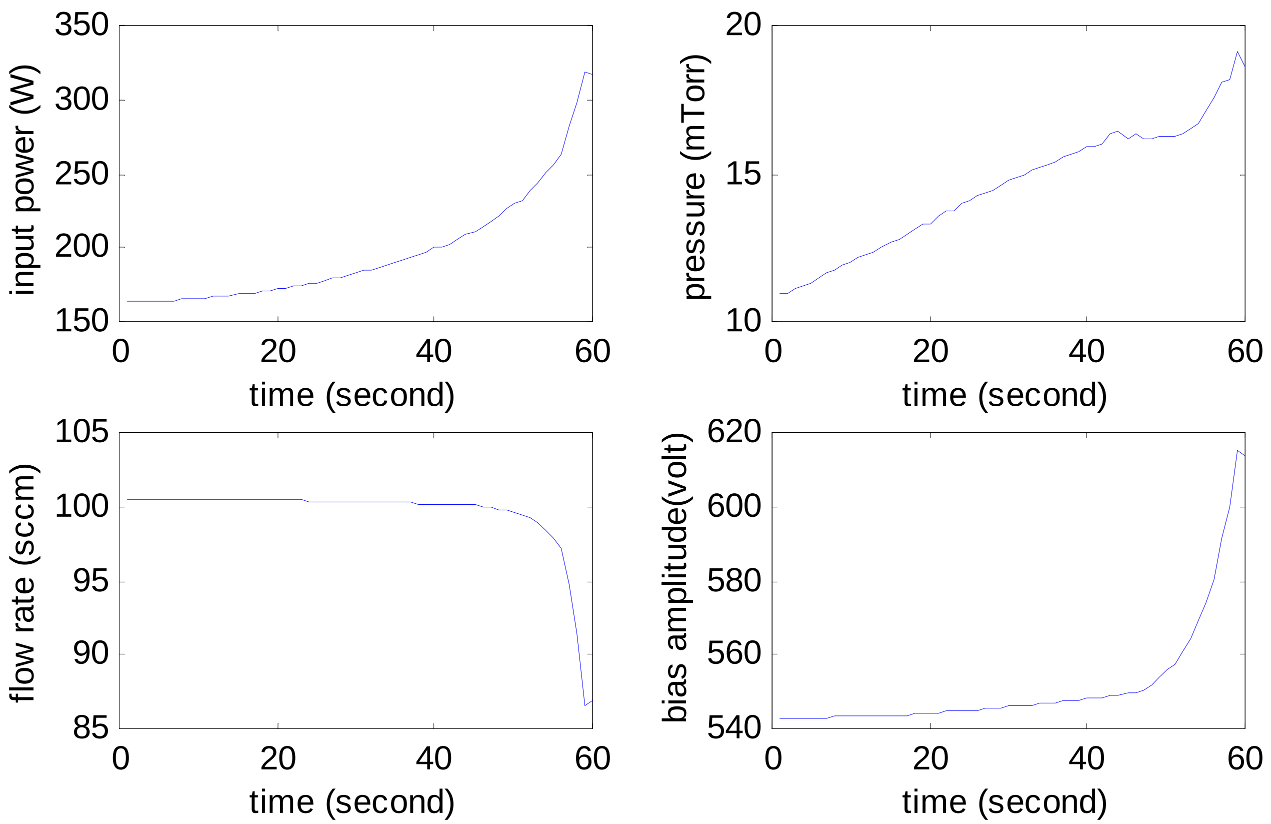
Results (Cont’d)

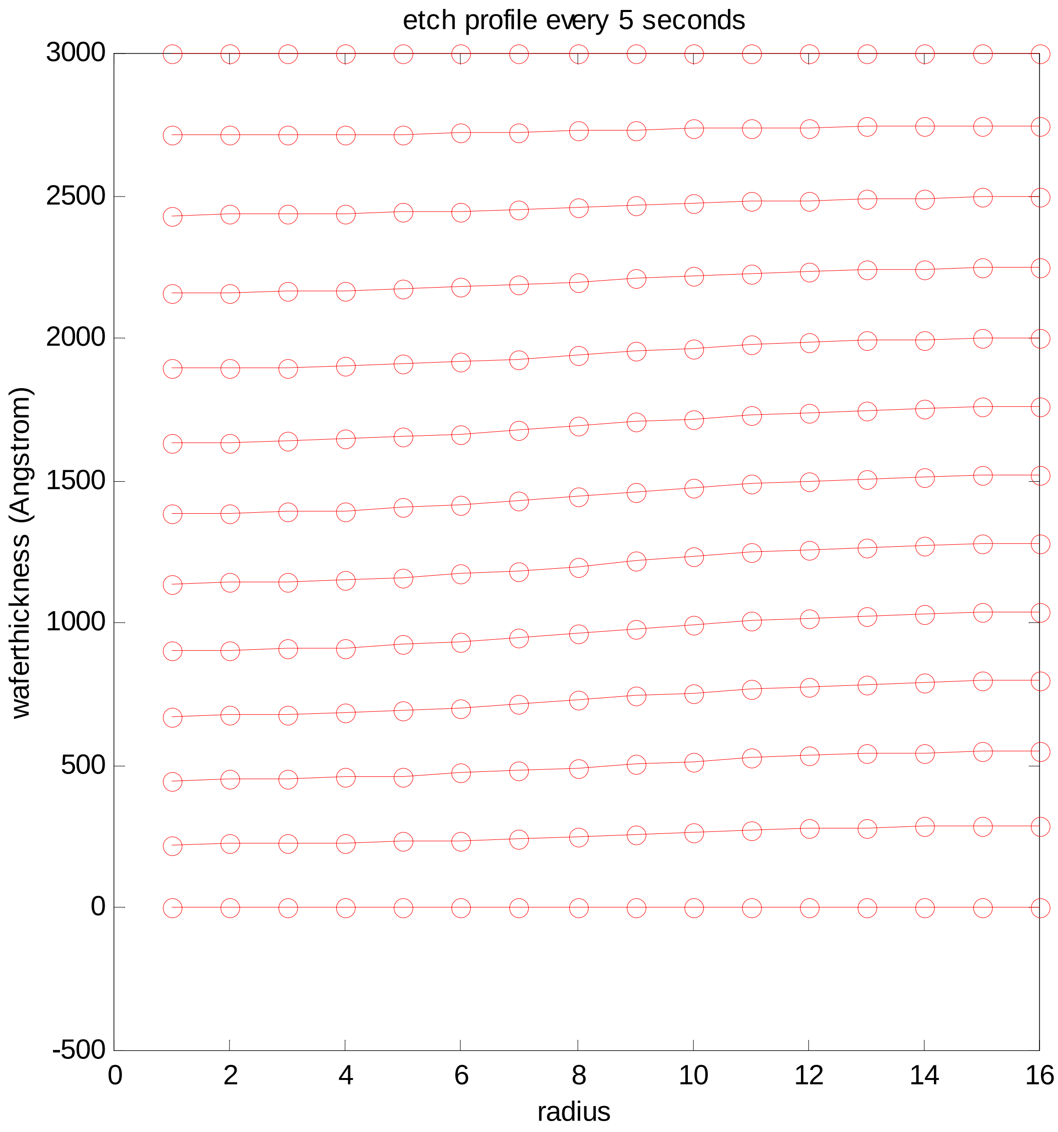


Input move [20 1 30 40]; etch rate constraint [45 to65];noise case



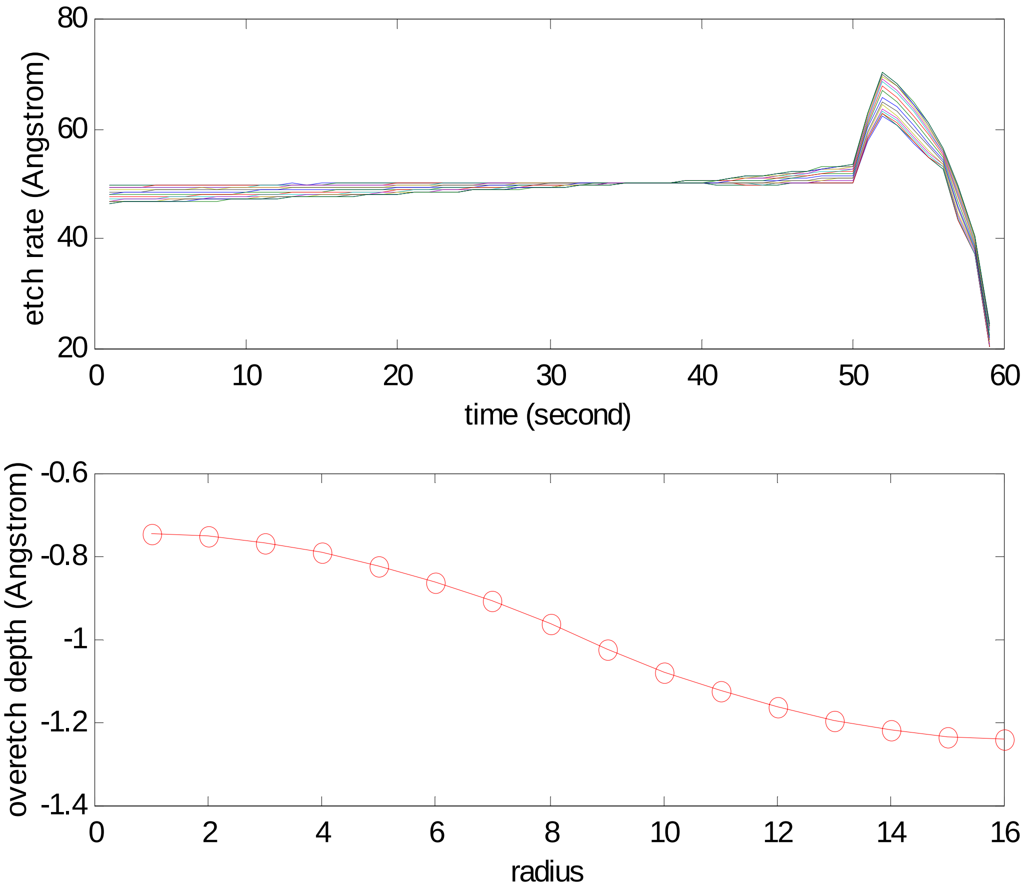
Results (Cont’d)



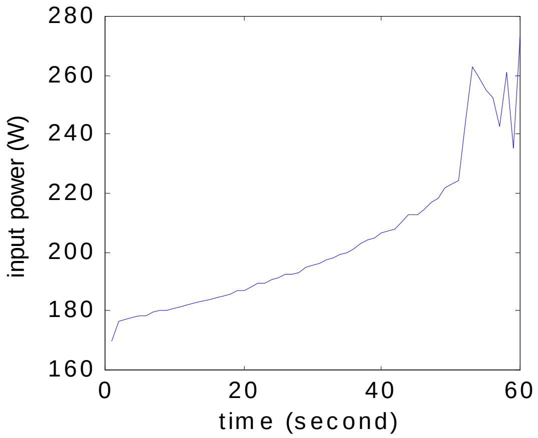

etch profile every 5 seconds
3000
2500
2000
1500
1000
500
0
-500
waferthickness (Angstrom)
0
2
4
6
8
10
12
14
16
radius

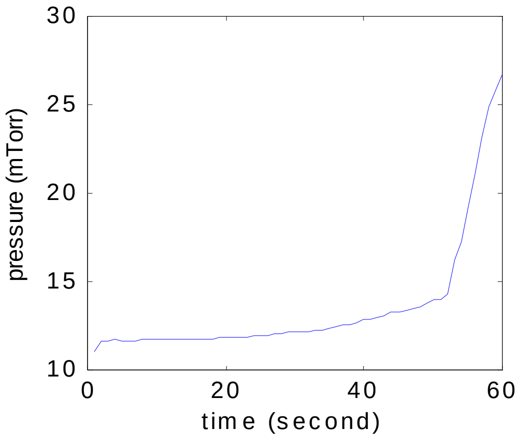
Input move [20 1 30 40];etch rate [10 80]; noise case

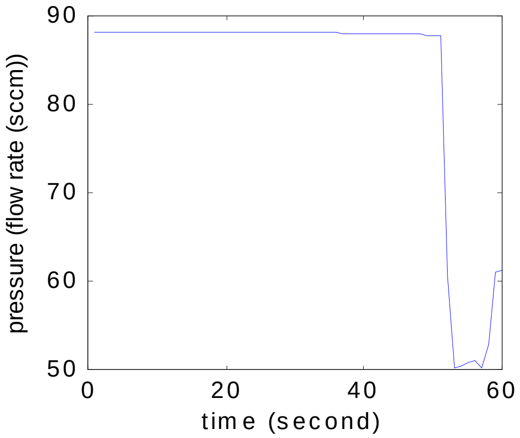
ERpediction/ERreal =0.8

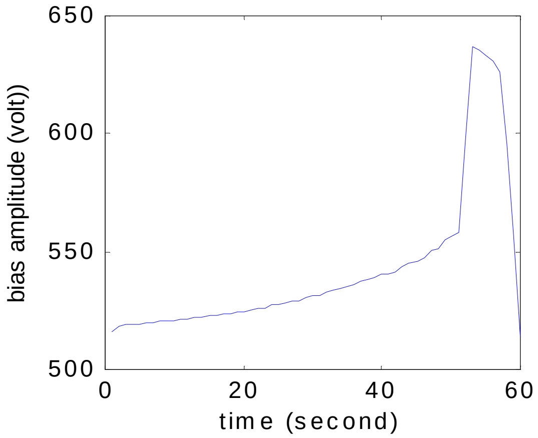


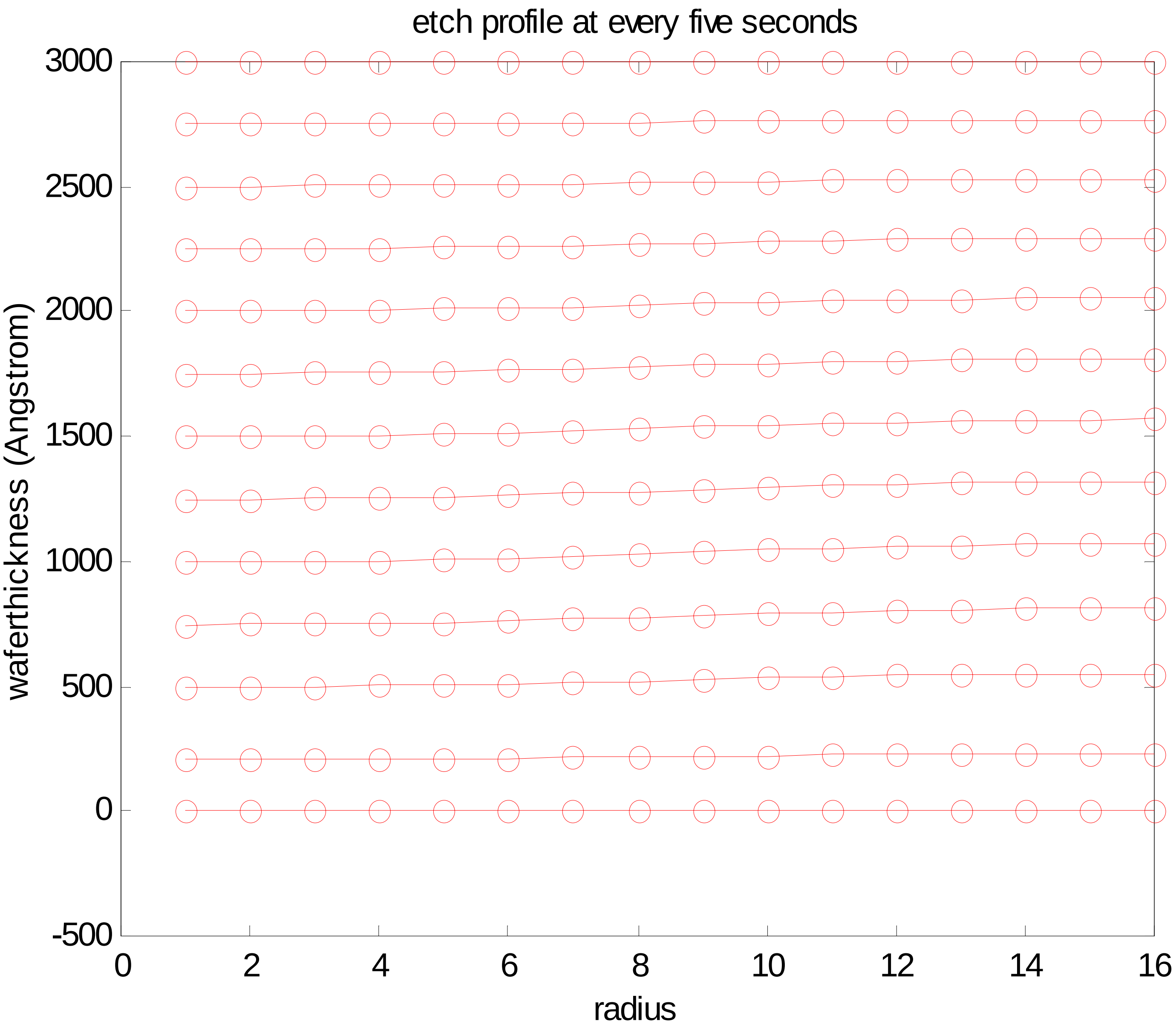
Results (Cont'd)



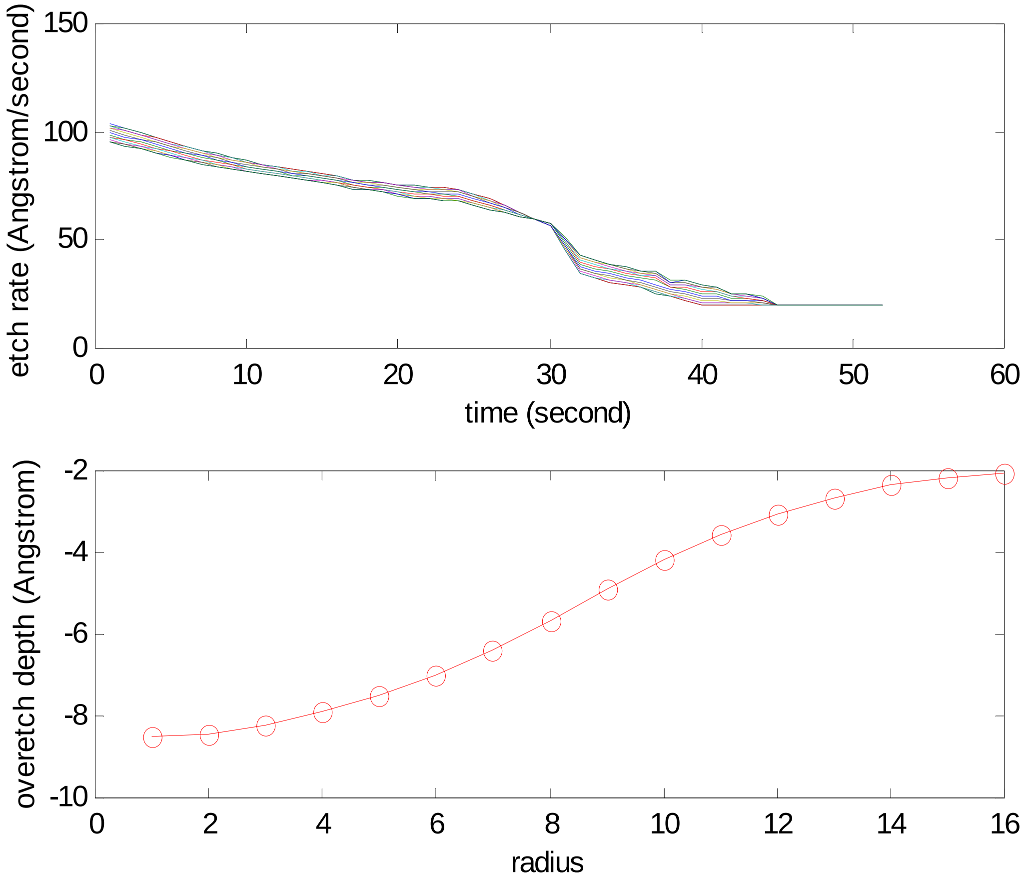




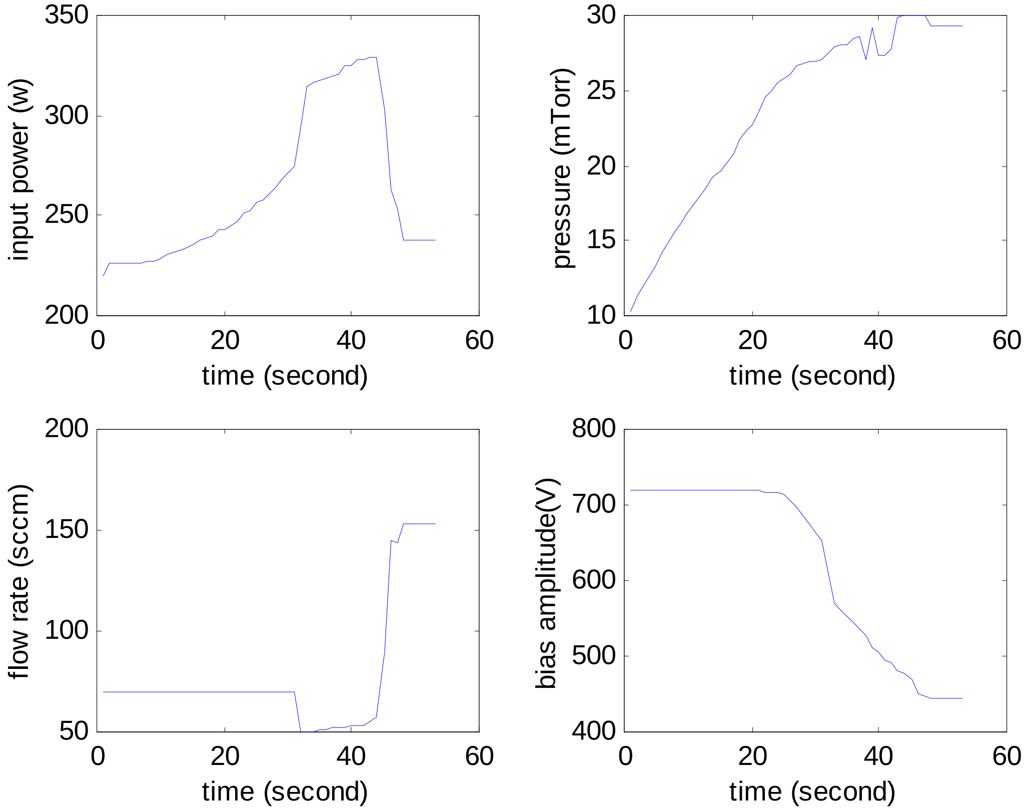


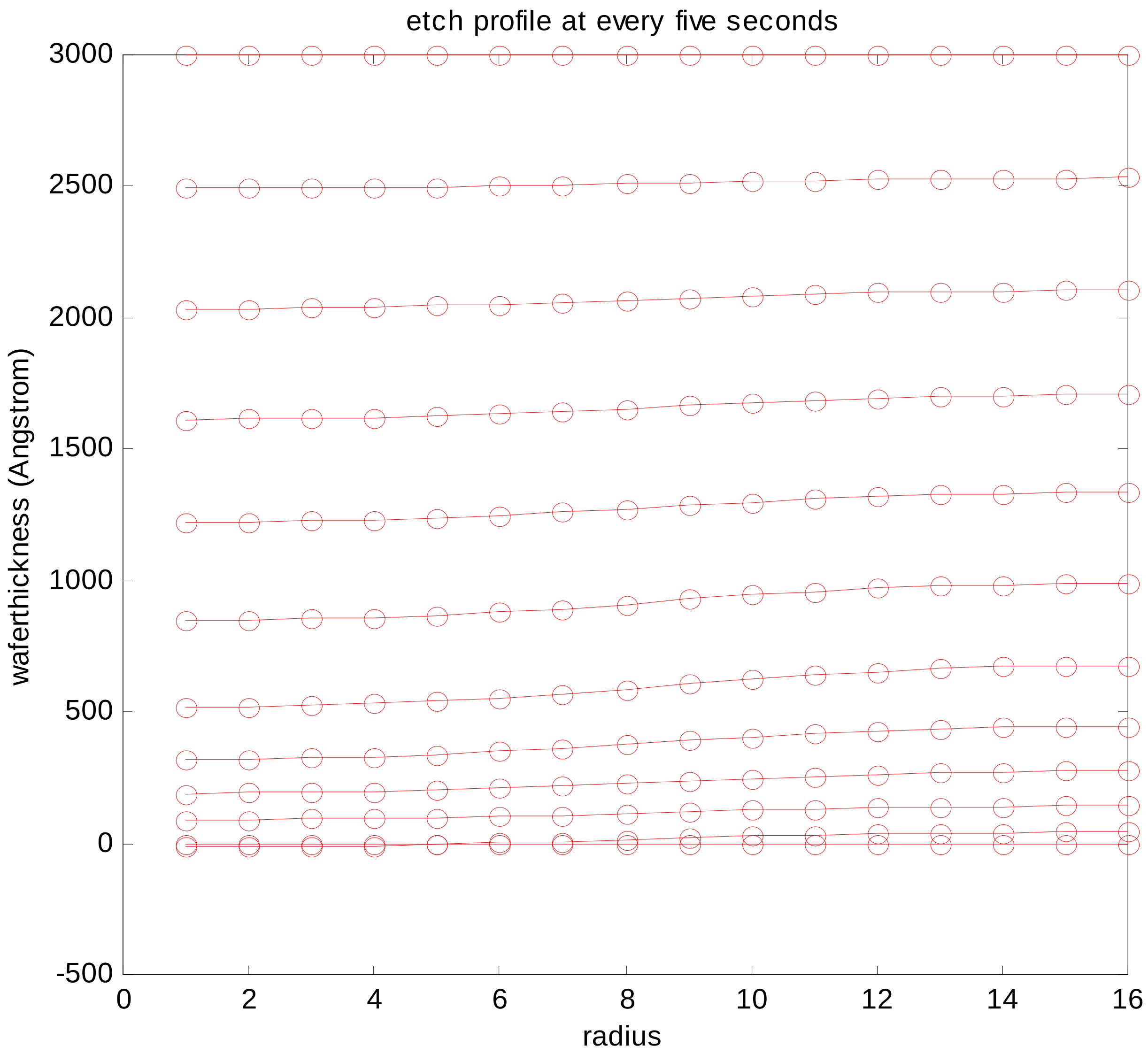

etch profile at every five seconds
waferthickness (Angstrom)
3000
2500
2000
1500
1000
500
0
-500
0
2
4
6
8
10
12
14
16
radius

Input move [20 1 30 40];etch rate [10 80]; noise case ERp/ERr =0.5; the whole etch done in 53 seconds



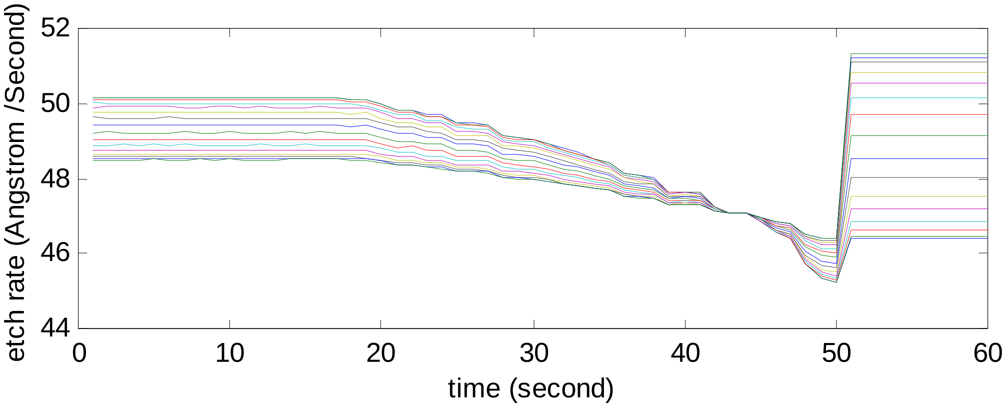
Results (Cont'd)

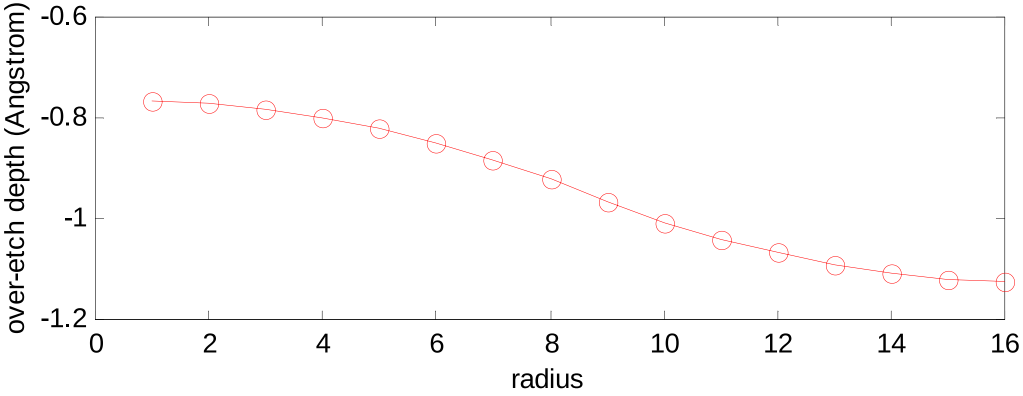



etch profile at every five seconds
3000
2500
2000
1500
1000
500
0
-500
waferthickness (Angstrom)
0
2
4
6
8
10
12
14
16
radius

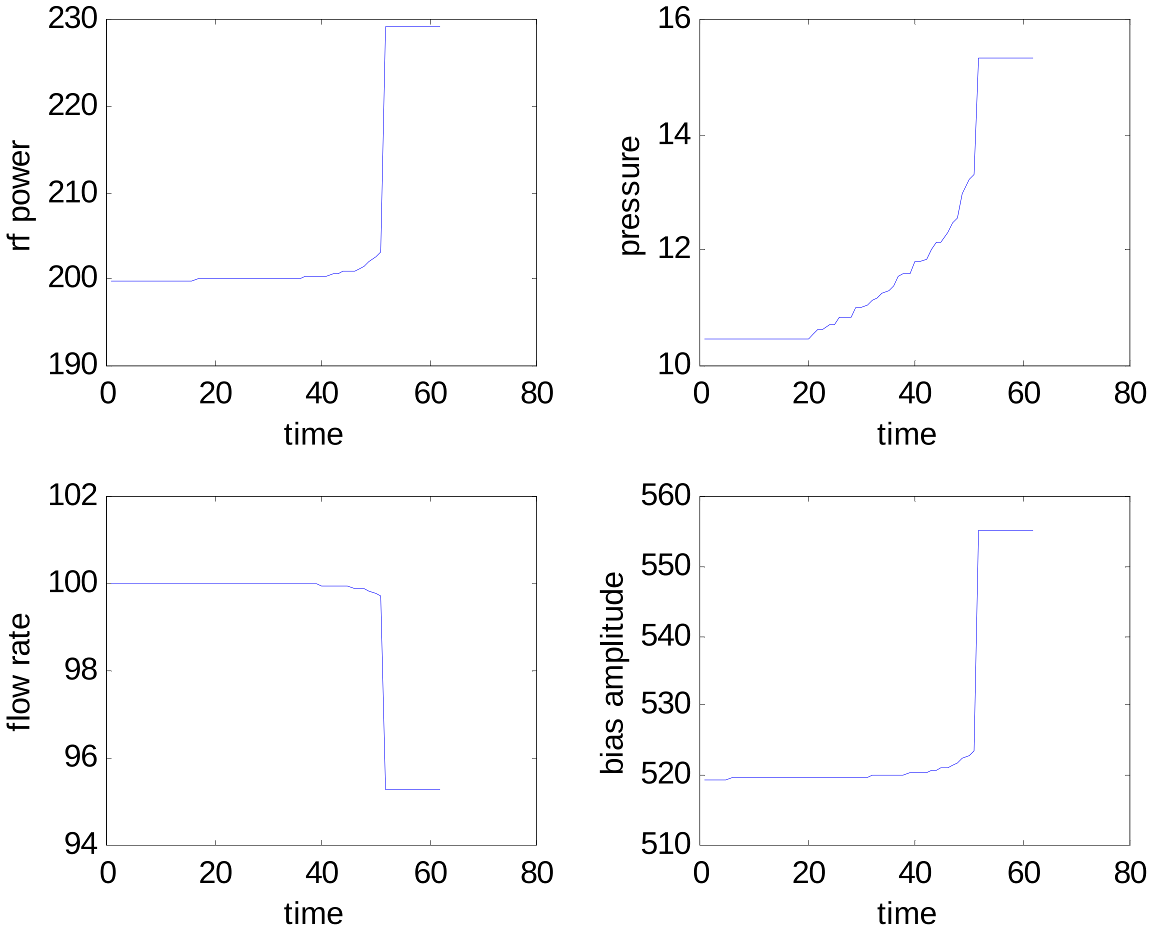
Input move [20 1 30 40];etch rate [10 80]; noise case

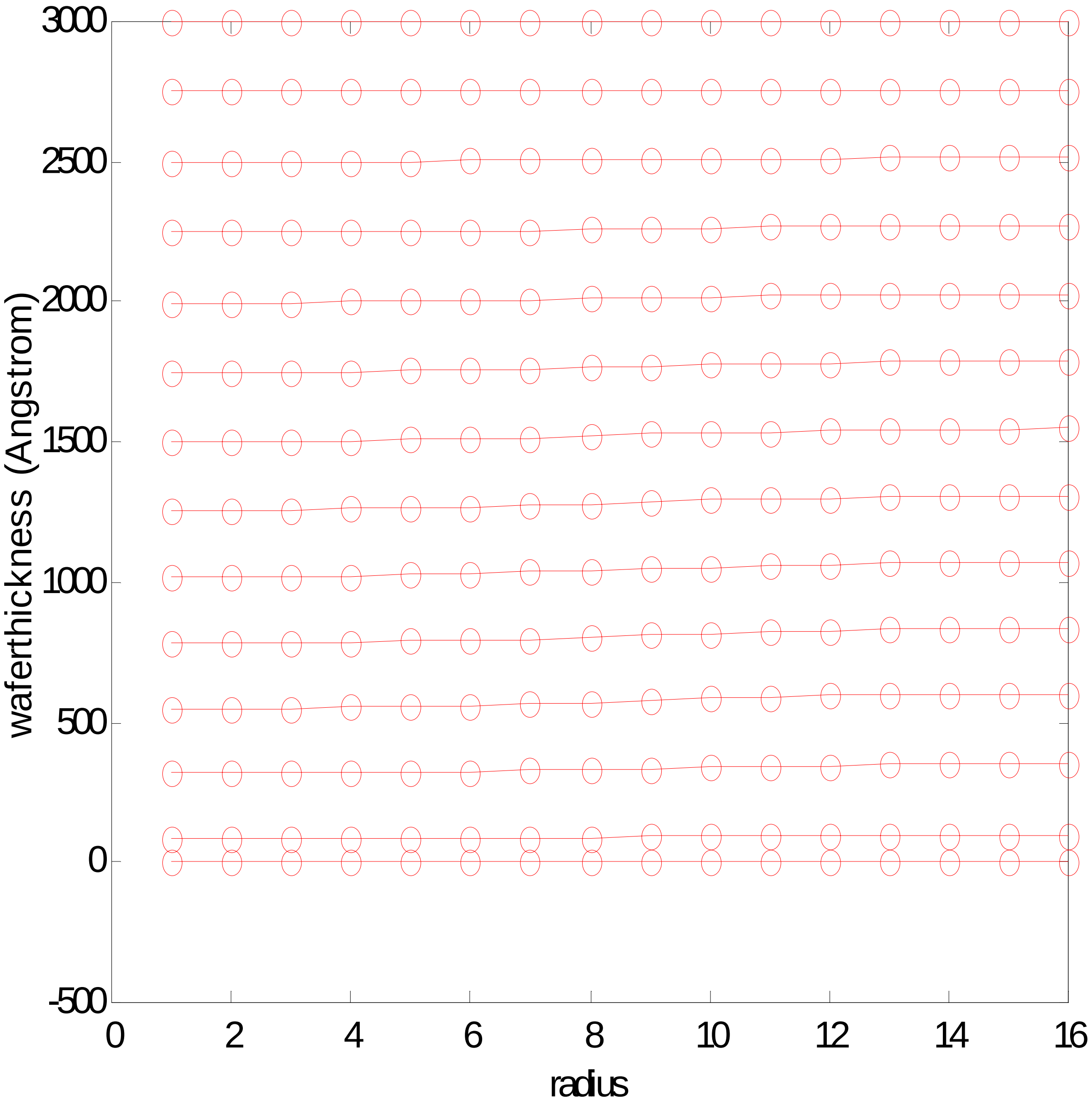
ERprediction/ERreal =1.2; the whole etch done in 62 seconds





Results (Cont'd)




3000
2500
2000
1500
1000
500
0
-500
waferthickness (Angstrom)
0
2
4
6
8
10
12
14
16
radius

Conclusions

- Real-time control of uniformity: Integrated approach
- Model, sensor, control
- Feedback control: Batch process approach

Future Work

- Experimental validation of proposed approach
- Refinement of control strategy:
  - Model
  - Sensor
  - Control

Acknowledgments

- Prof. D. Economou
- Applied Materials