In-chamber and on-wafer sensors

A Paradigm Shift

Overview

- Exact chamber environment control is relatively new
- Various sensors (pressure, gas flow, gas composition, temperature) are needed to accomplish it.
- An interesting transition to “on-wafer” sensors holds much promise...

Thermocouples

- operating principle

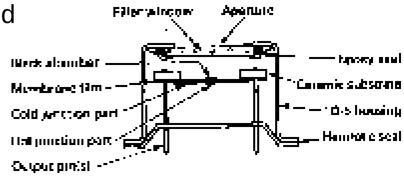
  Peltier-Seebeck effect, up to *3000^o C*

  T gradient along wires of different materials develop different emf

  emf measures junction *T*

  platinum rhodium alloy, or silicon based

  sensitivity *100-200μV /^{o}K*



- problems

  big problems with shield design

  radiative effects

  low signal -- need amplifiers or use thermopile

  invasive

  gas *T* measurement is very hard, especially < 10^{-4} torr

- comments

  inexpensive, low drift

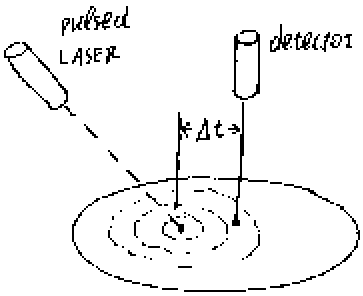
  accuracy ~+/- 5^o*C* at 800^o*C*

  low bandwidth

  where do you want to measure *T* ?

Acoustic Wave sensors

- operating principle
  - acoustic wave is transmitted through body
  - surface and internal waves propagate through body at *T* dependent speed
  - interference with source gives beats
  - beat frequency determines *T*
- issues
  - implementation difficulty
  - invasive
  - calibration



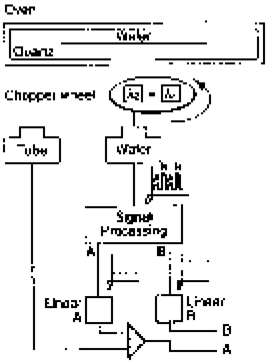
Pyrometry

- operating principle
  - hot objects radiate
  - radiation is wavelength dependent
  - radiation model for black bodies (Planck's Law)

$$R_l = \frac{37418}{l^5 (e^{14388/lT} - 1)}$$

λ in microns, T in ^oK, R_λ

  - for non-black bodies need to account for *emissivity*
- issues
  - surface properties affect radiation
  - multiple internal reflections
  - emissivity is wavelength and geometry dependent
  - can change during processing
  - calibrations via thermocouples, difficult

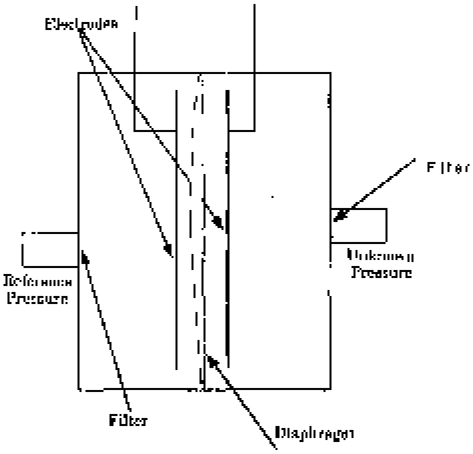


Pressure Sensors

- direct gauges
  - displacement of a solid or liquid surface
  - capacitance manometer, McLeod pressure transducer
- indirect gauges
  - measurement of a gas related property
  - momentum transfer, charge generation
- huge range of available sensors
  - cost
  - sensitivity
  - range

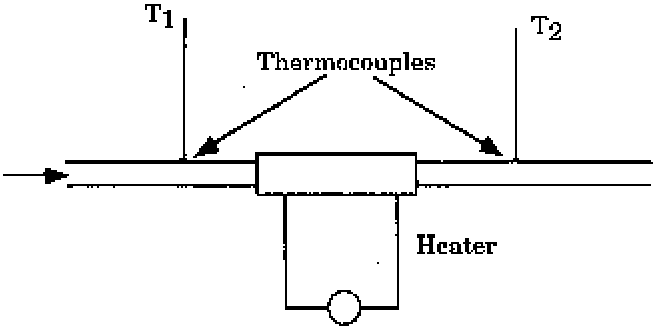
Capacitance manometer

- basic idea
  - pressure differential causes displacement of diaphragm
  - sense capacitance change between diaphragm and fixed electrode
  - resolution 10^{-2} % at 2 hertz and 10^{-3} torr



Gas flow meters

- differential pressure meters
- thermal mass flow meters
  - mass flow = $K / (T_1 - T_2)$
  - K depends on specific heat of gas etc.
  - must be calibrated for different gases
  - accuracy ~ 1 sccm at flows of 40 sccm
  - low bandwidth because of thermal inertia



Mass Spectrometers

- two types
  - – flux analyzers : sample gas through aperture
  - – partial pressure sensors : analysis in exhaust stack
- issues
  - – recombination in mass spec tube changes
  - – indistinguishable species : (ex: CO, N_2 and Si have same amu (28))
  - – pressure measurements are removed from processing chamber

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RGA

- basic idea

  special kind of mass spectrometer

  measures gas compositions

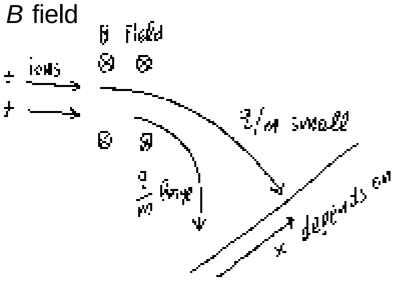
  works at low vacuum < 10^{-5} torr

  ion beam is produced from gas sample by e-bombardment

  beam is collimated by electric fields

  q/m ratio of ions determines bending in *B* field

  detection of ions via a Faraday cup



- issues

  quadrupole (magnetless design)

  very noisy !!

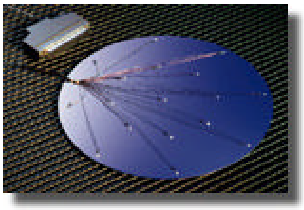
  good for diagnostics

  can withstand 500 °C

  can also be used at higher pressures with differential pumps

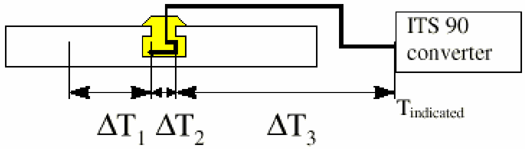
  mass range 50 amu, resolution 2 amu,

How about placing sensors on the wafer???

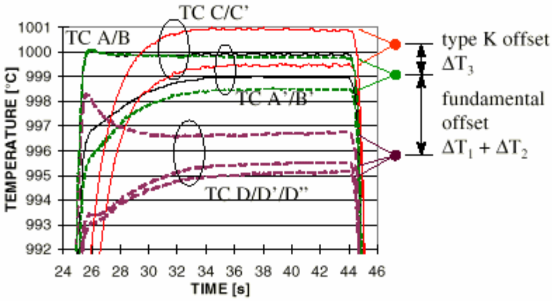


Sensarray products

Calibration is an issue...



Causes of offset between Si temperature and indicated temperature



<u>Fig. 5:</u> Temperature vs. Time for the 9 TC's used in the isothermal cavity. TC's A/A' (shield) are the thin full lines. TC's B/B' (top wafer) are the thin dashed lines. The thermocouples TC A and TC B, used for feedback control show a very good match with the 1000° setpoint. TC C/C' (R-type, top wafer) are the thick full lines. TCD/D'/D" (K-type 1530, outside cavity) are the dashed thick lines. TC's D/D'/D" show an average temperature that is 3.35°C below the average temperature of TC B/B'. This is the "fundamental" offset of a 1530 structure in a double side heated RTP system at 1000°C.

Long Term Reliability also an Issue...

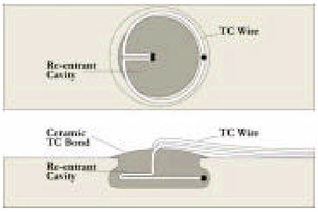


Fig. 1.1: In the new 1530 structure, each lead makes a separate 180 degree rotation around the edge and the leads are welded at the opposite side in an undercut area, close to the Si.

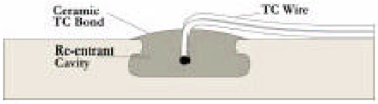


Fig. 1.2: In the 1501 structure, the thermocouple is mounted in the center of a reentrant cavity, filled with alumina based cement (the bond area).

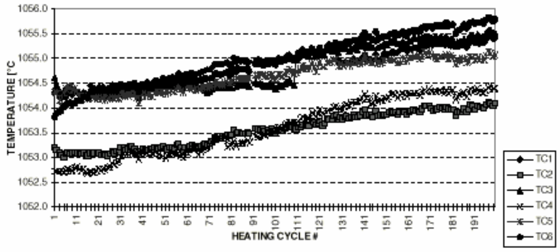
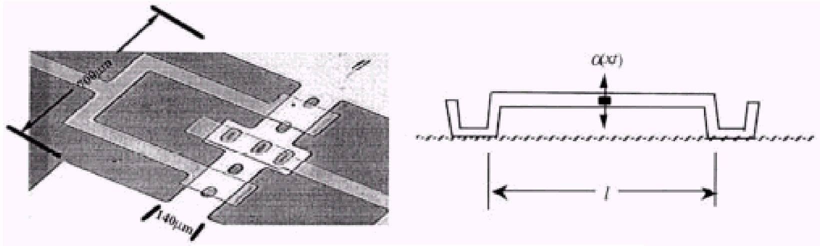


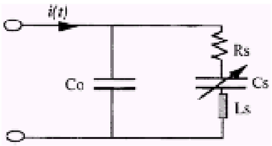
Fig. 2: Repeatability of thermocouples "1530" during 200 consecutive heating cycles with process P1050 (nominal 1050°C for 20 s), without moving the wafer (wafer #14). The upward drift is probably related to the formation of "haze" on the wafer.

On-Wafer Etch Rate by Resonant Structure



(a) (b)

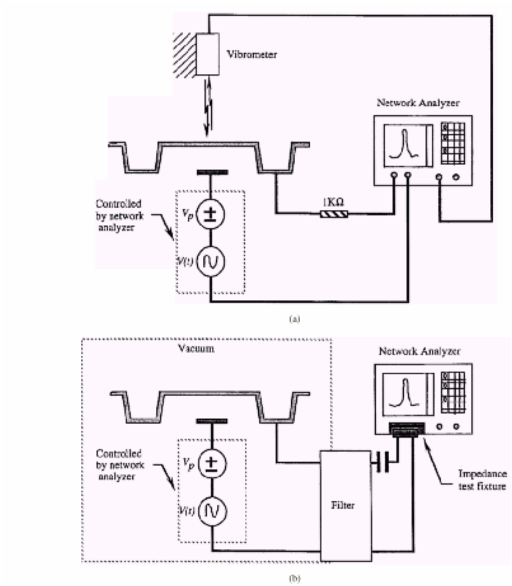
Fig. 2. (a) Micrograph of prototype sensor. (b) Schematic of platform structure indicating the direction of vibration.



Equivalent electrical circuit for micromachined platform.

IEEE TRANSACTIONS ON SEMICONDUCTOR MANUFACTURING, VOL. 11, NO. 2, MAY 1998
A Novel *In Situ* Monitoring Technique for Reactive Ion Etching Using a Surface Micromachined Sensor
Michael D. Baker, Frances R. Williams, *Student Member, IEEE,* and Gary S. May, *Senior Member, IEEE*

Remote reading of resonant sensor



Test setup for (a) electrostatic excitation and optical detection and (b) electrostatic excitation and capacitive detection.

Noise is the biggest problem...

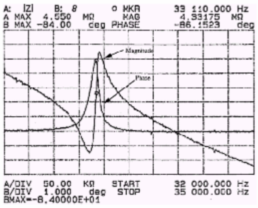
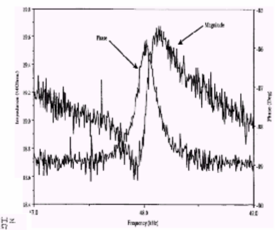


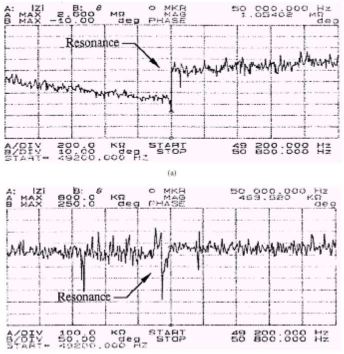
Fig. 9. Resonant frequency measurement made capacitively in a vacuum probe station.

On the bench...



12. Resonant frequency measurement made inside of the RIE chamber
r to exciting the plasma.

In the chamber...



When plasma is on...

But it works! (almost)

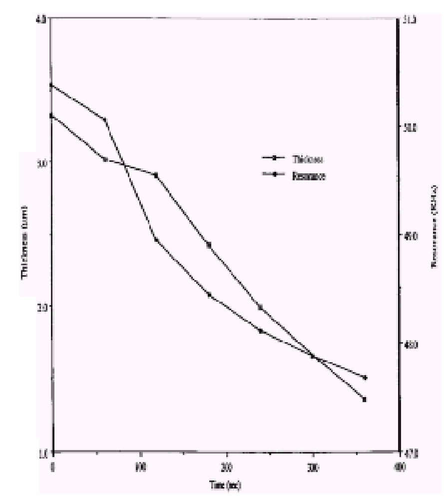


Fig. 15. Resonant frequency and film thickness plot for RIE sensor during plasma excitation.

Innovative

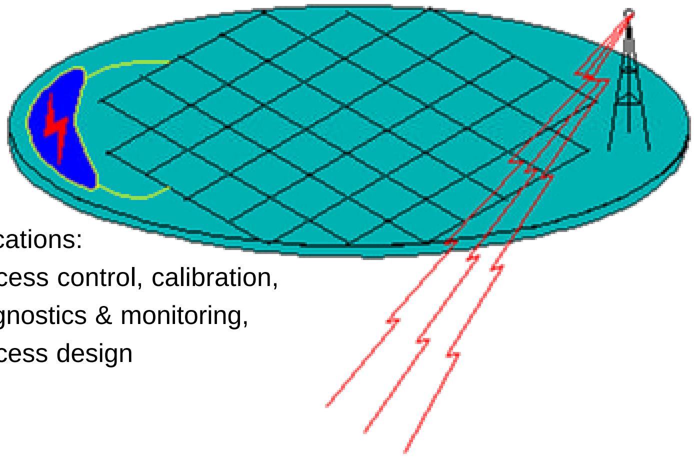
noisy

intrusive

may contaminate...

Our Vision

In-situ sensor array, with integrated power and telemetry



Applications:

- process control, calibration,
- diagnostics & monitoring,
- process design

Issues

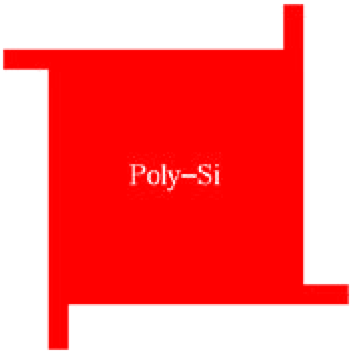
- Sensor arrays
  - inexpensive, modular
  - environmentally isolated
  - transparent to wafer handling robotics
  - on-board power & communications
- Operating mode
  - no equipment modifications !!
  - Smart “dummy” wafer for in-situ metrology

Test Case: Etch Rate

- Onboard etch-rate sensor for plasma etch
  - many sensor points on a wafer
  - accurate film thickness measurement
  - real-time data available
  - etch-friendly materials
  - wired power and communications (for now)

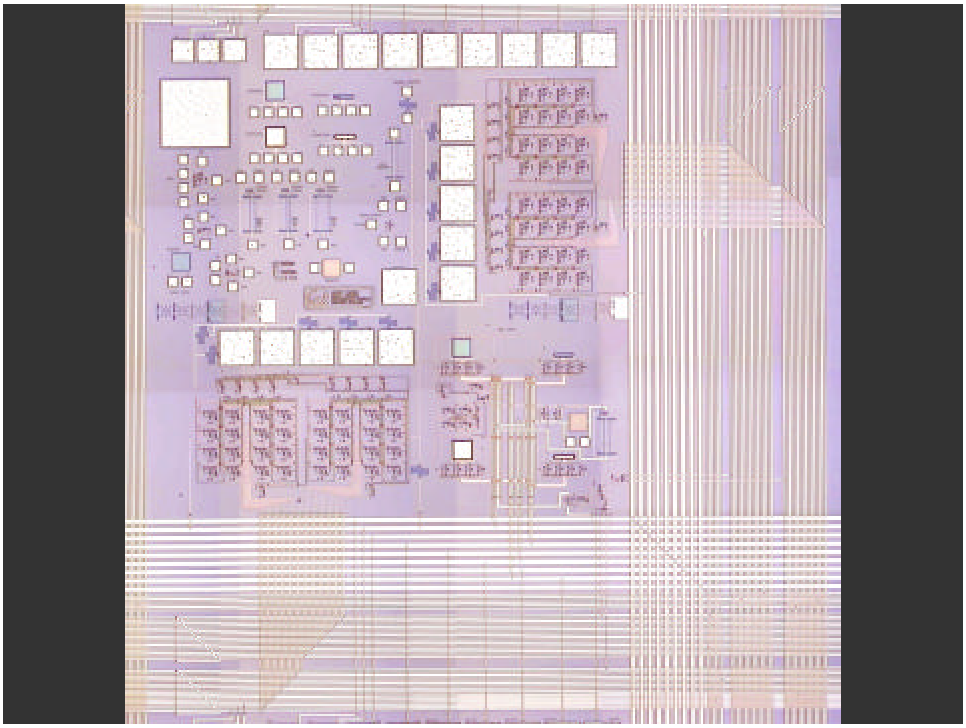
Transduction Scheme - Etch Rate

Van der Pauw structure: $t = \left(\frac{\ln 2}{p}\right)\left(\frac{I}{V}\right) r$



Current Design

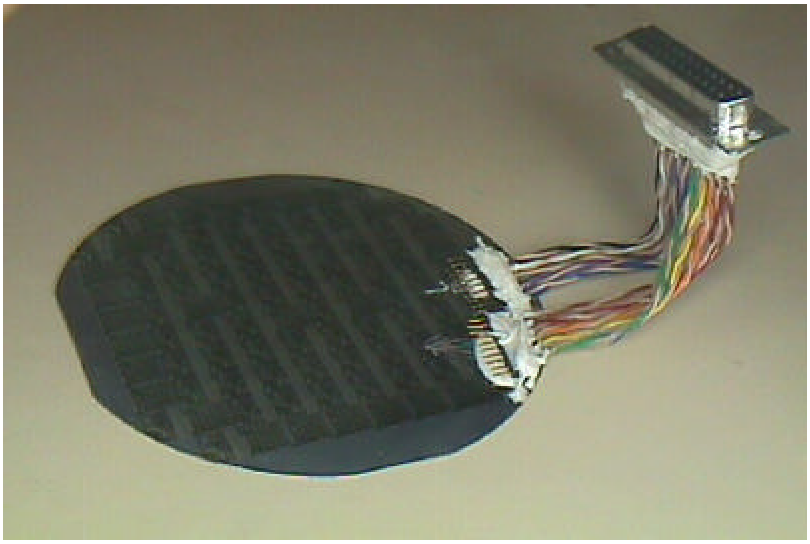
- Integrated Sensor Wafer Test Design
- 57 etch-rate sensors on a 4” wafer
- Full-wafer addressing of each sensor from a single die
- Redundant interconnect to enhance yield
- Four styles of sensor, selectable from a single die
- On-board current-sourcing
- Wired power and communications (at first)
- Expandable to allow wireless power and communication



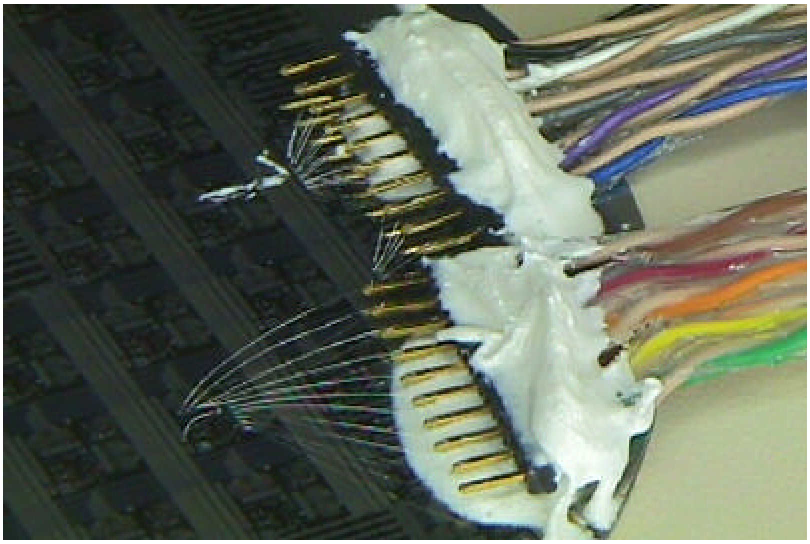
Experimental Procedure

- Bond wires to wafer
  - solder wires to “strip header”
  - glue header to wafer edge
  - wire bond from header to wafer’s bond pads
- Verify operation on bench
- Place wafer in XeF_2 Chamber
  - Measure film-thickness / etch-rate in real time
  - Calibrate using Nanospec thickness measurements

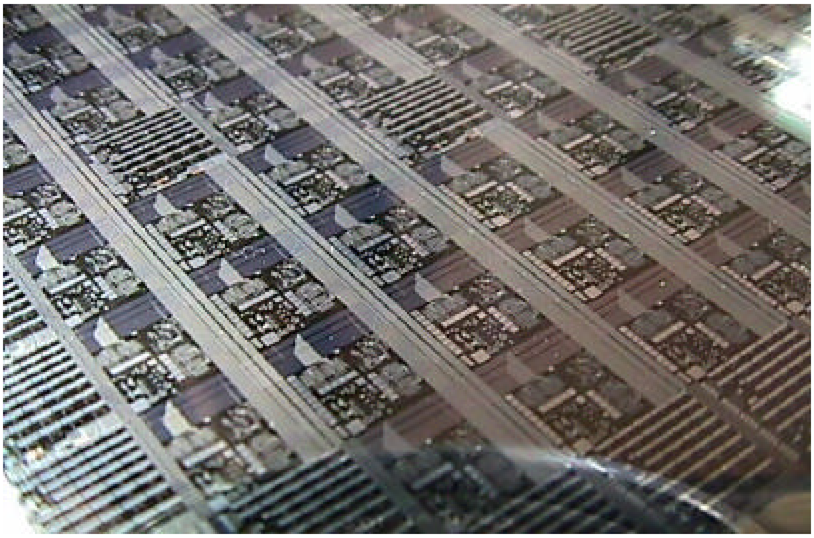
Pictures



Pictures



Pictures



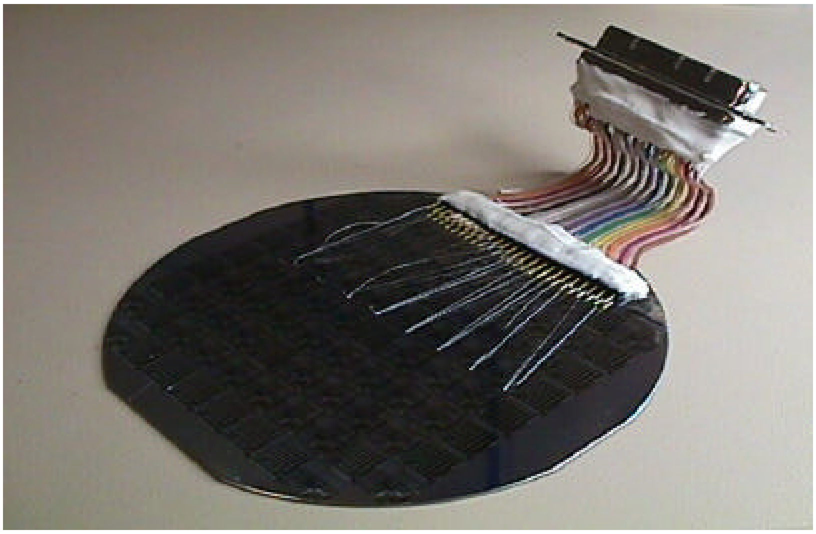
Pictures

Results

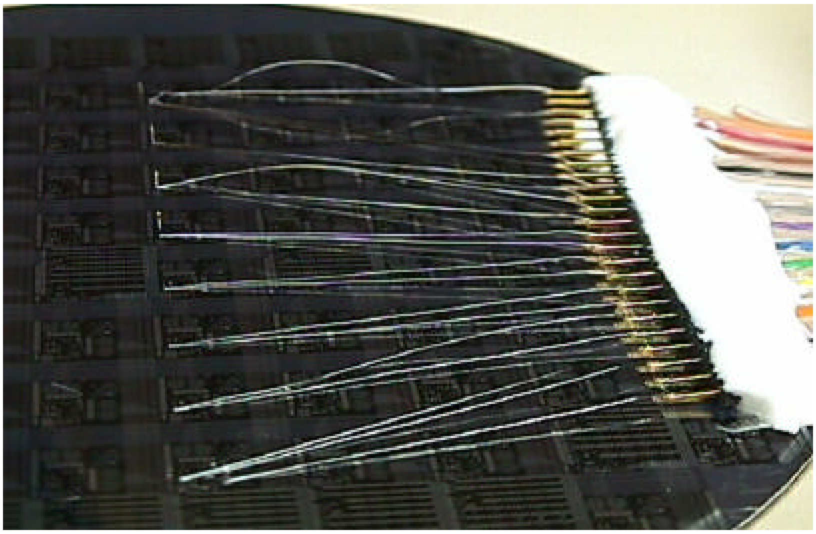
- Individual circuit elements work perfectly
- Overall circuit doesn’t work
  - Most likely due to flaw in decoder circuit, either due to yield problems or design flaw
- Individual (disconnected) sensors still work

$\Rightarrow$ Wire directly to sensors

Pictures



Pictures

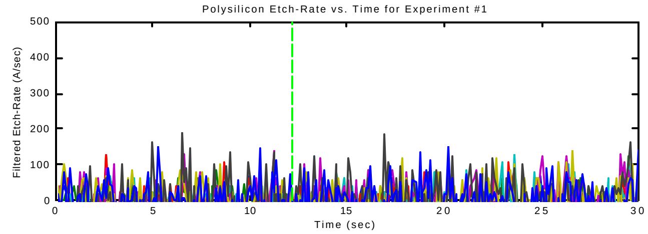


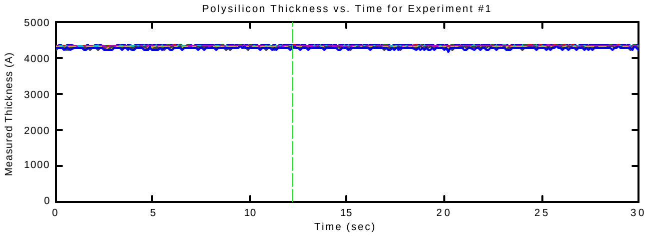
Results

- 8 sensors (in a row) wired together in *series*
- Everything works perfectly!
- *In-Situ* XeF_2 test performed
  - XeF_2 etch rate *much too fast* (~0.2µm/*sec*)
  - Sensor structure only 0.45 µm thick, gone in 2 sec
  - Sensors wired in series so when one etches through, all measurements stop

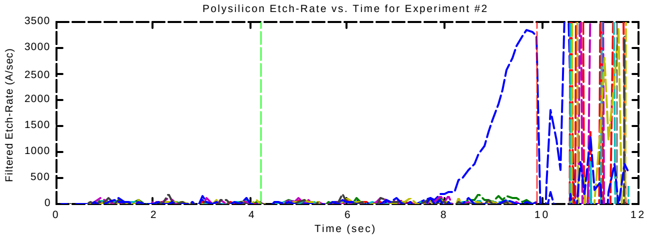
⇒ Data collected during etch, but no calibration available

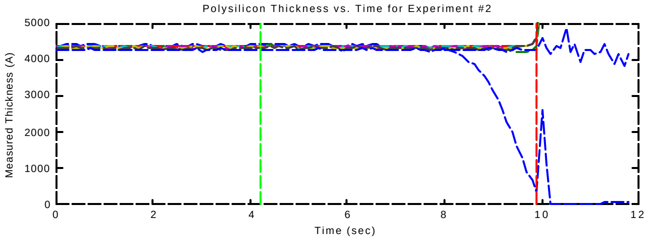
Data - Etch #1



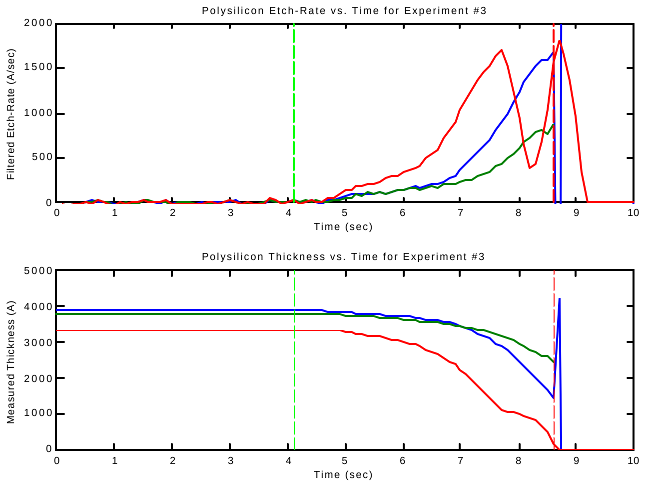


Data - Etch #2



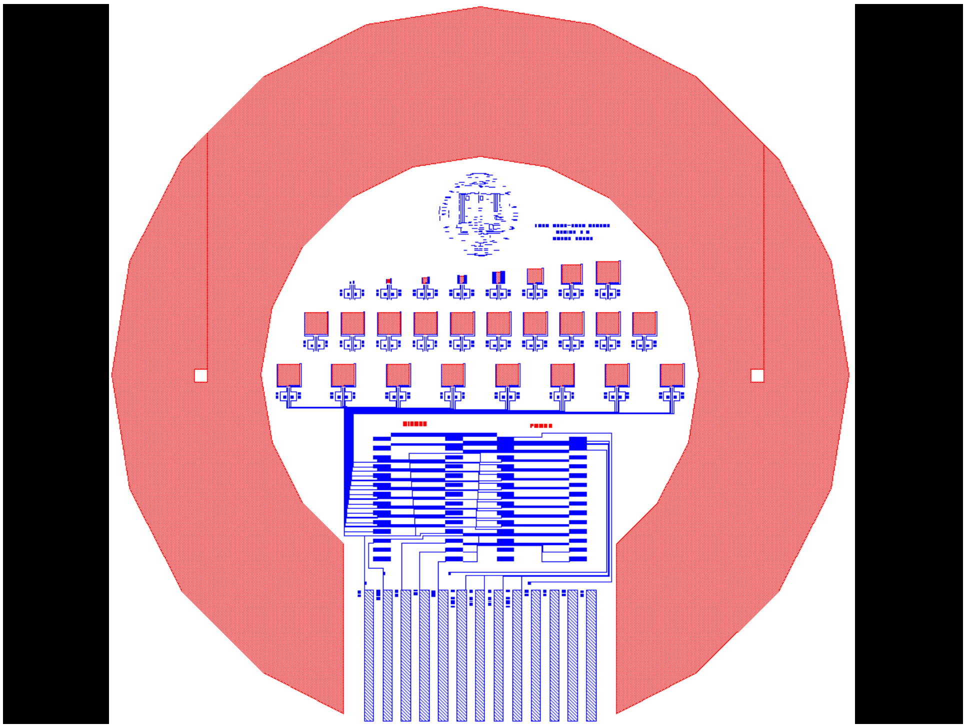


Data - Etch #3

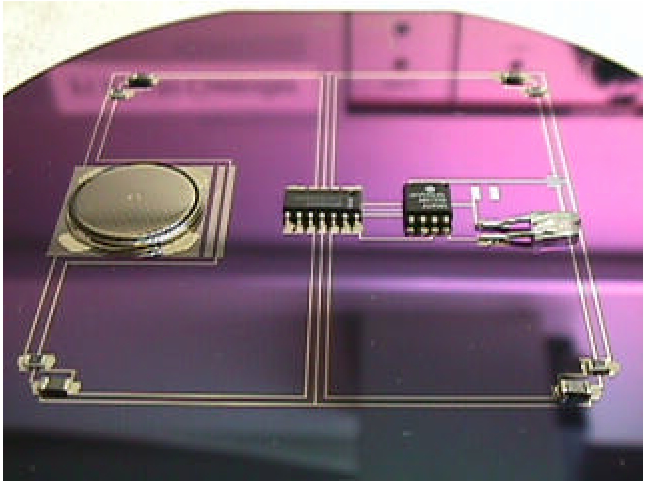


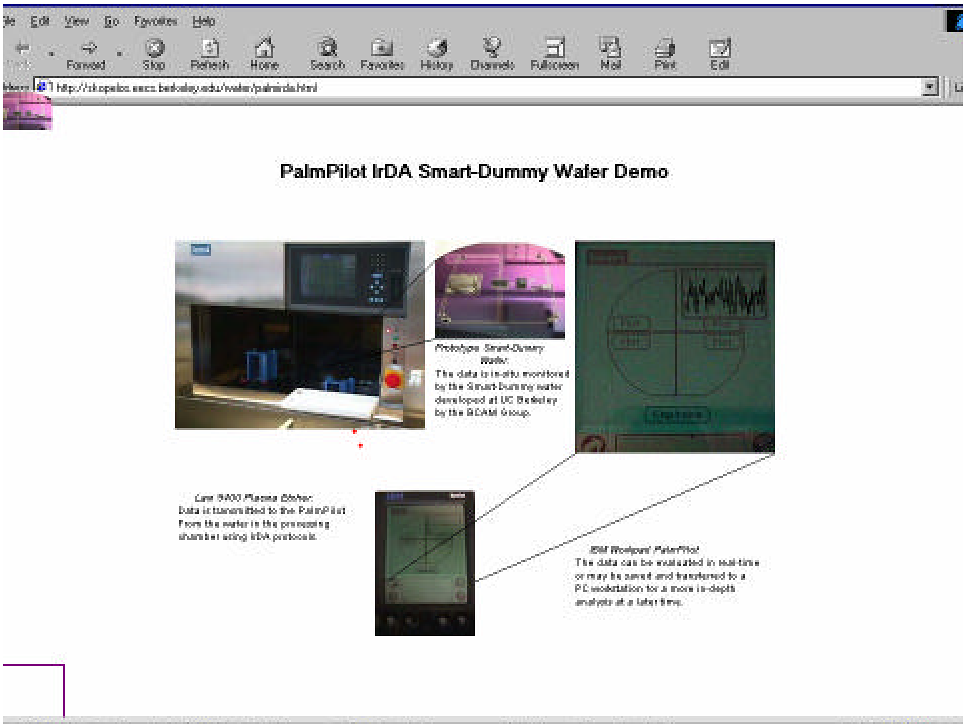
Plan

- Design new sensor wafer with no onboard electronics, only sensors
- Simple process $\Rightarrow$ one week turnaround time instead of one year
- Add several features
  - Polysilicon “guard ring” around sensors to reduce XeF_2 etch rate by “loading” the etcher
  - Larger sensors to allow *in-situ* reflectometry
  - Clip-on wires to decrease time-to-experiment
  - Parallel connection of sensors, for better reliability



How about completely wireless???





PalmPilot IrDA Smart-Dummy Wafer Demo

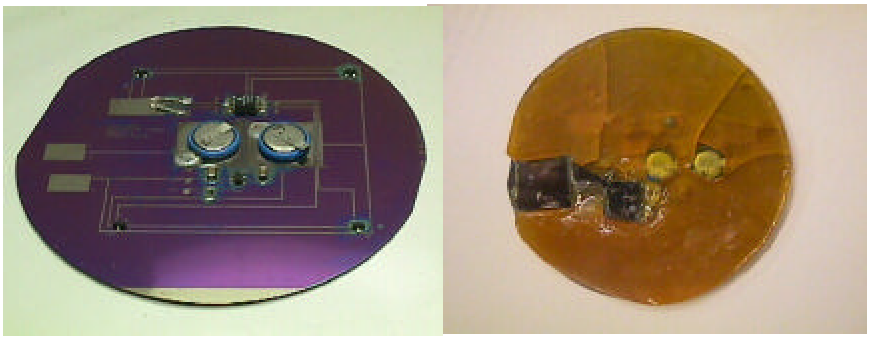
Prototype Smart-Dummy Wafer:
The data is in-situ monitored by the Smart-Dummy wafer developed at UC Berkeley by the BCAM Group.

Lam 9400 Plasma Etcher:
Data is transmitted to the PalmPilot from the wafer in the processing chamber using IrDA protocols.

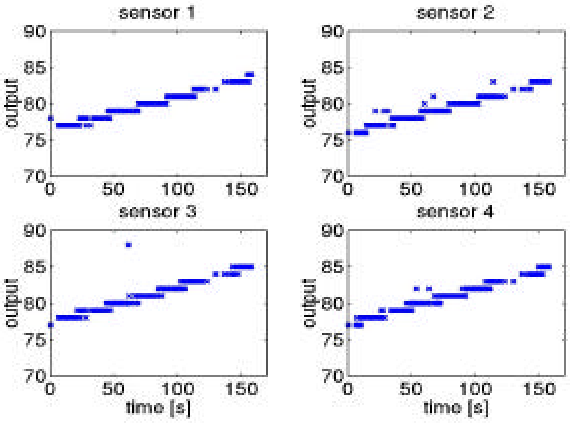
IBM Workpad PalmPilot
The data can be evaluated in real-time or may be saved and transferred to a PC workstation for a more in-depth analysis at a later time.

“Smart dummy” developed in 1998

- Developed and tested at the UC Berkeley Microfabrication Laboratory.
- 4 sensors, wafer covered with layer of epoxy
- LED used for real-time, one-way transmission



First Test results in plasma, 1999

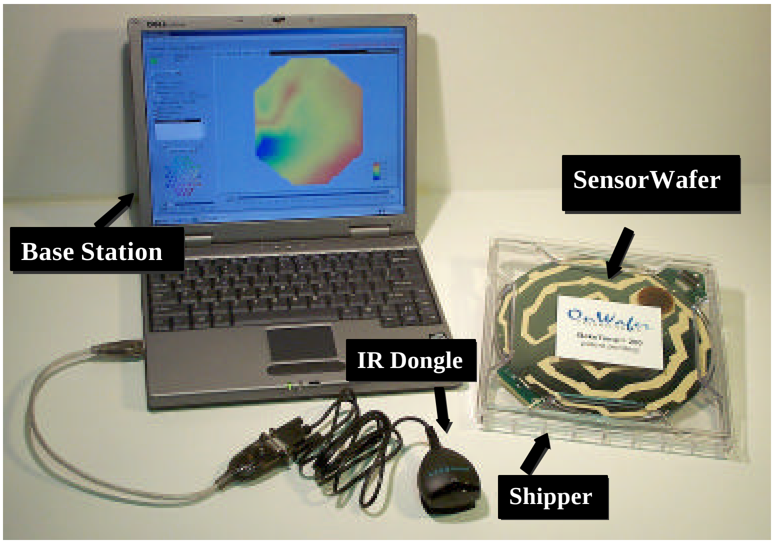


13.56MHz, 100W, 0.76 Torr, O_2

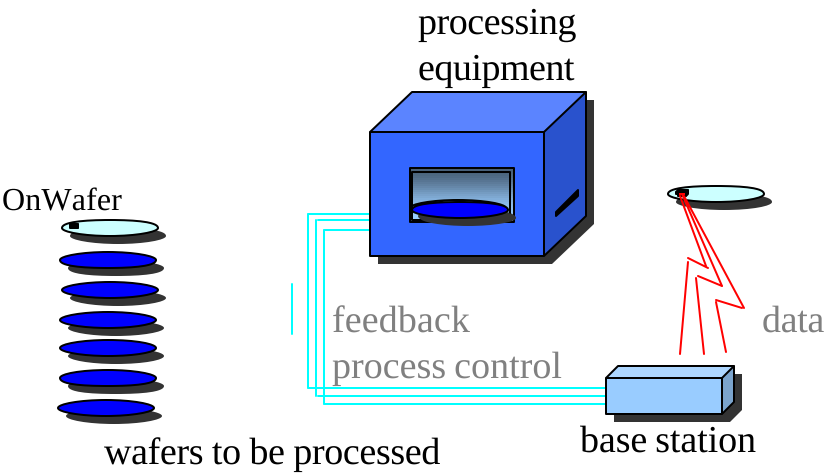
An Update on OnWafer Sensors

- OnWafer technologies Inc, a Berkeley startup, was founded in 2000.
- Today OnWafer products are in use in most of the major fabs around the world, and by most the major tool makers (LAM, Applied, TEL, Nikon).

Present OnWafer System



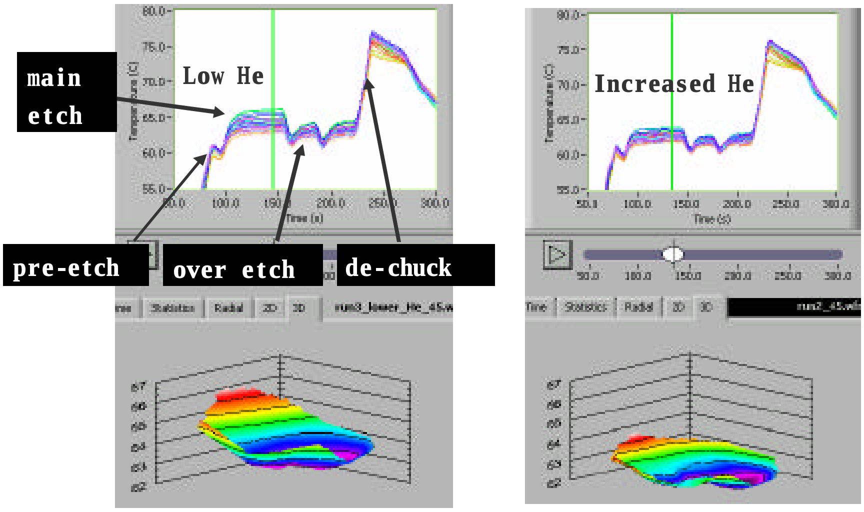
The Approach



PlasmaTemp SensorWafer

- 42 sensors/wafer, 1Hz
- 0.5 °C accuracy
- Rechargeable.
- Functional up to 140 °C, several kW RF
- Suitable for oxide/poly plasma etch
- Non-contaminating, cleanable and reusable

Example - Process Monitoring of 200mm Poly Etching



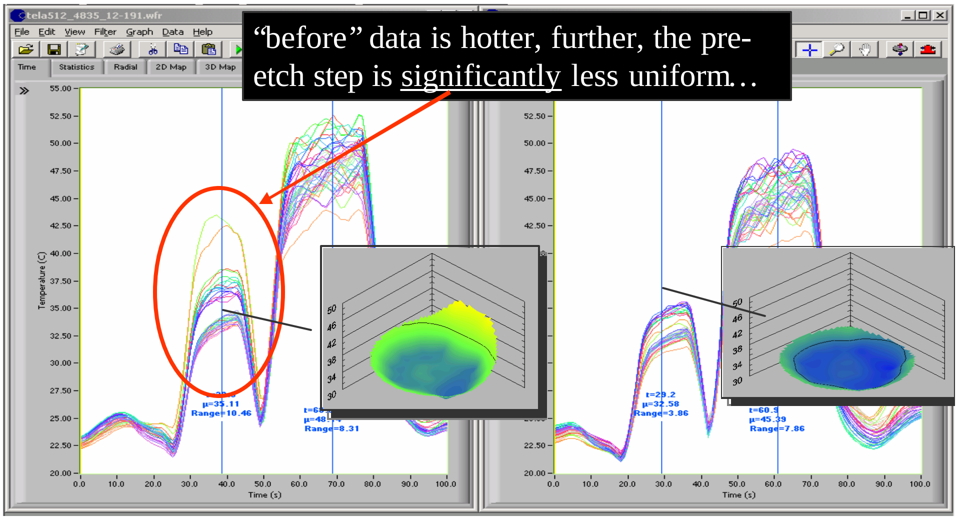
main etch

pre-etch

over etch

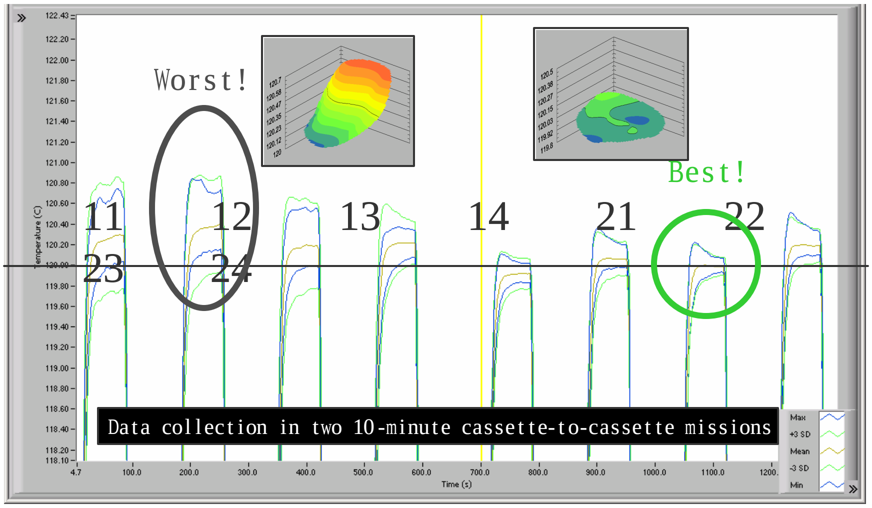
de-chuck

Example - Gas flow trouble in TEL DRM Etcher



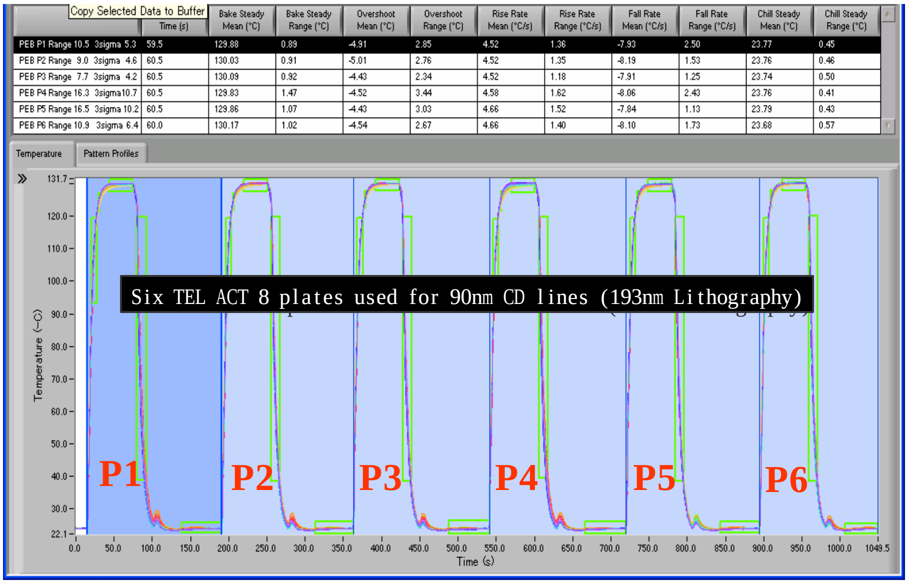
“before” data is hotter, further, the pre-etch step is significantly less uniform…

Example - Comparison between 8 PEB plates on a 193nm wafer track



Data collection in two 10-minute cassette-to-cassette missions

On-Wafer PEB / CD Analysis

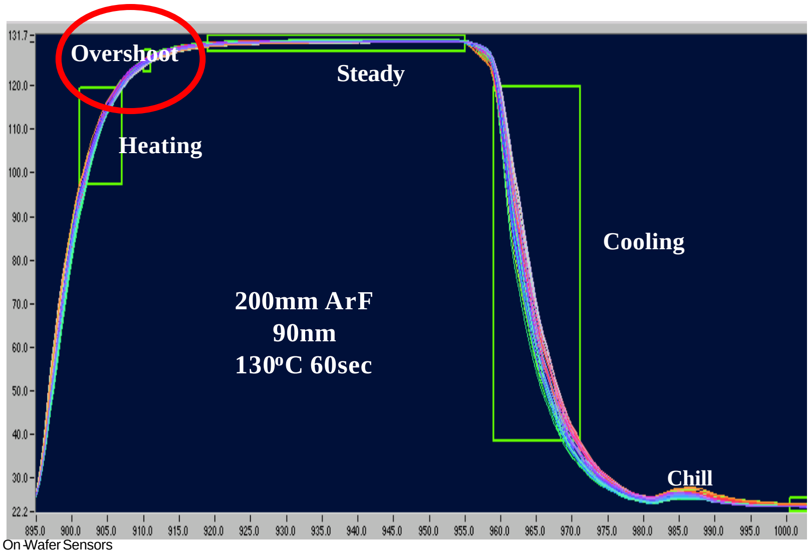


Copy Selected Data to Buffer

	Time (s)	Bake Steady Mean (°C)	Bake Steady Range (°C)	Overshoot Mean (°C)	Overshoot Range (°C)	Rise Rate Mean (°C/s)	Rise Rate Range (°C/s)	Fall Rate Mean (°C/s)	Fall Rate Range (°C/s)	Chill Steady Mean (°C)	Chill Steady Range (°C)
PEB P1 Range 10.5 3sigma 5.3	59.5	129.88	0.89	-4.91	2.85	4.52	1.36	-7.93	2.50	23.77	0.45
PEB P2 Range 9.0 3sigma 4.6	60.5	130.03	0.91	-5.01	2.76	4.52	1.35	-8.19	1.53	23.76	0.46
PEB P3 Range 7.7 3sigma 4.2	60.5	130.09	0.92	-4.43	2.34	4.52	1.18	-7.91	1.25	23.74	0.50
PEB P4 Range 16.3 3sigma10.7	60.5	129.83	1.47	-4.52	3.44	4.58	1.62	-8.06	2.43	23.76	0.41
PEB P5 Range 16.5 3sigma 10.2	60.5	129.86	1.07	-4.43	3.03	4.66	1.52	-7.84	1.13	23.79	0.43
PEB P6 Range 10.9 3sigma 6.4	60.0	130.17	1.02	-4.54	2.67	4.66	1.40	-8.10	1.73	23.68	0.57

Six TEL ACT 8 plates used for 90nm CD lines (193nm Lithography)

Analyzing PEB Plates using BakeInfo



200mm ArF
90nm
130°C 60sec