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° C
  
  $T$ gradient along wires of different materials develop different emf
  
  emf measures junction $T$
  
  platinum rhodium alloy, or silicon based
  
  sensitivity $100-200 \mu V / ^\circ K$

- **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 $\sim +/- 5^\circ C$ at $800^\circ C$
  
  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)
    \[ R_\lambda = \frac{37418}{\lambda^5 \left( e^{14388/\lambda T} - 1 \right)} \]
    \(
    \lambda \text{ in microns, } T \text{ in } ^\circ K, \ R_\lambda
    \)
  - 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\textsubscript{2} and Si have same amu (28))
  – pressure measurements are removed from processing chamber
RGA

• basic idea
  special kind of mass spectrometer
  measures gas compositions
  works at low vacuum < 10^{-5} \text{ 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...

Fig. 5: 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°C 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

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...

On the bench... In the chamber...

When plasma is on...
But it works! (almost)

Innovative
noisy
intrusive
may contaminate...

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

\[ t = \left( \frac{\ln 2}{\pi} \right) \left( \frac{I}{V} \right) \rho \]
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 XeF₂ Chamber
  – Measure film-thickness / etch-rate in real time
  – Calibrate using Nanospec thickness measurements
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* (~0.2 μm/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 #3

Polysilicon Etch-Rate vs. Time for Experiment #3

Polysilicon Thickness vs. Time for Experiment #3
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, O₂
An Update on OnWafer Sensors

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

OnWafer

processing equipment

feedback

process control

wafers to be processed

base station

data
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

**Low He**
- **Pre-etch**
- **Main Etch**
- **Over Etch**
- **De-chuck**

**Increased He**
- **Pre-etch**
- **Main Etch**
- **Over Etch**
- **De-chuck**
Cool chuck - 200mm Poly Etching

Temperature fluctuations during main etch
Can see rotating magnetic field!

- Phase delay in temp fluctuation
- Can calculate B-field period
- Can see rotation is clockwise
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 (+/- 0.1C accuracy)

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

Best!

Worst!
On-Wafer PEB / CD Analysis

Six TEL ACT 8 plates used for 90nm CD lines (193nm Lithography)
Much more than you ever wanted to know about Post Exposure Bake

200mm ArF
90nm
130°C 60sec

Courtesy OnWafer Technologies
Post Exposure Bake Track Equipment

Complexity is Increasing

Single Zone Control

Multi-Zone Control

10 Years of Product Evolution

PEB Evolved from a Single Zone to Multi-Zone Control System

Why?
PEB Hotplate Thermal Profile Optimization System

Plate Type Specific Thermal Profile Modeling Engine

AutoCal™

Offset Generator Engine

Offset Values Optimized for Both Within-Plate and Plate-to-Plate Thermal Profile Uniformities

Baseline Thermal Profile Condition

BakeTemp™ & OnView™

Courtesy OnWafer Technologies
PEB Temp Control

Before

After

16 plates, 120 °C Target

Courtesy OnWafer Technologies
Spatial PEB/CD Distribution Correlation

- Plotting both the bake plate temperature trajectory and $R^2$ from temperature-CD correlation against bake time:

Max $R^2$ during the transient heating period

Continued high $R^2$ during steady state due to poor temperature control in single-zone plate design
PEB Hotplate Critical Dimension Optimization System

- AutoCal™
  - Plate Type Specific Thermal Profile Modeling Engine

- AutoCD™
  - Resist & Litho Cell Specific CD Modeling Engine
  - Offset Values Optimized for Both Within-Plate and Plate-to-Plate Critical Dimensions Uniformities

- Offset Generator Engine
  - Baseline Thermal Profile Condition
  - BakeTemp™ & OnView™
  - Baseline CD Profiles per Plate

- Customer Provided

Courtesy OnWafer Technologies
CDU Improvement

Across Plate

Plate to Plate

AutoCD

AutoCal

POR

Courtesy OnWafer Technologies
The New Problem

How can we improve the across-wafer CDU?
How much can we improve CDU?
Supervisory Control with Wireless Metrology

Compensate for systematic spatial non-uniformities across the litho-etch sequence using all available control authority:

- Exposure step: die to die dose
- PEB step: temperature of multi-zone bake plate
- Etch: backside pressure of dual-zone He chuck

![Diagram showing the litho-etch sequence with control points for dose, temperature, and He pressure.]
Next Step: Zero-Footprint Metrology Wafer

Prototyping a zero-footprint metrology wafer with optical detection unit and encapsulated power source.
Proposed Architecture

Power Management & RF Transmission Unit

Self-contained wireless transmitter

Measurement Units

Integrated excitation/detection Unit

Power Unit

Thin film Battery

Lecture 20: On-Wafer Sensors
3 x 3 Pixels Optical Metrology Prototype

Bottom Wafer with LED Photodetector integrated

Top Wafer
Feasibility Test: Thickness Measurement

Shipley S1818 PR on Glass Slide

Test Coating

Glass Slide

Packaging Substrate

LED

PD

Si

Filter

Reflection Intensity (a.u.)

Excitation $\lambda=525\text{nm}$

Theoretical Curve

PR Thickness (nm)
Wireless Aerial Image Metrology

Mask image
NA
Partial coherence
Illumination aberrations
Defocus
magnification
Aerial image
Latent image
Resist image
An Integrated Aerial Image Sensor

Dark contact mask forms a “moving” aperture to capture incident electromagnetic field.

How can a μm detector retrieve nanometer-scale resolution of the aerial image?
Moiré Patterns for Spatial Frequency Shift

Narrow CD
- Patterns Overlap
- Pattern rotates 4°
- Pattern rotates 8°
- Pattern rotates 16°

Wide CD

Lecture 20: On-Wafer Sensors
Aperture pattern shift testing

Detector mask layout design

Mask layout

Measurement result
Near-Field Optical Simulation

Intensity at the center of the simulation domain
Present Status of “Active” CD Control

Exposure

PA Bake
Spin
HMDS
PEB
Develop
PD Bake

Etch

Poly Etch System

Etch

Etch

Photoresist Removal

ADI
AEI
ELM
On-wafer and in-line metrology in pattern transfer
CDU control has to incorporate many strategies

- Exposure
  - PA Bake
  - PEB
  - Spin
  - HMDS
  - Thin Film FB/FF Control
- Etch
  - T (t, x, y)
  - FF control
  - I (x, y)
  - Optimal Pattern Design
- Poly Etch System
  - E (t, x, y)
  - FF/FB Control, chuck diagnostics
- Etch
  - V (t, x, y)
- Photoresist Removal
  - OCD FB/FF Control
  - ELM
- OCD Profile Inversion FB Control
- FF/FB Control, chuck diagnostics