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 $3000^\circ C$
  - $T$ gradient along wires of different materials develop different emf
  - emf measures junction $T$
  - platinum rhodium alloy, or silicon based
  - sensitivity $100-200\mu V/K$

- **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
  - low bandwidth
  - accuracy $\sim +/- 5^\circ C$ at $800^\circ C$
  - 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)
    \[ R_{\lambda} = \frac{37418}{\lambda^5 (e^{14388/\lambda T} - 1)} \]
    \( \lambda \) in microns, \( T \) in °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, N₂ 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???

Calibration is an issue...

![Calibration Diagram]

*Fig. 2: Temperatures vs. Time for the 9 TCs used in the testbed and system. TC A/B (red) are the thin flat strips, TCs C/D (yellow) are the thick flat strips, the thermocouples TC A and TC B used for feedback control show a very good match with the 3000°F setpoint. TC C/C' (blue, top) and TC D/D' (blue, bottom) are the dual-disk A/B sides. TCs C/D/C' show an average temperature of 3.1°C below the controller temperature of 25°C. This is the "fundamental" offset of a 650°C system on a double sided heater. RIP systems at 1060°C. (Spanos & Poolla, EE290H F03)
Long Term Reliability also an Issue...

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

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:

\[ I = \frac{\ln 2}{\pi} \left( \frac{I}{V} \right)^p \]

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
Pictures

![Image of a sensor device with wires connected to it]

Pictures

![Image of another sensor device with wires connected to it]
Pictures

[Image of wafer sensors]

[Image of another sensor device]

Lecture 20: On-Wafer Sensors
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
  ⇒ 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* (~0.2 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 #1

Polysilicon Etch-Rate vs. Time for Experiment #1

Polysilicon Thickness vs. Time for Experiment #1

Data - Etch #2

Polysilicon Etch-Rate vs. Time for Experiment #2

Polysilicon Thickness vs. Time for Experiment #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???
“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

![Image of OnWafer System]

**The Approach**

- **Processing equipment**
- **Feedback**
- **Process control**
- **Data**
- **Base station**
- **Wafers to be processed**

OnWafer
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
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

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

Analyzing PEB Plates using BakeInfo