In-chamber and on-wafer sensors

What dreams may come

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/°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°C at 800°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)
    \[ R_\lambda = \frac{37418}{\lambda^5 (e^{\frac{14388}{\lambda T}} - 1)} \]
    \( \lambda \) 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, 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\textsuperscript{-9} 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...

Fig. 7. Temperature vs. time for the 4 TC's used in the bistable cavity. TC's A/B (right) are the rise/fall lines. TC's C/D (left) are the flat lines. The photovoltaics TC A and TC B, used for feedback control, show a very good match with the 1000° setpoint. TC C/D (K-type, top half) are the thick flat lines. TC's D/E/F (K-type, bottom) are the dashed flat lines. TC D/F/G show an average temperature that is 3.5°C below the average temperature of TC B/C.
Long Term Reliability also an Issue...

Fig. 1. In the new L300 structure, each lead makes a separate 180 degree rotation around the edge and the leads are welded at the opposite side from each other, near the Si.

Fig. 2. In the L500 structure, the thermocouple is arranged in the center of a resonant cavity, filled with alumina-based cement (the bond area).

On-Wafer Etch Rate by Resonant Structure

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

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 plots for BSE sensor during photo 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: \[ t = \left( \frac{\ln 2}{\pi} \right) \frac{I}{V} \rho \]

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
Pictures

![Image 1](image1.jpg)

Pictures

![Image 2](image2.jpg)
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
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

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
Plan

- Design new sensor wafer with no onboard electronics, only sensors
- Simple process ⇒ 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???