# Optoacoustic Metrology for Copper Interconnects Using Impulsive Stimulated Thermal Scattering (ISTS)

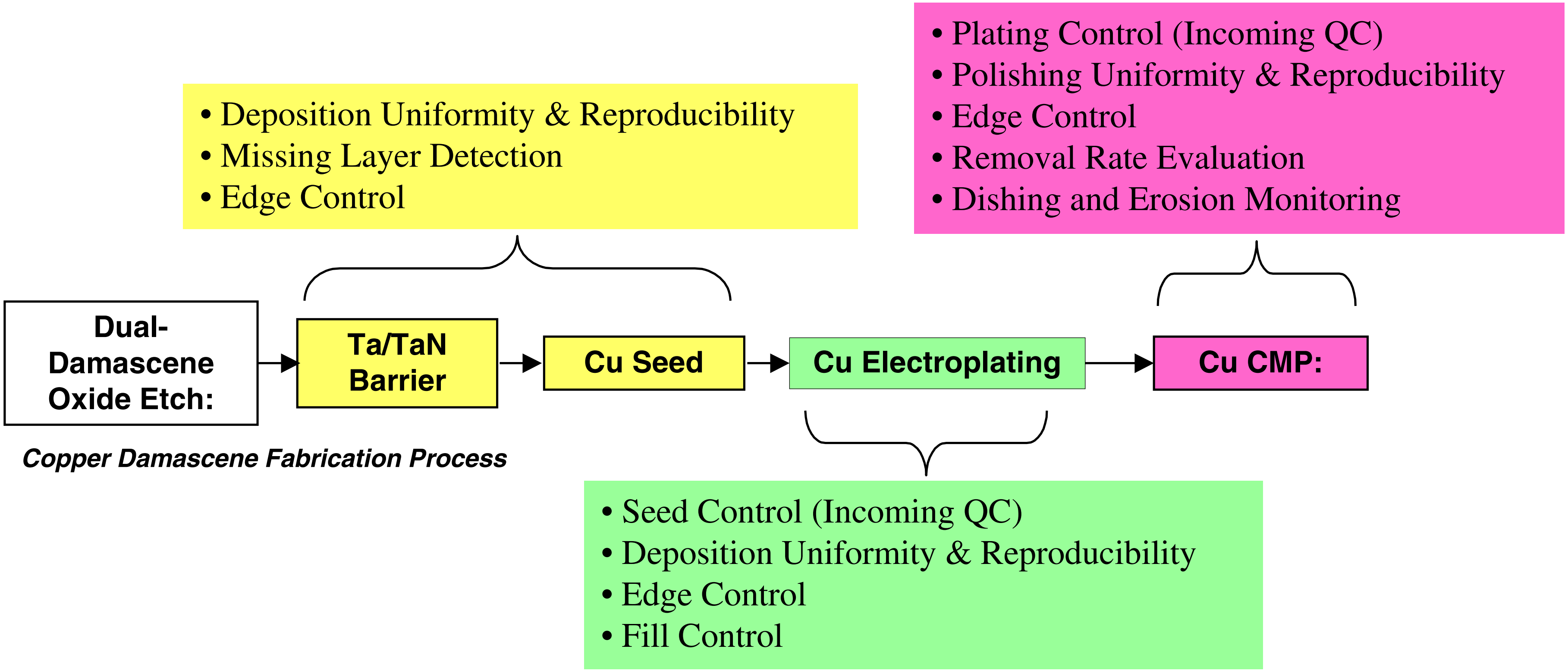
M. Gostein, M. Joffe, A.A. Maznev, M. Banet, C.J.L. Moore
Philips Analytical, 12 Michigan Drive, Natick, MA  01760, (508) 647-1100

# Outline

- Introduction
- Principles
    - Overview of ISTS
    - Single-Layer Measurement
    - Bi-Layer Measurement
    - Measurement on Patterns
- Applications
- Future Directions

# Introduction

# Copper Interconnect Film Thickness Metrology Issues



- Deposition Uniformity & Reproducibility
- Missing Layer Detection
- Edge Control

- Plating Control (Incoming QC)
- Polishing Uniformity & Reproducibility
- Edge Control
- Removal Rate Evaluation
- Dishing and Erosion Monitoring

**Dual-Damascene Oxide Etch:** → **Ta/TaN Barrier** → **Cu Seed** → **Cu Electroplating** → **Cu CMP:**

*Copper Damascene Fabrication Process*

- Seed Control (Incoming QC)
- Deposition Uniformity & Reproducibility
- Edge Control
- Fill Control

# Metrology Trends

- Non-contact measurement
- Measurement on patterned structures

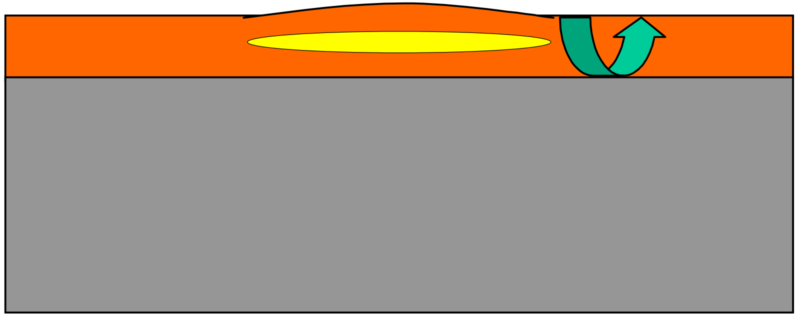
⇩

**On-product metrology**

# Photoacoustic Methods

## **PULSE**

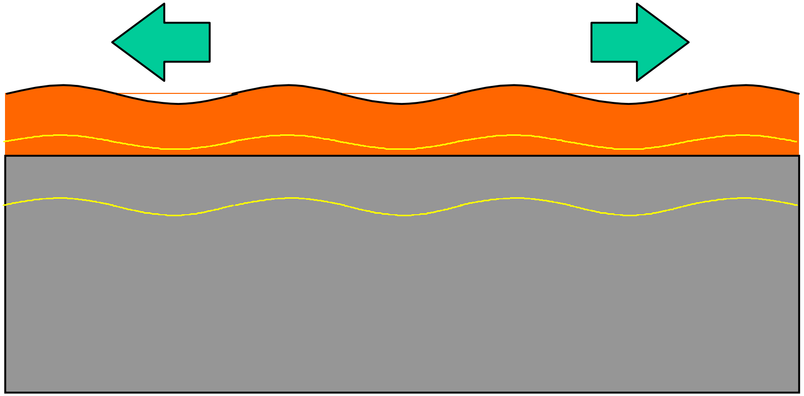
- Observe echoes — *⊥ to film plane*
- Time resolution needed: *~0.1 ps*
- *Time-domain*



- Detect *ΔReflectivity*

## **ISTS**

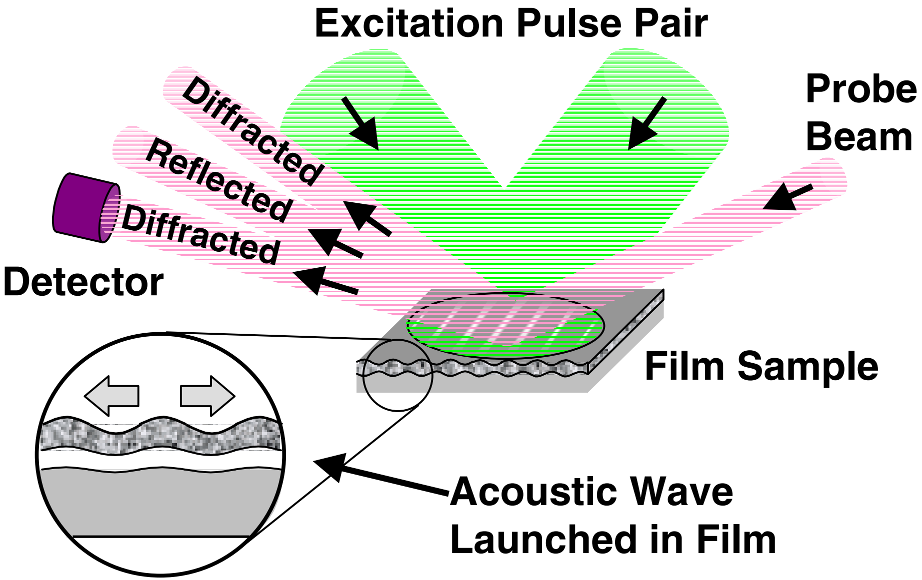
- Observe velocity — *// to film plane*
- Time resolution needed: *~250 ps*
- *Frequency-domain*

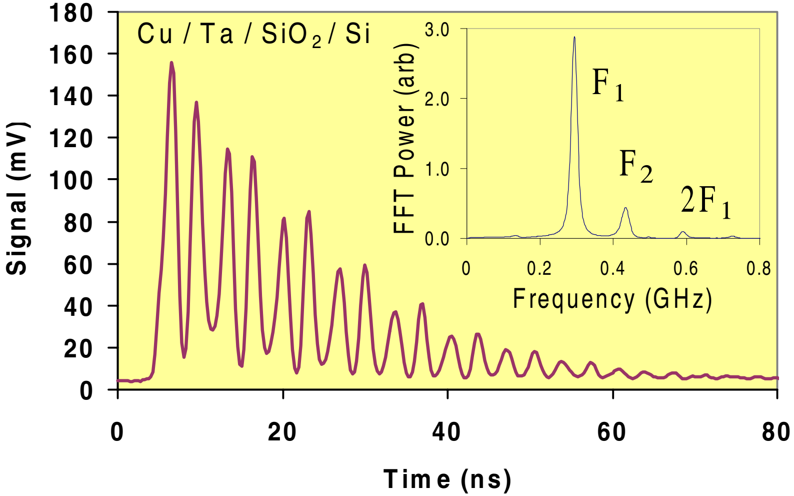


- Detect *diffraction* from wave

# Overview of ISTS

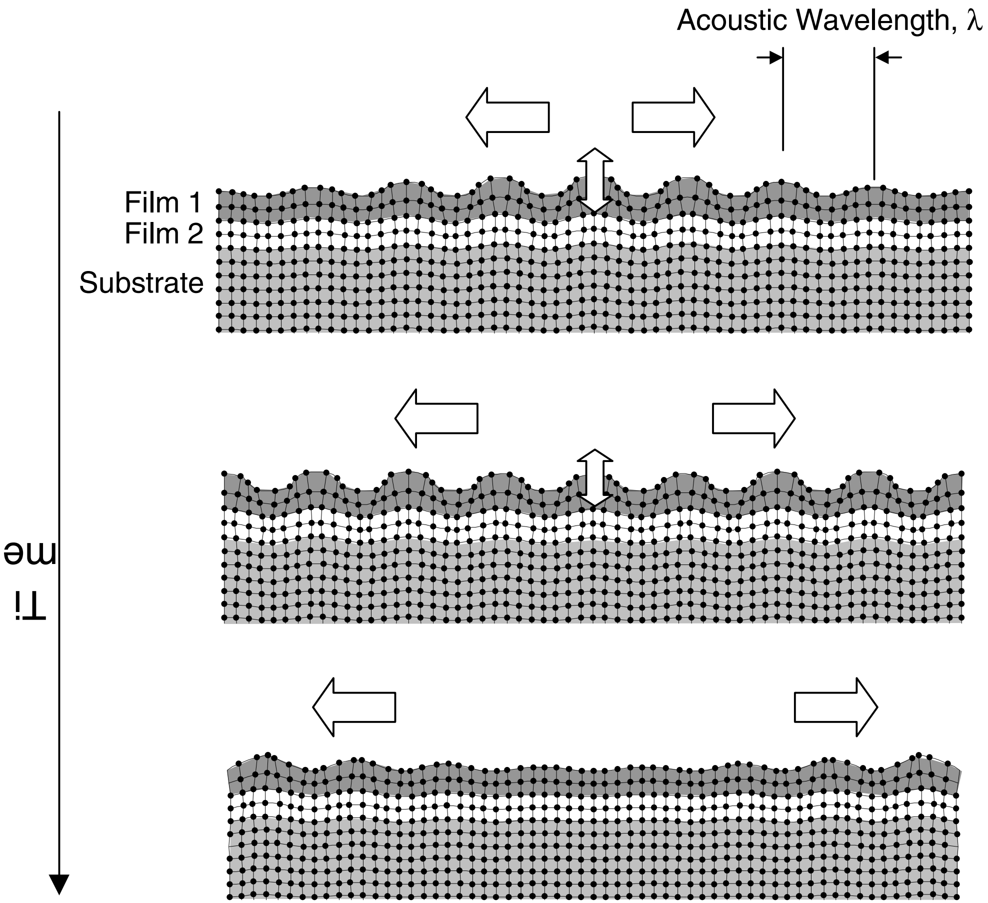
# Schematic of ISTS Technique





- **Robust optical arrangement**
- **Rapid (~1 second / site)**

# Wave Motion

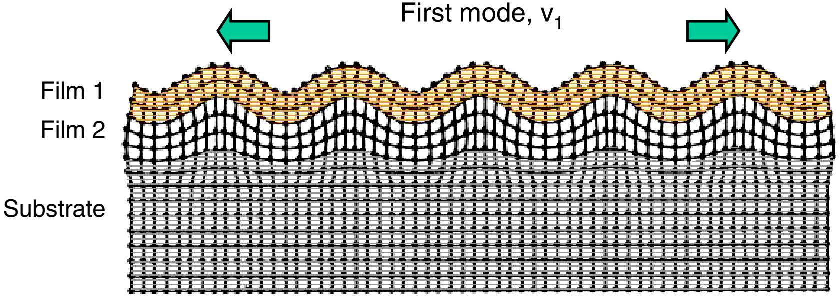


**MOVIE:**

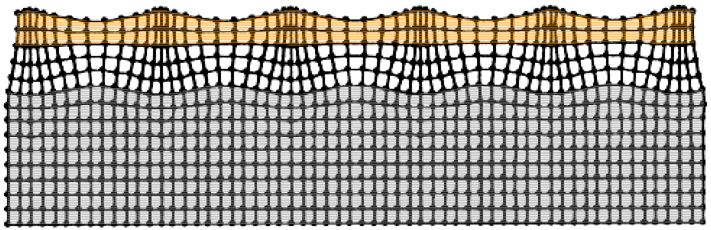
**ISTS Wave Excitation, Propagation, and Detection**

# Oscillation Modes

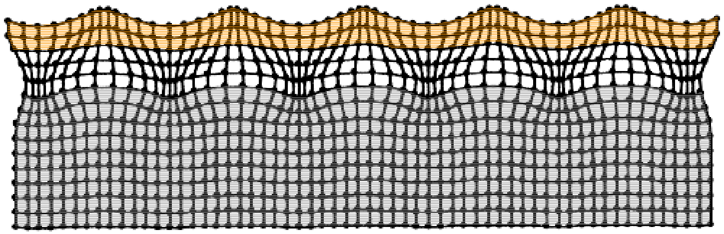
First mode, $v_1$



Second mode, $v_2 > v_1$



Third mode, $v_3 > v_2$

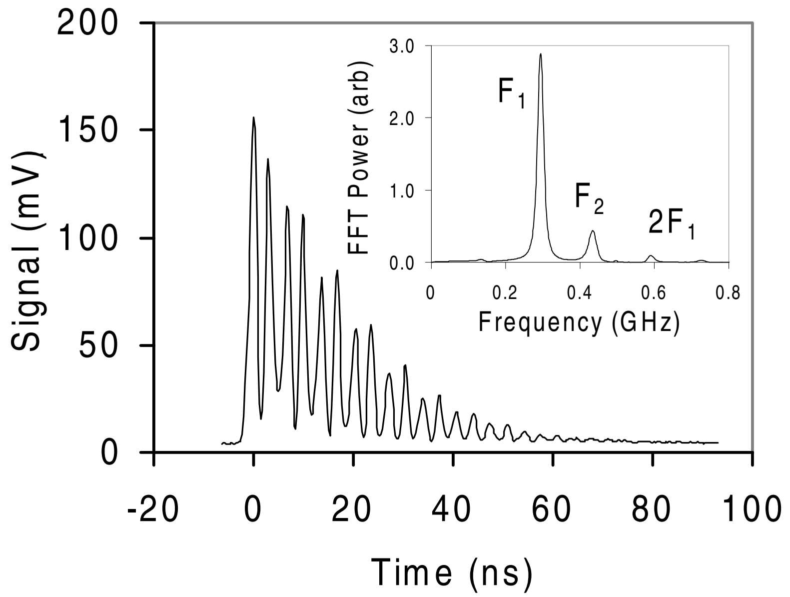


**Each oscillation mode has a different pattern of motion, resulting in a different wave velocity.**

**FAQ:** Does number of oscillation modes depend on number of film layers?

**Answer:** No.

# Waveform



$$F_1 = v_1 / \lambda$$

$$F_2 = v_2 / \lambda$$

---

$$S(t>0) \propto \Big[\underbrace{A_T \exp(-t/\tau)}_{\text{Thermal}} + \underbrace{A_1 \cdot G_1(t) \cdot \cos(2\pi F_1 t)}_{\text{First Mode}} + \underbrace{A_2 \cdot G_2(t) \cdot \cos(2\pi F_2 t)}_{\text{Second Mode}} + \ldots\Big]^2$$

*(Approximate description)*

# Film Properties Determining Observed Signal

**Mechanical:**

- Thickness
- Density
- Young's Modulus
- Poisson's Ratio

→ Frequency Spectrum

**Optical:**

- Optical absorption coefficient

→ Signal Strength

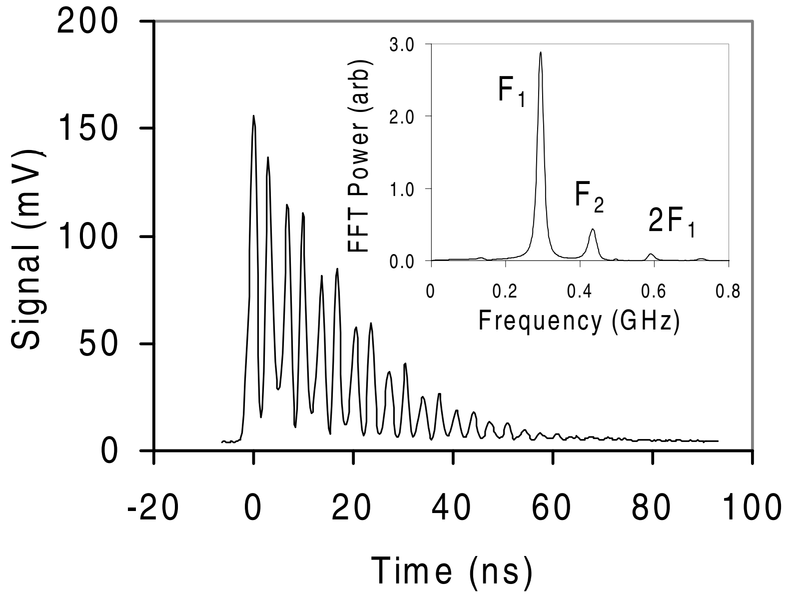
**Thermal:**

- Thermal expansion coefficient
- Thermal diffusivity

→ Signal Strength, Decay Rate

# Single-Layer Measurement

# Single-Layer Measurement

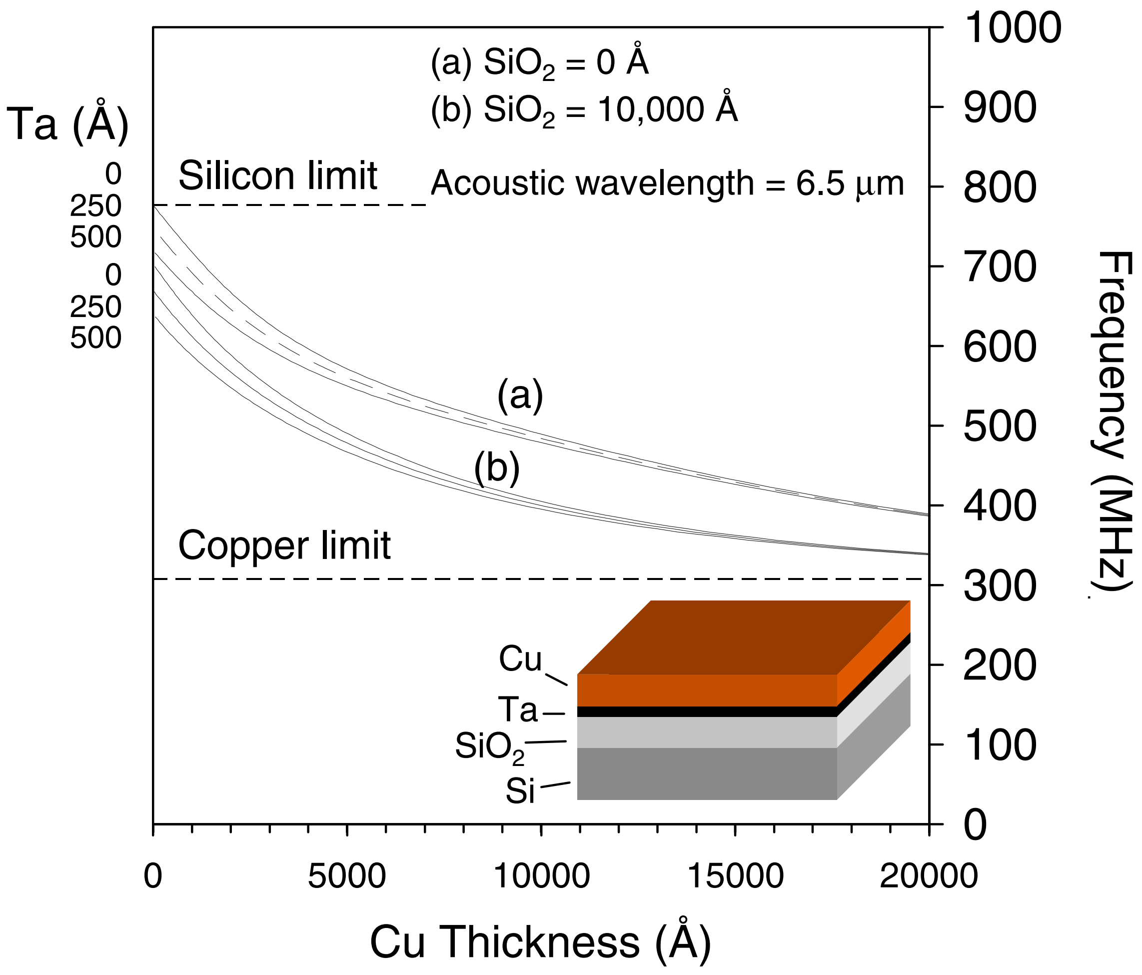


Analyze dominant frequency only.

$$S(t>0) \propto \Big[\underbrace{A_T \exp(-t/\tau)}_{\text{Thermal}} + \underbrace{A_1 \cdot G_1(t) \cdot \cos(2\pi F_1 t)}_{\text{First Mode}} + \underbrace{A_2 \cdot G_2(t) \cdot \cos(2\pi F_2 t) + \ldots}_{\text{Second Mode}}\Big]^2$$

*(Approximate description)*

# Frequency Versus Thickness

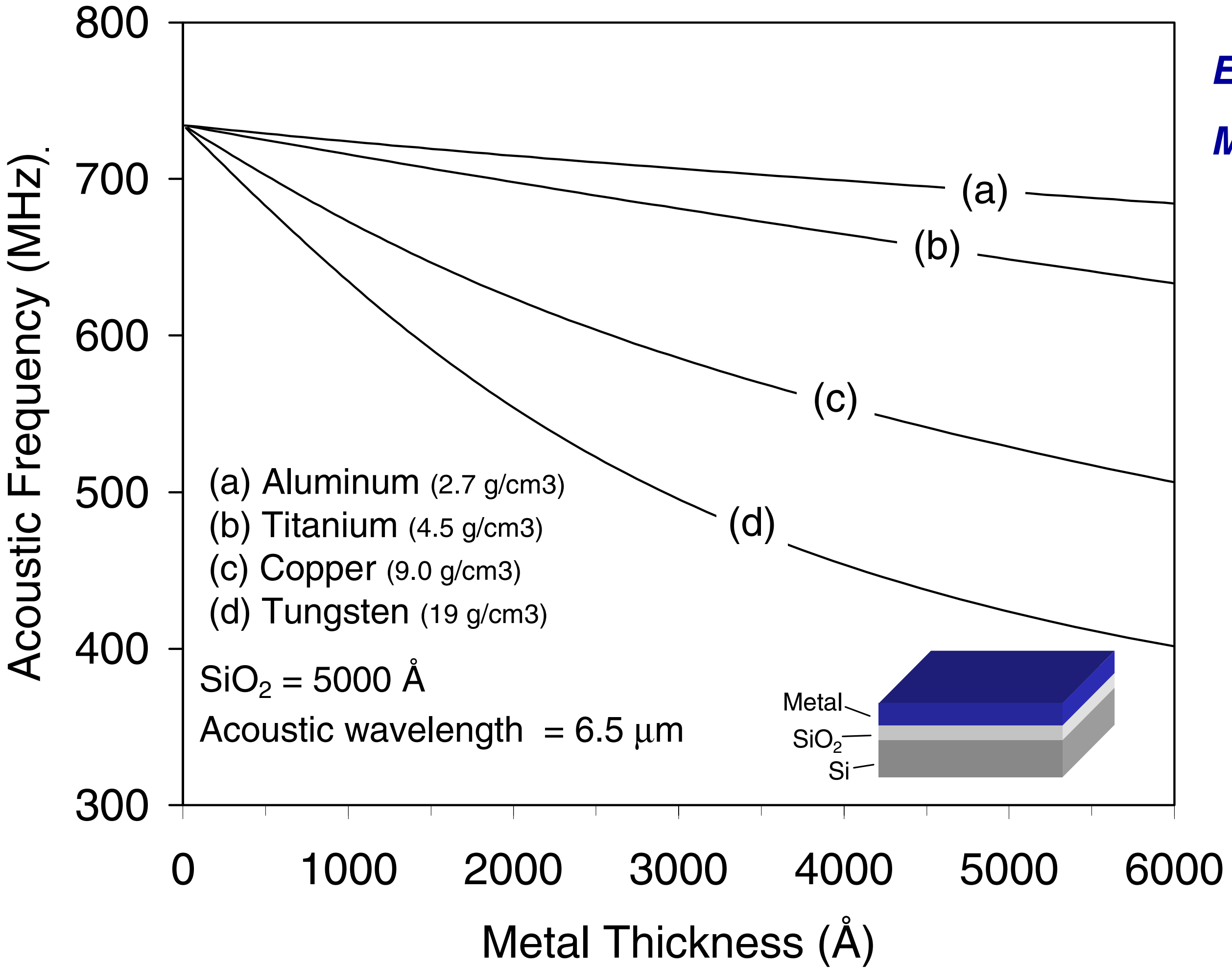


***Example:***

***Cu / Ta / $SiO_2$ / Si stack.***

- Thicker Cu = lower frequency.
- Measured frequency yields Cu thickness (if other layers are known)
- Frequency precision is ~0.05 MHz ➩ Cu precision ~1-2 Å

# Frequency vs Thickness and Material

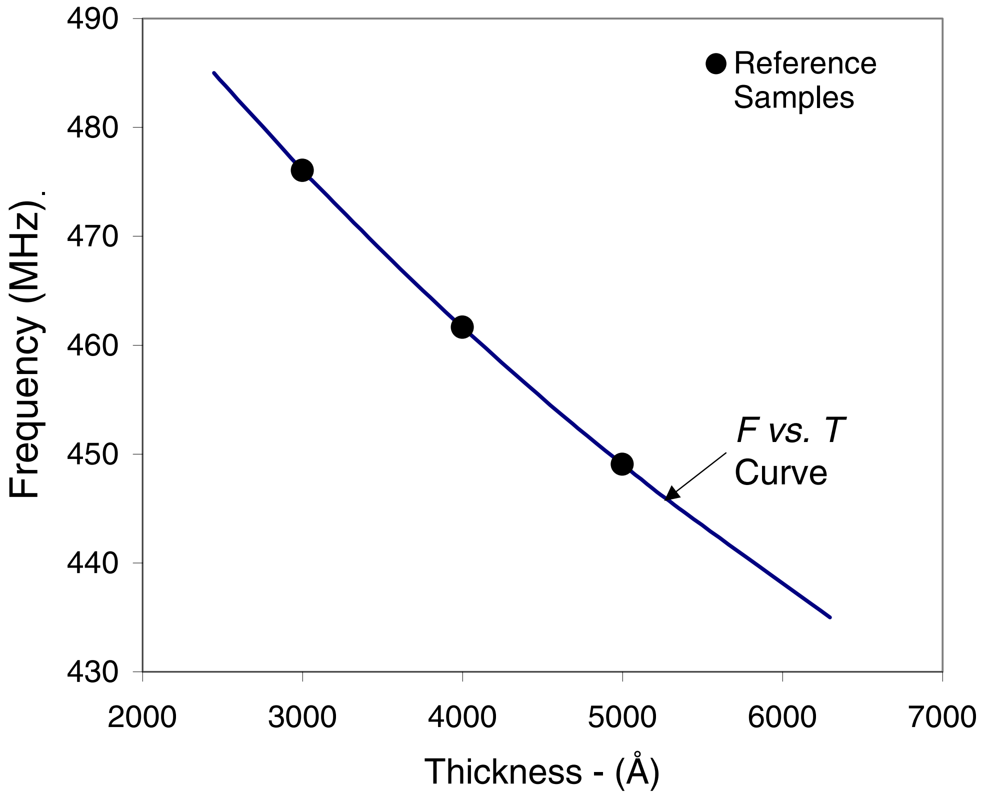


***Example:***

***Metal / $SiO_2$ / Si stack.***

- Denser metal = faster decrease in frequency per angstrom of metal.

# Calibration



Prepare 2 (or more) reference samples with different thickness - bracketing range of interest.

↓

Determine thickness with independent reference technique (e.g. SEM, XRR.)

↓

Measure acoustic frequency on opto-acoustic tool.

↓

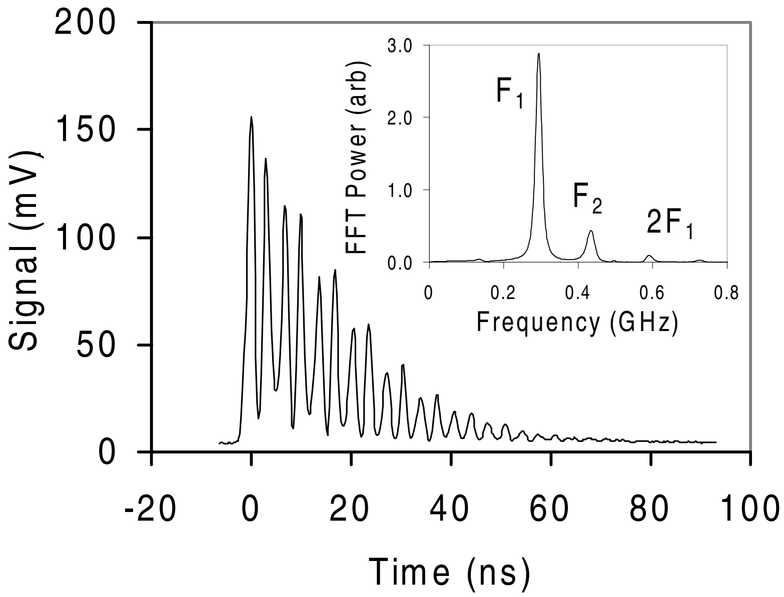
Adjust recipe parameters to get calibration curve matching the reference measurements.

↓

**Calibrated Recipe**

# Bi-Layer Measurement

# Bi-Layer Measurement - General



Analyze dominant frequency

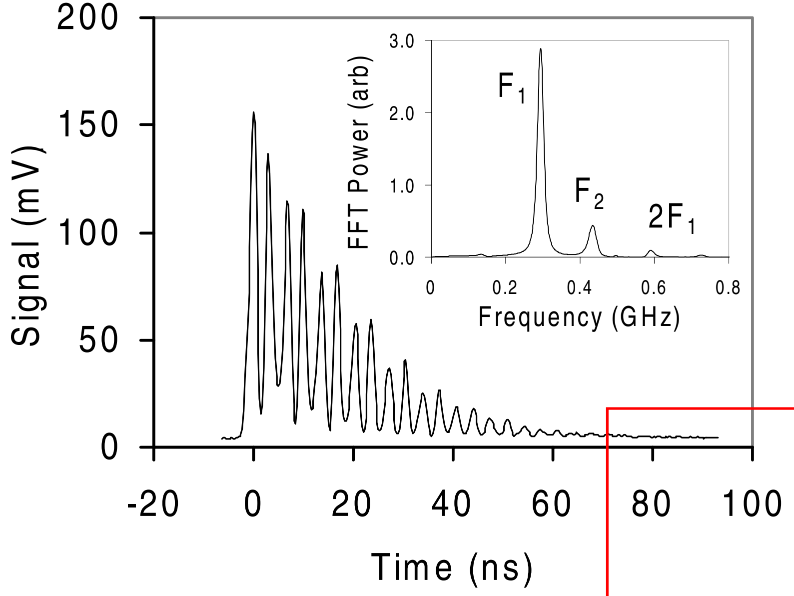
+

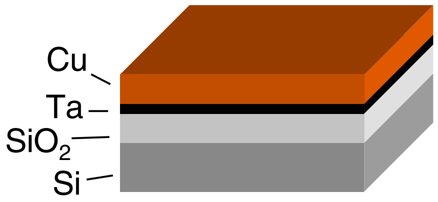
One other parameter.

$$S(t>0) \propto \Big[\overbrace{\underbrace{A_T \exp(-t/\tau)}_{\text{Thermal}} \;+\; \underbrace{A_1 \cdot G_1(t) \cdot \cos(2\pi \boxed{F_1 t})}_{\text{First Mode}} \;+\; \underbrace{A_2 \cdot G_2(t) \cdot \cos(2\pi F_2 t) \;+\; \ldots}_{\text{Second Mode}}}\Big]^2$$

*(Approximate description)*

# Example - Cu seed and Barrier





Analyze dominant frequency

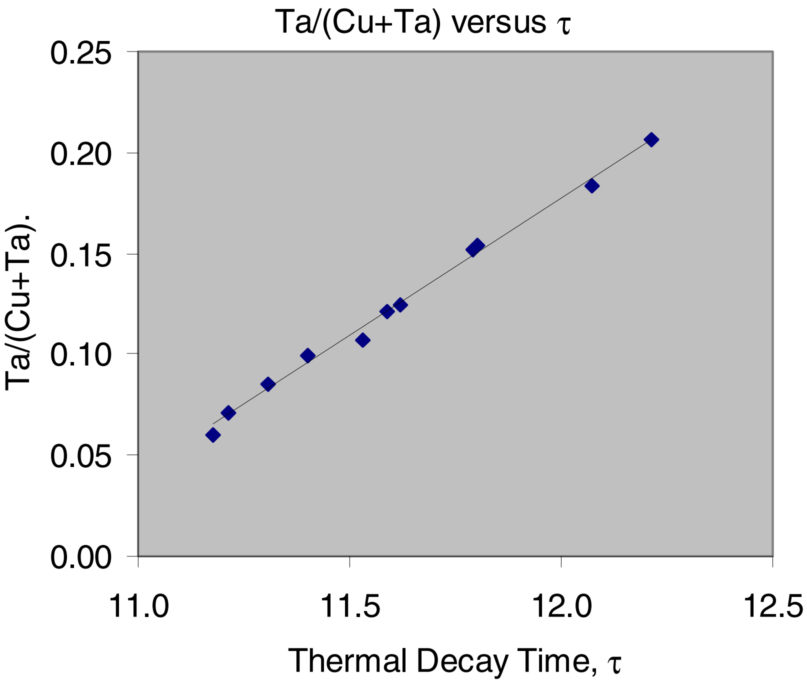
\+

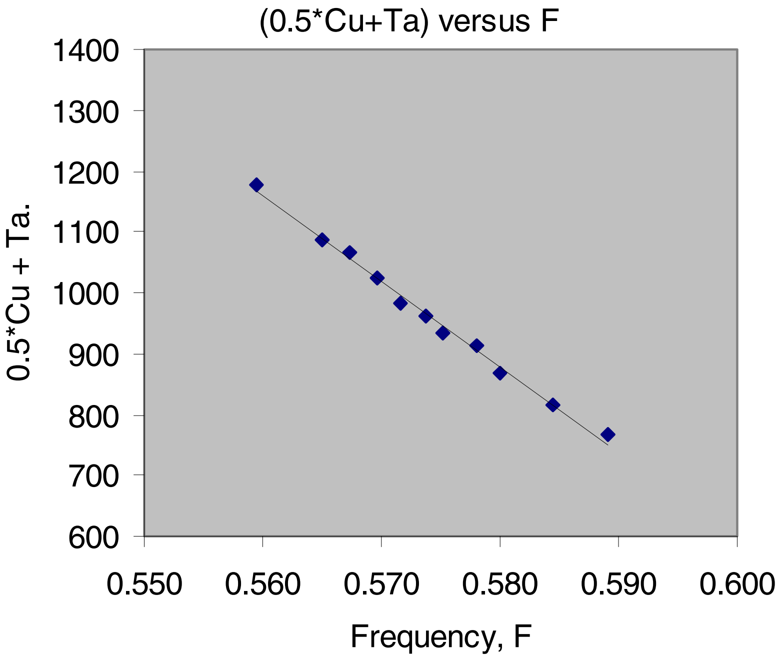
Thermal decay time

$$S(t>0) \propto \Big[\underbrace{A_T \exp(-t/\tau)}_{\text{Thermal}} + \underbrace{A_1 \cdot G_1(t) \cdot \cos(2\pi F_1 t)}_{\text{First Mode}} + \underbrace{A_2 \cdot G_2(t) \cdot \cos(2\pi F_2 t) \; + \; \ldots}_{\text{Second Mode}}\Big]^2$$

*(Approximate description)*

# Cu/Ta Bilayer Principle





**Thermal decay time correlates to Ta fraction (~Ta/(Ta+Cu)).**

**Frequency correlates to ~total metal mass (~0.5*Cu + Ta)**

# Cu/Ta Bilayer - Sample Results

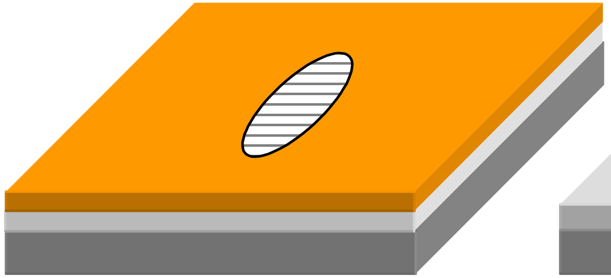
| Wafer Number | Cu |  |  | Ta |  |  |
|---|---|---|---|---|---|---|
|  | XRR (Å) | ISTS (Å) | Difference (Å) | XRR (Å) | ISTS (Å) | Difference (Å) |
| 1 | 1290 | 1284 | -6 | 121 | 124 | 3 |
| 2 | 1588 | 1627 | 39 | 121 | 114 | -7 |
| 3 | 1892 | 1868 | -24 | 120 | 131 | 11 |
| 4 | 1278 | 1284 | 6 | 176 | 184 | 8 |
| 5 | 1576 | 1618 | 42 | 174 | 173 | -1 |
| 6 | 1280 | 1301 | 21 | 228 | 232 | 4 |
| 7 | 1594 | 1608 | 14 | 226 | 224 | -2 |
| 8 | 1899 | 1820 | -79 | 227 | 244 | 17 |
| 9 | 1291 | 1326 | 35 | 289 | 282 | -7 |
| 10 | 1593 | 1560 | -33 | 289 | 296 | 7 |
| 11 | 1295 | 1301 | 6 | 337 | 333 | -4 |

The Cu and Ta were deposited on 4000 Å of $SiO_2$ atop Si wafers.

# Measurement on Patterns

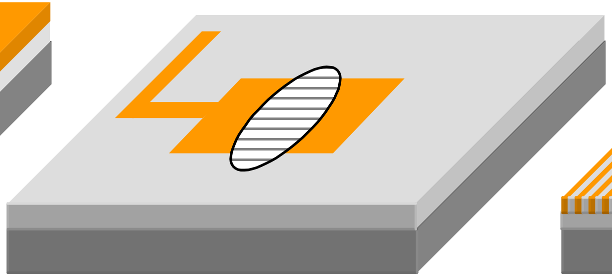
# Types of Measurement Sites

**Large Features**



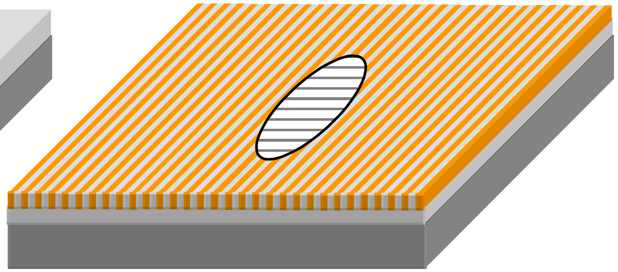
e.g. Blanket

**Intermediate**



e.g. Bond Pad

**Small Features**

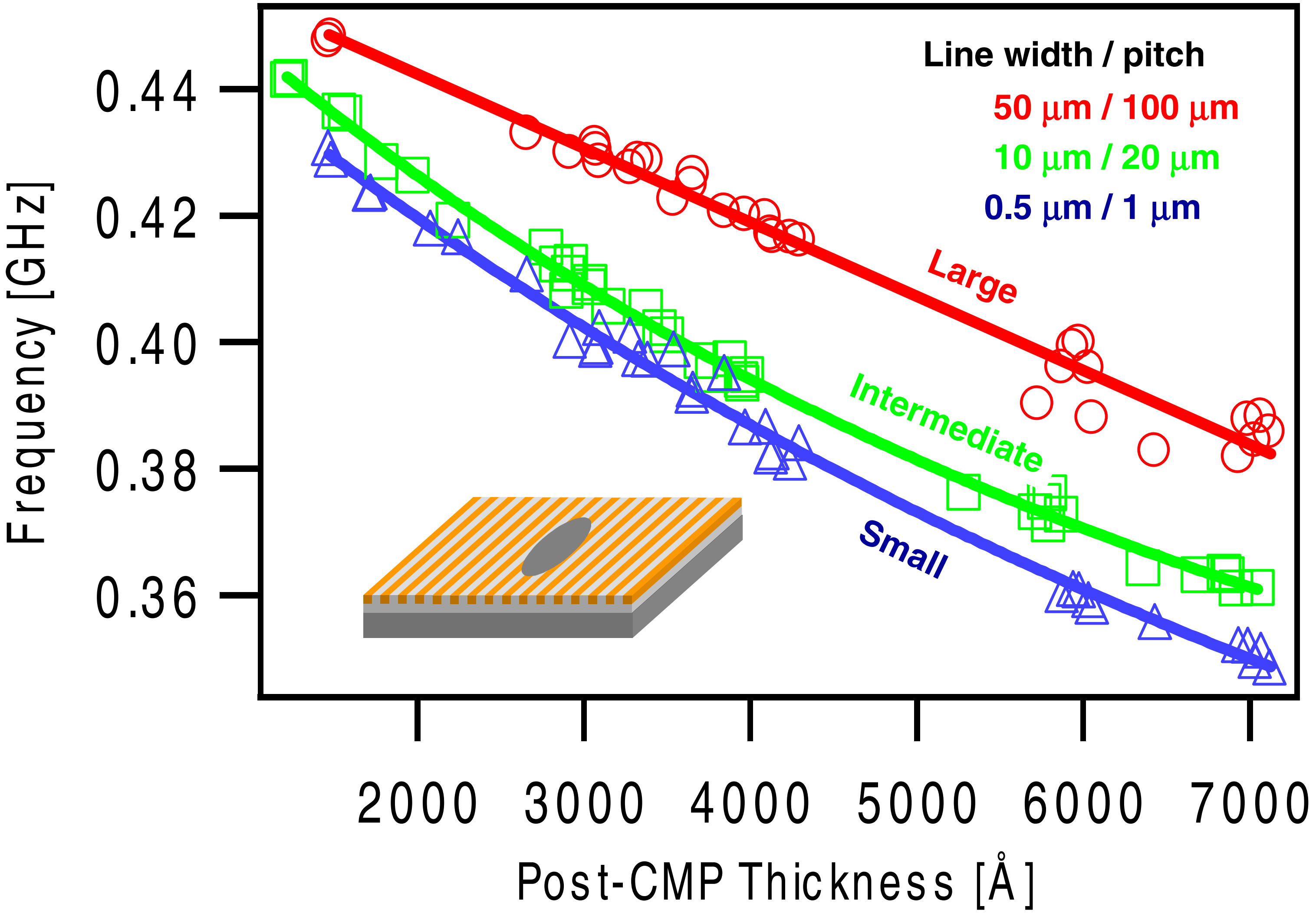


e.g. Sub-micron lines

(Probe averages over multiple lines)

## Compare feature size to probe spot ($\sim 25 \times 90\ \mu m$) and fringe spacing ($5\text{-}15\ \mu m$)

# Calibration on Patterns

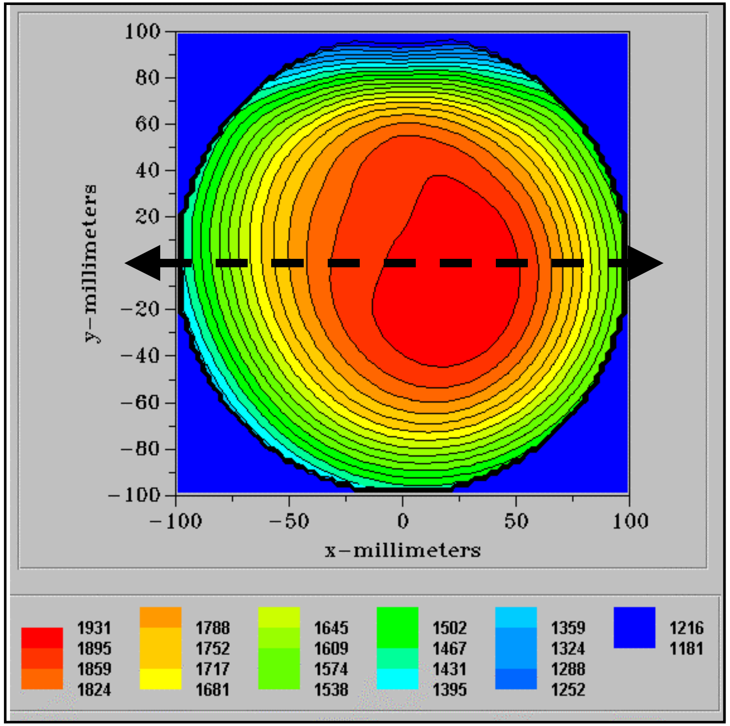


# Applications

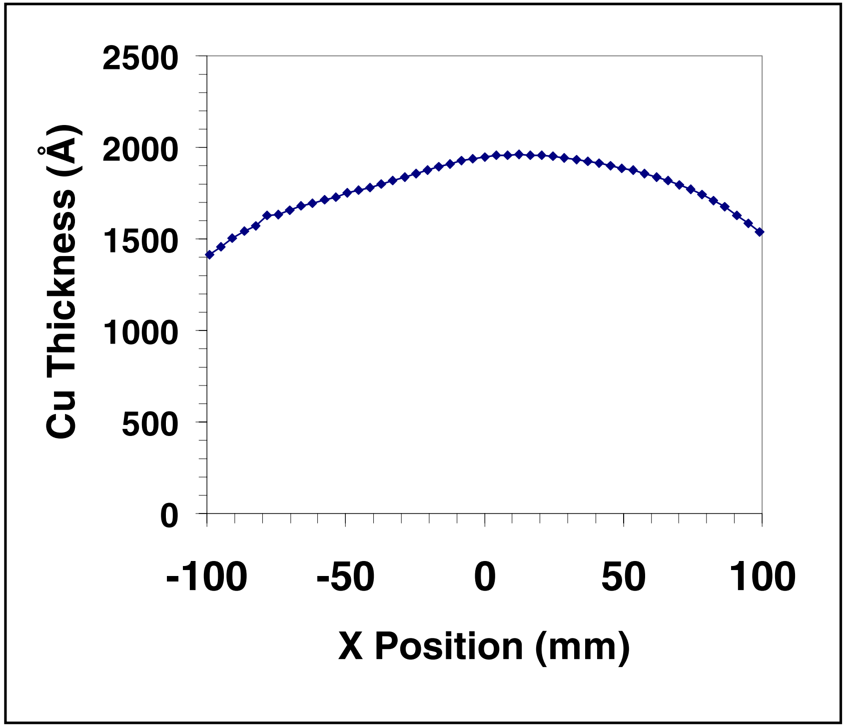
# Contours and Uniformity of Cu Seed Layer

**Film: Si / 100 Å Oxide / 250 Å Ta / 2000 Å PVD Cu**

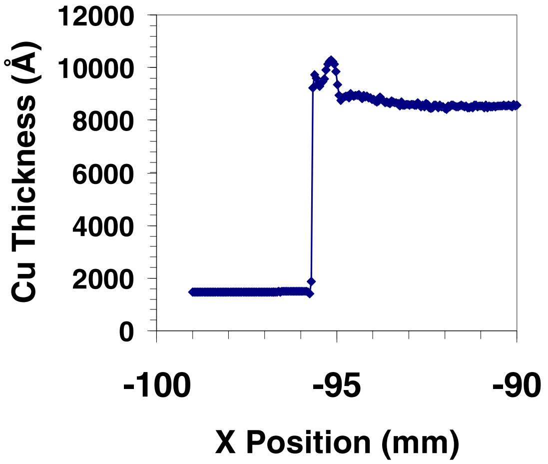
**49-pt Map**



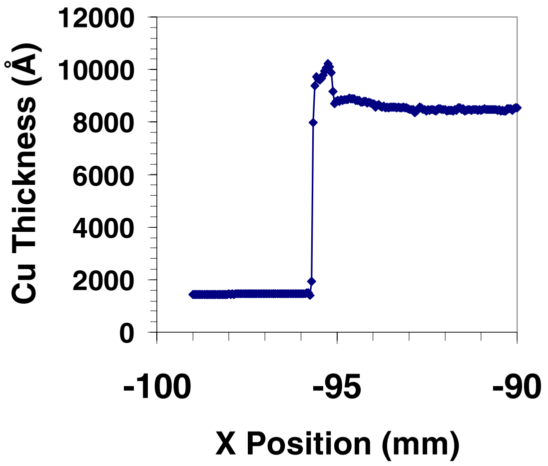
**Diameter Scan**



# Ridges at Edges of ECD Cu Films

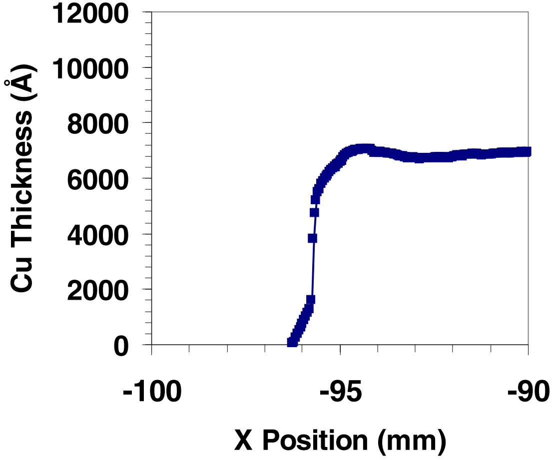


ECD Cu / Ta / SiO2



ECD Cu / Ta / SiO2

+ Anneal



ECD Cu / Ta / SiO2

+ Anneal

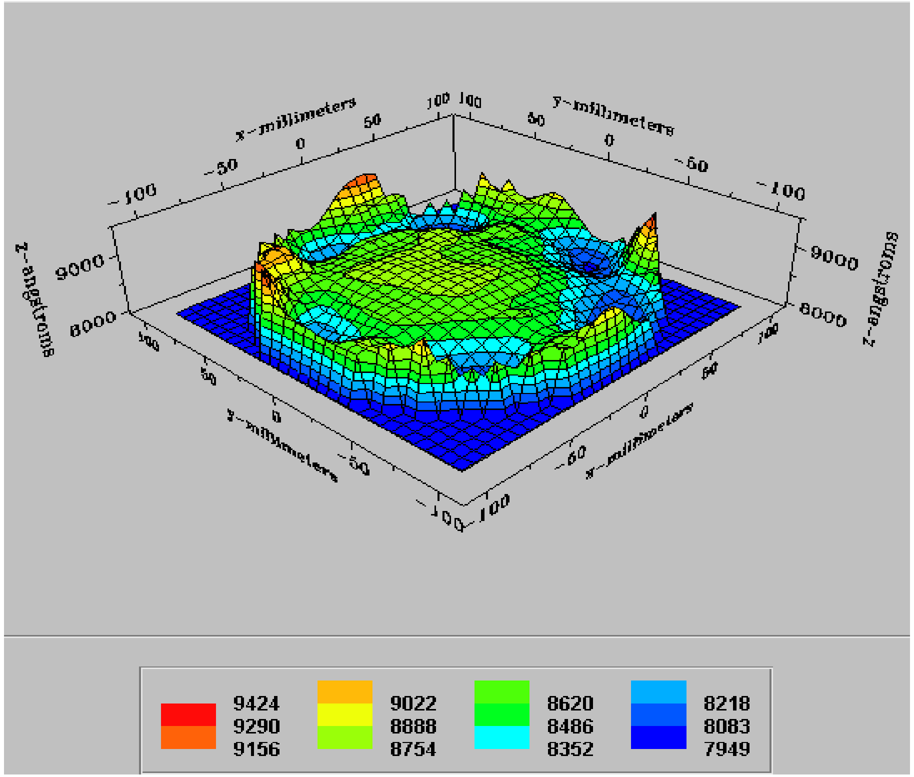
+ CMP

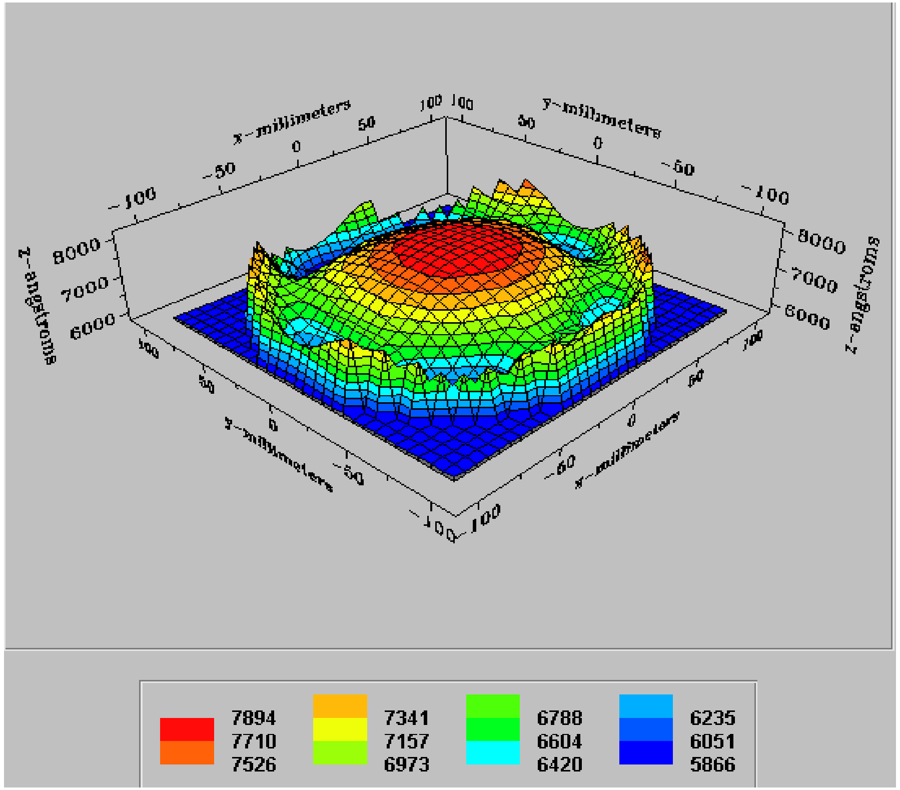
# Full-Wafer Thickness Maps for CMP Performance Analysis

ECD Copper wafer before CMP

225 points

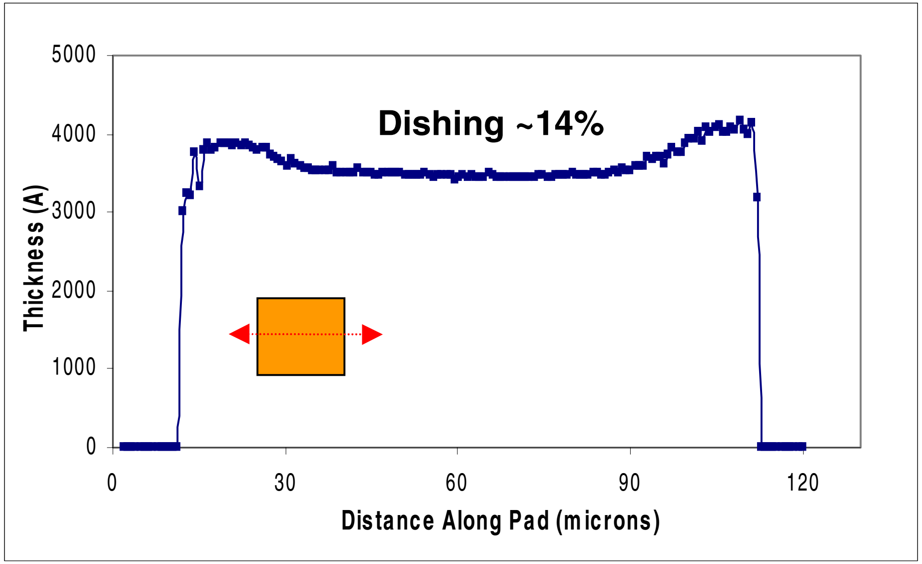
ECD Copper wafer after CMP



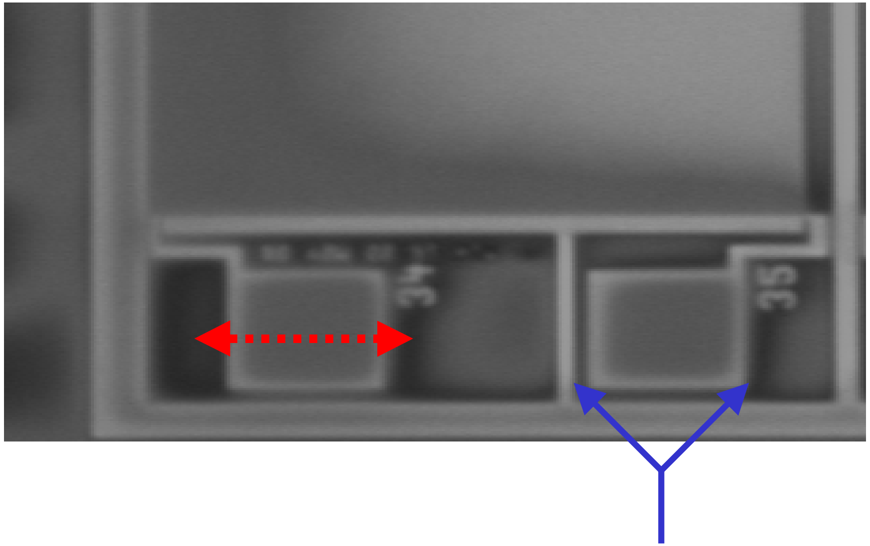


**Conformal polishing - CMP did not correct the incoming topography**

# Post-CMP Copper Dishing Measurement: Line Scan Across Bond Pad



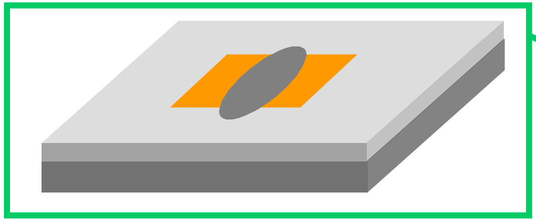
***Line scans indicate dishing in bond pads***

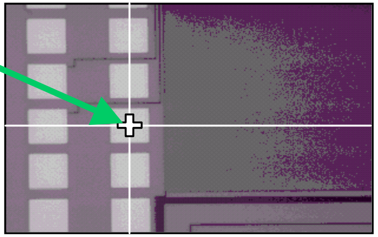


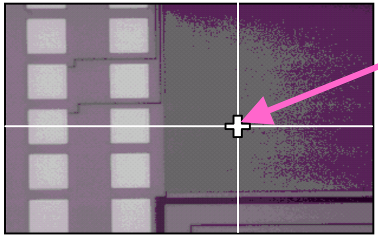
***Visible indication of dishing***

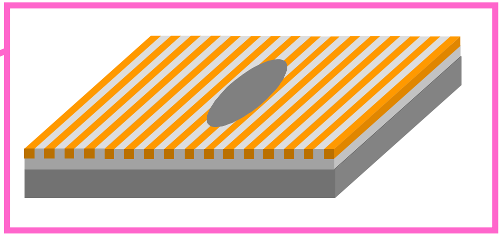
# Post-CMP On-Product Non-Uniformity Measurements

## Within-Wafer Non-Uniformity is Feature-Dependent!







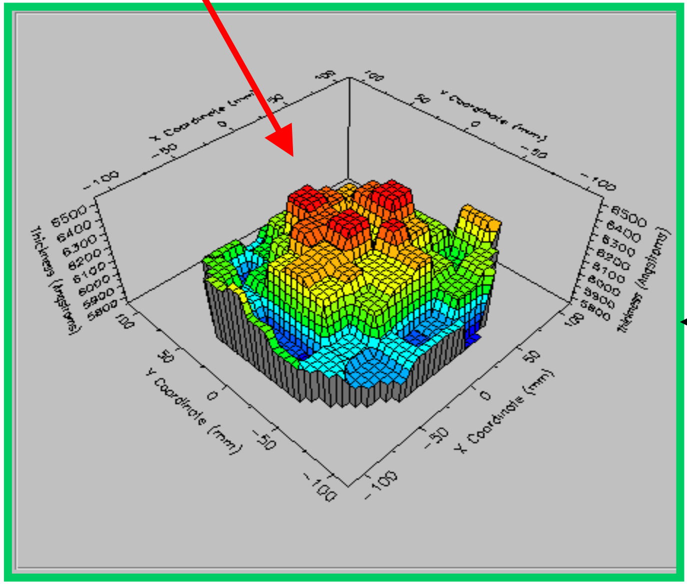


**100x100 µm Pads**

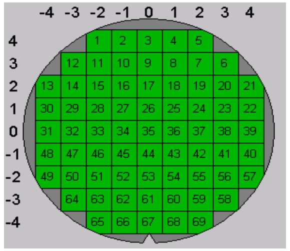
*Center-Slow Polishing*

**Sub-micron Lines**

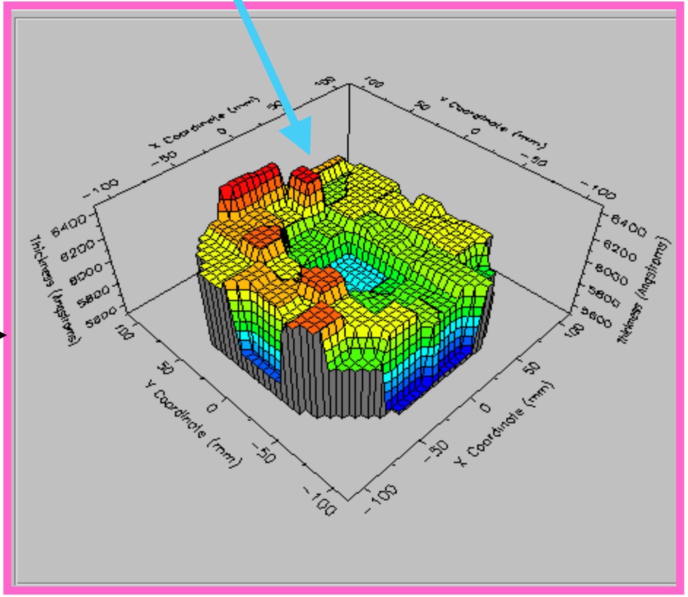
*Center-Fast Polishing*



**Rapid Full-Wafer Mapping**



|  | -4 | -3 | -2 | -1 | 0 | 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| 4 |  |  | 1 | 2 | 3 | 4 | 5 |  |  |
| 3 |  | 12 | 11 | 10 | 9 | 8 | 7 | 6 |  |
| 2 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 |
| 1 | 30 | 29 | 28 | 27 | 26 | 25 | 24 | 23 | 22 |
| 0 | 31 | 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 |
| -1 | 48 | 47 | 46 | 45 | 44 | 43 | 42 | 41 | 40 |
| -2 | 49 | 50 | 51 | 52 | 53 | 54 | 55 | 56 | 57 |
| -3 |  | 64 | 63 | 62 | 61 | 60 | 59 | 58 |  |
| -4 |  |  | 65 | 66 | 67 | 68 | 69 |  |  |

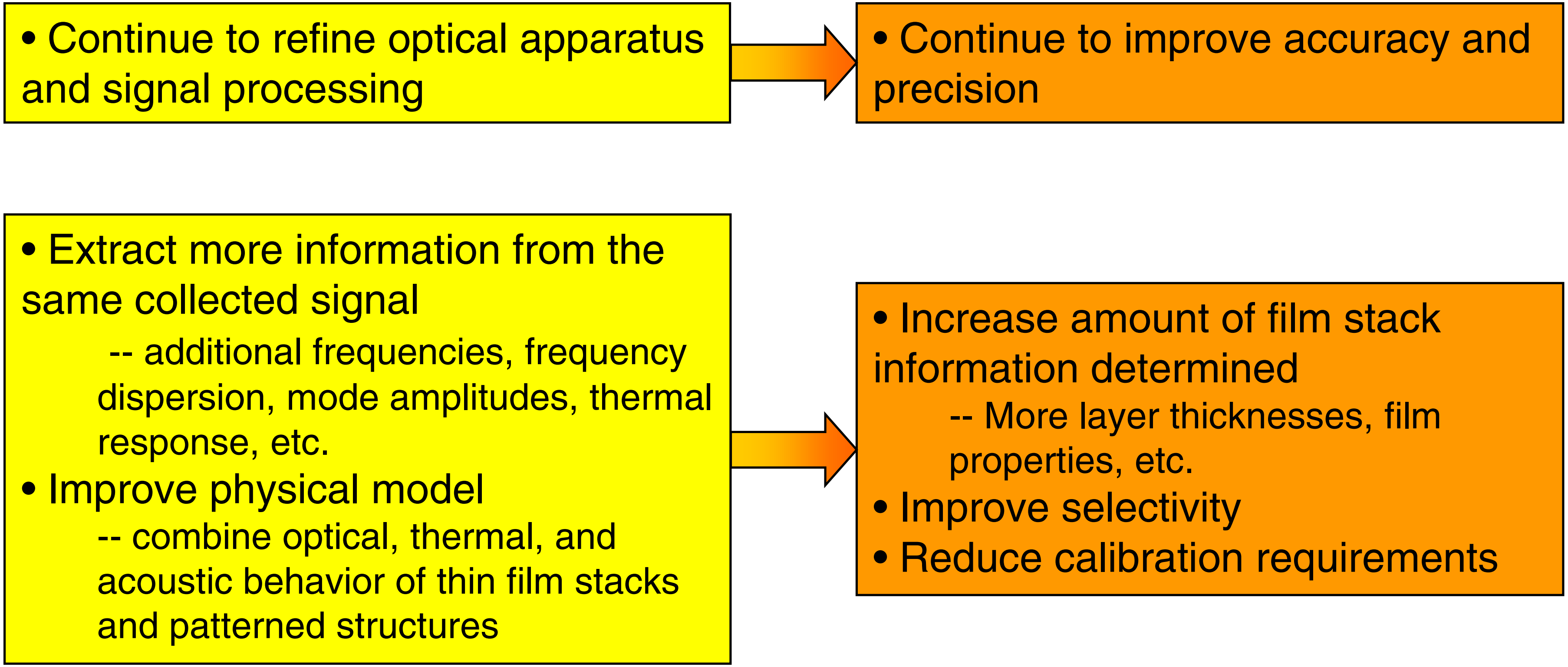


2000 International Conference on Characterization and Metrology for ULSI Technology, June 2000

**Philips Analytical**

# Future Directions

# Future Directions



- Continue to refine optical apparatus and signal processing

- Continue to improve accuracy and precision

- Extract more information from the same collected signal
  -- additional frequencies, frequency dispersion, mode amplitudes, thermal response, etc.
- Improve physical model
  -- combine optical, thermal, and acoustic behavior of thin film stacks and patterned structures

- Increase amount of film stack information determined
  -- More layer thicknesses, film properties, etc.
- Improve selectivity
- Reduce calibration requirements

# Acknowledgements

- SEMATECH
- NIST
- Novellus
- Applied Materials
- Philips Analytical Tempe applications lab