Semiconductor Related Programs at NIST

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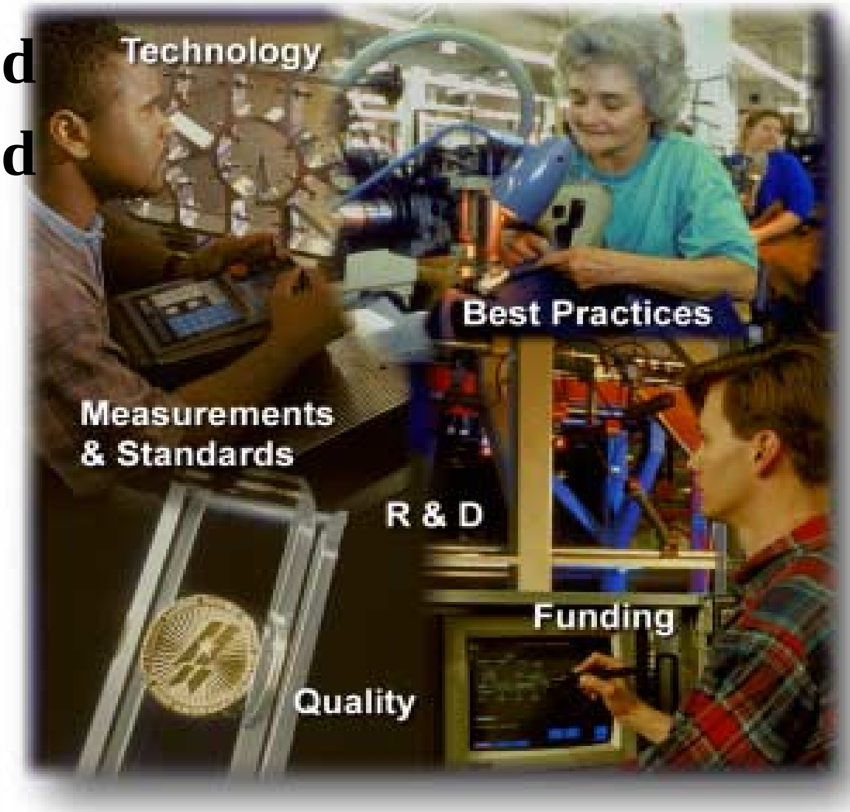
Outline

- Brief Introduction to NIST
- Areas of Work
- Applications
- Summary

National Institute of Standards and Technology

NIST strengthens the U.S. economy and improves the quality of life by working with industry to develop and apply technology, measurements, and standards.



NIST Assets Include:

- **National measurement standards**
- **3,200 employees**
- **$720 million annual budget**
- **1,200 industrial partners**
- **2,000 field agents**
- **1,600 guest researchers**
- **$1.6 billion R&D partnerships with industry**
- **Baldrige Quality Award**

NIST Major Programs

NIST Laboratories

Nation's ultimate reference point for measurements and standards to support industry, science, health care, safety, defense.

Baldrige National Quality Program

Annual Baldrige awards in manufacturing, service, small business, education, and health care promote business excellence.

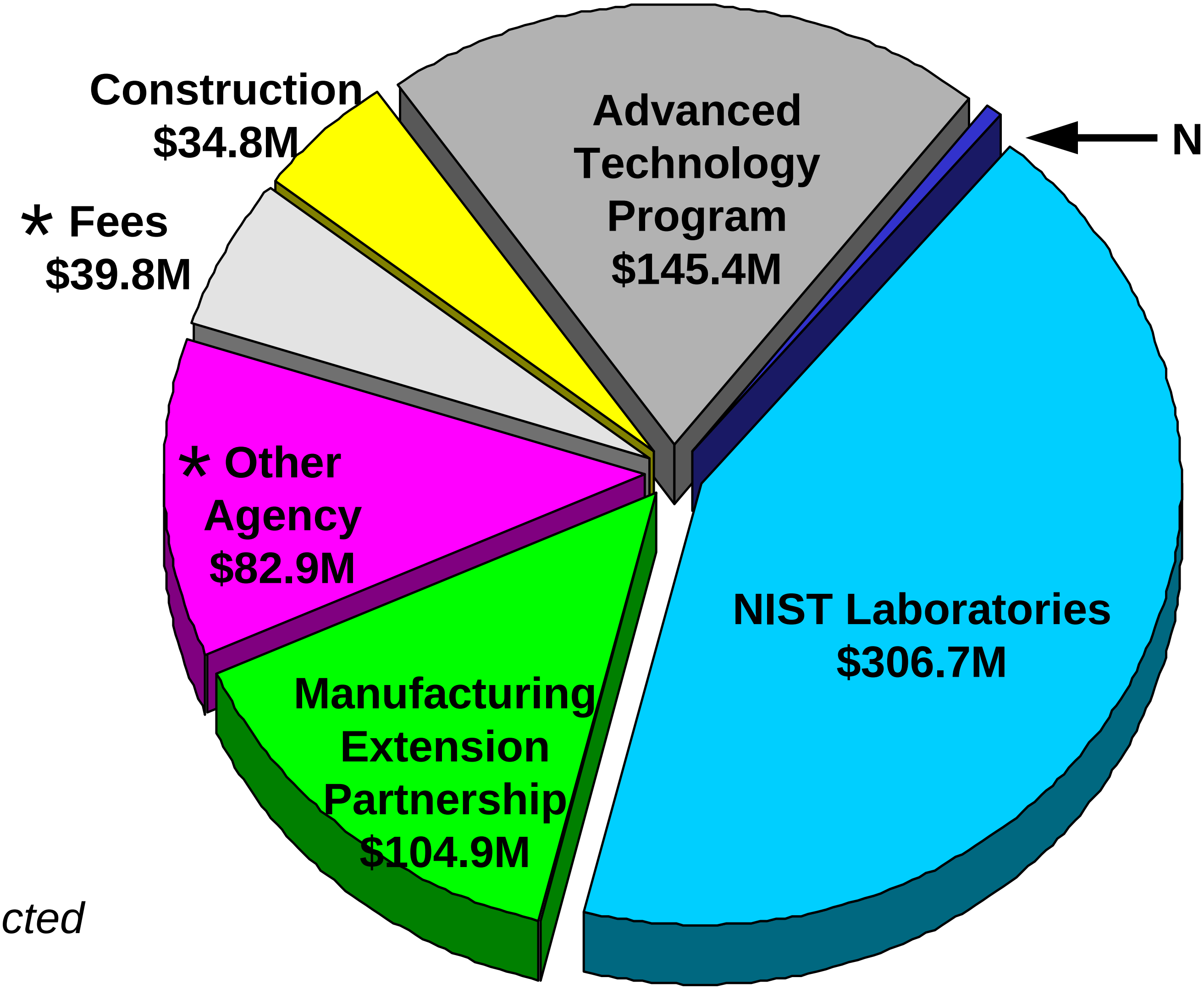
Advanced Technology Program

R&D partnerships with private sector to develop broadly beneficial new technologies.

Manufacturing Extension Partnership

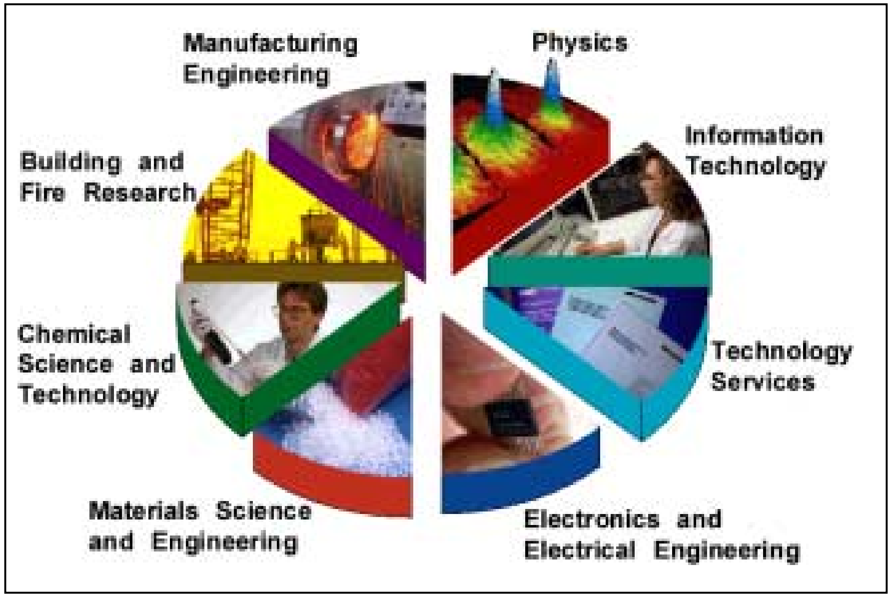
Nationwide network of extension centers assisting the Nation's 385,000 smaller manufacturers in all 50 states and Puerto Rico.

NIST FY2001 Budget



* *Projected*

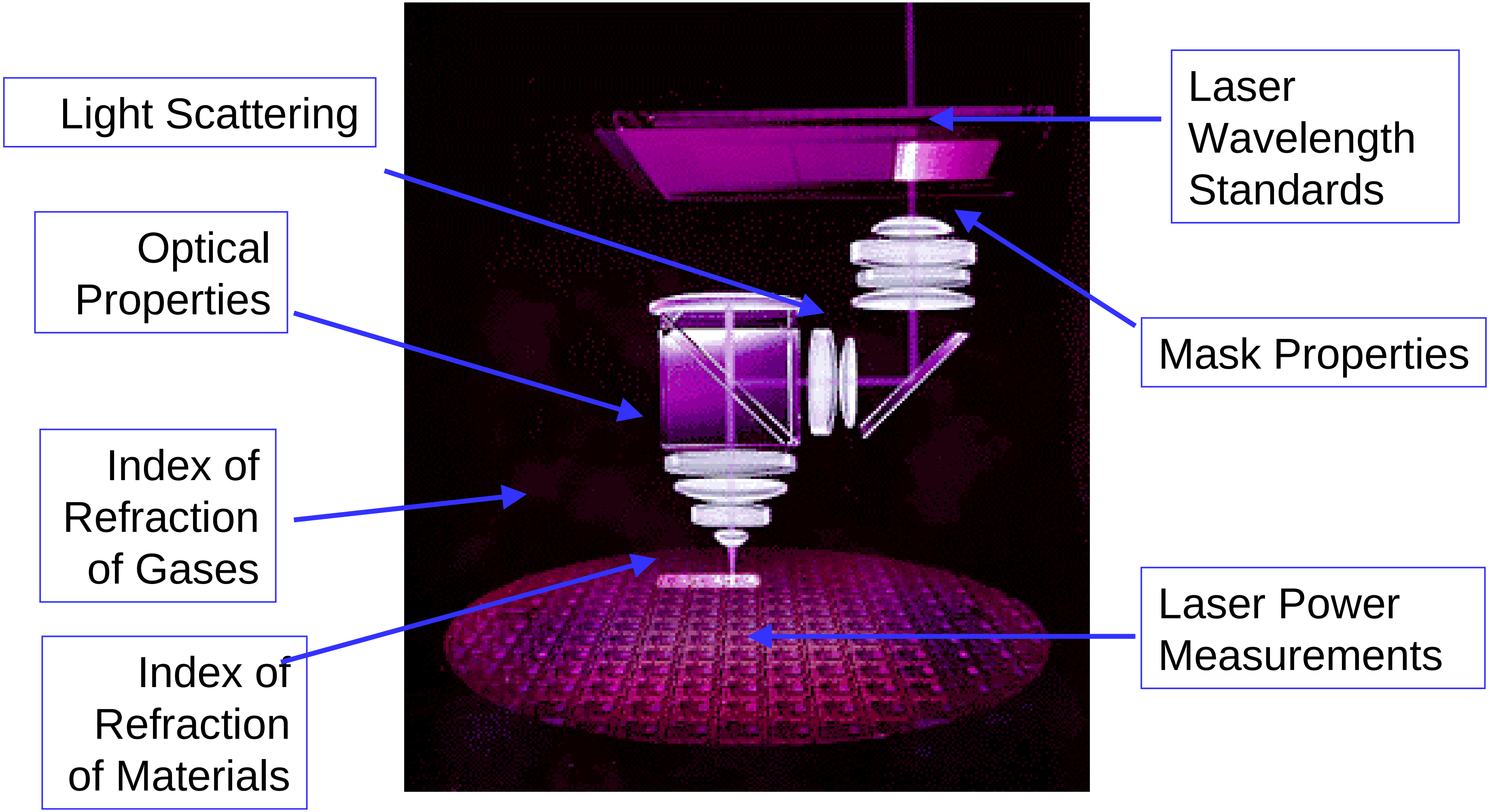
NIST Laboratories



- **Measurements and standards are critical enablers of the technology infrastructure**
- **Serve the American people through support of all major economic and scientific activities including:**
- **Health care**
  - Standards for clinical tests, radiation diagnostics and treatment, many others.
- **Manufacturing**
  - Semiconductors, automotive, discrete parts, many others.
  - Dimensional standards, chemical and physical properties data, many others.
- **Information technology & telecommunications**
  - Standards and tests for computer security, interoperability, software performance, communications infrastructure, many others

NIST Measurements & Standards for Manufacturing

NIST support for the entire lithography process to manufacture microelectronic devices



Light Scattering

Optical Properties

Index of Refraction of Gases

Index of Refraction of Materials

Laser Wavelength Standards

Mask Properties

Laser Power Measurements

Areas of Work

- Lithography Metrology
- Critical Dimension and Overlay Metrology
- Thin Film and Shallow Junction Metrology
- Interconnect and Packaging Metrology
- Wafer Characterization and Process Metrology
- Test Metrology

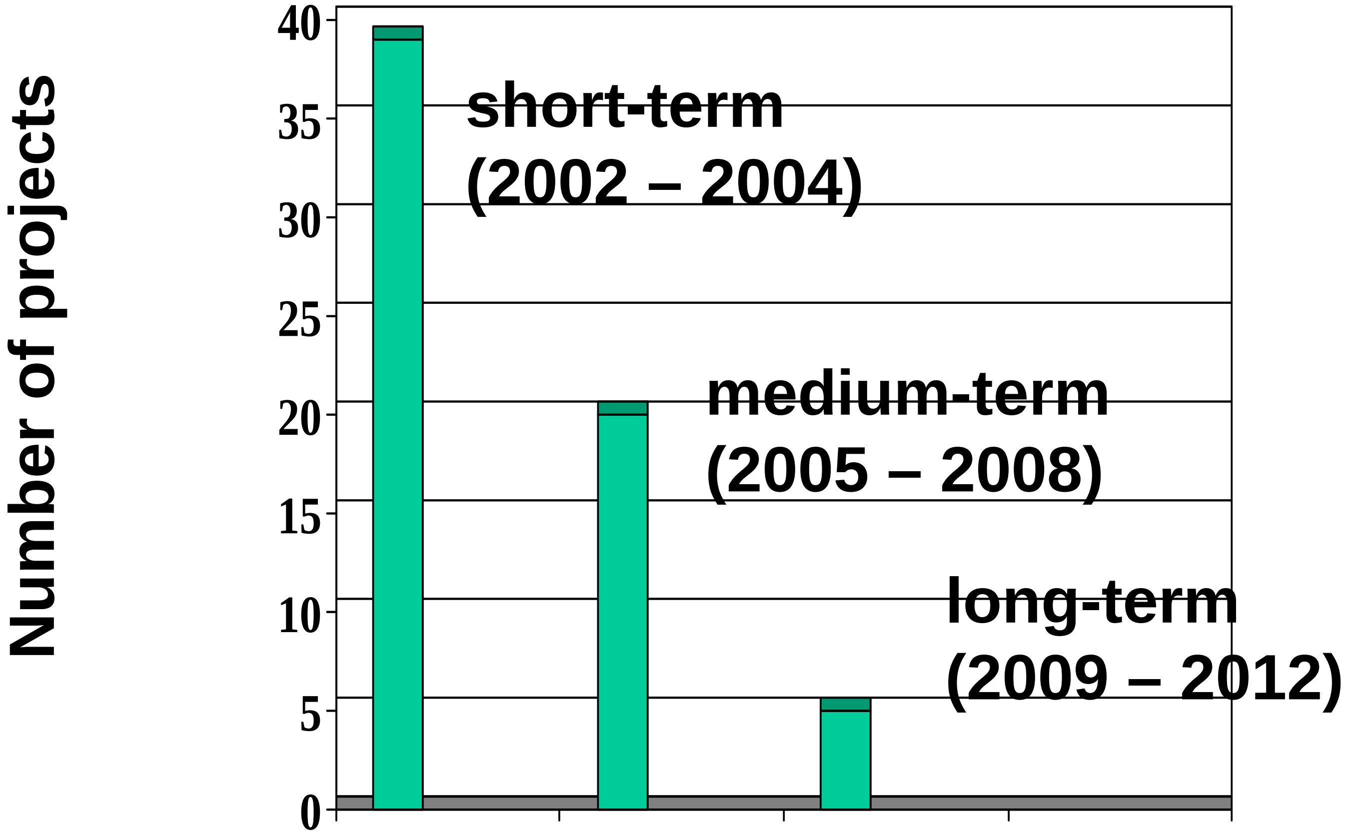
Areas of Work (2)

- Lithography Metrology
  - 3 Projects
- Critical Dimension and Overlay Metrology
  - 6 Projects
- Thin Film and Shallow Junction Metrology
  - 3 Projects

Areas of Work (3)

- Interconnect and Packaging Metrology
  - ☐ 8 Projects
- Wafer Characterization and Process Metrology
  - ☐ 10 Projects
- Test Metrology
  - ☐ 2 Projects

Time Base of Programs



Applications

Intrinsic Birefringence of CaF_2

Birefringence in Cubic Crystals

I. Stress-Induced Birefringence

grown-in or externally applied (mounts, gravity, etc.)

- variable magnitude and orientation (sample-to-sample and within sample)
- weak dispersion visible-UV (NIST-SEMATECH 157 Review 11/00)
- can in principle be reduced to any desired value

II. Intrinsic Birefringence

due to symmetry breaking effect of finite q of photon at short λ

preliminary measurements in CaF_2 (above 157nm and 193nm target values)

- magnitude and orientation fixed by crystal (no sample dep., uniform)
- strong dispersion $\sim 1/\lambda^2$
- CANNOT be reduced! (inherent property of crystal)

(but since fully predictable and symmetric, can be corrected for in principle)

Has been measured in, e.g., Si[1] and GaAs[2]

[1] J. Pastrnak and K. Vedam, Phys. Rev. B **3**, 2567 (1971).

[2] P.Y. Yu and M. Cardona, Solid State Commun. **9**, 1421 (1971).

Implications

1) Intrinsic birefringence $\Delta n(157\text{ nm}) \approx 6.5 \times 10^{-7}$ (6.5 nm/cm)

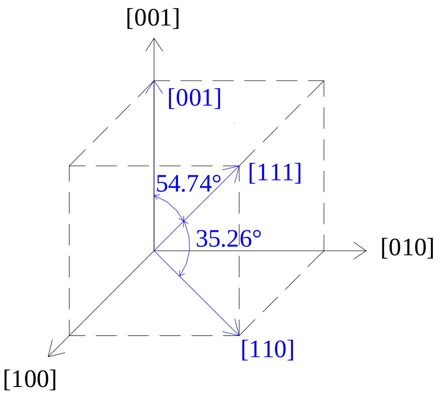
- exceeds birefringence target value for 157 nm lithography (1 nm/cm) (1st Int. Symp. On 157 nm Lithography, May 2000)

2) Intrinsic birefringence $\Delta n(193\text{nm}) = 3.6 \times 10^{-7}$ (3.6 nm/cm)

- may exceed birefringence requirements of 193 nm lithography

3) $\Delta n = 0$ for [111] direction (lens orientation)

- but [110] only $\theta = \cos^{-1}(2/3)^{1/2} = 35.26°$ away
- concern for high NA systems



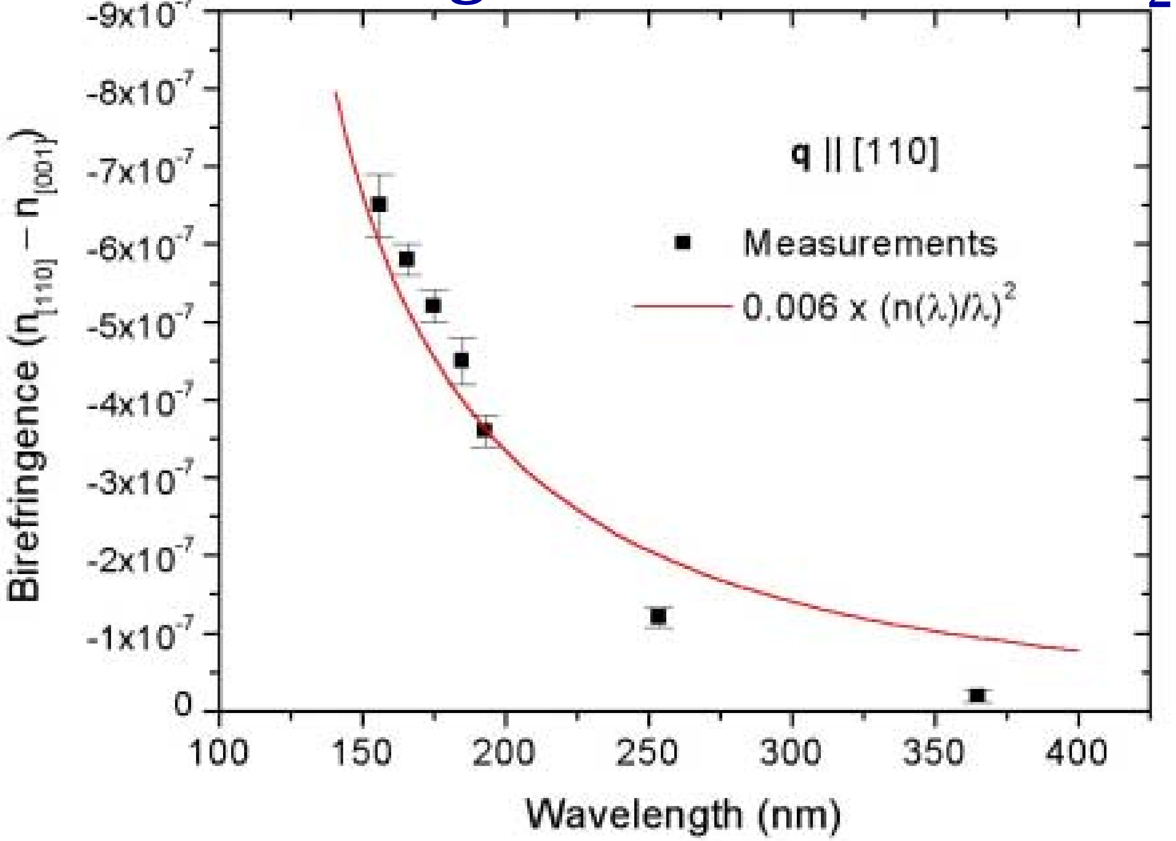
4) Good news: effect completely predictable and symmetric

- thus can correct for in principle

5) Need to know the full angle dependence of the effect

- fortunately this is completely determined by symmetry alone

Birefringence Results for CaF_2



Measurements of Birefringence of CaF_2 in the UV

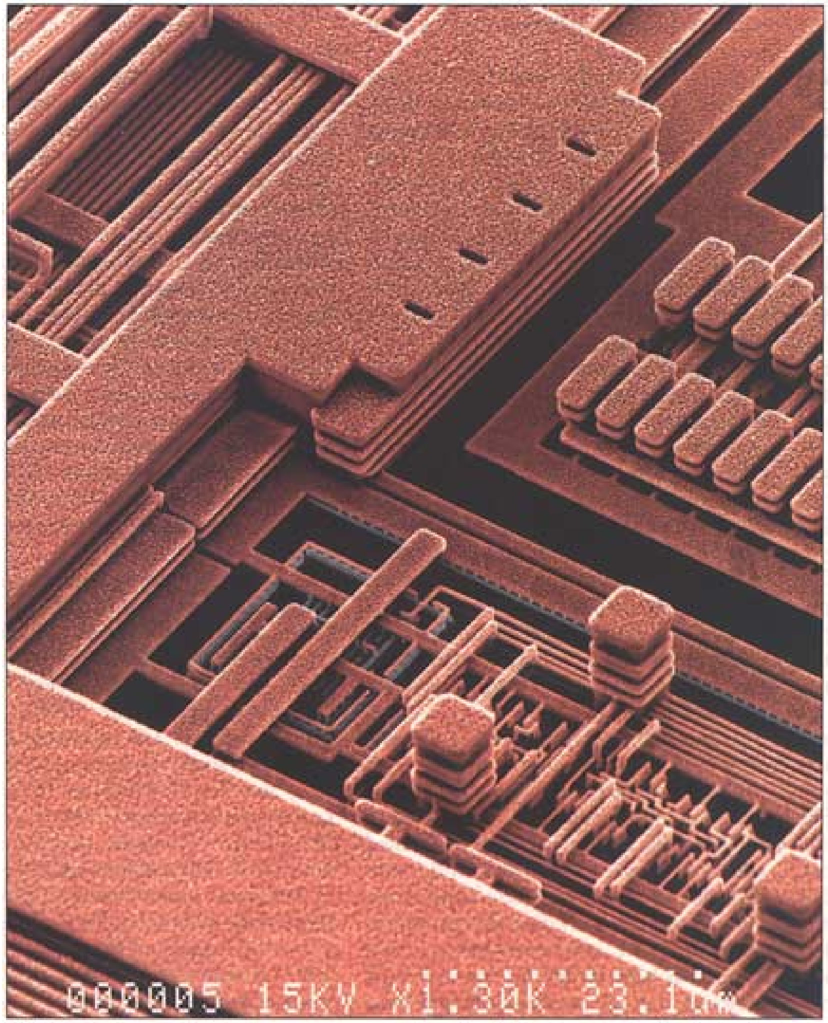
Wavelength (nm)	Line Source	$10^7\times(n_{<\bar{1}10>} - n_{<001>})$
365.062	Hg I	-0.19 ± 0.08
253.652	Hg I	-1.2 ± 0.1
193.09	C I	-3.6 ± 0.2
184.95	C I	-4.5 ± 0.3
175.19	C I	-5.2 ± 0.2
165.72	C I	-5.8 ± 0.2
156.10	C I	-6.5 ± 0.4

$$\mathbf{q} \parallel [001] \rightarrow \Delta n = 0$$

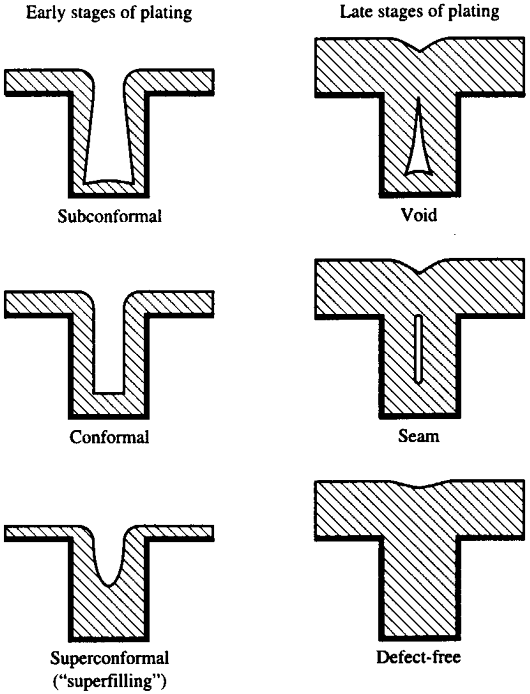
$$\mathbf{q} \parallel [111] \rightarrow \Delta n = 0$$

Electroplating of Cu

Electrolytic Copper
On-Chip Metallization



[1] IBM Corp.'s new CMOS 7S process for manufacturing ICs uses copper for its six levels of interconnections, and has effective transistor channel-lengths of only 0.12 µm. It is the first commercial fabrication process to use copper wires [see "The Damascus connection," p. 25].



Physical Vapor Deposition (PVD)
Chemical Vapor Deposition (CVD)
Electrodeposition
"superconformal deposition"

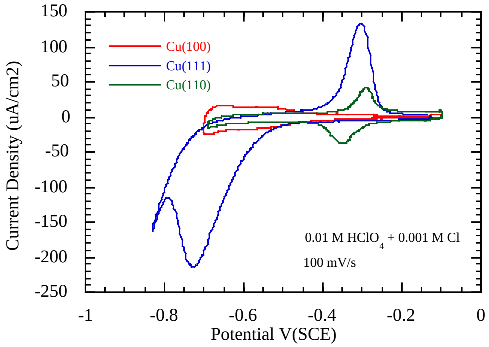
The Problem: Copper Metallization – 5-10 Years Out

ITRS --> several interconnect roadblocks at 70 nm node (2008)

Input: 1999 Advanced Metallization Conf.
Panos Andricacos (IBM)
Richard Alkire (Illinois)
Alan West (Columbia)
Tom Ritzdorf (Semitool)

Superconformal Deposition

extendibility beyond 100 nm (?)
lack of fundamental understanding



Why NIST? Expertise

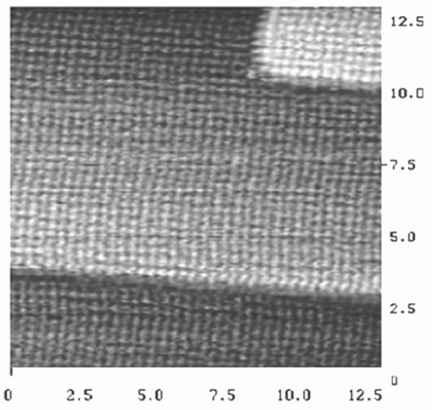
- electrochemistry
- surface characterization
- electron microscopy
- lithography

Environment

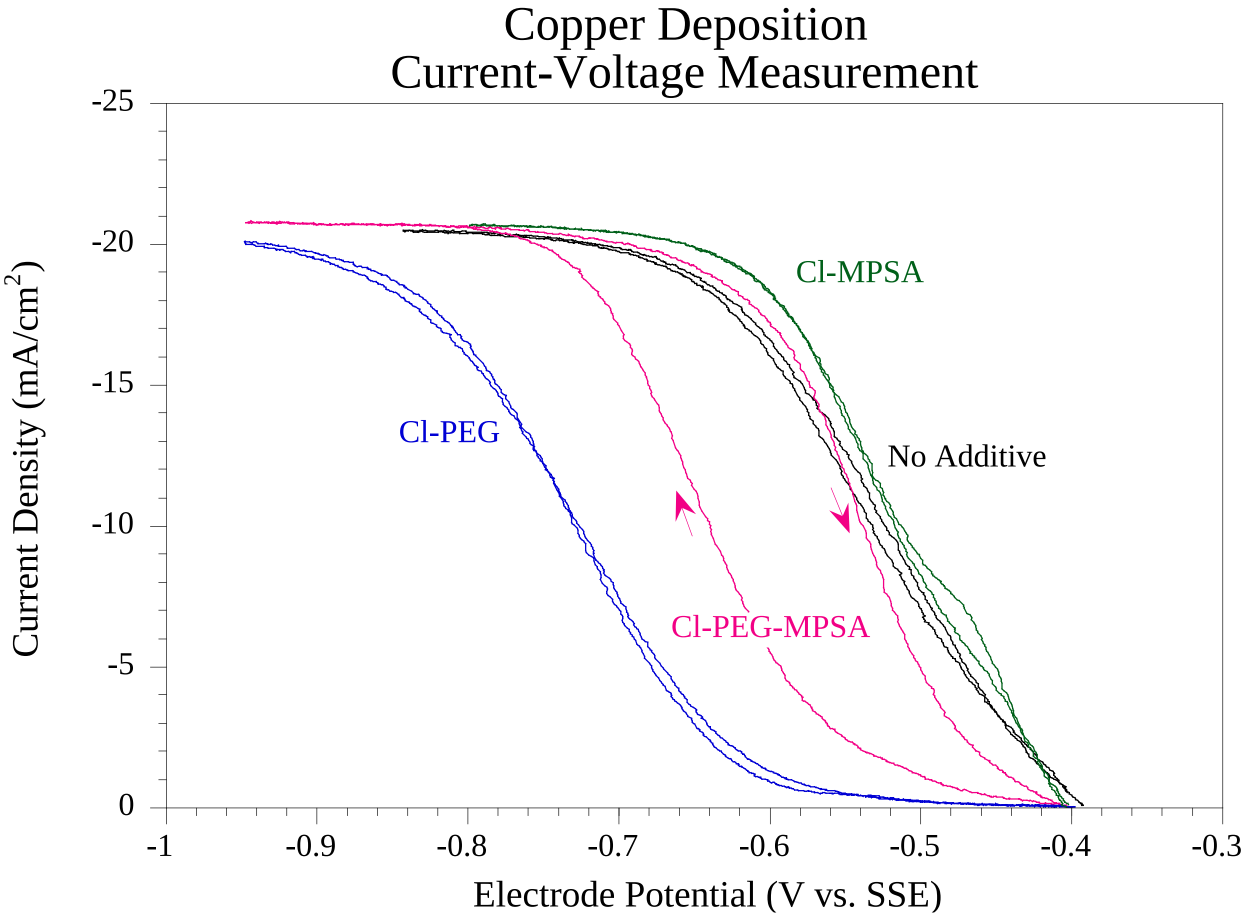
- fosters collaboration
- 3+ years out

Broad Application

- fundamental electrodeposition issues
- measurement opportunities
- MEMS/NEMS



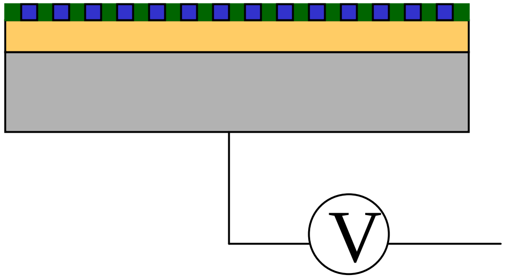
Cl-PEG-MPSA → Hysteresis in Cu Kinetics



Cl-PEG-MPSA

Competitive Adsorption

$Cu^{2+} + 2e^{-} \rightarrow Cu$



All data needed for the model obtained directly from hysteresis measurements on *planar electrodes*

Local time-dependent surface coverage:

$$\frac{d\theta}{dt} = k_{eff}C_i\left(1-\theta\right) + \frac{i\Omega}{2F}\kappa\theta$$

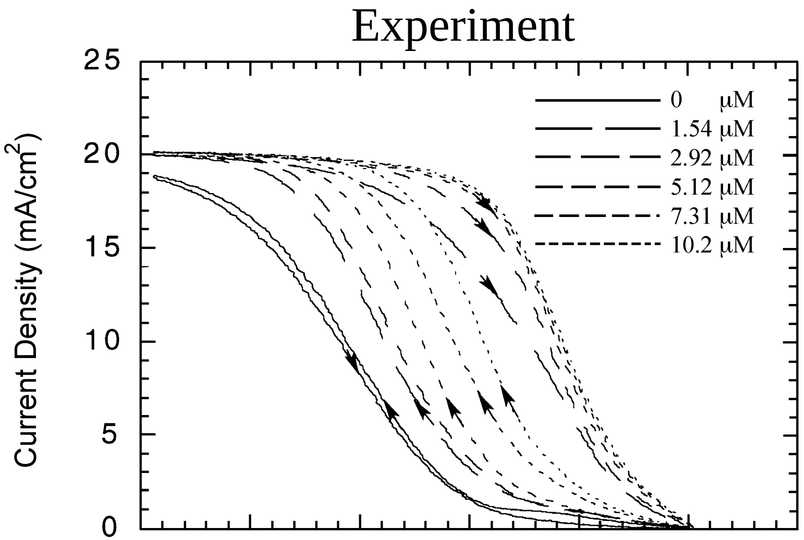
$\kappa = 0$ on flat electrodes,

$$\frac{d\theta}{dt} = k_{eff}C_i\left(1-\theta\right) = \frac{D_{MPSA}}{\Gamma}\frac{\left(C_{MPSA} - C_i\right)}{\delta}$$

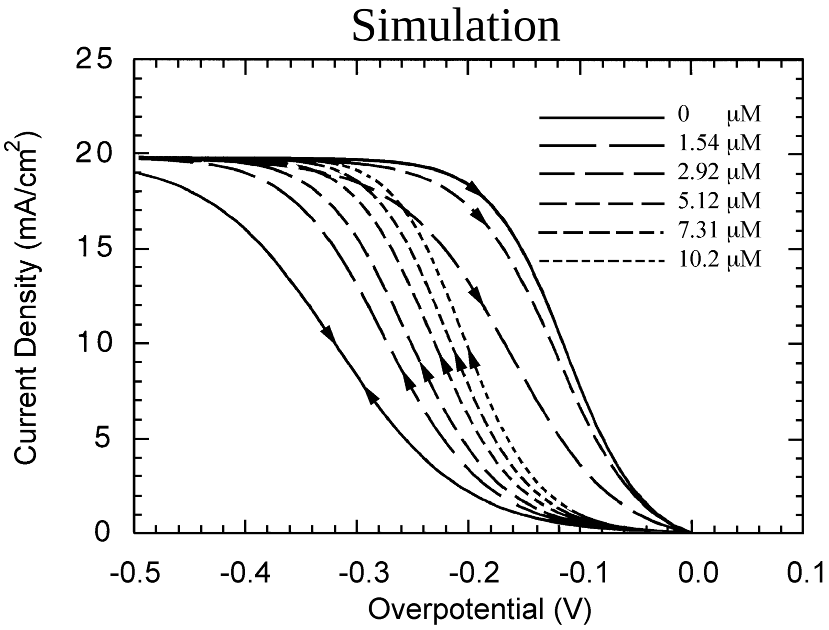
D_{MPSA} = MPSA diffusion coefficient
C_{MPSA} = MPSA bulk concentration
Γ = maximum MPSA coverage
δ = diffusion layer thickness

Electrochemical kinetics for Cu deposition:

$$i(\theta) = i_o(\theta)\left(1-\frac{i(\theta)}{i_L}\right)\exp\left(\frac{-\alpha(\theta)F}{RT}\eta\right)$$



Experiment

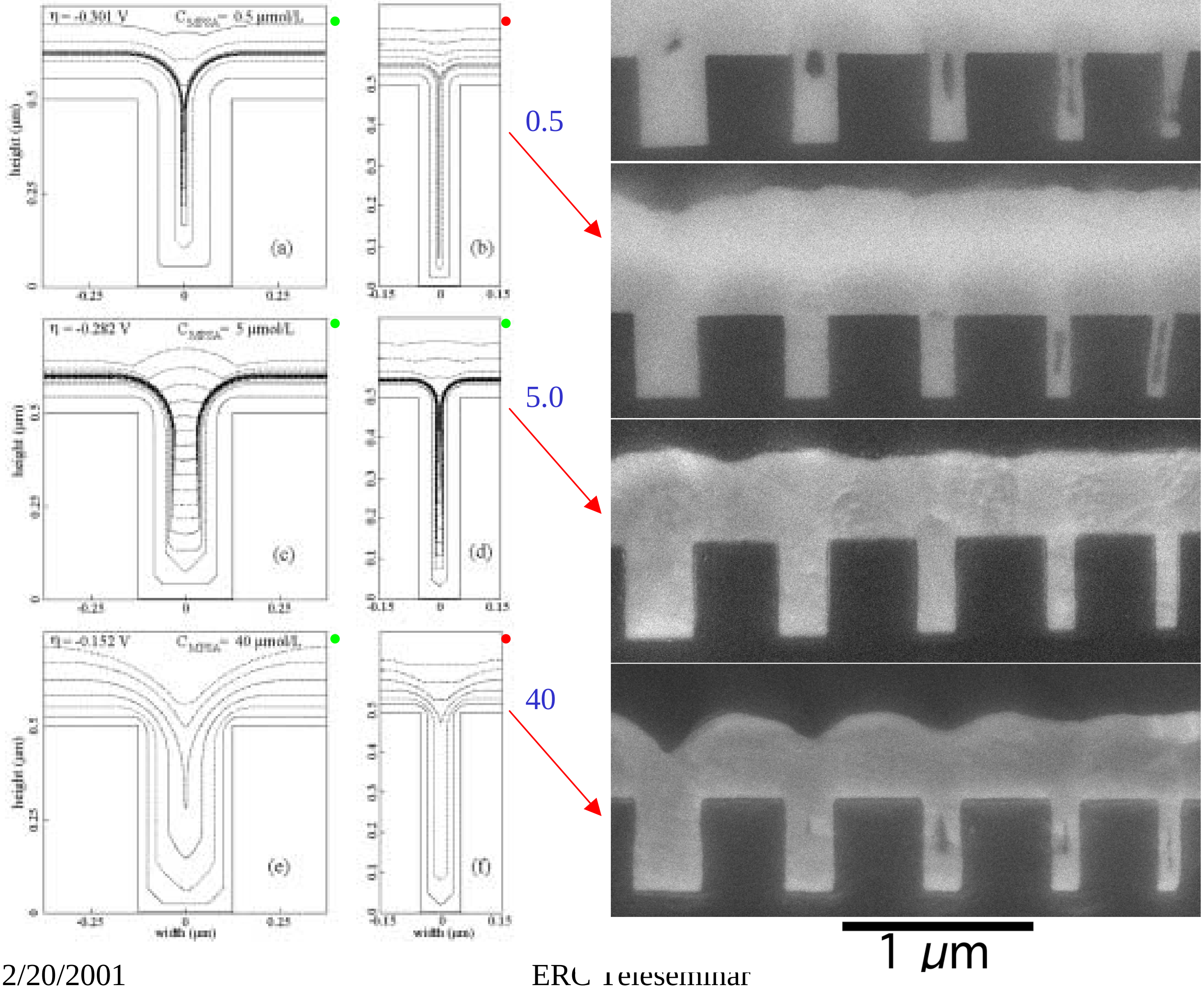


Simulation

Simulation: MPSA Concentration

250 nm

100 nm



0.0 μmol/L
MPSA

0.5 μmol/L
MPSA
Low θ
Insufficient
Acceleration

5.0 μmol/L
MPSA
Optimum θ
Superconformal
Growth

40 μmol/L
MPSA
Uniform
Saturation
Conformal
Growth

Accomplishments/Impact

Developed a cross-laboratory program on measurements and modeling for superconformal copper deposition (MSEL, EEEL, CSTL)

- developed the first non-proprietary bath that yields superfill down to dimensions of 60 nm and aspect ratios of 3:1
- demonstrated that inhibition alone is *not* sufficient to ensure superfill in direct contradiction to current thinking and models

New time saving measurement, on *planar substrates*, for determining superfill efficacy

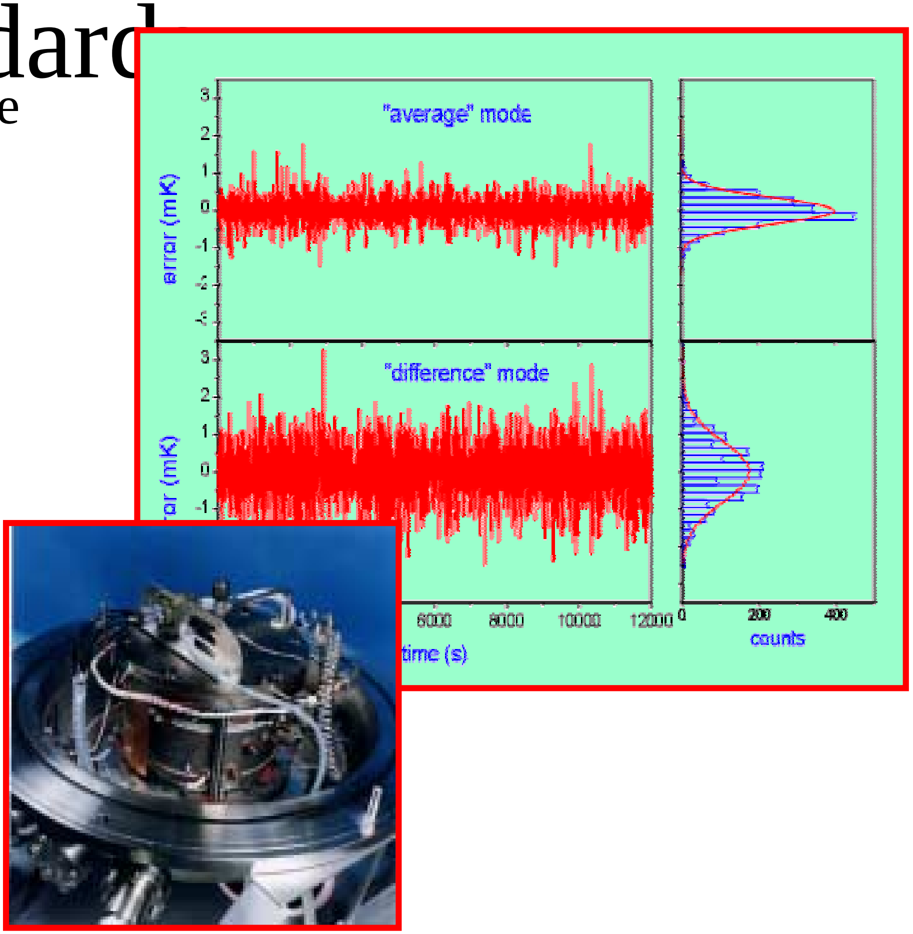
- demonstrated one-to-one correlation between I-V hysteresis, resistance drop (recrystallization rate) and superfill efficacy of electrolytes
- incorporated into control software by ECI Technology, a leading supplier of analytical plating and processing tools, to complement their CVS (cyclic voltammetric stripping) quality control technology.

Theory predicts processing windows for superconformal deposition

- alternative to the transport-limited inhibition model
- provide the theoretical underpinning for filling nanometer scale features

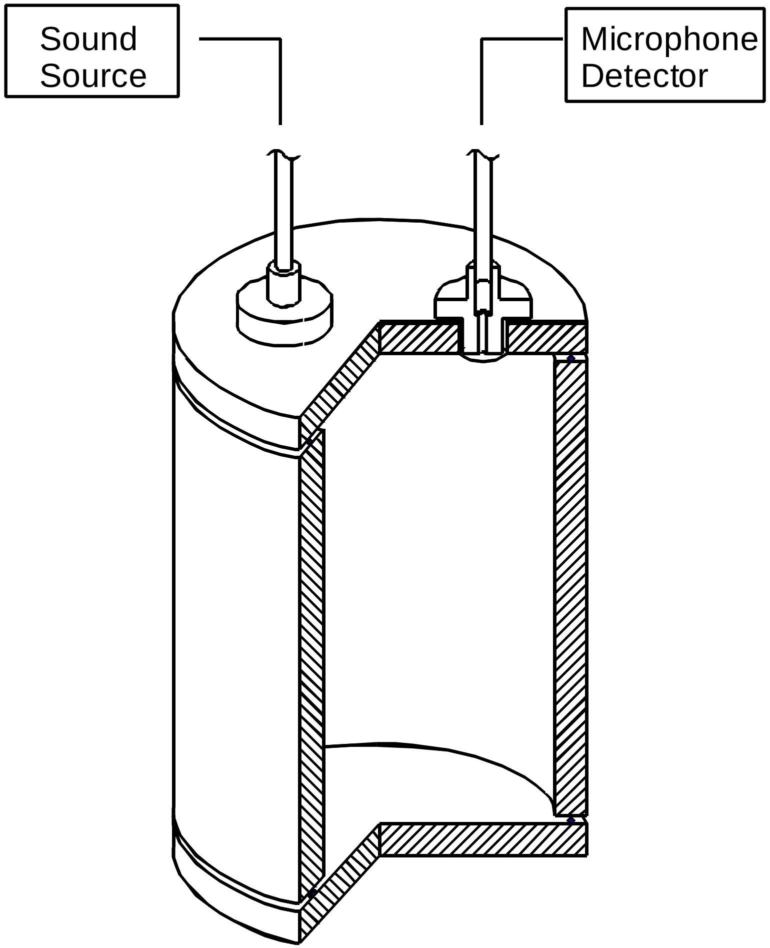
Moisture Calibration

Low Concentration Humidity Standard

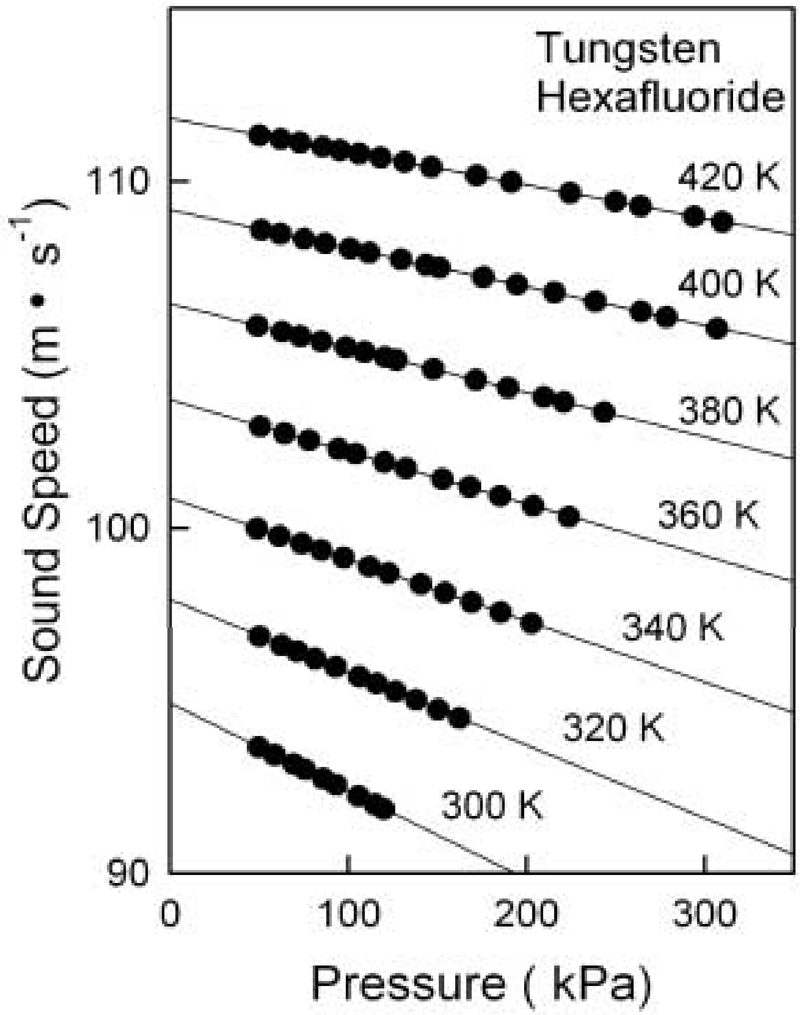


- Developed Standards for Low-Moisture Concentrations in Gases - Low-Frost Point Generator (LFPG)
  - High Precision Moisture Generator
    - **Humidity levels:**
      5 nmol/mol to ~ 5,000 µmol/mol
    - **Operating temperature: 173 to 273 K**
      (±2.5 mK stability at 173 K)
  - Planned improvements - 200 ppt (153K or -120° C operating temp.)
- **Calibrated laser absorption hygrometer based on Wavelength Modulation Spectroscopy (WMS) between 5 and 2500 nmol/mol**
- **Incorporated WMS system as a check standard into the LFPG system as a null detector between LFPG and other humidity generators, e.g., permeation tube generators**

Thermodynamic Properties of Reactive Gases



- Measurements of the speed of sound in reactive gases yield values for thermodynamic properties of the gases.
- These properties had only been estimated in the past due to the difficulties associated with making the measurements directly.


Tungsten
Hexafluoride
420 K
400 K
380 K
360 K
340 K
320 K
300 K
Sound Speed (m • s^{-1})
110
100
90
0
100
200
300
Pressure (kPa)

allene	C_3H_4	phosgene	$COCl_2$	
arsenic trifluoride	AsF_3	phosphorous trifluoride	PF_3	
arsine	AsH_3	phosphorous pentafluoride	PF_5	
trimethyl arsine	$As(CH_3)_3$	phosphine	PH_3	
diborane	B_2H_6	sulfur dioxide	SO_2	RED - measurements
pentaborane	B_5H_9	stibine	SbH_3	completed
boron trichloride	BCl_3	silane	SiH_4	
bromine	Br_2	disilane	Si_2H_6	GREEN - Identified by
carbon monoxide	CO	silicon tetrachloride	$SiCl_4$	industry as a priority
chlorine	Cl_2	silicon tetrafluoride	SiF_4	for FY02
chlorine trifluoride	ClF_3	titanium tetrachloride	$TiCl_4$	
ethylene oxide	C_2H_4O	tungsten hexafluoride	WF_6	BLACK - Identified as
hydrogen bromide	HBr	uranium hexafluoride	UF_6	next priority level
hydrogen chloride	HCl	vinyl bromide	C_2H_3Br	
hydrogen fluoride	HF	vinyl fluoride	C_2H_3F	
hydrogen sulfide	H_2S	vinyl chloride	C_2H_3Cl	
molybdenum hexafluoride	MoF_6	trimethyl gallium	$Ga(CH_3)_3$	
nitric oxide	NO	triethyl gallium	$Ga(C_2H_5)_3$	
nitrous oxide	NO_2	trimethyl indium	$In(CH_3)_3$	
nitrogen trifluoride	NF_3			

Summary

- NIST has an extensive set of programs in support of the semiconductor industry
- These programs address issues across all the important technological areas needed by the industry
- NIST collaborates intensely with ISMT, companies, and universities
- More information can be obtained by calling us (301-975-4400) or going to www.nist.gov or www.eeel.nist.gov/omp