

MEMS Metrology

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Fundamentals of Micromachining



Metrology

- What is metrology?
 - It is the science of weights and measures
 - Refers primarily to the measurements of length, weight, time, etc.
- Mensuration- A branch of applied geometry
 - It measure the area and volume of solids from lengths and angles
- It also includes other engineering measurements for the establishment of a flat, plane reference surface



What is a Measurement

- A measurement is an act of assigning a specific value to a physical variable
- The physical variable becomes the measured variable
- Measurements provide a basis for judgements about
 - Process information
 - Quality assurance
 - Process control



Measurable Parameters

- | | |
|--------------------------------|--------------|
| • What do we want to measure? | • Pressure |
| • Length or distance | • Forces |
| • Mass | • Stress |
| • Temperature | • Strain |
| • Elemental composition | • Friction |
| • Viscosity | • Resistance |
| • Displacements or distortions | • Roughness |
| • Time | • Depth |
| | • Intensity |
| | • etc. |

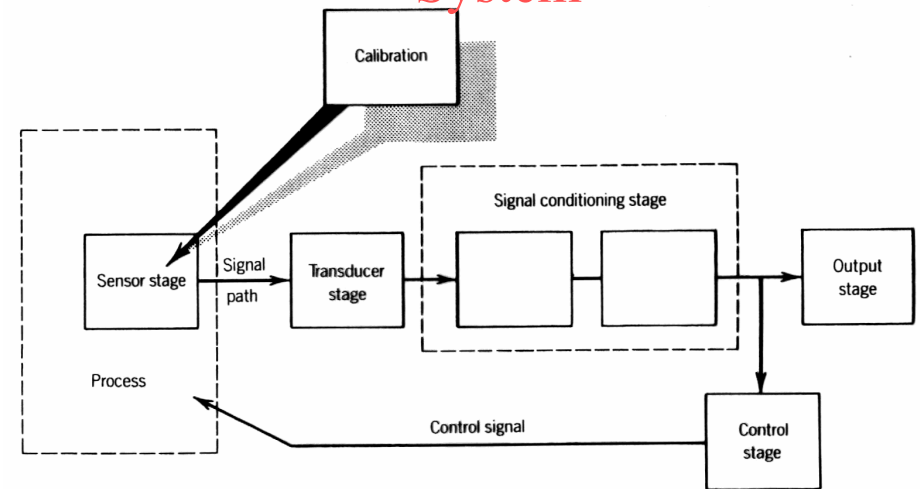


Measurement Systems and Tools

- Measurement systems are important tools for the quantification of the physical variable
- Measurement systems extend the abilities of the human senses, while they can detect and recognize different degrees of physical variables
- For scientific and engineering measurement, the selection of equipment, techniques and interpretation of the measured data are important



Components of a Measuring System



Importance of Metrology

- In human relationships, things must be counted and measured
- Metrology is an absolute necessity for human development
 - This necessity increased greatly with the advent of the industrial age
- As society develops further, metrology must also be refined further



How Important are Measurements?

- Measurement is the language of science
- It helps us communicate about size, quantity, position, condition, time, etc.
- Simple measurement errors can cost a company a contract, work, jobs, and lots of money
- Three areas to which the basic principles of measurement can be applied
 - Communication of the measurement
 - Act and application of the measurement
 - Codification of the measurement



Human Interaction in Measurements

- Almost always require the use of vision
 - Other senses not always good at “measurement”
- Measurements usually require tools
 - They rely on the visual process
- What happens if object is too small to perceive?
 - At what size do things become too small to measure?
 - Handling and/or perception problems
 - Limits of vision/ perception without aid or assistance



What is Microsystem Metrology

- Measurement of physical dimensions of microsystems or structures that are at the dimension scale below our ability to perceive without the help of measurements systems or instruments
- Microsystems: IC, MEMS
- Microstructures: Line widths, film thickness, surface structure and roughness, step heights, particle size, atomic composition, defect inspections, etc
- Nanosystem metrology is emerging now!



Where Metrology at the Micro Level is Used

- Precision engineering and measurements
- Micron and nano manufacturing
- Research and development
- Calibration of instruments and standards



MEMS Measurement

- Statistics and probability
- Statistical process control
- Optical microscopy
- Scanning electron microscopy (SEM)
- Atomic force microscopy (AFM)
- Scanning tunneling microscopy (STM)
- Near- field microscopy
- Laser/ White light interferometry
- Video Microscopy
- Surface Profiler
- Roughness Tester
- Ellipsometry



Statistics and Probability

- Statistical terms and definitions
- Infinite statistics
- Finite statistics
- Standard deviations
- Probability density functions
- Confidence intervals
- Uncertainty analysis
- Error sources
- Bias and precision errors
- Error propagation
- Regression analysis
- Least squares methods
- Linear polynomials
- Student's t-Test
- Single and multiple measurement errors
- Zero and higher order uncertainties
- Correlation coefficient



Statistical Process Control

- Concept of variation
- Importance of SPC in production processes
- Controlled and uncontrolled variation
- Common and special causes
- Control charts
- Statistical inference
- Running records
- Population parameters
- Control limits
- Subgroup average and range
- Three sigma limits
– Six now!

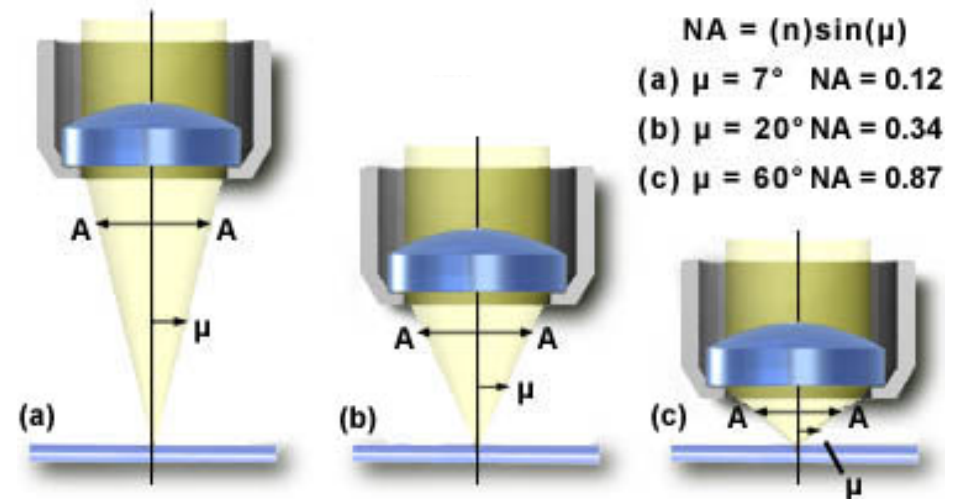


Optical Microscopy

- Light propagation and Snell's law
- Mirrors, prisms, lenses and beam splitters
- Image formation, interference and diffraction
- Simple and compound microscopes
- Mirror and thin lens equations
- Resolving power and resolution
- Aberrations and corrections
- Depth of field and focus
- Measurement on the optical microscopic scale

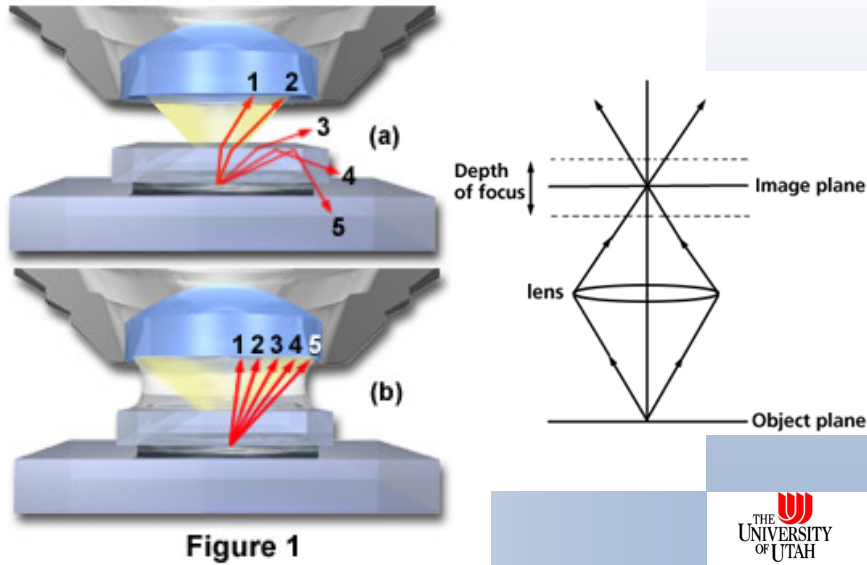


Numerical Aperture



MEMS Optical Microscopy Problems

Oil Immersion and Numerical Aperture

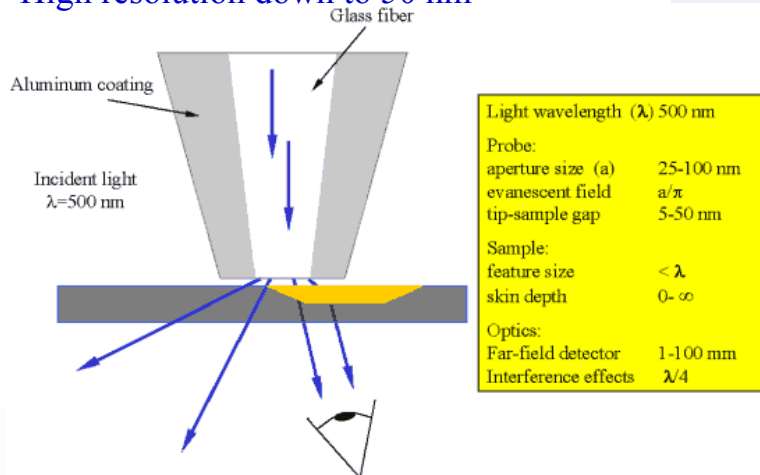


Scanning Electron Microscopy

- Used for observation, analysis, and measurement
- Can produce images over a wide range of magnifications
 - High magnification and great depth of field
 - High resolution (down to 2.5 nm)
- Can provide morphological, compositional, and physical information
- 3D appearance of image
- Greater degree of freedom

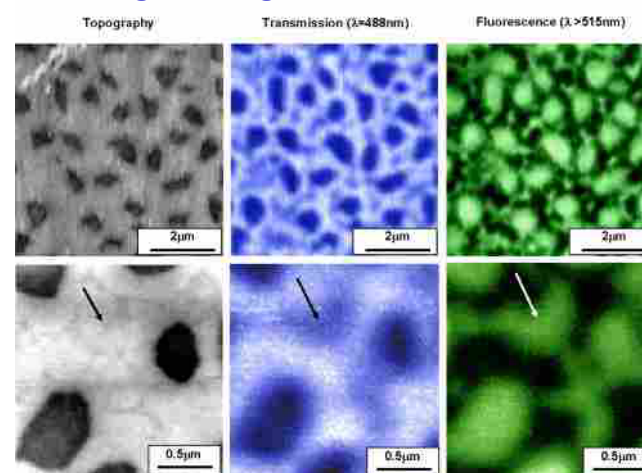
Near Field Scanning Optical Microscopy

- Used to get below the limits of “far-field diffraction”
- High resolution down to 50 nm



NSOM

Images using NSOM



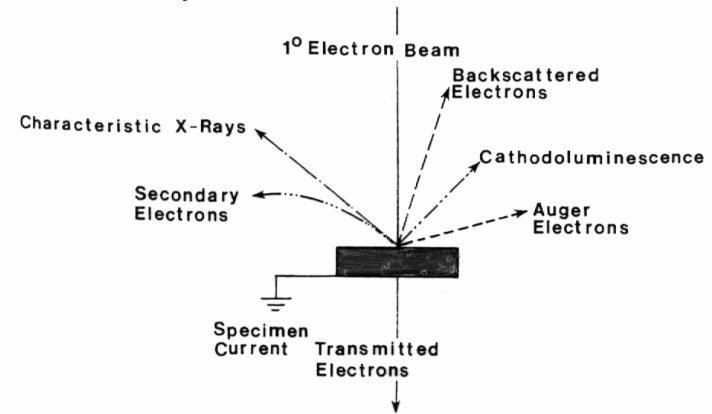
SEM Components

- Electron gun assembly
 - Stable source of primary electrons
- Electromagnetic lenses and apertures
 - Focus electron beam
- Vacuum system
 - Allows passage of electrons without interference
- Electron collector, display, and recorder
- Specimen stage
 - Goniometer stage



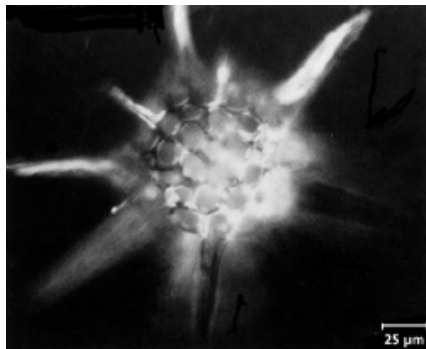
SEM Operation

- Small area irradiated by electrons
- E-beam can be static or swept
- Secondary and backscattered electrons detected

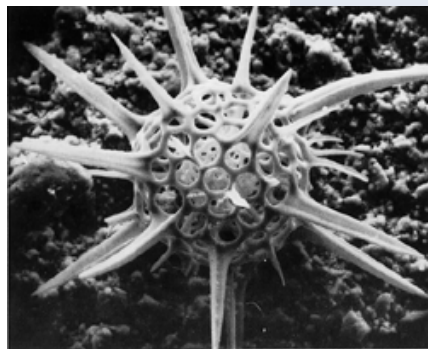


SEM Operation

- Current in the focused e-beam determines magnitude of emitted signals
- Size of focused beam determines the resolution



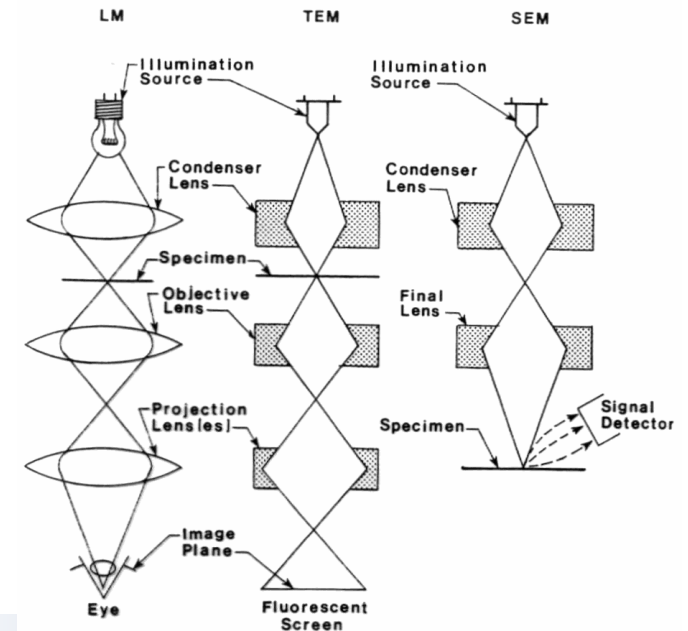
Optical



SEM

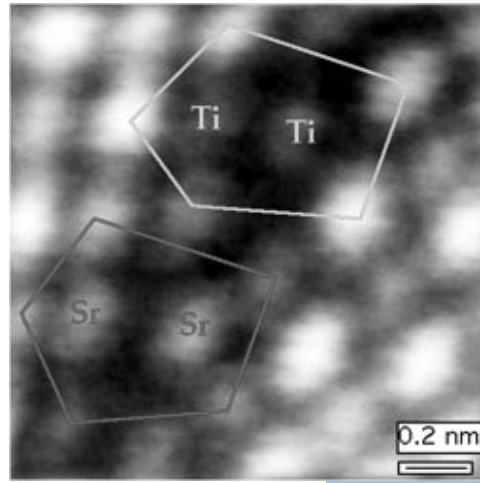


Comparison of Systems



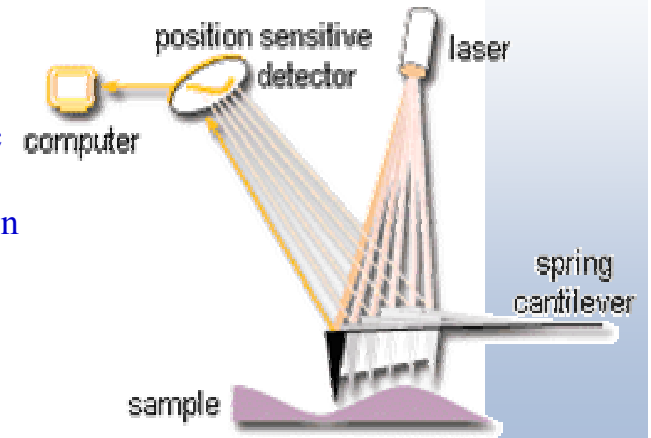
Transmission Electron Microscopy (TEM)

- Only for thin materials
- Usually used to study crystals
- Gives good information on nanometer structure



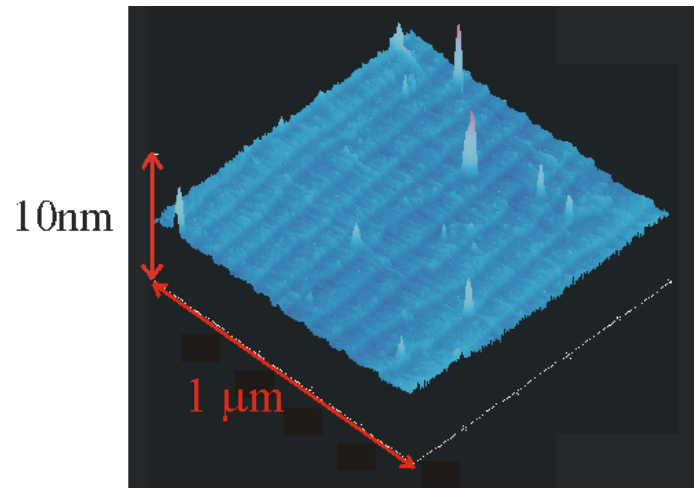
Atomic Force Microscopy

- Atomically sharp tip
- Measures minute atomic forces that cause repulsion
- Can measure individual atoms

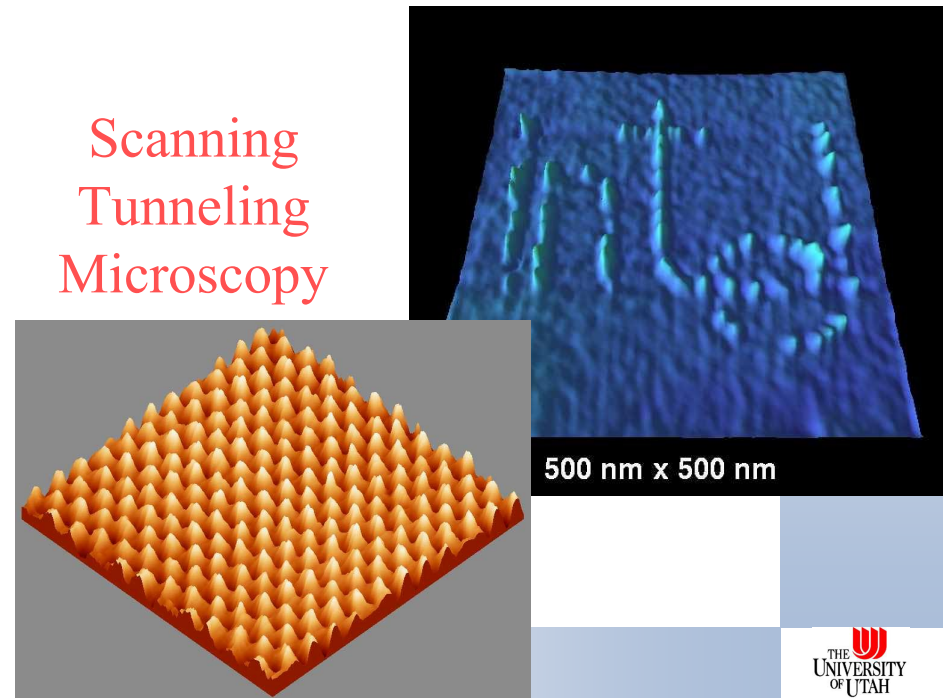


AFM Image of Silicon

- Silicon (111) plane- ridges 0.38 nm high

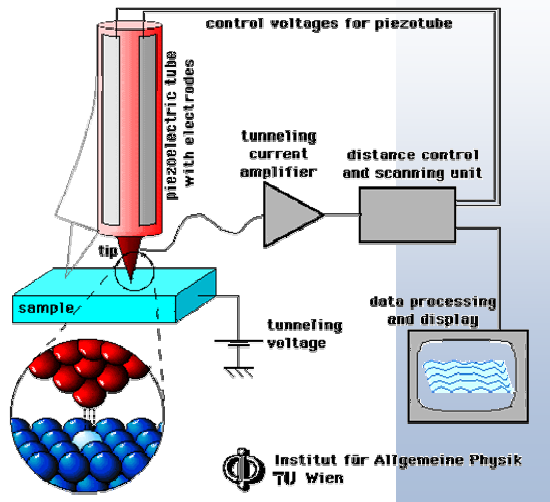


Scanning Tunneling Microscopy



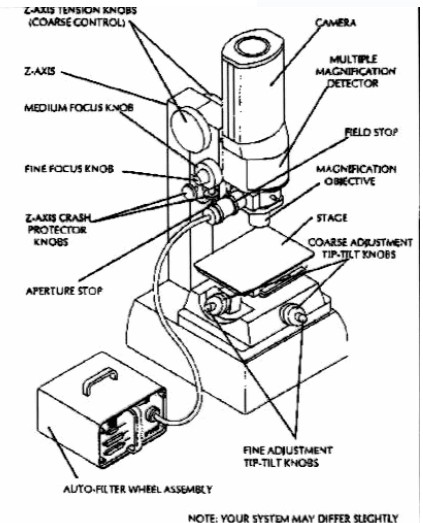
Scanning Tunneling Microscopy

- Sharp tip
- Tunneling current or voltage measured
- Current increases rapidly on approach to surface
- Atomic resolution



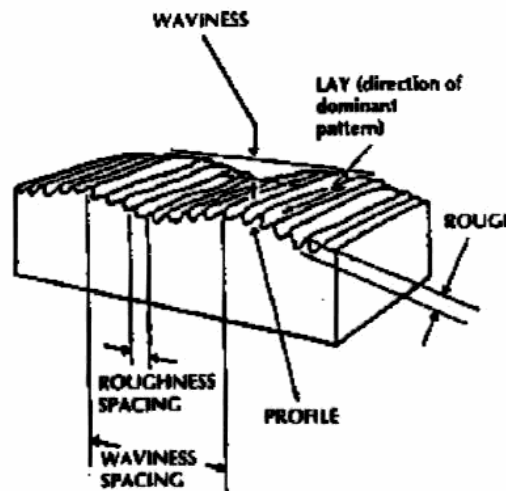
Roughness Step Tester (RST)

- Surface characterization
- Interference microscope
- Optical measurement of surface



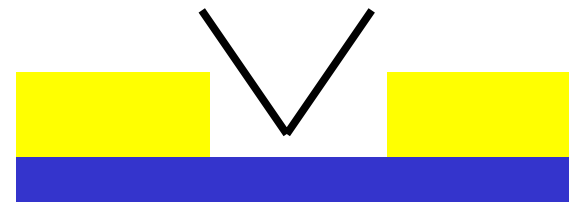
Surface Texture

- Definition
 - Repetitive or random deviation from nominal surface that forms the 3-D topography of the surface
- Roughness
 - Closely spaced irregularities
- Waviness
 - Wider spaced irregularities (tool marks)
- Form
 - Does not contribute to surface texture



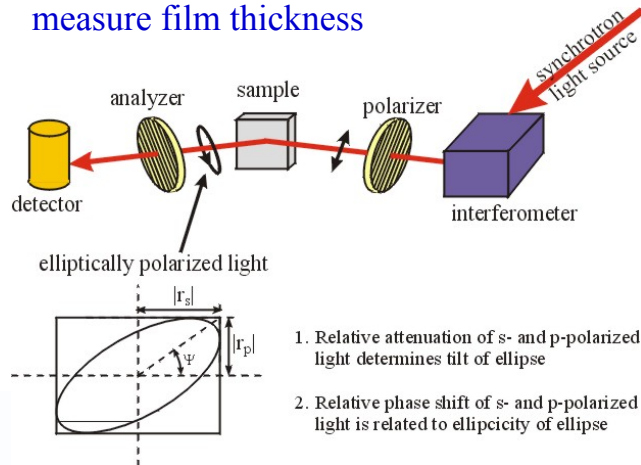
Surface Profiler

- Large tip scans across surface
- Excellent for measuring height of objects
- Sidewalls are not accurate
- Variation dependent on tip diameter
- Vertical accuracy in angstroms



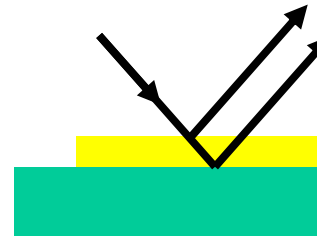
Ellipsometry

- Light is rotated as it passes through medium
- If dielectric constant is known, can be used to measure film thickness



Interferometry

- Reflected light waves interfere with each other
- Used to measure thickness of thin films or deflections
- Interference occurs at different locations based on wavelength



Film Thickness (μm)	Color and Comments	Film Thickness (μm)	Color and Comments
0.05	Tan	0.63	Violet red
0.07	Brown	0.68	"Bluish" (Not blue but borderline between violet and blue green. It appears more like a mixture between violet red and blue green and looks grayish)
0.10	Dark violet to red violet	0.72	Blue green to green (quite broad)
0.12	Royal blue	0.77	"Yellowish"
0.15	Light blue to metallic blue	0.80	Orange (rather broad for orange)
0.17	Metallic to very light yellow green	0.82	Salmon
0.20	Light gold or yellow—slightly metallic	0.85	Dull, light red violet
0.22	Gold with slight yellow orange	0.86	Violet
0.25	Orange to melon	0.87	Blue violet
0.27	Red violet	0.89	Blue
0.30	Blue to violet blue	0.92	Blue green
0.31	Blue	0.95	Dull yellow green
0.32	Blue to blue green	0.97	Yellow to "yellowish"
0.34	Light green	0.99	Orange
0.35	Green to yellow green	1.00	Carnation pink
0.36	Yellow green	1.02	Violet red
0.37	Green yellow	1.05	Red violet
0.39	Yellow	1.06	Violet
0.41	Light orange	1.07	Blue violet
0.42	Carnation pink	1.10	Green
0.44	Violet red	1.11	Yellow green
0.46	Red violet	1.12	Green
0.47	Violet	1.18	Violet
0.48	Blue violet	1.19	Red violet
0.49	Blue	1.21	Violet red
0.50	Blue green	1.24	Carnation pink to salmon
0.52	Green (broad)	1.25	Orange
0.54	Yellow green	1.28	"Yellowish"
0.56	Green yellow	1.32	Sky blue to green blue
0.57	Yellow to "yellowish" (not yellow but is in the position where yellow is to be expected. At times it appears to be light creamy gray or metallic)	1.40	Orange
0.58	Light orange or yellow to pink borderline	1.45	Violet
0.60	Carnation pink	1.46	Blue violet
		1.50	Blue
		1.54	Dull yellow green

Thin Films Change Colors

CCD Cameras (Video Imaging)

- Charge Coupled Devices (CCD)
 - Metal - insulator - semiconductor devices (MIS)
 - Incident light generates charge on gate
 - Induced voltage causes charge separation
- CCD cameras are arrays of MIS devices
 - Can be 10 microns square
 - Charge collected and moved sequentially to edge of device
 - Dyes can be applied to transistor to detect colors

