Characterization of Thin Films

- Film thickness
- Surface morphology
- Film composition
- Film properties

Characterization methods are very diverse

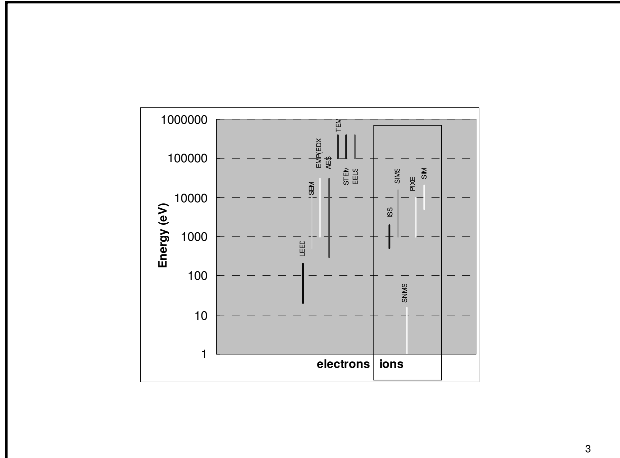
- Size of equipment. Compare desktop interferometer with 2 m accelerator of RBS
- Cost. \$$10^1$ – \$$10^6$
- Environment. Ambient – 10^{-10} Torr
- Complexity. Scotch tape – SEM, TEM etc.

1

Primary beam	Energy range	Secondary signal	Acronym	Technique	Application
Electron	20 - 200 eV 0.3 - 30 keV 1 - 30keV 500eV-10keV 100 -400 keV 100 -400 keV 100 -400 keV	Electron Electron X-ray Electron Electron Electron, X-ray Electron	LEED SEM EMP (EDX) AES TEM STEM EELS	Low-energy electron diffraction Scanning electron microscopy Electron microprobe Auger electron spectroscopy Transmission electron microscopy Scanning TEM Electron energy loss spectroscopy	Surface structure Surface morphology Surface region composition Surface layer composition High-resolution structure Imaging, X-ray analysis Local small-area composition
Ion	0.5 -2.0 keV 1 - 15 keV 1-15 eV 1 keV and up 5-20 keV >1 MeV	Ion Ion Atom X-ray Electron Ion	ISS SIMS SNMS PIXE SIM RBS	Ion-scattering spectroscopy Secondary ion mass spectroscopy Secondary neutral mass spectrometry Particle-induced X-ray emission Scanning ion microscopy Rutherford backscattering	Surface composition Trace composition vs depth Trace composition vs depth Trace composition Surface characterization Composition vs depth
Photon	>1 keV >1 keV >1 keV Laser Laser	X-ray X-ray Electron Ion Light	XRF XRD ESCA, XPS - LEM	X-ray fluorescence X-ray diffraction X-ray photoelectron spectroscopy Laser microprobe Laser emission microprobe	Composition (1 μm depth) Crystal structure Surface composition Composition of irradiated area Trace element analysis

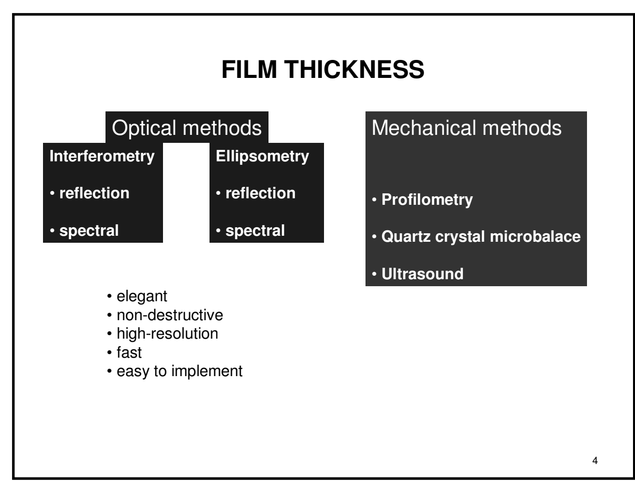
J.B. Bindel, in *VLSI Technol*, McGraw-Hill, NY88

2



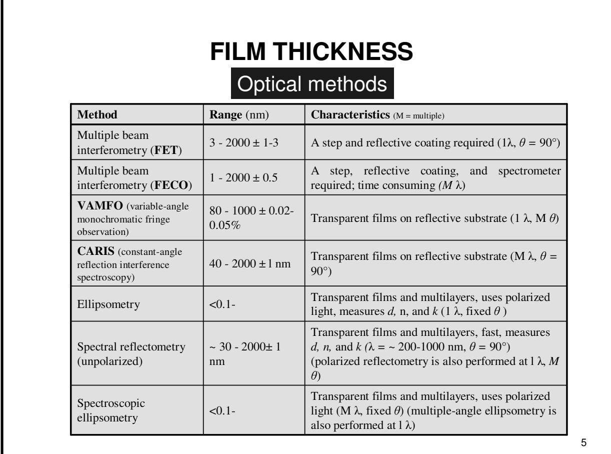
3

FILM THICKNESS



- elegant
- non-destructive
- high-resolution
- fast
- easy to implement

4



FILM THICKNESS

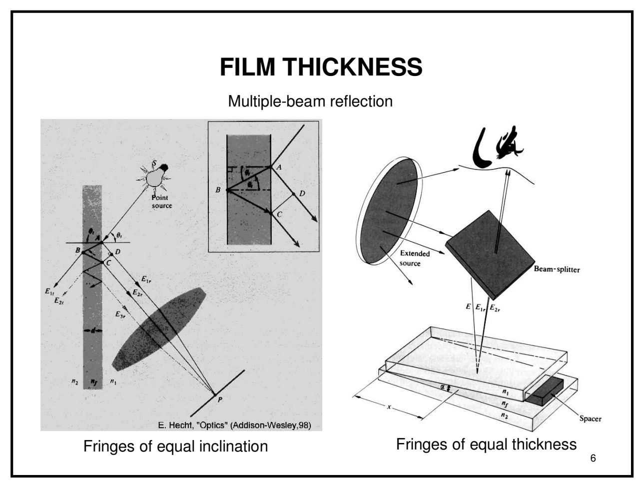
Optical methods

Method	**Range** (nm)	**Characteristics** (M = multiple)
Multiple beam interferometry (**FET**)	3 - 2000 ± 1-3	A step and reflective coating required (1λ, θ = 90°)
Multiple beam interferometry (**FECO**)	1 - 2000 ± 0.5	A step, reflective coating, and spectrometer required; time consuming *(M λ)*
VAMFO (variable-angle monochromatic fringe observation)	80 - 1000 ± 0.02-0.05%	Transparent films on reflective substrate (1 λ, M θ)
CARIS (constant-angle reflection interference spectroscopy)	40 - 2000 ± l nm	Transparent films on reflective substrate (M λ, θ = 90°)
Ellipsometry	<0.1-	Transparent films and multilayers, uses polarized light, measures *d,* n, and *k* (1 λ, fixed θ)
Spectral reflectometry (unpolarized)	~ 30 - 2000± 1 nm	Transparent films and multilayers, fast, measures *d, n,* and *k* (λ = ~ 200-1000 nm, θ = 90°) (polarized reflectometry is also performed at l λ, *M* θ)
Spectroscopic ellipsometry	<0.1-	Transparent films and multilayers, uses polarized light (M λ, fixed θ) (multiple-angle ellipsometry is also performed at l λ)

5

FILM THICKNESS

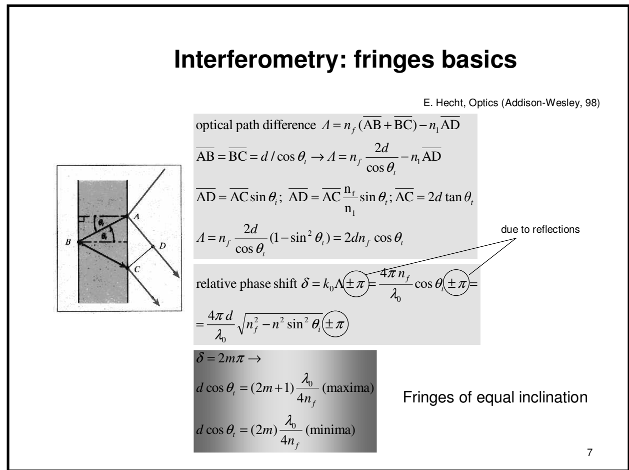
Multiple-beam reflection

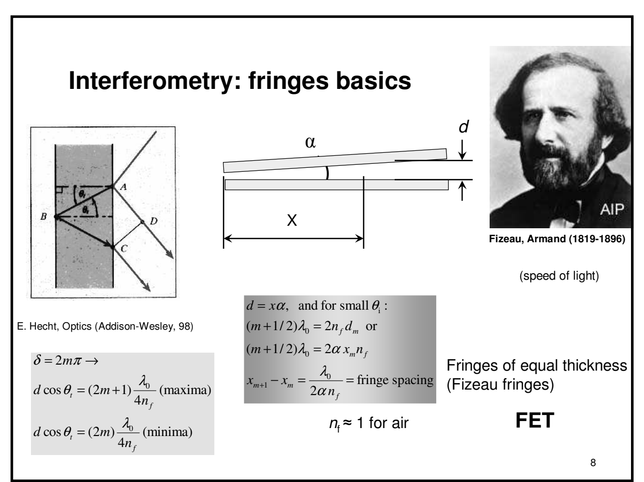


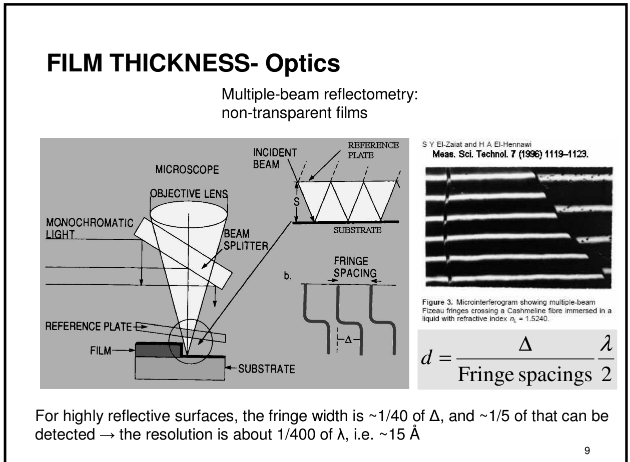
Fringes of equal inclination

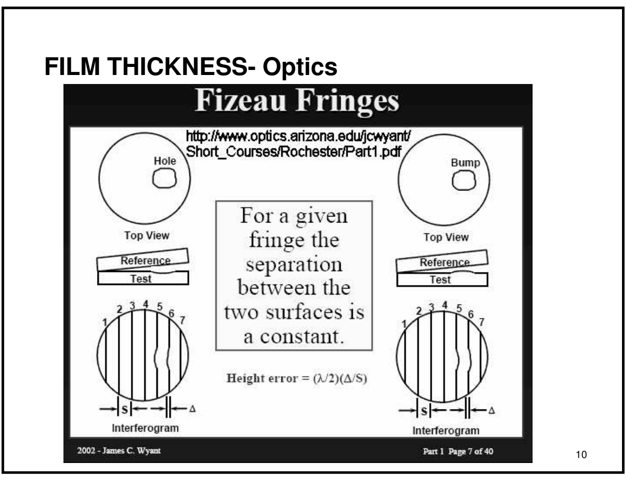
Fringes of equal thickness

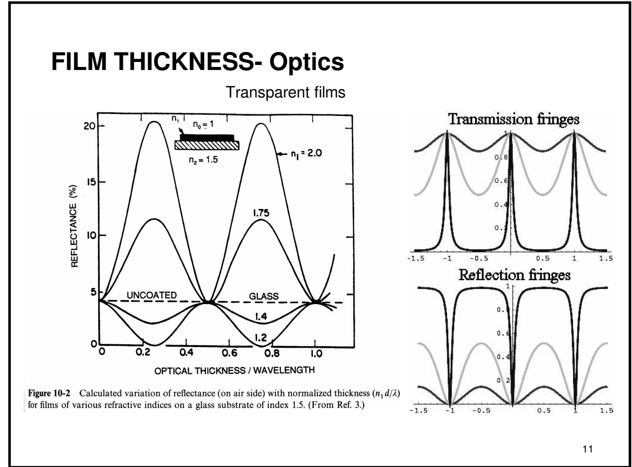
6

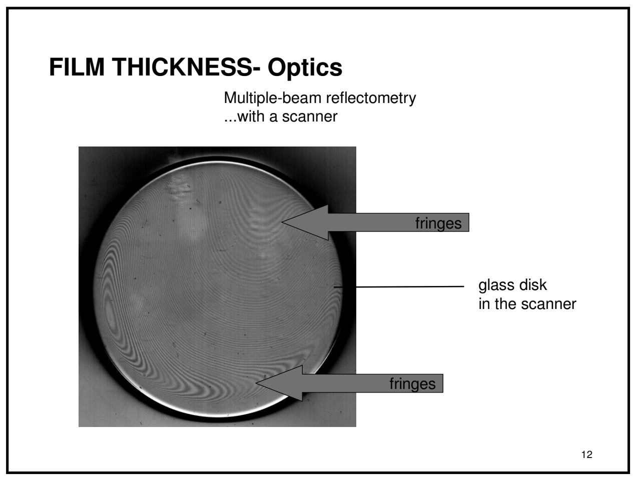

Interferometry: fringes basics
E. Hecht, Optics (Addison-Wesley, 98)
optical path difference $\Lambda = n_f(\overline{AB}+\overline{BC}) - n_1\overline{AD}$
$\overline{AB}=\overline{BC}=d/\cos\theta_t \rightarrow \Lambda = n_f \frac{2d}{\cos\theta_t} - n_1\overline{AD}$
$\overline{AD}=\overline{AC}\sin\theta_i;\ \overline{AD}=\overline{AC}\frac{n_f}{n_1}\sin\theta_t;\ \overline{AC}=2d\tan\theta_t$
$\Lambda = n_f \frac{2d}{\cos\theta_t}(1-\sin^2\theta_t) = 2dn_f\cos\theta_t$
due to reflections
relative phase shift $\delta = k_0\Lambda(\pm\pi) = \frac{4\pi n_f}{\lambda_0}\cos\theta_t(\pm\pi) =$
$= \frac{4\pi d}{\lambda_0}\sqrt{n_f^2 - n^2\sin^2\theta_i}(\pm\pi)$
$\delta = 2m\pi \rightarrow$
$d\cos\theta_t = (2m+1)\frac{\lambda_0}{4n_f}$ (maxima)
$d\cos\theta_t = (2m)\frac{\lambda_0}{4n_f}$ (minima)
Fringes of equal inclination
7

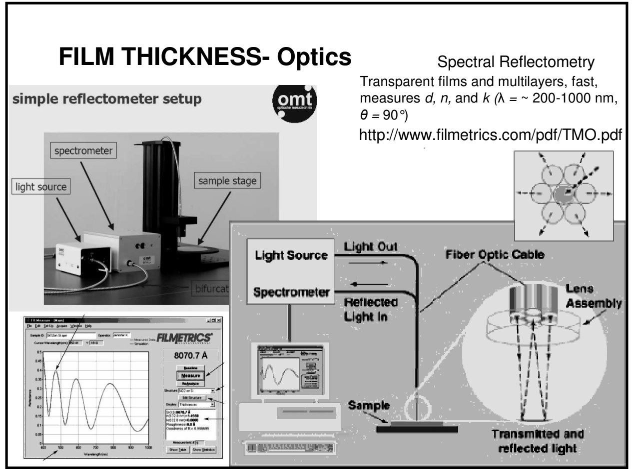

Interferometry: fringes basics
α
d
x
AIP
Fizeau, Armand (1819-1896)
(speed of light)
E. Hecht, Optics (Addison-Wesley, 98)
$\delta = 2m\pi \rightarrow$
$d\cos\theta_t = (2m+1)\frac{\lambda_0}{4n_f}$ (maxima)
$d\cos\theta_t = (2m)\frac{\lambda_0}{4n_f}$ (minima)
$d = x\alpha$, and for small θ_t:
$(m+1/2)\lambda_0 = 2n_f d_m$ or
$(m+1/2)\lambda_0 = 2\alpha x_m n_f$
$x_{m+1} - x_m = \frac{\lambda_0}{2\alpha n_f}$ = fringe spacing
$n_f \approx 1$ for air
Fringes of equal thickness
(Fizeau fringes)
FET
8

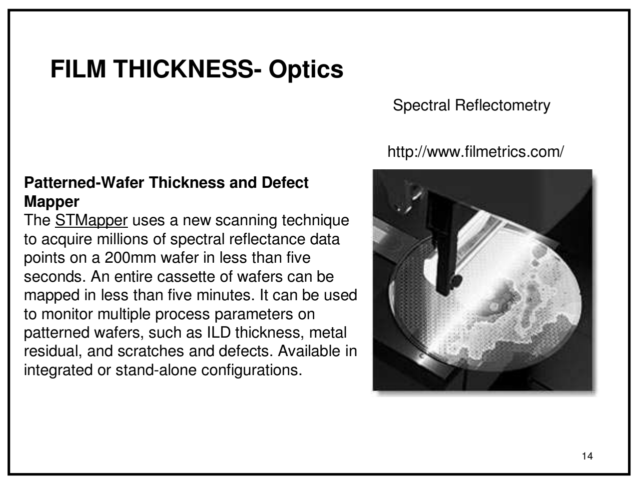

FILM THICKNESS- Optics
Multiple-beam reflectometry:
non-transparent films
MICROSCOPE
INCIDENT BEAM
REFERENCE PLATE
OBJECTIVE LENS
MONOCHROMATIC LIGHT
BEAM SPLITTER
SUBSTRATE
FRINGE SPACING
REFERENCE PLATE
FILM
SUBSTRATE
S Y El-Zaiat and H A El-Hennawi
Meas. Sci. Technol. 7 (1996) 1119–1123.
Figure 3. Microinterferogram showing multiple-beam Fizeau fringes crossing a Cashmeline fibre immersed in a liquid with refractive index n_L = 1.5240.
$d = \frac{\Delta}{\text{Fringe spacings}}\frac{\lambda}{2}$
For highly reflective surfaces, the fringe width is ~1/40 of Δ, and ~1/5 of that can be detected → the resolution is about 1/400 of λ, i.e. ~15 Å
9

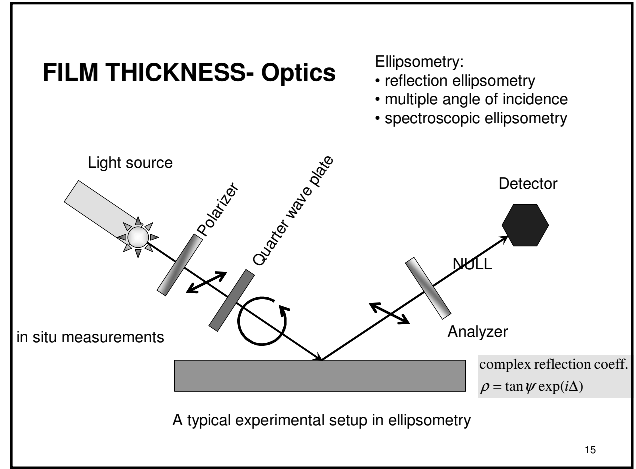

FILM THICKNESS- Optics
Fizeau Fringes
http://www.optics.arizona.edu/jcwyant/
Short_Courses/Rochester/Part1.pdf
Hole
Bump
Top View
Reference
Test
For a given fringe the separation between the two surfaces is a constant.
Height error = (λ/2)(Δ/S)
Interferogram
2002 - James C. Wyant
Part 1 Page 7 of 40
10

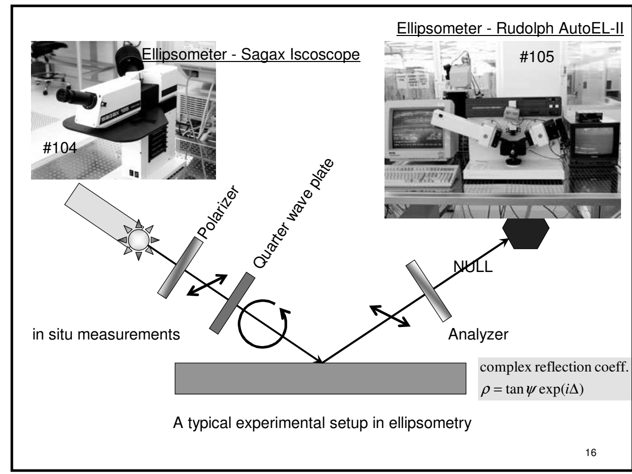

FILM THICKNESS- Optics
Transparent films
REFLECTANCE (%)
OPTICAL THICKNESS / WAVELENGTH
UNCOATED
GLASS
n_f = 2.0
1.75
1.4
1.2
n_0 = 1
n_2 = 1.5
Transmission fringes
Reflection fringes
Figure 10-2 Calculated variation of reflectance (on air side) with normalized thickness $(n_1 d/\lambda)$ for films of various refractive indices on a glass substrate of index 1.5. (From Ref. 3.)
11

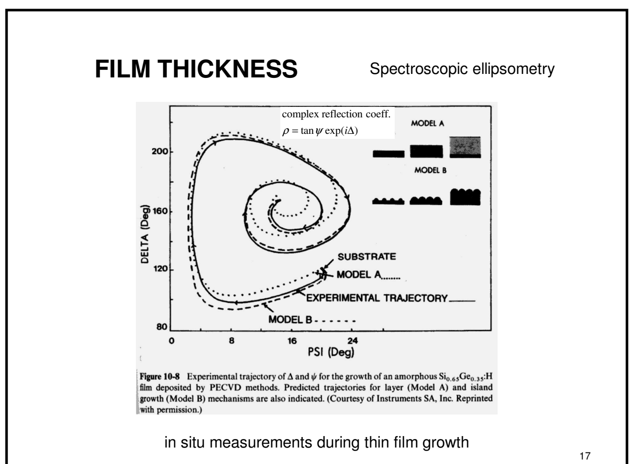

FILM THICKNESS- Optics
Multiple-beam reflectometry
...with a scanner
fringes
glass disk
in the scanner
fringes
12

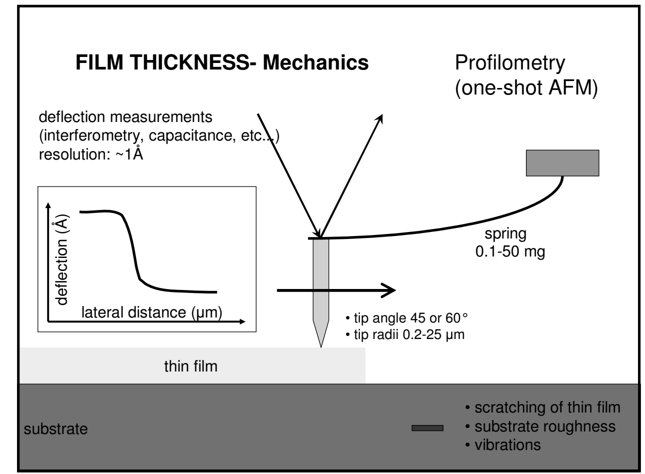

FILM THICKNESS- Optics
Spectral Reflectometry
Transparent films and multilayers, fast, measures d, n, and k (λ = ~ 200-1000 nm, θ = 90°)
http://www.filmetrics.com/pdf/TMO.pdf
simple reflectometer setup
spectrometer
light source
sample stage
Light Source
Spectrometer
Light Out
Reflected Light In
Fiber Optic Cable
Lens Assembly
Sample
Transmitted and reflected light

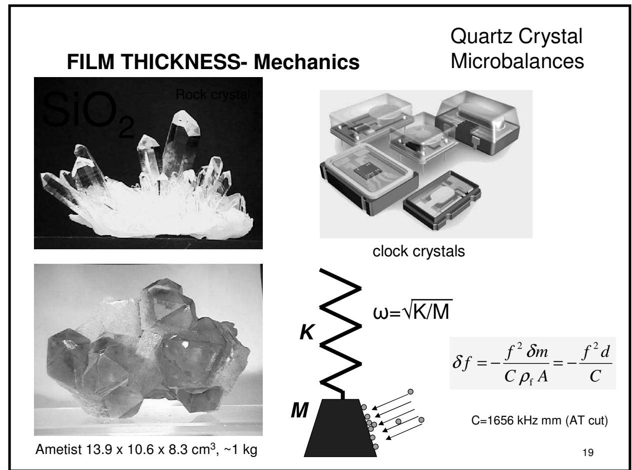

FILM THICKNESS- Optics
Spectral Reflectometry
http://www.filmetrics.com/
Patterned-Wafer Thickness and Defect Mapper
The STMapper uses a new scanning technique to acquire millions of spectral reflectance data points on a 200mm wafer in less than five seconds. An entire cassette of wafers can be mapped in less than five minutes. It can be used to monitor multiple process parameters on patterned wafers, such as ILD thickness, metal residual, and scratches and defects. Available in integrated or stand-alone configurations.
14

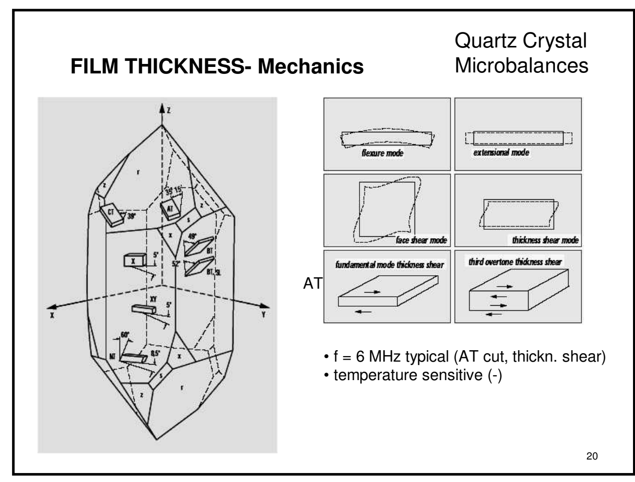

FILM THICKNESS- Optics
Ellipsometry:
• reflection ellipsometry
• multiple angle of incidence
• spectroscopic ellipsometry
Light source
Polarizer
Quarter wave plate
Detector
NULL
Analyzer
in situ measurements
complex reflection coeff.
$\rho = \tan\psi \exp(i\Delta)$
A typical experimental setup in ellipsometry
15

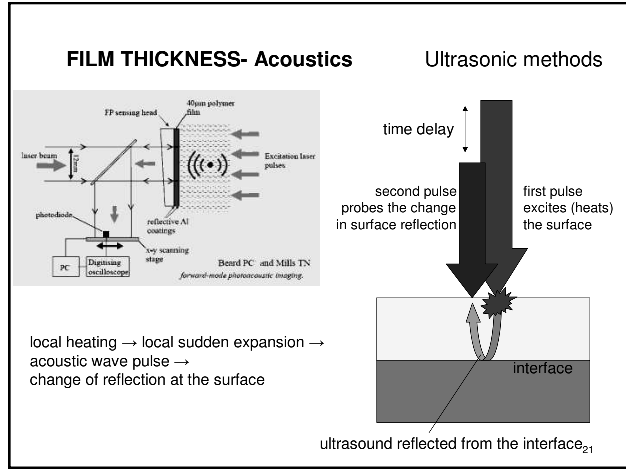

Ellipsometer - Rudolph AutoEL-II
Ellipsometer - Sagax Iscoscope
#104
#105
Polarizer
Quarter wave plate
NULL
Analyzer
in situ measurements
complex reflection coeff.
$\rho = \tan\psi \exp(i\Delta)$
A typical experimental setup in ellipsometry
16

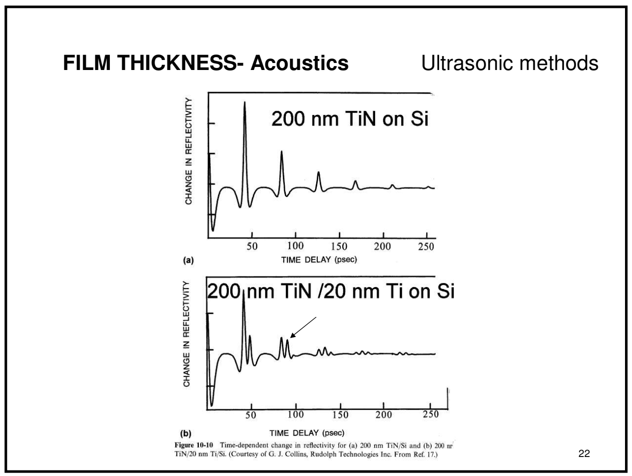

FILM THICKNESS
Spectroscopic ellipsometry
complex reflection coeff.
$\rho = \tan\psi \exp(i\Delta)$
MODEL A
MODEL B
DELTA (Deg)
PSI (Deg)
SUBSTRATE
MODEL A
EXPERIMENTAL TRAJECTORY
MODEL B
Figure 10-8 Experimental trajectory of Δ and ψ for the growth of an amorphous $Si_{0.65}Ge_{0.35}$:H film deposited by PECVD methods. Predicted trajectories for layer (Model A) and island growth (Model B) mechanisms are also indicated. (Courtesy of Instruments SA, Inc. Reprinted with permission.)
in situ measurements during thin film growth
17

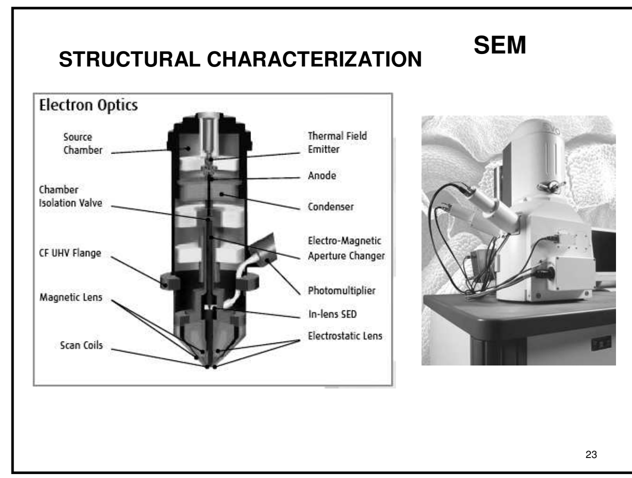

FILM THICKNESS- Mechanics
Profilometry
(one-shot AFM)
deflection measurements
(interferometry, capacitance, etc...)
resolution: ~1Å
deflection (Å)
lateral distance (µm)
spring
0.1-50 mg
• tip angle 45 or 60°
• tip radii 0.2-25 µm
thin film
substrate
• scratching of thin film
• substrate roughness
• vibrations

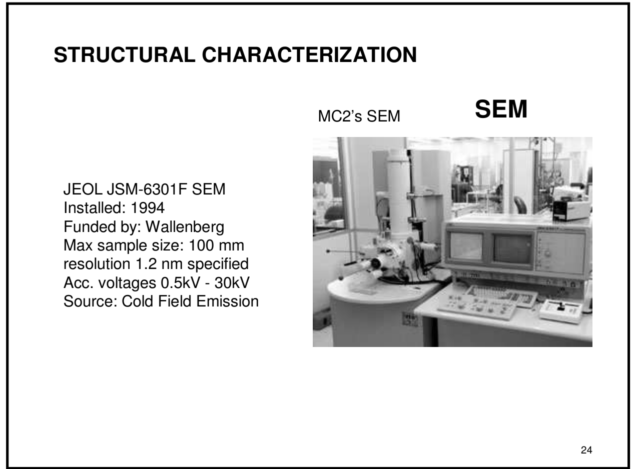

FILM THICKNESS- Mechanics
Quartz Crystal Microbalances
SiO2
Rock crystal
clock crystals
ω=√K/M
K
M
$\delta f = -\frac{f^2 \delta m}{C \rho_f A} = -\frac{f^2 d}{C}$
C=1656 kHz mm (AT cut)
Ametist 13.9 x 10.6 x 8.3 cm3, ~1 kg
19

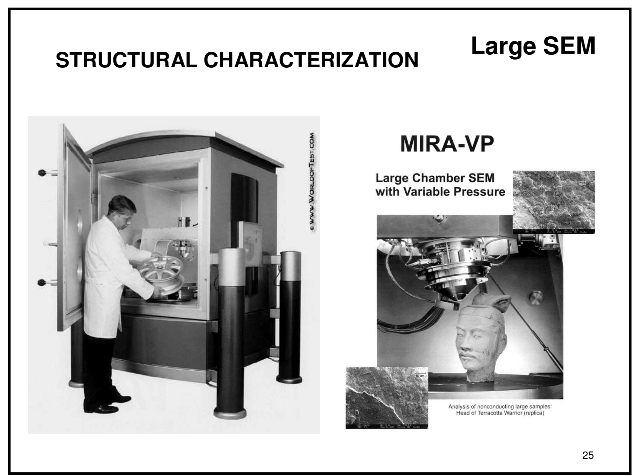

FILM THICKNESS- Mechanics
Quartz Crystal Microbalances
flexure mode
extensional mode
face shear mode
thickness shear mode
fundamental mode thickness shear
third overtone thickness shear
AT
• f = 6 MHz typical (AT cut, thickn. shear)
• temperature sensitive (-)
20

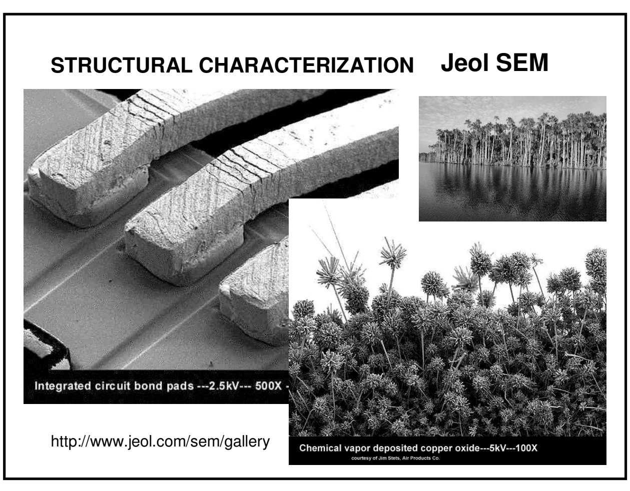

FILM THICKNESS- Acoustics
Ultrasonic methods
time delay
second pulse probes the change in surface reflection
first pulse excites (heats) the surface
local heating → local sudden expansion → acoustic wave pulse → change of reflection at the surface
interface
ultrasound reflected from the interface
21

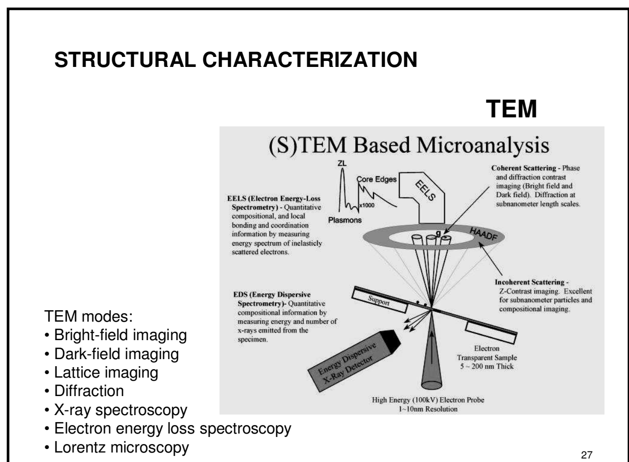

FILM THICKNESS- Acoustics
Ultrasonic methods
200 nm TiN on Si
200 nm TiN /20 nm Ti on Si
CHANGE IN REFLECTIVITY
TIME DELAY (psec)
22

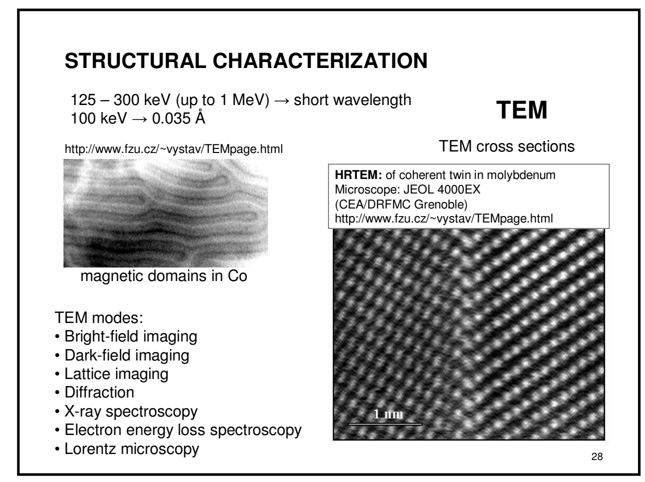

STRUCTURAL CHARACTERIZATION
SEM
Electron Optics
Source Chamber
Chamber Isolation Valve
CF UHV Flange
Magnetic Lens
Scan Coils
Thermal Field Emitter
Anode
Condenser
Electro-Magnetic Aperture Changer
Photomultiplier
In-lens SED
Electrostatic Lens
23

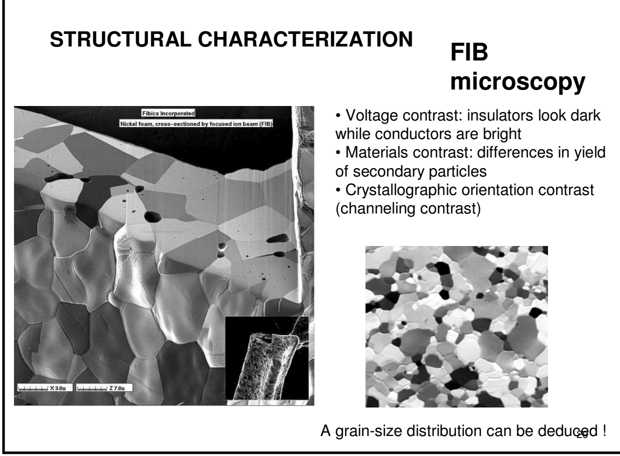

STRUCTURAL CHARACTERIZATION
MC2's SEM
SEM
JEOL JSM-6301F SEM
Installed: 1994
Funded by: Wallenberg
Max sample size: 100 mm
resolution 1.2 nm specified
Acc. voltages 0.5kV - 30kV
Source: Cold Field Emission
24

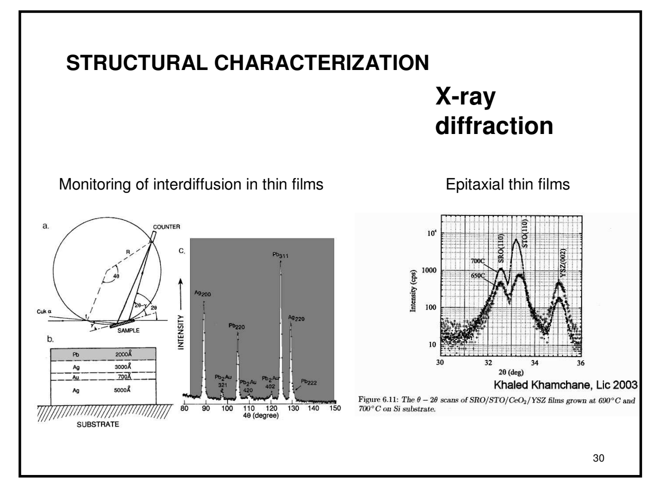

STRUCTURAL CHARACTERIZATION
Large SEM
MIRA-VP
Large Chamber SEM with Variable Pressure
25

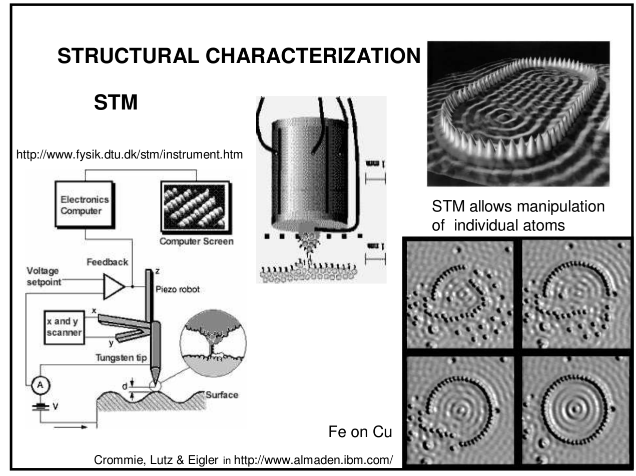

STRUCTURAL CHARACTERIZATION
Jeol SEM
Integrated circuit bond pads ---2.5kV--- 500X
http://www.jeol.com/sem/gallery
Chemical vapor deposited copper oxide---5kV---100X

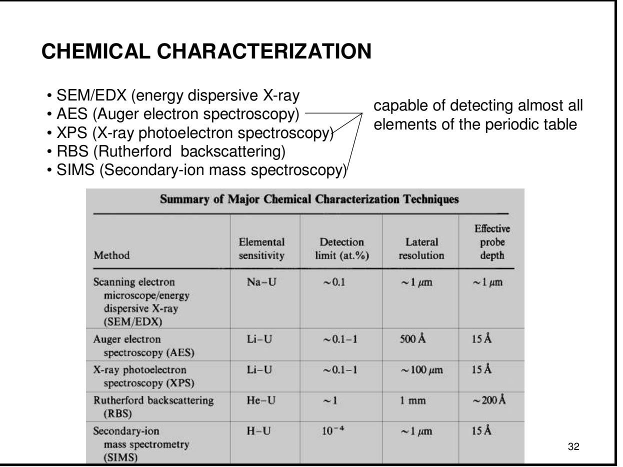

STRUCTURAL CHARACTERIZATION
TEM
(S)TEM Based Microanalysis
TEM modes:
• Bright-field imaging
• Dark-field imaging
• Lattice imaging
• Diffraction
• X-ray spectroscopy
• Electron energy loss spectroscopy
• Lorentz microscopy
27


STRUCTURAL CHARACTERIZATION
125 – 300 keV (up to 1 MeV) → short wavelength
100 keV → 0.035 Å
TEM
http://www.fzu.cz/~vystav/TEMpage.html
TEM cross sections
HRTEM: of coherent twin in molybdenum
Microscope: JEOL 4000EX
(CEA/DRFMC Grenoble)
http://www.fzu.cz/~vystav/TEMpage.html
magnetic domains in Co
TEM modes:
• Bright-field imaging
• Dark-field imaging
• Lattice imaging
• Diffraction
• X-ray spectroscopy
• Electron energy loss spectroscopy
• Lorentz microscopy
1 nm
28


STRUCTURAL CHARACTERIZATION
FIB microscopy
Fibics Incorporated
Nickel foam, cross-sectioned by focused ion beam (FIB)
• Voltage contrast: insulators look dark while conductors are bright
• Materials contrast: differences in yield of secondary particles
• Crystallographic orientation contrast (channeling contrast)
A grain-size distribution can be deduced !

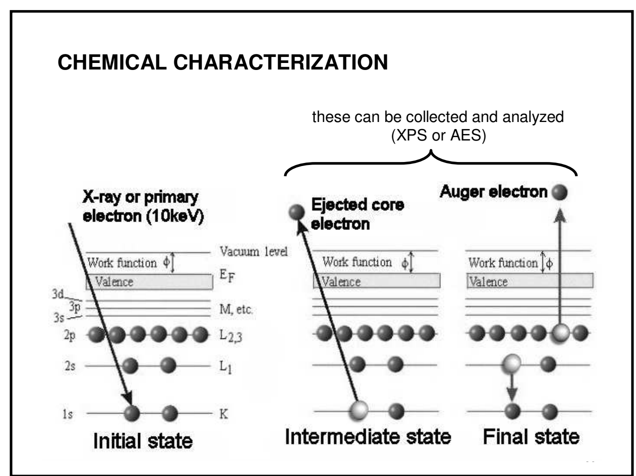

STRUCTURAL CHARACTERIZATION
X-ray diffraction
Monitoring of interdiffusion in thin films
Epitaxial thin films
COUNTER
SAMPLE
SUBSTRATE
INTENSITY
Khaled Khamchane, Lic 2003
30

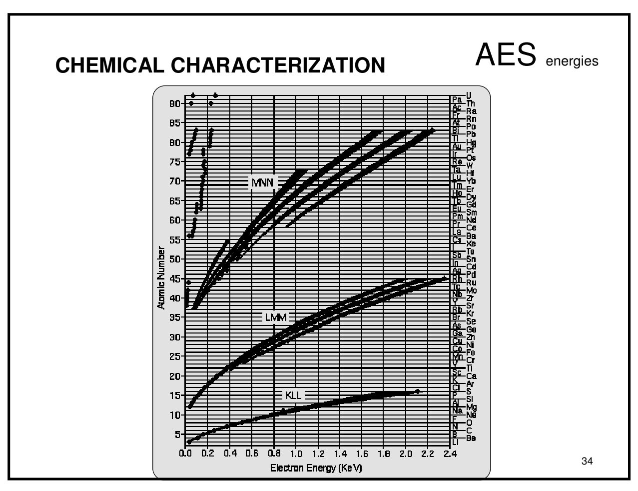




Summary of Major Chemical Characterization Techniques

Method	Elemental sensitivity	Detection limit (at.%)	Lateral resolution	Effective probe depth
Scanning electron microscope/energy dispersive X-ray (SEM/EDX)	Na–U	~0.1	~1 μm	~1 μm
Auger electron spectroscopy (AES)	Li–U	~0.1–1	500 Å	15 Å
X-ray photoelectron spectroscopy (XPS)	Li–U	~0.1–1	~100 μm	15 Å
Rutherford backscattering (RBS)	He–U	~1	1 mm	~200 Å
Secondary-ion mass spectrometry (SIMS)	H–U	10^{-4}	~1 μm	15 Å





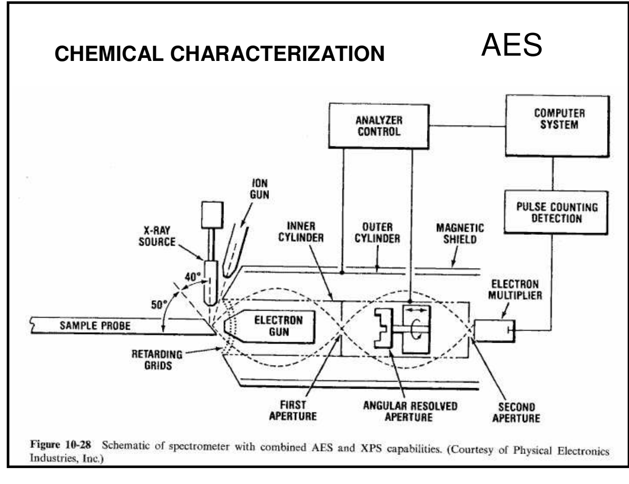
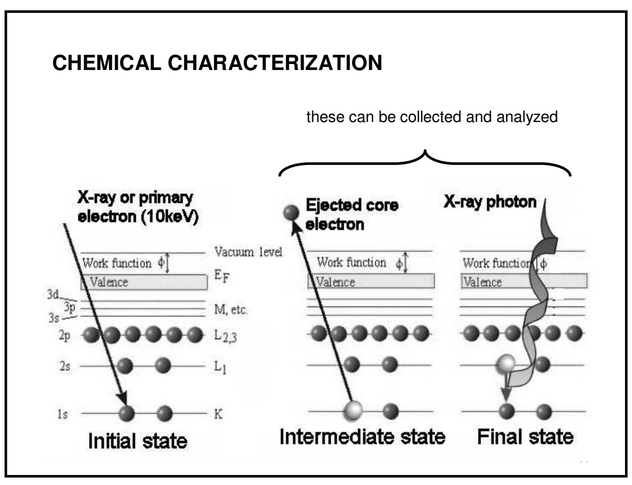


Figure 10-28 Schematic of spectrometer with combined AES and XPS capabilities. (Courtesy of Physical Electronics Industries, Inc.)



CHEMICAL CHARACTERIZATION

Auger Electron Spectroscopy (AES)
• The sample is irradiated with a high energy primary electron beam (2 - 10 keV).

• Backscattered, secondary, and Auger electrons can be detected and analyzed. These can also be used for imaging purposes similar to that in SEM.

• The Auger electrons are emitted at discrete energies, that are characteristic of the elements present on the sample surface (the peak positions are used to identify the elements and their chemical states) All elements in the periodic table, except hydrogen and helium, can be detected, and

• The depth of analysis is 3 - 5 nm

• In the scanning mode, the secondary electrons yield information on the surface topography. Excellent spatial resolution (0.5 μm).

• Top layers can be spattered with ions and depth profiles can be measured.

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Films

CHEMICAL CHARACTERIZATION

X-RAY PHOTOELECTRON SPECTROSCOPY (XPS)
also Electron Spectroscopy for Chemical Analysis (ESCA)
- The sample is irradiated with soft X-rays photons (1-2 keV) which induces direct emission of photoelectrons.
- The energy of photoelectrons is characteristic of the material.
- Depth 2-20 atomic layers.
- Peak position and area are used to study the composition. The peak shape give information about the chemical bonds of the elements.

Modes of Operation
1. Energy spectrum. Survey spectra (0-1000 eV) - to estimate the composition, while high-resolution spectra (10-20 eV) - information about the chemical bonds.
2. Mapping. Choosing a single peak and scanning the focal point across the sample gives information on the lateral distribution of species on the surface.
3. Imaging with high spatial resolution (<10-15 μm) and high sensitivity.

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CHEMICAL CHARACTERIZATION

XPS vs AES (are complimentary to each othe)
- Give similar information.
- The Auger spot size is smaller than the XPS.
- The XPS spectra are well-documented -> study of surface chemical bonding through the use of tabulated chemical shifts. The Auger chemical shifts are weaker.
- X-rays produce less damage to the surface compared to the primary electrons of AES.

39

CHEMICAL CHARACTERIZATION

Secondary Ion Mass SpectroscopyDescription **(SIMS)**
The most sensitive method for detection of elements.
- masses up to 10^4 mass units can be detected;
- separation of isotopes can be made;
- chemical information can be obtained by identifying sputtered ions;
- detection limits of 1 ppm of a monolayer;
- surface sensitivity < 1nm; depth resolution < 1nm; lateral resolution 100 nm.

Modes of operation:
1. Surface analysis – (Static SIMS) - low primary ion densities to prevent surface destruction
2. Imaging. Focused ion beam scanning over the surface produces images of the surface (recall FIB !)
3. Depth profiling (Dynamic SIMS) - high primary ion dose densities to remove the surface layer by layer. Spectra taken during the sputtering can give the thickness distribution of elements

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CHEMICAL CHARACTERIZATION

http://hyperphysics.phy-astr.gsu.edu/hbase/magnetic/maspec.html

Ionization
Accelerating voltage applied
Velocity selector
Magnetic field region
B out toward viewer
Detector

After ionization, acceleration, and selection of single velocity particles, the ions move into a mass spectrometer region where the radius of the path and thus the postion on the detector is a function of the mass.

$$r = \frac{mv}{qB} = \frac{mE_s}{qBB_s}$$

The mass spectrometer is an instrument which can measure the masses and relative concentrations of atoms and molecules.

It makes use of the magnetic force on a moving charged particle.

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CHEMICAL CHARACTERIZATION

SIMS

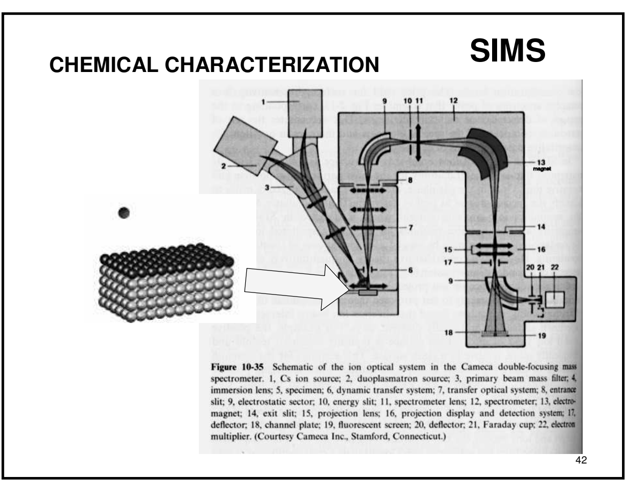

Figure 10-35 Schematic of the ion optical system in the Cameca double-focusing mass spectrometer. 1, Cs ion source; 2, duoplasmatron source; 3, primary beam mass filter; 4, immersion lens; 5, specimen; 6, dynamic transfer system; 7, transfer optical system; 8, entrance slit; 9, electrostatic sector; 10, energy slit; 11, spectrometer lens; 12, spectrometer; 13, electromagnet; 14, exit slit; 15, projection lens; 16, projection display and detection system; 17, deflector; 18, channel plate; 19, fluorescent screen; 20, deflector; 21, Faraday cup; 22, electron multiplier. (Courtesy Cameca Inc., Stamford, Connecticut.)

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CHEMICAL CHARACTERIZATION **RBS**

Easiest to understand: two-body elastic scattering

Rutherford backscattering is an analytical technique in which a high energy beam (2 - 4 MeV) of low mass ions (He ++) is directed at a surface. A detector collects particles which scatter from the sample at close to a 180 degree angle.

•The energy of scattered ions depend on their incident energy and on the mass of the sample atom which they hit. The energy of scattered ions therefore indicates the chemical composition of the sample.

•RBS can be used to perform a depth profile of the composition of a sample. This is especially useful in analysis of thin-film materials.

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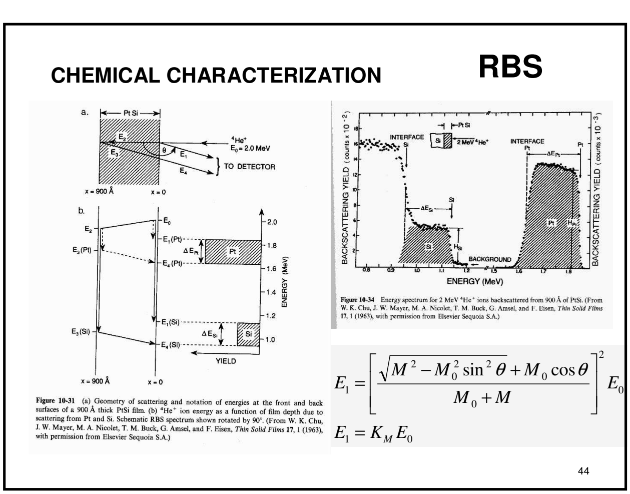
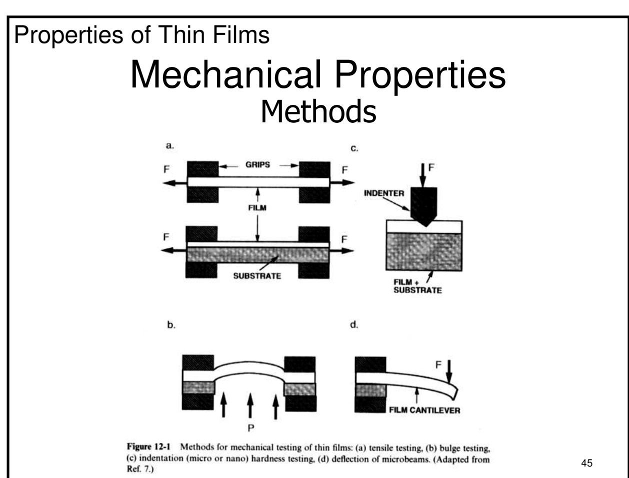
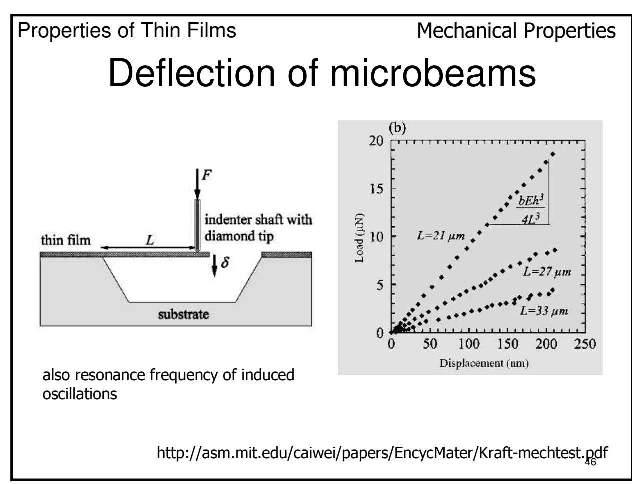
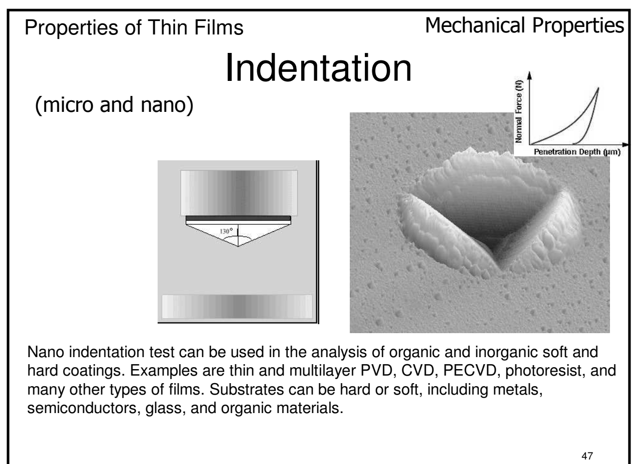
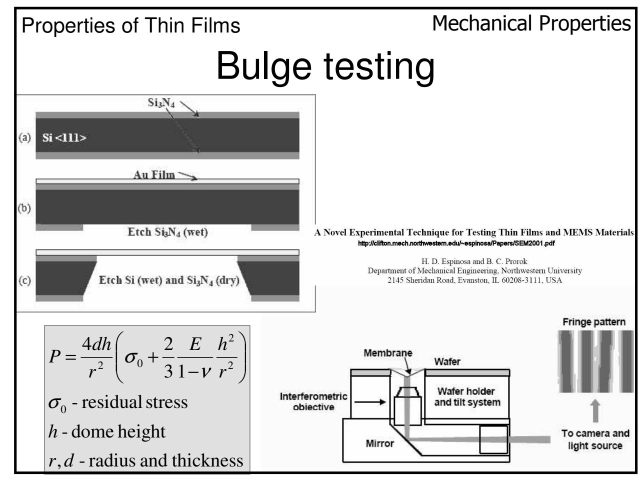
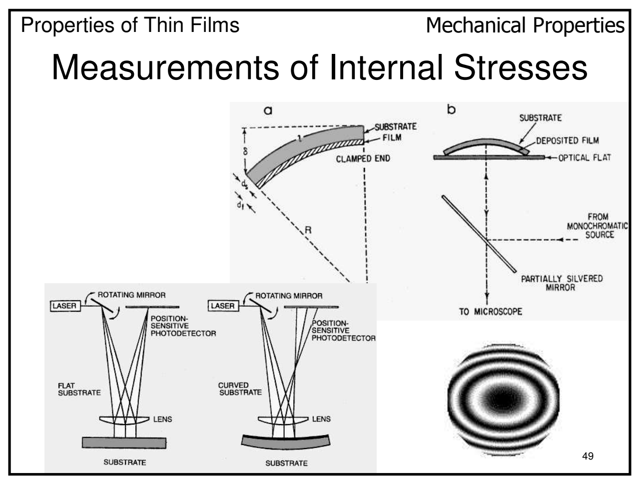


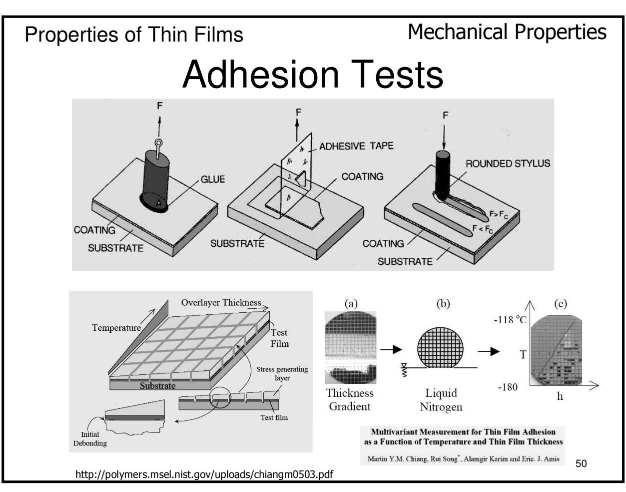


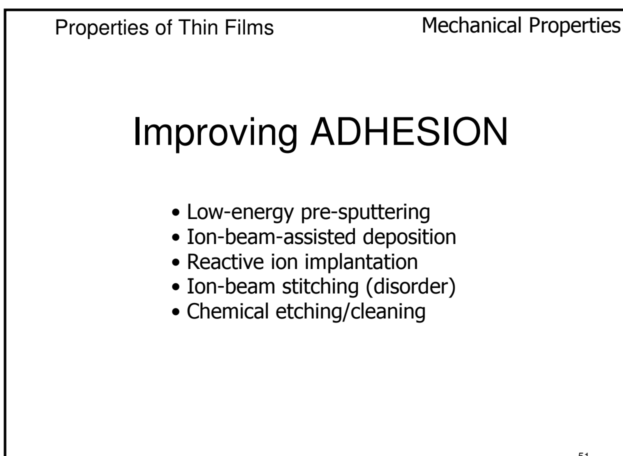


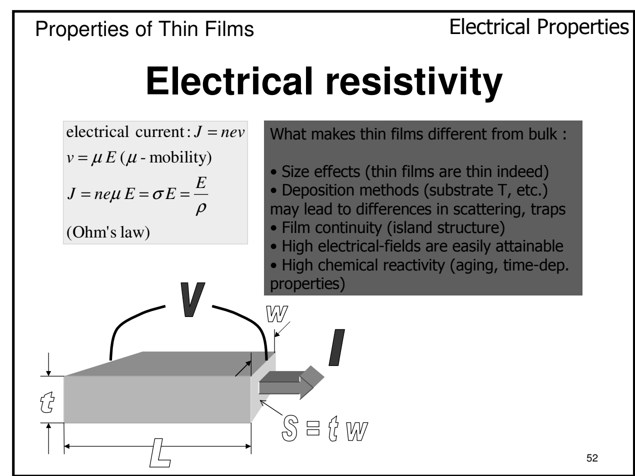


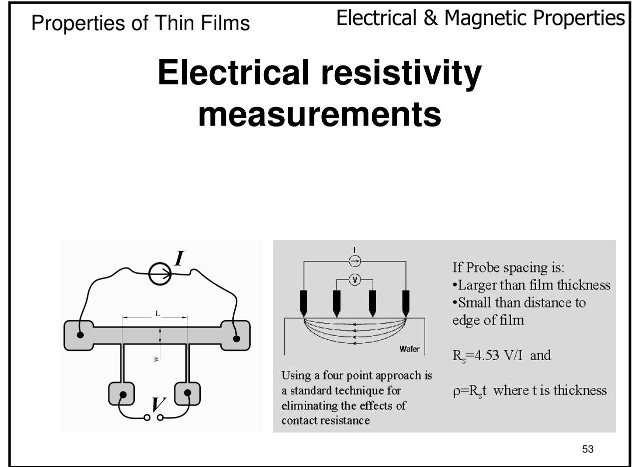


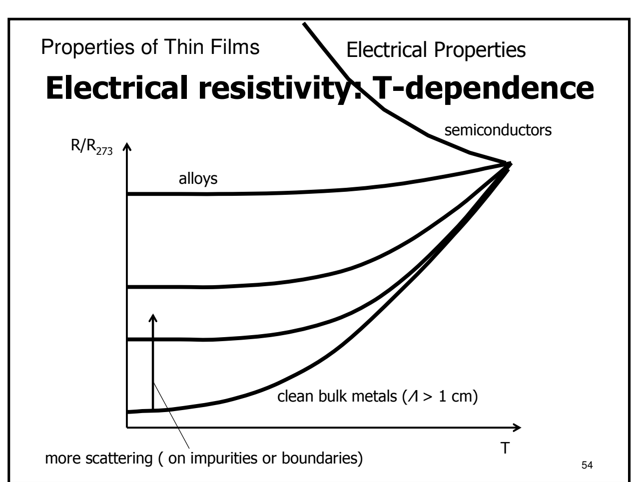

Properties of Thin Films
Mechanical Properties
Measurements of Internal Stresses
SUBSTRATE
FILM
CLAMPED END
DEPOSITED FILM
OPTICAL FLAT
FROM MONOCHROMATIC SOURCE
PARTIALLY SILVERED MIRROR
TO MICROSCOPE
LASER
ROTATING MIRROR
POSITION-SENSITIVE PHOTODETECTOR
FLAT SUBSTRATE
CURVED SUBSTRATE
LENS
49


Properties of Thin Films
Mechanical Properties
Adhesion Tests
GLUE
ADHESIVE TAPE
COATING
ROUNDED STYLUS
SUBSTRATE
Overlayer Thickness
Temperature
Test Film
Substrate
Stress generating layer
Test film
Initial Debonding
Thickness Gradient
Liquid Nitrogen
-118 °C
-180
Multivariant Measurement for Thin Film Adhesion as a Function of Temperature and Thin Film Thickness
http://polymers.msel.nist.gov/uploads/chiangm0503.pdf
50


Properties of Thin Films
Mechanical Properties
Improving ADHESION
• Low-energy pre-sputtering
• Ion-beam-assisted deposition
• Reactive ion implantation
• Ion-beam stitching (disorder)
• Chemical etching/cleaning
51


Properties of Thin Films
Electrical Properties
Electrical resistivity
electrical current: $J = nev$
$v = \mu E$ (μ - mobility)
$J = ne\mu E = \sigma E = \frac{E}{\rho}$
(Ohm's law)
What makes thin films different from bulk :
• Size effects (thin films are thin indeed)
• Deposition methods (substrate T, etc.) may lead to differences in scattering, traps
• Film continuity (island structure)
• High electrical-fields are easily attainable
• High chemical reactivity (aging, time-dep. properties)
V
w
I
t
L
S = t w
52


Properties of Thin Films
Electrical & Magnetic Properties
Electrical resistivity measurements
I
V
Wafer
Using a four point approach is a standard technique for eliminating the effects of contact resistance
If Probe spacing is:
•Larger than film thickness
•Small than distance to edge of film
R_s=4.53 V/I and
ρ=R_st where t is thickness
53


Properties of Thin Films
Electrical Properties
Electrical resistivity: T-dependence
R/R_{273}
semiconductors
alloys
clean bulk metals (Λ > 1 cm)
more scattering (on impurities or boundaries)
T
54

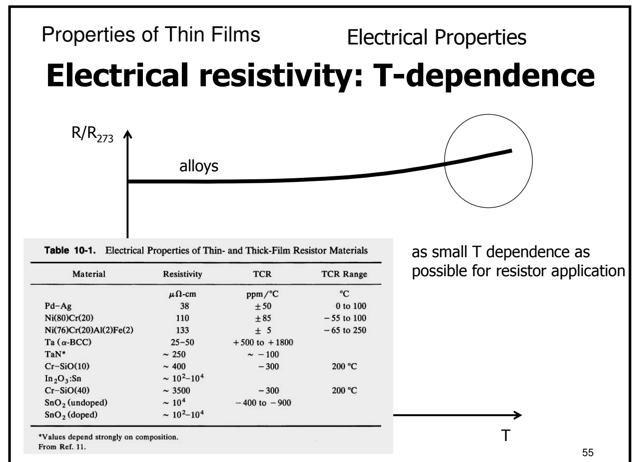
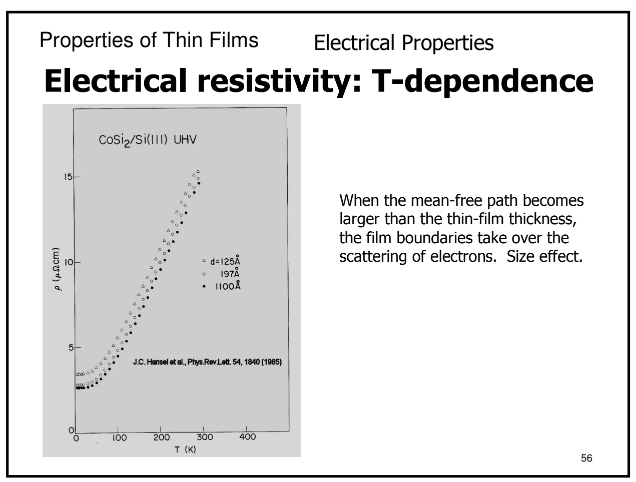
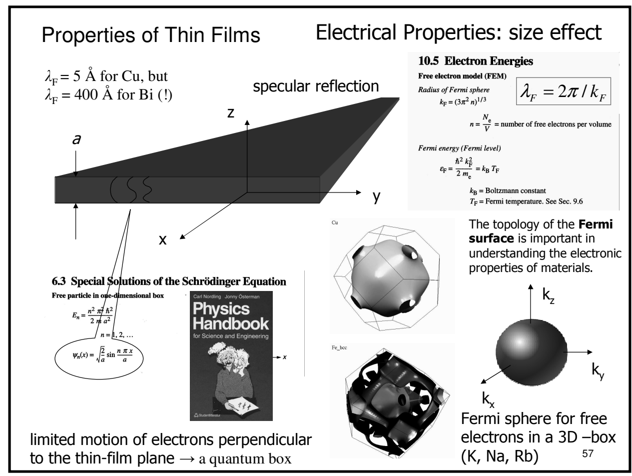


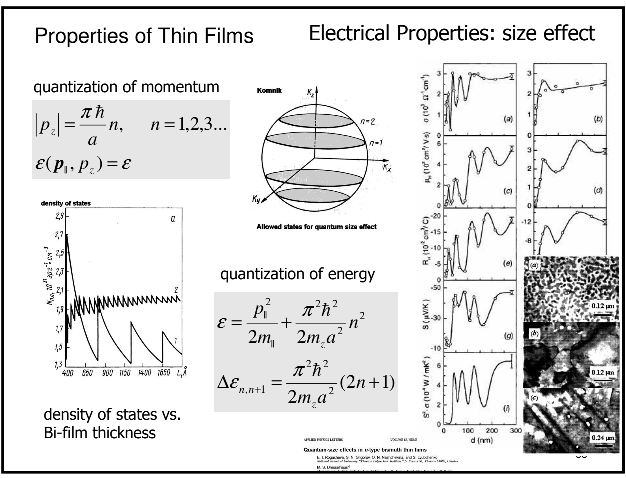
Table 10-1. Electrical Properties of Thin- and Thick-Film Resistor Materials

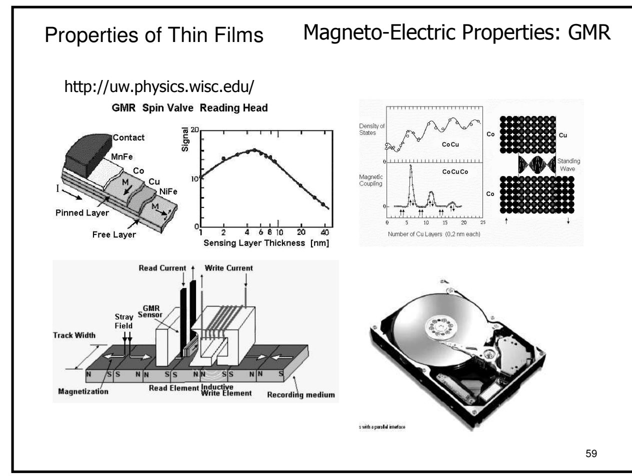
Material	Resistivity	TCR	TCR Range
	μΩ-cm	ppm/°C	°C
Pd–Ag	38	±50	0 to 100
Ni(80)Cr(20)	110	±85	−55 to 100
Ni(76)Cr(20)Al(2)Fe(2)	133	± 5	−65 to 250
Ta (α-BCC)	25–50	+500 to +1800	
TaN*	~ 250	~ −100	
Cr–SiO(10)	~ 400	−300	200 °C
In_2O_3:Sn	~ 10^2–10^4		
Cr–SiO(40)	~ 3500	−300	200 °C
SnO_2 (undoped)	~ 10^4	−400 to −900	
SnO_2 (doped)	~ 10^2–10^4		

*Values depend strongly on composition.
From Ref. 11.









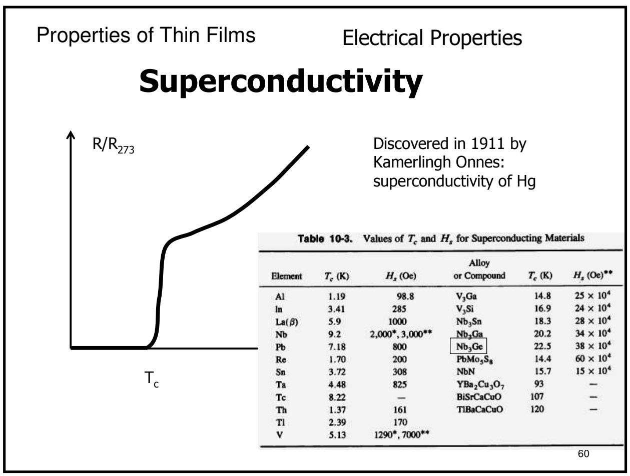
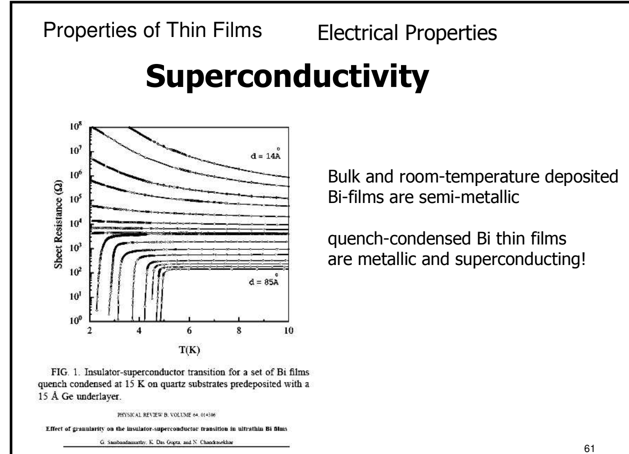


Table 10-3. Values of T_c and H_s for Superconducting Materials

Element	T_c (K)	H_s (Oe)	Alloy or Compound	T_c (K)	H_s (Oe)**
Al	1.19	98.8	V_3Ga	14.8	25 × 10^4
In	3.41	285	V_3Si	16.9	24 × 10^4
La(β)	5.9	1000	Nb_3Sn	18.3	28 × 10^4
Nb	9.2	2,000*, 3,000**	Nb_3Ga	20.2	34 × 10^4
Pb	7.18	800	Nb_3Ge	22.5	38 × 10^4
Re	1.70	200	$PbMo_5S_8$	14.4	60 × 10^4
Sn	3.72	308	NbN	15.7	15 × 10^4
Ta	4.48	825	$YBa_2Cu_3O_7$	93	—
Tc	8.22	—	BiSrCaCuO	107	—
Th	1.37	161	TlBaCaCuO	120	—
Tl	2.39	170			
V	5.13	1290*, 7000**			


Properties of Thin Films
Electrical Properties
Superconductivity
Sheet Resistance (Ω)
T(K)
d = 14Å
d = 85Å
Bulk and room-temperature deposited Bi-films are semi-metallic
quench-condensed Bi thin films are metallic and superconducting!
FIG. 1. Insulator-superconductor transition for a set of Bi films quench condensed at 15 K on quartz substrates predeposited with a 15 Å Ge underlayer.
Effect of granularity on the insulator-superconductor transition in ultrathin Bi films
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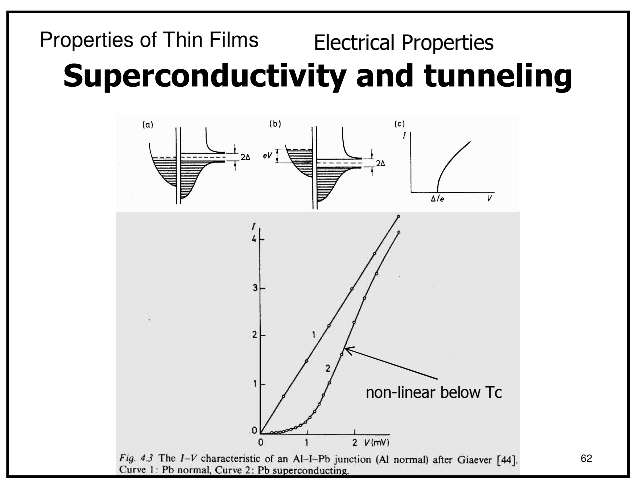
Properties of Thin Films
Electrical Properties
Superconductivity and tunneling
non-linear below Tc
Fig. 4.3 The I–V characteristic of an Al–I–Pb junction (Al normal) after Giaever [44]. Curve 1: Pb normal, Curve 2: Pb superconducting.
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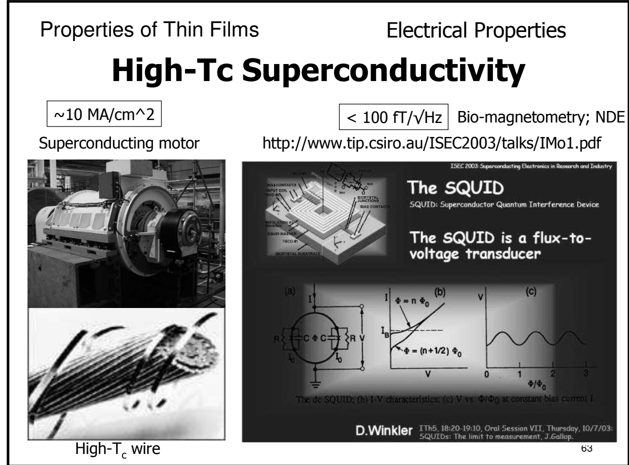
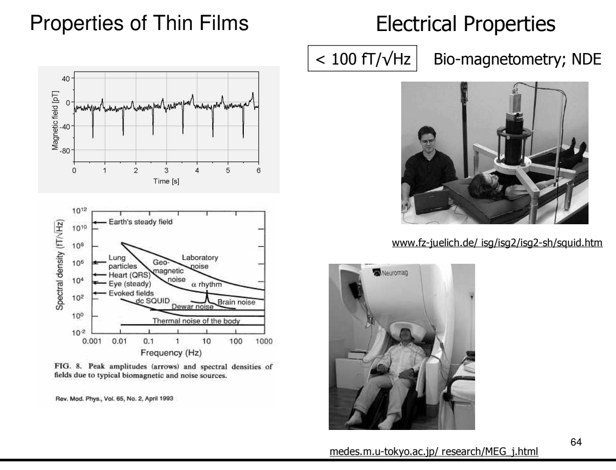

Properties of Thin Films
Electrical Properties
High-Tc Superconductivity
~10 MA/cm^2
Superconducting motor
< 100 fT/√Hz
Bio-magnetometry; NDE
http://www.tip.csiro.au/ISEC2003/talks/IMo1.pdf
The SQUID
SQUID: Superconductor Quantum Interference Device
The SQUID is a flux-to-voltage transducer
D.Winkler
High-Tc wire
63


Properties of Thin Films
Electrical Properties
< 100 fT/√Hz
Bio-magnetometry; NDE
Magnetic field [pT]
Time [s]
Earth's steady field
Spectral density (fT/√Hz)
Frequency (Hz)
FIG. 8. Peak amplitudes (arrows) and spectral densities of fields due to typical biomagnetic and noise sources.
Rev. Mod. Phys., Vol. 65, No. 2, April 1993
www.fz-juelich.de/ isg/isg2/isg2-sh/squid.htm
medes.m.u-tokyo.ac.jp/ research/MEG_j.html
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