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Thickness Measurement

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One can measure thickness on many scales. The galaxy is a spiral disk about 100 Em (10^{20} m) thick. The solar system is pancake-like, about 1 Tm (10^{12} m) thick. The rings of Saturn are about 10 km thick. Closer to home, Earth's atmosphere is a spherical shell about 40 km thick; the weather occurs in the troposphere, about 12 km thick. The outermost shell of the solid Earth is the crust, about 35 km thick. The ocean has a mean depth of 3.9 km. In the Antarctic, the recently discovered objects believed to be microfossils indicative of ancient Martian life are less than 100 nm thick. In terms of the man-made environment, industry must contend with thickness varying from meters, for construction projects, to millimeters on assembly lines, to micrometers and nanometers for the solid-state, optical, and coatings industries. Perhaps the most familiar way of measuring thickness is by mechanical means, such as by ruler or caliper. Other means are sometimes called for, either because both sides of an object are not accessible, the dimension is either too big or too small for calipers, the object is too fragile, too hot, or too cold for direct contact, or the object is in motion on an assembly line — it may not even be a solid. Thickness may also be a function of position, as either the object may have originally been made with nonuniform thickness, deliberately or not, or the thickness may have become nonuniform with time due either to corrosion, cracking, or some other deterioration. The thickness may also be changing with time due to deliberate growth or etching, as example for thin films. Thus it follows that, in more general terms, measuring thickness might require measuring the topography or height profile of two surfaces and taking the difference. Alternatively, the measurement technique may produce a reading directly related to the difference. Table 7.1 lists some of the many techniques suited to determining thickness, together with the range of usefulness and some comments on accuracy and/or precision.

TABLE 7.1 Thickness Measuring Techniques

Technique	Range	Comments
Mechanical		
Caliper gage, micrometer	1 μm–100 mm	±3 μm accuracy
Electronic gages: LVDT	0–1 m	Precision depends on noise level
Pneumatic gaging	50 nm minimum	
Optical/focusing, shadowing, comparing		
Microscope	5 μm minimum	About 1% accuracy
Comparators/projectors	25–250 nm	
Laser caliper	100 μm–100 mm	Precision of 6 μm or better
Weighing	Range depends on area	
Capacitive gaging	From <1 μm to about 1 cm	
Inductive gaging (eddy current sensing)	0–1.5 mm	Precision of 2.5 μm
Magnetic induction	0–4 mm	10% accuracy
Hall effect gage	0–10 mm	1–3% accuracy
Far-field/time-of-flight		
Sonar/ultrasound	0.5–250 mm	25 μm accuracy
Radar	0.1 to few hundred km	
Lidar	10 m–5 km	
THz technology		
Far-field/resonance		
Resonant ultrasound		
Interferometry: spectral and spatial	1 nm–100 μm	Accuracy about $\lambda/50$
Ellipsometry	0.3 nm–10 μm	0.1 nm accuracy
Far-field/absorption, scattering, emission		
Gamma-ray backscatter	Range to 25 mm	0.5% precision
Beta-transmission	2 μm–1 mm	0.2% precision
Beta-backscatter	100 nm–50 μm	3 to 20% precision
X-ray fluorescence	0–30 μm	
Infrared absorption	Depends on material	
Scanning techniques: scanning probe microscopy		Precision better than 0.1 nm
Destructive techniques: electrolytic	15 nm–50 μm	

7.1 Descriptions of the Relatively Mature Measuring Techniques

The following descriptions will also refer to some of the relevant vendors, whose addresses are found in Table 7.2. Additional vendor information, with specific price or model number identification, is found in Table 7.3. The words "gage" and "gauge" are used interchangeably.

Mechanical

The fundamental tool for measuring thickness is the line-graduated instrument [1, 2]. It is the only mechanical means to make direct measurements. Graduated spacings that represent known distances are used as direct comparisons to the unknown distance. Instruments include bars, rules, and tapes generically called rulers; caliper gages, which employ a positive contact device for improved alignment of the distance boundaries; and micrometers, which typically have greater precision due to a combination of linear and circumferential scales. Caliper precision can be improved with vernier scales or linear transducers. Fixed gages are often used to measure objects on a pass/fail basis. An object of fixed geometry (length, tapered bore, thread, etc.) is compared to a test piece typically for part inspection. Variations include the master gage, an object used to represent the nominal dimension of the part; the limit gage, an object used to represent the limit condition for tolerance dimensioning; and gage blocks or Johansson blocks, an object of fixed length used as a dimensional reference standard. Dial indicators are used to sense displacement

TABLE 7.2 Vendor addresses.

Vendor	Address
Bomem	Quebec, Canada
Brown & Sharpe	North Kingstown, RI
CMI International	Elk Grove Village, IL
Conductus	Sunnyvale, CA
deFelsko	Ogdensburg, NY
Digilab	Cambridge, MA
Digital Instruments	Santa Barbara, CA
Electromatic	Cedarhurst, NY
Fischer	Windsor, CT
Hewlett Packard	Englewood, CO
Kta-Tator	Pittsburgh, PA
Magnetic Analysis Corp.	Mount Vernon, NY
Mattson	Madison, WI
Measurex	Cupertino, CA
Micro Photonics	Allentown, PA
Midac	Costa Mesa, CA
Mitutoyo	Plymouth, MI
Moore Products Co	Spring House, PA
NDC Systems	Irwindale, CA
Nicolet	Madison, WI
Ono Sokki	Addison, IL
Oxford Instruments	Concord, MA
Panametrics	Waltham, MA
Park Scientific Instruments	Sunnyvale, CA
Penny + Giles	Attleboro, MA
Perkin Elmer	Norwalk, CT
Phase-Shift Technology	Tucson, AZ
Rudolf Instruments	Fairfield, NJ
Scantron	Dist. by Micro Photonics
Schaevitz	Pennsauken, NJ
Sentech	Dist. by Micro Photonics
SolveTech	Claymont, DE
Starrett	Athol, MA
Stresstel	Scotts Valley, CA
Transicoil Inc.	Valley Forge, PA
Trans-Tek	Ellington, CT
Willrich Precision Instrument Co.	Cresskill, NJ
J.A. Woolam Co., Inc.	Lincoln, NE
Wyko	Tucson, AZ
Zygo	Middlefield, CT

from a reference plane and display the deviation thereof. The display can be electronically coupled for amplification and/or display purposes. The range of a measuring instrument may be extended if multiple copies of the object to be measured are available. For example, the thickness of a sheet of paper may be measured by a simple ruler if 500 sheets of paper are stacked. (Vendors: Brown & Sharpe, Starrett, Mitutoyo. Also see [3].)

Electronic Gages

A Linear Variable Differential Transformer (LVDT), utilizes multiple toroidal transformers to sense axial displacement of an iron core that is attached to a measuring contact, either directly or by another joint (such as a lever). The displacement has a direct correlation to the distance that other electronics display. Thus, the LVDT serves as a replacement for a lined ruler or micrometer, incorporating an electrical readout. (Vendors: Penny + Giles; Schaevitz; Transicoil Inc.; Trans-Tek.)

TABLE 7.3 Instruments for measuring thickness.

Manufacturer	Model Number	Price	Description
KTa-Tator	TI-12	$1595.	General-purpose ultrasonic gage, 0.75 mm to 75 mm range
NDC Systems	6100TC	$49,300.	Backscatter gamma gage for 60 in. web, 25 mm range
NDC Systems		$66,600.	Transmission beta gage, for continuous web products
Panametrics	25DL	$2200. to $3800.	Single-element ultrasonic gage, 50 mm range
Panametrics	26DL Plus	$1400. to $2500.	Dual-element ultrasonic gage, 250 mm range
Panametrics	8000	$6500.	Hall effect magnetic gage, for nonferrous materials, 6 mm range
DeFelsko	Positest 1000-N	$1995.	Eddy current sensor, Apple Newton read-out, measure out to 1.5 mm nonferrous, nonconducting coating on conducting substrate
Magnetic Analysis	Various	$1500. to $100,000.	Ultrasonic, time-of-flight gages
Fischer	Deltascope MP2C	$1200.	Magnetic induction gage, measure nonmagnetic coating on ferromagnetic substrate
Fischer	IsoScope MP1C	$1200.	Eddy current gage, measure nonconducting coating on nonferrous conducting substrate
Fischer	Fischerscope MMS	$6500.	Beta-backscatter system to measure coating thickness
Fischer	Fischerscope X-Ray 1020 video	$34,000.	X-ray fluorescence system to measure coating thickness
Fischer	Couloscope Sx	$2500.+ accessories	Electrolytic, destructive system to measure coating thickness
J.A. Woollam Co. Inc.	M-44	Application specific	Variable angle, multiwavelength spectroscopic ellipsometer
Rudolf Instruments	431A31WL633	$10,100.	Manual, HeNe wavelength ellipsometer
Rudolf Instruments	444A12	$34,000.	Automatic, HeNe wavelength ellipsometer
Hewlett Packard	HP8712C	$13,500.	RF vector network analyzer, measure transmission/reflection frequency response to 1.3 GHz, optional to 3 GHz
Stresstel	T-Mike Programmable	$995.	Dual-element ultrasonic system
Stresstel	TM1D	$1795.	Single-element ultrasonic system
Measurex	DMC480	Application specific	High-speed X-ray thickness gage
Bomem	MB series	$20,000. and up	1 cm^{-1} resolution Fourier transform spectrometer
Park Scientific Instruments	Autoprobe CP	$65,000.	Ambient scanning probe microscope
Park Scientific Instruments	Autoprobe VP2	$130,000.	UHV scanning probe microscope
Digital Instruments	Nanoscope IIIa/D3000	$90,000.	Small sample scanning probe microscope

Pneumatic Gaging

Pneumatic gages have pressurized air exiting gage orifices. The air velocity differential or backpressure is a function of the separation of the gage and the part. In the direct or open jet method, the pressurized air experiences backpressure due to the impedances posed by the measured part. The typical scenario is that the gage head and the measured part have similar geometry (i.e., a cylindrical gage in a bored hole). By placing two gages on either side of a flat plate, the thickness may be inferred. In the indirect or contact method, the pressurized air pushes on a contact piece that directly contacts the part. Tolerances as small as 50 nm can be measured. (Vendors: Willrich Precision Instrument Co.; Moore Products Co.)

Optical: Focusing, Shadowing, Comparing

This includes microscopes, which can determine thickness either by comparison with a known reference, or by focusing on the front and rear surfaces of a sample, noting the difference in focus position. Comparators project onto a screen what might be noted through a microscope. Laser calipers retrieve dimensions by measuring the shadowing of a laser beam. (Vendors: NDC Systems for laser caliper; Scantron for laser profilometer.)

Weighing

Given a plate of material with known density, first measure the area with some type of calibrated video system. Then, a measurement of weight can be simply converted to an estimate of the thickness. As is common with this technique and most of the following techniques, estimating the thickness requires knowledge of some other property of the material to be measured — in this case, the density.

Capacitive Gaging

Capacitive gaging is realized by inserting a nonmetallic material into a known electric field. Knowing the gage sensor area and the material's dielectric constant, the thickness can be determined. Submicron thickness levels can be achieved. (Vendors: Ono Sokki; SolveTech.)

Inductive Gaging (Eddy Current Sensing)

The principle here is that ac currents in a coil induce eddy currents in a nearby conducting plate [4, 5]. These eddy currents can be sensed by a pickup coil, which may be the exciting coil or a second coil. The presence of the eddy currents manifests itself as a modification of the apparent inductance and/or the loss of the pickup coil. This technique is appropriate for nonferrous metals, and is especially sensitive to thickness variations due to flaws such as cracks or corrosion. There is one particular instance in which it is common to measure thickness rather than variations. That would be the thickness of a nonconducting coating on a nonferrous conducting substrate. The coating thickness creates a gap (lift-off) between the exciting coil and the eddy currents, thereby affecting the eddy current signal. The range of this technique would be about 1 mm. Fischer has an instrument designed for measuring the thickness of a newly laid road surface coating to a depth of 40 cm, by burying a conductive plate below the road. (Vendors: Fischer; deFelsko; CMI International.)

Magnetic Induction

This technique is also used to measure coating thickness, in this case a nonmagnetic coating on a ferromagnetic substrate. The nonmagnetic coating creates a gap (lift-off) between the ferromagnetic substrate and a probe. One way to measure the gap and thereby the thickness is by measuring the force required to pull away a magnetic probe. Another technique would be to magnetically couple the ferromagnetic substrate to a transformer core, with a gap between the substrate and the core. This technique would have a range of about 4 mm. CMI International has an informative brochure describing the relative merits of measuring coating thickness via eddy current, magnetic induction, beta-backscatter, microresistance, and X-ray fluorescence; the choice of technique depends, among other things, on the material to be tested. (Vendors: Fischer; CMI International; Electromatic; deFelsko.)

Hall Effect Gage

This sensor measures the thickness of nonferrous materials with 1% accuracy by sandwiching the material being measured between a magnetic probe on one side and a small target steel ball on the other side [6].

It measures up to 10 mm. The Hall effect sensor is used to measure the magnetic field, as a dc measurement; ac Hall effect measurements can be made more precisely because they eliminate bias and are done with less noise. (Vendor: Panametrics.)

Far-Field/Time-of-Flight: Ultrasound, Radar, Lidar

Using 1940s sonar principles and today's microprocessor technology, high-frequency (1–20 MHz) ultrasound waves can be used to measure thickness by sending pulsed sound waves through a material and measuring the transit time of the reflected signal [5, 7]. Knowing the sound velocity of the material, materials from 0.5 mm to 250 mm can be measured, often as fine as 25 μm. Media include metal, glass, ceramic, liquid, rubber, fiberglass, plastic, and concrete. Ultrasound can also be used to measure living tissues, as is often done in the agricultural and medical fields. Fat layers of cattle and pigs can influence marketability. Skin burn depths can direct treatment procedures. The depth of foreign objects in the body is useful for microsurgery. Ultrasonic thickness determination has expanded to include mulitdimensional echolocation applications, such as imagery and acoustic microscopes that can resolve in the submicron level. The principles behind ultrasound also apply to electromagnetic waves. In the gigahertz range, this is called radar. Radar can be used to estimate the thickness of atmospheric layers such as cloud layers. The light-wave version of radar, called lidar, can be used to measure the thickness of water vapor layers in the lower atmosphere. (Ultrasonic vendors: KTa-Tator; deFelsko; Stresstel; Magnetic Analysis Corp.; Panametrics; Electromatic.)

Far-Field/Resonance: Ultrasound, Interferometry, Ellipsometry

The idea here is that when waves such as ultrasound impinge on a plane-parallel slab of material, there will be reflected power from both the front and rear surfaces; depending on whether the slab thickness is an odd or even number of quarter-wavelengths, the reflected beams will be in constructive or destructive interference. If the frequency is swept, the distance in frequency between successive maxima and minima may be related to the slab thickness, if the index of refraction is known. Since the natural, or resonant, modes of an object depend on the properties and dimensions of an object, knowledge of the properties enables estimation of dimensions from the resonant frequencies. Compared with time-of-flight ultrasound, resonant ultrasound is much less common. It has been used to characterize concrete, and is quite sensitive to flaws, as anyone who has heard a cracked bell would know. Resonant techniques are much more common with visible [8], infrared, or microwave [4] radiation. Spectral interferometry would be appropriate to characterize the thickness of transparent substrates with reasonably flat surfaces, sufficiently parallel to one another. A common way to do this would be to measure a transmission spectrum with a spectrometer such as a Fourier transform spectrometer (FTS). The successive maxima and minima are here called the Fabry–Perot effect, and their appearance in a spectrum is called channeling. Thickness can also be measured with spatial interferometry, which is essentially a way of measuring surface topography. An example would be the phenomenon of Newton's rings, which occur when the surface to be tested is in contact with an optical flat. Using a transparent optical flat, transmit monochromatic light such as a mercury lamp through the flat and onto the interface between the flat and the test surface. If there are variations in the height of the test surface, then the two return beams from the optical flat and the test surface will alternate between constructive and destructive interference, producing fringes or rings. The sensitivity is not limited to the scale of the wavelength λ: with sufficient stability and signal-to-noise, dimensions down to 1/1000 of a fringe can be measured. With sources of longer coherence length, such as lasers, the test surface and the optical flat need not be in direct contact.

Another optical way to measure thickness is with ellipsometry [9], typically used to measure properties of thin, transparent films from a few tenths of nanometers to several hundreds of nanometers thick. This includes metals, as long as the metal is sufficiently thin to be partially transparent. By measuring the change in polarization state for nonnormal incidence light, both the thickness and refractive index of a thin layer may be inferred. Additional information (e.g., the properties of multiple layers) can be obtained by varying the angle of incidence and by observing at multiple wavelengths. The ability to estimate both thickness and refractive index is an important advantage of this technique, as often the refractive index of a material in thin film form is not the same as the bulk value, and indeed may be a property of the deposition conditions. (FTS vendors: Bomem; Digilab; Mattson; Midac; Nicolet; Perkin-Elmer. FTS system pricing may range from about $15,000 to over $100,000, depending on the application. Spatial interferometer vendors: Zygo; Wyko, Phase-Shift Technology. Ellipsometer vendors: J.A. Woollam Co., Inc.; Rudolf Instruments; Sentech. The cost of an ellipsometer may range from $10,000 for a manual, single-wavelength system to $200,000 for an automatic, multiwavelength system. Microwave resonance vendor: Hewlett-Packard.)

Far-Field/Absorption, Scattering, Emission: Beta, Gamma, X-Ray, Infrared

These techniques depend on the extinction (scattering or absorption) or emission of photons or massive particles (electrons, protons, neutrons) when transiting the material to be measured. Typically, the extinction or emission shows an exponential dependence on thickness; the dependence becomes linear if the absorption is sufficiently low. These techniques, in particular gamma-ray backscatter and beta-ray transmission, are used to measure continuously moving web materials (paper, metals, fabrics) on assembly lines. Infrared absorption is also suitable if the moisture content is controlled. Beta-backscatter and X-ray fluorescence [10] are used for measuring coatings. In X-ray fluorescence, upon exposure to X-rays, certain elements fluoresce (emit) X-rays at characteristic wavelengths. The strength of this emission is related to thickness. These absorption/emission techniques may sometimes be better suited than time-of-flight ultrasound to the dimensional measurement of objects with complex shapes. (Gamma gage vendor; NDC Systems. X-ray absorption vendor: Measurex. X-ray fluorescence vendors: Fischer; NDC Systems; CMI International. Beta-backscatter vendor: Fischer; Electromatic; CMI International; Measurex. Infrared absorption vendor: NDC Systems. The prices for these systems will depend on the application; a typical system could cost $500,000.)

Destructive Techniques

Fischer markets a system that removes a coating into an electrolyte and then electrolytically deposits the removed coating. The electrical charge required for deposition is related to the coating thickness.

7.2 Future Directions in Thickness Measurement

Concerning Techniques Mentioned Above

Concerning capacitive sensors, the NASA Langley Research Center is developing sensors based on patterns of conductors sandwiched between insulating layers. The presence of ice over the conductors changes the capacitance, providing a way of sensing ice build-up on aircraft wings. With respect to eddy current sensing, one limitation is that a nonsuperconducting sense coil responds best to high-frequency excitations, and not at all to dc magnetic fields. This limits the technique to fairly high frequencies and thus low penetration depths, since the skin depth becomes shallower with increasing frequency. One possibility is to use a SQUID (superconducting quantum interference detector) as the sensor, since the SQUID is probably the most sensitive sensor of dc and low-frequency magnetic fields. One disadvantage of the SQUID has been the need for liquid helium for cooling for low-temperature superconductors; with the recent availability of high-temperature superconductors (HTS, above 90 K) and now HTS SQUIDS, cooling can be done with liquid nitrogen or single-stage mechanical coolers. In the area of spatial interferometry, work at Lawrence Livermore National Laboratory replaces the reference surface with a single-mode fiber in a process called phase-shifting diffraction interferometry. A measurement accuracy of 1.44 nm rms is quoted, with a goal of 0.1 nm rms. (HTS SQUID vendor: Conductus.)

THz Technology

With the availability of femtosecond pulsed lasers, Bell Labs has been investigating a technique using 100 fs pulses to pulse an antenna in the range of 0.1 THz to 3.0 THz. The terahertz pulses are sent through the material to be tested, detected, and the received pulse shape is analyzed to extract constituent information. This technique may also provide information on thickness.

Nanoscale-Scanning Probe Microscopy

Scanning probe microscopes (SPMs) are used in a wide variety of disciplines, including fundamental surface science, routine surface roughness analysis, and spectacular three-dimensional imaging — from atoms of silicon to micron-sized protrusions on the surface of a living cell [11]. The scanning probe microscope is an imaging tool with a vast dynamic range, spanning the realms of optical and electron microscopes. It is also a profiler with unprecedented 3-D resolution. In some cases, scanning probe microscopes can measure physical properties such as surface conductivity, static charge distribution, localized friction, magnetic fields, and elastic moduli. As a result, applications of SPMs are very diverse. The scanning tunneling microscope (STM), the progenitor of SPMs, utilizes a sharp conductive tip with a bias voltage applied between the tip and the sample. When the tip is within 1 nm of the sample, electrons from the sample begin to tunnel through the 1 nm gap into the tip. If the bias voltage is reversed, the tunneling occurs into the sample. The tunneling current is a function of the separation. Both the tip and the sample must be conductors or semiconductors.

The atomic force microscope (AFM) utilizes a small tip at the end of a cantilever. Forces between the tip and sample cause a deflection in the cantilever, which is translated into a signal. The tip or sample can be scanned covering a large area, producing a topographical map. AFMs can be used on insulators or conductors. AFMs are used in two modes: contact and noncontact. In contact mode, the tip is brought within about 200 pm — about the length of a chemical bond. The electron clouds of the tip and sample atoms interact, netting a repulsive force. For this reason, the contact mode is also called repulsive. Vertical resolution of about 50 pm can be achieved. In noncontact mode, a vibrating cantilever is used in the attractive regime of the van der Waals interactions. The cantilever is typically 2 nm to 20 nm away from the sample surface and has low total force. Noncontact AFM is subsequently less sensitive; thus, sensitive ac detection systems must be employed. The low force does have the advantage of not contaminating the sample surface and is preferred for applications involving silicon wafers and soft or elastic tissues. In noncontact mode, the cantilever is resonated with a small amplitude. As the tip comes near the sample surface, the resultant force changes the spring constant, translating into a deviation of the resonance frequency. This change in resonance (or vibrational amplitude) reflects changes in the sample topology.

Intermittent-contact mode is a combination of noncontact and contact modes and best suited for soft, adhesive, or fragile samples. Contact mode can damage the tip and the sample due to frictional or shear forces and/or create data artifacts from tip/surface adhesion. Noncontact mode produces lower amplitudes and hence lower resolution. Furthermore, surface monolayers of adsorbed gases such as water vapor can produce erroneous results. Intermittent-contact mode avoids these pitfalls by placing the tip in contact with the surface, providing high resolution and then removing the tip to prevent dragging and/or lateral forces. The cantilever is resonated via a piezoelectric crystal (50 kHz to 500 kHz in ambient, 5 kHz to 40 kHz in fluids) overcoming the tip/sample adhesion forces.

In magnetic force microscopy (MFM), the noncontact mode is employed using a tip coated with a ferromagnetic film. Both magnetic and van der Walls interactions are present, but at larger tip/sample separations, the magnetic forces dominate. Multiple scans as a function of tip/sample distance allow differentiation of magnetic forces and topographic information. Magnetic domain structures are resolved to 50 nm via this technique. Current applications of MFM include data storage devices, imaging of micromagnetic structures, IC analysis, imaging of magnetotactic bacteria, and magnetic geophysics. Lateral force microscopy (LFM) is used to generate profiles of changes in surface friction and/or height variations. The probe tip is deflected laterally, indicating some sort of twist. Electronics measure the cantilever deflection. To differentiate between the two effects, LFM and AFM images should be obtained simultaneously. Phase detection microscopy or phase imaging is an extension of intermittent-contact AFM. It utilizes the phase lag between the driving frequency (cantilever) and the output signal frequency, generating a map of specific mechanical properties such as adhesion, elasticity, and friction. Identification of contaminants, composite materials, and regions of hardness and low surface adhesion can be obtained at the nanometer scale. Additional techniques include force modulation microscopy, where a periodic signal is applied to the cantilever, generating a map of the sample's elastic modulus and/or contaminants; electrostatic force microscopy, where a charged tip is scanned over the sample, revealing the locally charged domains generating a map of the charge carrier density; scanning capacitance microscopy, where a charged tip, kept at a constant tip/sample distance, generates a map of capacitance correlated information such as dielectric material thickness and subsurface charge carrier distributions (i.e., dopant profiles of ion implanted semiconductors); thermal scanning microscopy, where the tip in noncontact mode and a bimetal cantilever are used to map the thermal conductivity of the sample. (Vendors: Park Scientific Instruments; Digital Instruments; Oxford Instruments.)

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