Equipment

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Automated Spectroscopic Ellipsometry

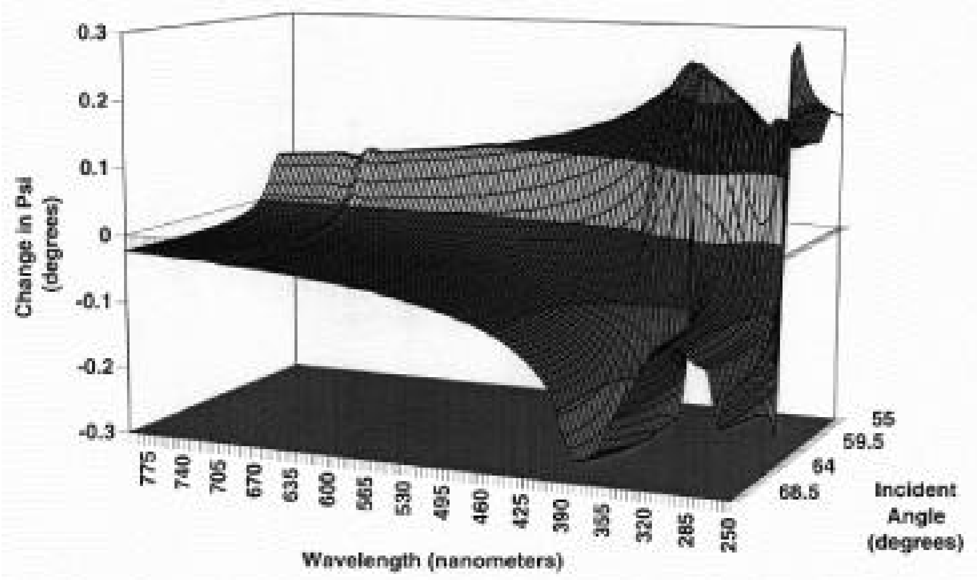

Figure 2 Sensitivity plot for a 5% change in thickness of a 20-nm polymer film on glass.

Over the past decade, microprocessors and computers have zipped into an ever-increasing number of consumer products. At the same time, computers have heightened the power of scientific instruments—including those used in industry. By adding a chip, many industrial instruments grew faster, "smarter," and more suitable for new applications. An outstanding example can be seen in the field of automated spectroscopic ellipsometry.

Historically, ellipsometers have been used to measure the thicknesses of very thin films, such as the microelectronic components on ever-shrinking integrated circuits. It turns out that few tools are as accurate, convenient, economical, and fast as ellipsometers for nanometer-scale dimensions. For example, a spectroscopic ellipsometer can measure the 8-nm-thick gate oxide of a metal-oxide semiconductor field-effect transistor (MOSFET) with a precision of better than 0.01 nm. Moreover, ellipsometer measurements are completely nondestructive, do not require mechanical contact with the sample, and can be made easily and rapidly with computer control.

The system's slant

To make a measurement with spectroscopic ellipsometry, linearly polarized light is aimed at the material being studied, the light gets reflected (or transmitted) at an oblique angle of incidence, and the polarization of the resulting elliptically polarized light is measured (Figure 1). The measured parameters in ellipsometry include psi (Ψ) and delta (Δ), which relate to the relative amplitude and phase, respectively.

Getting the most accurate measurements requires the optimum angle of incidence and incident-light wavelength. For example, Figure 2 illustrates how psi varies with wavelength and angle of incidence for ellipsometry on a thin polymer on glass. The selected measurement conditions (wavelength and angle) should provide the highest sensitivity of psi and delta to a small change in thickness. Frequently, there are several unknown parameters—such as the thicknesses of several layers—to determine from the measurements; generating sensitivity plots for each unknown allows the data to be taken over a range that is optimum for all of them.

We should point out that ellipsometers differ from reflectometers. The former measure the relative amplitude and phase of reflected light, and the latter measure the intensity of reflected light relative to a standard. The phase measurement makes ellipsometers much more sensitive for thin films, down to an atomic monolayer (Figure 3). On the other hand, reflectometers work well for thicker films, say greater than 100 nm.

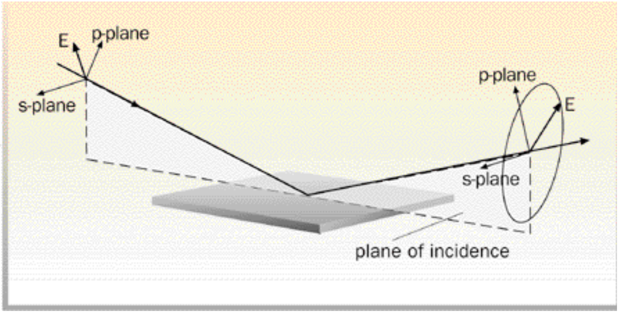

Figure 1 Linearly polarized light reflects off a sample, resulting in elliptically polarized light.

Instrumental upgrades

Although ellipsometry has been around for nearly a century, computers have greatly automated the process—resulting in dramatic improvements in data acquisition and analysis. Today, commercially available devices provide spectral coverage from the vacuum ultraviolet to the infrared (190 nm to 14 μm), and the angle of incidence can be controlled by computer-driven stepper motors with a precision of better than 0.01°. Depending on the specific instrument and range of measurements, a data set can be produced in minutes at worst, and perhaps as fast as fractions of a second.

Moreover, advanced software permits sophisticated analysis of complex materials systems. Once analysis of a particular system becomes routine, software appropriate for technician use is available, including such capabilities as mapping material properties over the surface of a 300-mm-diameter silicon wafer or an indium– tin–oxide coated glass plate for a flat-panel display.

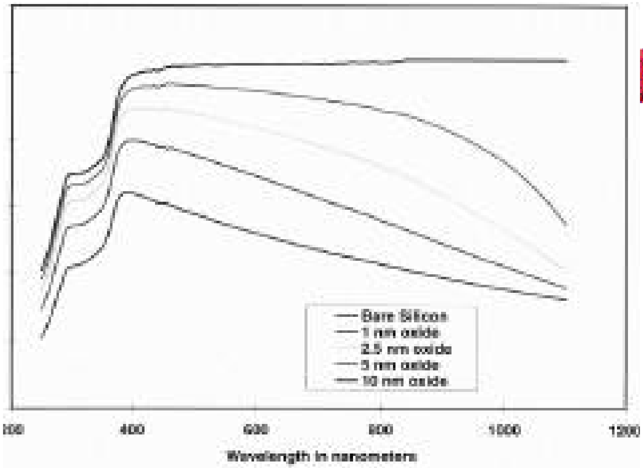

Figure 3 Ellipsometric data for thin oxides on silicon

Industrial applications

The introduction of ever-faster personal computers with ever-increasing memory capacity has driven the recent advances in ellipsometry. As a result, this technique can now be applied usefully to a host of new industrial applications.

For instance, automated spectroscopic ellipsometry can be used in a variety of multilayer-measurement and compositional-analysis tasks for many materials, including multilayered films for flat-panel displays, thin-film magnetic layers on dielectric layers of computer read–write heads, photoresists on polymers for integrated-circuit thin-film technologies, indium–tin–oxide on glass for thermally efficient coatings, quantum-well superlattices for high-speed electronic materials, and photoreceptors for imaging.

Spectroscopic ellipsometry can also be applied to a variety of process-monitoring and control tasks, including chemical vapor deposition growth of compound semiconductors for optoelectronic and high-speed electronic materials, microelectronic material lithography for ion-beam and plasma etching, and sputtering and evaporation of microelectronic and dielectric materials.

There are numerous other materials and materials–systems examples. These simply represent some of the major industrially relevant categories.

Doing more with the data

Beyond measuring a layer's thickness, spectroscopic ellipsometry can be applied to many other problems. Clever data-acquisition schemes and simultaneous data analysis from measurements on multiple samples permit unique determinations of many unknown parameters, including alloy fractions, surface and interfacial roughness, material interdiffusion, void fractions of porous films, and so on. We will describe several examples.

The authors at SVT Associates have used a fast multiwavelength ellipsometer to monitor and control the layer thicknesses, alloy fraction (aluminum-to-gallium ratio), and temperature during growth of vertical-cavity laser structures based on thin gallium–arsenide and aluminum–gallium–arsenide multilayers. The growth was carried out on a rotating 3-inch-diameter wafer, which demonstrated that the ellipsometer accommodated the rotation-related wobble typically observed in molecular-beam epitaxy (MBE). This work demonstrates precise material and structure control using in situ ellipsometry, which leads to better performance of optoelectronic devices.

MBE chambers are not the only vacuum-process chambers in which spectroscopic ellipsometers are used for process control. The Kurt J. Lesker Company (Clairton, Pennsylvania) manufactures vacuum chambers for both sputtering and evaporation in which ellipsometer systems are integrated. An example is a cryopumped chamber at the Center for Microelectronic and Optical Materials Research at the University of Nebraska (Lincoln). This system produces sophisticated multilayer-material and device structures with four guns that sputter metals and insulators. The in situ ellipsometer allows rapid and precise calibration of sputter-deposition rates without removing the samples from the chamber. Furthermore, layer thickness, composition, optical properties, and surface roughness can be measured on each of the four materials (one from each gun) during deposition. After deposition, the oxidation (or nitridation) kinetics can easily be studied in situ. Finally, computer control of the substrate’s rotation, sputter process, and data acquisition from the ellipsometer permit automatic, highly precise deposition of entire multilayer-material systems, such as the automated deposition of thin magnetic and nonmagnetic metal layers for disk-drive heads.

Pat Ruzakowski Athey and her colleagues at PPG Industries (Pittsburgh) recently used spectroscopic ellipsometers to establish deposition-parameter “windows” during startup of a manufacturing process for a low-emissivity coating on large-area float glass. PPG Industries also uses ellipsometry in developmental laboratories to help characterize new thin-film coatings deposited on glass by precisely determining the film’s thickness, its index of refraction, and the extinction coefficient of the coating by modeling the data from ellipsometry.

The Eastman Kodak Company uses spectroscopic ellipsometers for optical characterization of a broad range of materials, including organic films, which can be optically complex. Organic films often exhibit optical birefringence with the optical axes at unusual directions relative to the film and its perpendicular; such birefringence can be caused by stretched polymer sheets, injection-molded parts, or Langmuir–Blodgett films. So ellipsometers can be used in manufacturing to assure process repeatability.

Other products from Kodak are composed of multilayered polymeric films. These films usually possess sufficient refractive-index contrast between layers to produce significant interference fringes, and spectroscopic ellipsometry can be used to detect interfacial diffusion between two polymeric layers. In some cases, the interdiffusion may be needed to enhance adhesion; in other cases, it may be unwanted. Either way, the ellipsometer quantifies the interfacial mixing.

Seagate Technology uses spectroscopic ellipsometers in its clean room, where thin-film magnetic read–write heads are manufactured for computer drives. The ellipsometers measure the thicknesses of magnetic and dielectric layers and determine their composition-dependent optical properties. In addition, the ellipsometers determine the surface roughness of the magnetic layer.

NASA is sponsoring an X-ray astronomy experiment—called the Advanced X-ray Astronomical Facility—that will be launched on a shuttle flight in 1999. For proper operation, the iridium thin-film material that reflects the X-rays must be smooth and contamination-free. A spectroscopic ellipsometer will be used to monitor nanometer-scale problems on the mirror surfaces.

Light's limits

Physics imposes a limit to what can be done with optical methods, and it emerges from "parameter correlation" during data analysis. When parameters are correlated, the solution set is not unique and therefore not quantitatively measurable.

For example, when an ellipsometer is being used to measure the index of refraction and the thickness of very thin films (less than a few tens of nanometers), only the product of these parameters can be uniquely determined. The light does not have much material to propagate through, which results in reduced sensitivity to the film's index. So a thicker film must be used to measure the film's index, and then the thin film's thickness can be determined.

The problem of parameter correlation cannot be eliminated from optical measurements, but it can be reduced with dispersion relations, especially those that force compliance with the so-called Kramers–Kronig relation. The good news is: Many materials systems do not face a problem with parameter correlation. Also, new techniques allow measurements that minimize correlation. Finally, software is available that shows the user how much, if any, correlation a system produces. Then simple software for repeated high-volume measurements in a manufacturing environment can be used confidently.

Applications of spectroscopic ellipsometry in industry are progressing quickly, largely because of advantages in personal computer speed, memory, and ease of use.

Recommended Reading

R. M. A. Azzam and N. M. Bashara. Ellipsometry and Polarized Light. Amsterdam: North-Holland, 1977.

John A. Woollam and Paul G. Snyder. Variable Angle Spectroscopic Ellipsometry, VASE. In Encyclopedia of Materials Characterization. Boston: Butterworth-Heinemann, 1992.

Harland G. Tompkins. User's Guide to Ellipsometry. Boston: Academic Press, 1993.

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