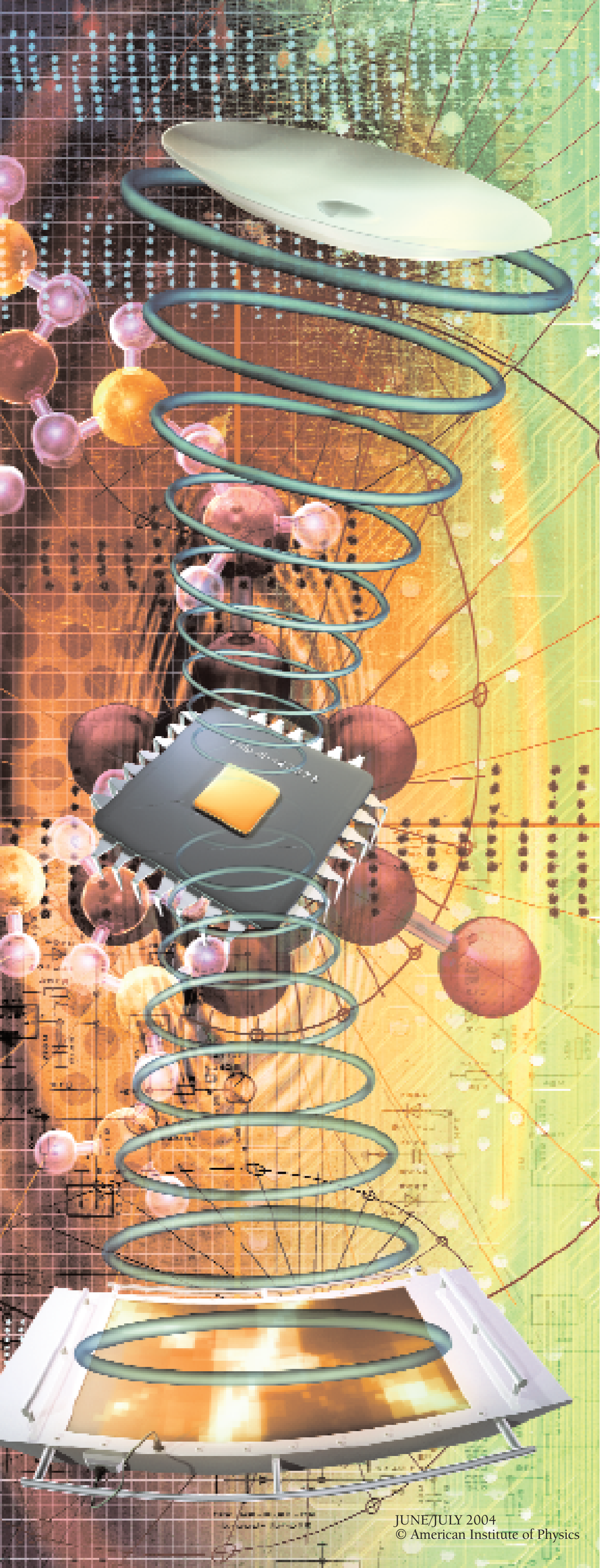

Anthony Robinson

Seeing with Sound

Acoustic microscopy advances beyond failure analysis

by Jennifer Ouellette

About 5,000 years ago in ancient Assyria, scribes recorded on clay tablets the existence of magical magnifying stones that made objects seem larger. These stones were actually broken shards of meteorites whose centers had fused into glass during the intense heat of entry into Earth's atmosphere, melting it in such a way that they formed a primitive lens. Although the Assyrians did not know it, they were practicing the earliest known optical microscopy, a technology that has unequivocally revolutionized almost every aspect of science. Now its cousin, acoustic microscopy, is making inroads into areas such as materials characterization, biology, and medical diagnosis, and giving researchers yet another valuable tool in their imaging arsenal.

Acoustic microscopy essentially replaces light waves with sound waves. Whereas optical microscopy provides an image of the optical (or electrical) properties of a material, acoustic microscopy provides an image of the acoustic (or elastic) properties. Russian physicist Sergei Y. Sokolov first proposed the concept in 1928, but it took another 40 years before computer and ultrasound technologies became sufficiently developed to enable the building of practical instruments. Two separate systems emerged in the 1970s: one at Zenith Laboratories in Chicago, and another at Stanford University. Since then, more-advanced systems have entered the marketplace, but the basic design has remained much the same.

Sound qualities

In acoustic microscopy, the familiar optical lens is replaced by an acoustic lens, which serves the same function but redirects sound waves rather than light. A sound wave is sent through a piece of quartz or glass coated with a thin layer of piezoelectric material that resonates at a specific frequency—for example, 1 GHz. The bottom of the glass lens is hollowed into a bowl-shape to form an inverted, or concave, lens. The sound waves are reflected to the edge of the lens, and then they pass through a film of water on a glass slide, which focuses them for scanning over a sample's surface. The waves are then reflected back up through the lens and piezoelectric crystal, which serve as a detector and amplifier. The sound waves are recorded electronically and then translated into an image on a video monitor.

An acoustic microscope's ability to provide information about the mechanical properties of a sample makes it a valuable tool, particularly for materials and biomedical uses, notes Joie Jones, a professor of radiology at the University of California, Irvine. "It gives you an entirely new dimension of information about a tissue sample or material," he says. "Acoustic microscopy enables you to

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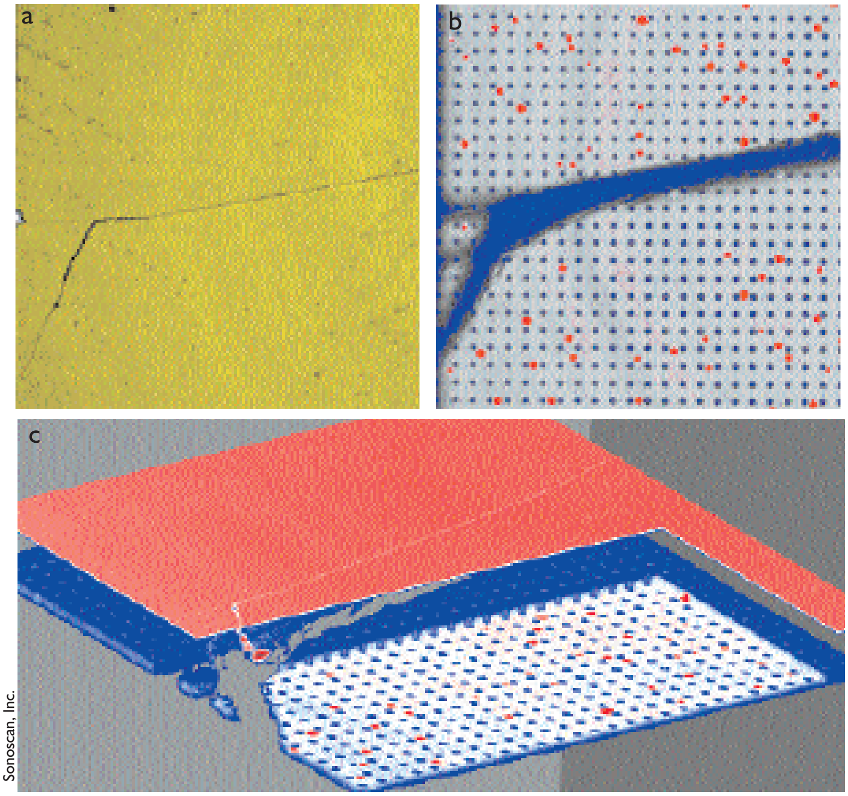
see subtleties in materials that you just cannot see with conventional optical microscopy." As an example, Jones points to small, stressed areas in materials that are prone to breakage—defects often missed by optical methods. Because the sound wave is a mechanical wave, it can interact with a material's elastic properties.

Acoustic microscopy has its limitations, mostly stemming from the differences in the physical properties of light waves compared with sound waves. The wavelength or frequency of the light used in any optical microscopy system ultimately determines the resolution capabilities of the instrument. This is also true of acoustic microscopy. With visible light, resolution is limited to about 0.5 μm, with a magnification of about 2,000 times. The human ear is capable of hearing sounds only in a limited range of frequencies, between 20 and 20,000 Hz. These frequencies have much longer wavelengths than light, so to build an acoustic microscope with resolution on a par with optical instruments, scientists must use ultrasonic sound waves with frequencies of around 1 GHz.

Failure analysis

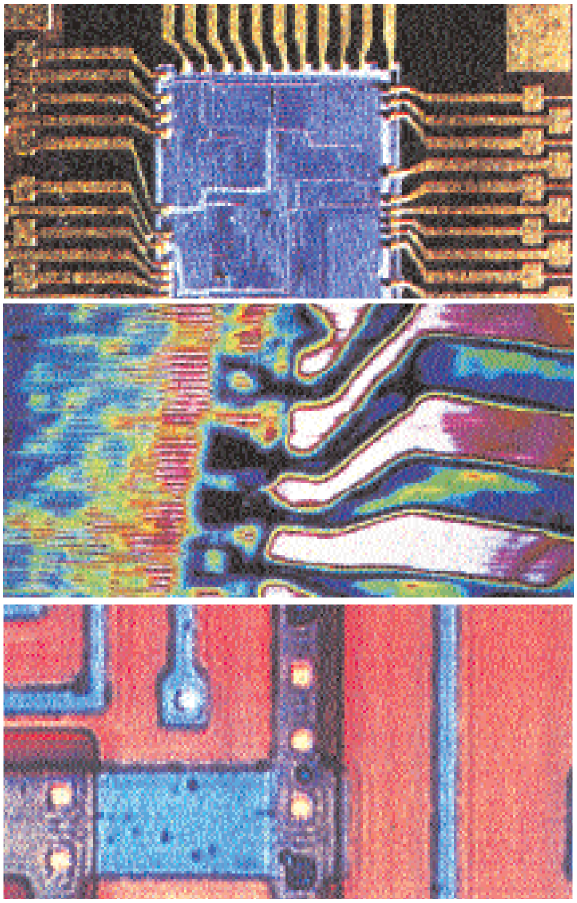
This is, perhaps, one reason why acoustic microscopy has tended to remain a niche technology. Its primary application to date has been for failure analysis in the multibillion-dollar microelectronics industry. The technique is especially sensitive to variations in the elastic properties of semiconductor materials, such as air gaps, known as delaminations or voids, according to Larry Kessler, president of Sonoscan (Elk Grove Village, IL). Acoustic microscopy enables nondestructive internal inspection of plastic integrated-circuit (IC) packages (Figure 1), and, more recently, it has provided a tool for characterizing packaging processes such as die attachment and encapsulation. Even as ICs continue to shrink, their die size becomes larger because of added functionality; in fact, devices measuring as much as 1 cm across are now common. And as die sizes increase, cracks and delaminations become more likely at the various interfaces (Figure 3).



Sonoscan, Inc.

Figure 2. Acoustic images of a flip chip show a crack running through the surface of the die (a), voids (red) in the underfill and a blue line due to the crack in the die above this level (b), and a virtual volumetric view showing both levels (c).

Sonoscan, the leading manufacturer of acoustic microscopes, recently introduced a system specifically for semiconductor manufacture that is designed to weed out bad products before shipping. This system is still not fast enough for today's high-throughput manufacturing processes, and many companies only spot-check their inexpensive components rather than inspect every one. According to Kessler, a pioneer in the field, the technology's use depends on economics. "If a component costs $10, it will be worth it for the manufacturer to test every single one," he says. "But if it only costs a penny, it will not be worth it." Because ICs are typically worth several hundred dollars each, most chip manufacturers want to screen 100% of them. Sonoscan is now developing next-generation acoustic microscopes that operate at much higher frequencies—and hence higher resolutions—to



College of Medicine, Department of Radiological Sciences, Division of Physics and Engineering, University of California, Irvine

Figure 1. Scanning acoustic microscope images of an integrated circuit in increasing detail (top to bottom) from an Olympus Corporation prototype show details that are unavailable to an optical microscope because the circuit is optically opaque.

keep pace with the continued decrease in the size of microelectronic components. “The world is going to flip-chip now, with components embedded in substrates and microscopic linewidths; so high-frequency resolution is becoming much more of an issue,” says Kessler.

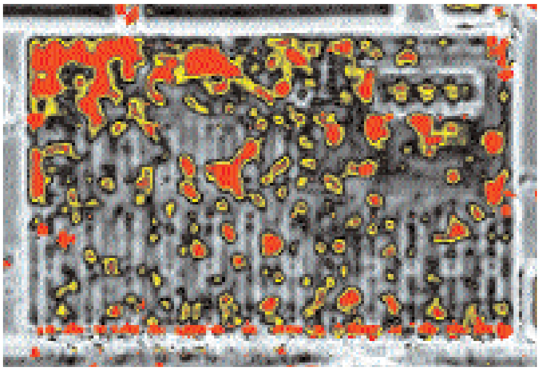

Sonoscan, Inc.

Figure 3. Acoustic examination of a soldered die attachment through the substrate indicates voids and delaminations (red).

Nextek, Inc. (Madison, AL) has recently added scanning acoustic-microscope capabilities to its analytical laboratory. The company provides precision engineering, manufacturing, and analytical services to the electronics industry. Acoustic microscopy allows Nextek to perform nondestructive internal imaging of structures and boundaries that may not be visible with more standard techniques such as X-rays. It can isolate critical defects in a variety of microelectronic components, including the new flip-chip assemblies. For example, a so-called underfiller is now used in flip-chip assemblies to improve resistance to mechanical stress arising from temperature changes. The underfiller must not contain voids or delaminations, and so acoustic microscopy is an ideal nondestructive technique for detecting these tiny defects (Figure 2). Unforeseen stress fractures in a device can lead to a line shutdown, scrapped product, and missed shipment dates—all of which cost chip manufacturers a great deal of lost revenue.

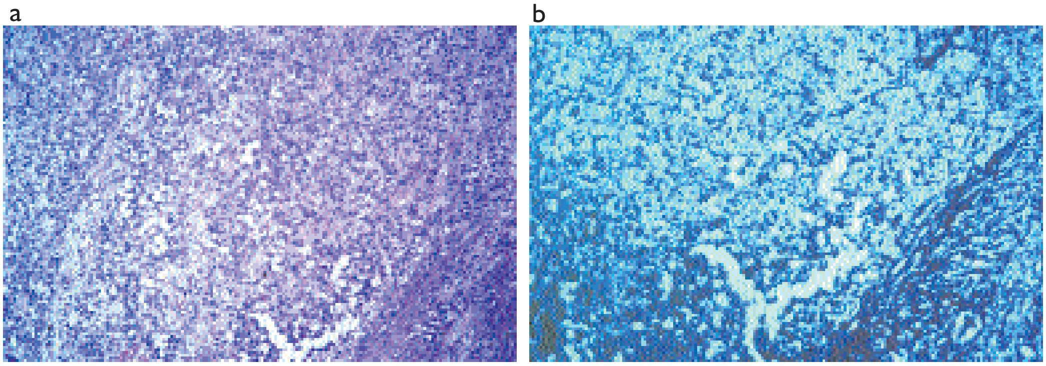


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Figure 4. To obtain an optical microscope image of a biopsy specimen with a malignant melanoma (a), the sample must be fixed and stained, which is not necessary for a scanning acoustic microscope image (b) of an adjacent tissue sample.

IBM, Motorola, and Hewlett-Packard are among the manufacturers who use acoustic microscopy as part of their failure-analysis procedure. The technique weeds out electrical failures caused by bent, missing, or dirty leads. It also can help engineers identify root causes of device failures related to stress on IC packaging materials and its correlation to device electrical malfunctions. Ralph Carbone of Hewlett-Packard reports that, in the company’s experience, if acoustic imaging reveals a crack, void, or other gap defect in a component package, physical cross-sectioning will ultimately show the same defect in that same location. But physical sectioning takes hours and destroys the component, and if the defect is missed, it may not be possible to section the component again. Acoustic microscopy requires no special preparation of the component package and takes only about 15 s. In fact, Hewlett-Packard’s failure-analysis laboratory in Roseville, California, has largely abandoned physical cross-sectioning and now relies primarily on acoustic microscopy and an occasional X-ray analysis.

Materials characterization

A related, more research-oriented application of acoustic microscopy lies in materials characterization. Ken Telschow and his colleagues at the Idaho National Engineering and Environmental Laboratory use lasers to generate and detect sound waves in an acoustic microscope. For example, to image a microelectronic circuit, a pulsed or chopped laser beam heats a localized region of the sample about 10 μm in diameter, while a second green laser beam detects the ultrasonic motion of the local surface using an interferometer. Thus, Rayleigh surface waves and longitudinal bulk waves can be observed traveling through the circuit, which allows making measurements of properties such as film thickness, substrate bonding, and substrate flaws. The source laser can be focused to 1–2 μm and can generate and detect frequencies of about 1 GHz. This is important because at gigahertz frequencies, the acoustic wavelengths are on the order of a few micrometers, with corresponding resolution.

Telschow and his colleagues use the instrument to study ultrasonic wave propagation in material microstructures at the individual-grain level. “Materials fail because of things that are happening at the single-grain level,” he says. As materials bend back and forth, the stress causes dislocations to occur—not quite a fracture, just a small change in the crystalline structure. However, such dislocations tend to multiply and eventually create a tiny crack in the material, usually at grain boundaries. Ideally, materials scientists would like to construct materials that can be subjected to a great deal of stress and fatigue without cracking.

“We’re down to resolutions where every grain is like a small crystal, and we know very well how acoustic waves act in crystals,” Telschow says. “So we can measure and predict the properties of the acoustic waves as they go from one crystal to another." By modeling that entire process, Telschow hopes to develop an acoustic model of sound-wave propagation at the micrometer scale, which would make acoustics more useful for measuring materials' microstructural properties. Being able to map what he terms a material's "road to failure" would enable researchers and nondestructive testing engineers to tell when a material is likely to fail, thereby extending the service lifetime of materials.

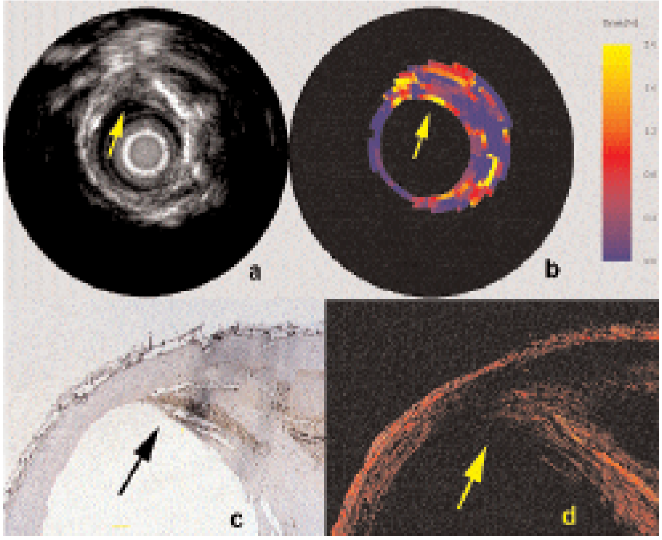

Figure 5. Information inside an artery about a lipid deposit covered by a cap that could break away and cause a stroke or heart attack is obtained by intravascular ultrasound (a), an elastogram (b), and histology (c and d).

Erasmus University, Rotterdam, The Netherlands

Biological uses

Only a few research groups to date have applied acoustic microscopy to biology and diagnostic medicine. "For some reason, the technique has never gotten the attention I think it deserves," says Jones, whose work in the field dates back to its infancy in the 1970s. "I thought it would play a major role in biomedicine, and I have been proven wrong." Despite this, Jones believes that biomedical applications could become a major growth area for the technology. Many biological materials have a wider range of values for their elastic properties—which vary as much as 2 orders of magnitude—than for their optical properties, whose variation is only 0.5%. Thus, optical microscopes have a limited contrast capability. Specimens must be prepared with appropriate stains designed to bring out particular features of the sample, such as specific pathologies or biochemical processes. Acoustic microscopy, however, provides a sensitive tool for imaging soft-tissue structures without the need for staining or elaborate sample preparation (Figure 4).

Acoustic microscopy could provide an immediate assessment of pathology long before conventional methods, according to Jones. For example, applying a special ultrasound scanner directly to the skin of a patient could provide real-time microscopy, and pathological assessments of skin tumors or lesions could be made noninvasively. Jones is developing such an acoustic instrumentation for virtual biopsies and mapping the configuration and extent of tumors prior to surgery. He has also used the technique to study acupuncture points in the body—particularly what happens in response to stimulation by needles—and he has observed the mechanical responses of these points using a 100-MHz acoustic microscope. He found that the nerves that form the points twist themselves around an inserted needle, which may explain the tactile sensation known among acupuncturists as stickiness.

Although the resolution of acoustical microscopy is currently limited to the cellular rather than the molecular level—the maximum resolution is about 0.1 μm—the technique can still provide uniquely useful information on the mechanical properties of biological tissues, such as Alzheimer's plaques. Acoustic microscopy is already advancing cardiology, specifically in the area of intravascular ultrasound (IVUS), in which physicians are able to thread a small ultrasound device into the body to examine artery blockage.

Scientists at Tohoku University in Japan, for example, are using a scanning acoustic microscope for IVUS to gather basic data on the fatty deposits or arterial plaques that cause atherosclerosis, a condition difficult to study in vivo. Atherosclerosis contributes to heart attacks and strokes that kill about 640,000 U.S. residents annually, according to the American Heart Association.

In The Netherlands, Ton van der Steen and his colleagues at the Erasmus Medical Center (Rotterdam) have developed a clinical technique called IVUS elasticity imaging, which can detect the arterial plaques most likely to rupture and cause a heart attack or stroke. The technique measures the local deformation of atherosclerosis caused by variations in blood pressure. It does this by using the phase information of high-frequency ultrasound. According to van der Steen, high deformation (or strain) indicates the presence of a lipid deposit covered by a thin fibrous (and usually inflamed) cap. Caps weakened by inflammation may break apart and release pieces of debris that can lead to a thrombosis, causing a stroke or heart attack. The primary drawback of the technique is that several sets of data must be taken and analyzed to make an accurate diagnosis. The Erasmus researchers are currently focusing on finding ways to eliminate the number of false positives that result from the instrument detecting high-strain spots that are not plaques vulnerable to rupture but are caused by other phenomena (Figure 5).

Finally, acoustic microscopy of cells or tissue in culture enables scientists to examine living structures without killing them, as happens using optical means. Tissue requires the use of light at extremely high frequencies to obtain adequate resolution, which in turn damages or destroys the cells. "Biologists could put cells growing in a petri dish under an acoustic microscope and image those cells continuously in real time," Jones says. "You could study the cells as they grow and develop, and learn a great deal about cell structure in the process."