The Radiant Side of Sound

Samples for each experiment are taken from 10-centimeter-diameter silicon wafers layered with gallium nitride. Each wafer is sputter-coated with an aluminum layer (reflective surface) only a few hundred nanometers thick.

SOUND is an integral part of the human existence. It propagates through the environment at various frequencies, allowing us to hear music from our radios and voices through our cell phones. But not all sound is audible to the human ear. Some acoustic waves have terahertz frequencies—that is, they oscillate at 10^{12} cycles per second. Sound in this range is too high for humans to hear, but researchers are finding that these high-frequency waves are exceedingly useful for scientific research.

In collaboration with Los Alamos National Laboratory and Nitronex Corporation, Livermore physicists Evan Reed and Michael Armstrong have discovered that by propagating acoustic waves through materials with different piezoelectric coefficients, they can transform waves at terahertz frequency into electromagnetic radiation of the same frequency. "We have developed a fundamentally new technological pathway to get into terahertz regimes," says Reed. "We first predicted this phenomenon using molecular dynamics simulations." With the help of an ultrafast laser and piezoelectric micrometer-thick heterostructures, they have become the first to observe the predicted behavior.

Reed and Armstrong, both of whom work in the Laboratory's Science and Technology Principal Directorate, want to measure acoustic waves up to approximately 10 terahertz—the frequencies predicted to occur at the front of shock waves. Funded by Livermore's Laboratory Directed Research and Development Program, their research is primarily geared toward developing high-resolution diagnostics for examining the shock and strain that materials undergo during laser experiments. Their new terahertz radiation generation and detection method is sparking interest outside the Laboratory as well. Within the semiconductor industry, it could serve as an improved, more direct approach for investigating the structural properties of thin films used to make computer chips.

Blazing a New Trail

Research over the last several years has shown that intense optical pulses from lasers can generate acoustic waves and radiation at frequencies of about 2 terahertz. Optical probes detect the acoustic wave by measuring the reflection of a laser beam from the material that has been modified by the acoustic front. As an example, the Livermore-developed diagnostic called VISAR (Velocity Interferometer System for Any Reflector) combines an external probe and sophisticated electronics to measure strain in materials during high-energy-density laser experiments. Optical probe techniques have time resolutions from 0.1 to 1 nanosecond (where 1 nanosecond is one-billionth of second). "This range is too slow to accurately measure the time history of strain waves at the highest acoustic frequencies," says Armstrong. "Our new detection method allows us to probe the actual wave."

For the experiments, Nitronex Corporation in Durham, North Carolina, supplied the Livermore team with silicon substrates coated with a layer of gallium nitride (GaN). The team sputter-coated each substrate with a 260- to 700-nanometer-thick layer of aluminum. An ultrafast laser then generates a 100-femtosecond-long pump pulse (where a femtosecond is one-quadrillionth of a second) with an 800-nanometer wavelength and approximately 1 millijoule of power and fires it at each substrate. The aluminum absorbed the energy from each pulse, causing that layer to heat and expand. This surface expansion created strain in the material, and the resulting acoustic wave propagated through the aluminum to the interface between the aluminum and GaN layers. At that boundary, material compression from the acoustic wave generated polarization currents through the piezoelectric effect, producing terahertz radiation, or light, which was then emitted from the material.

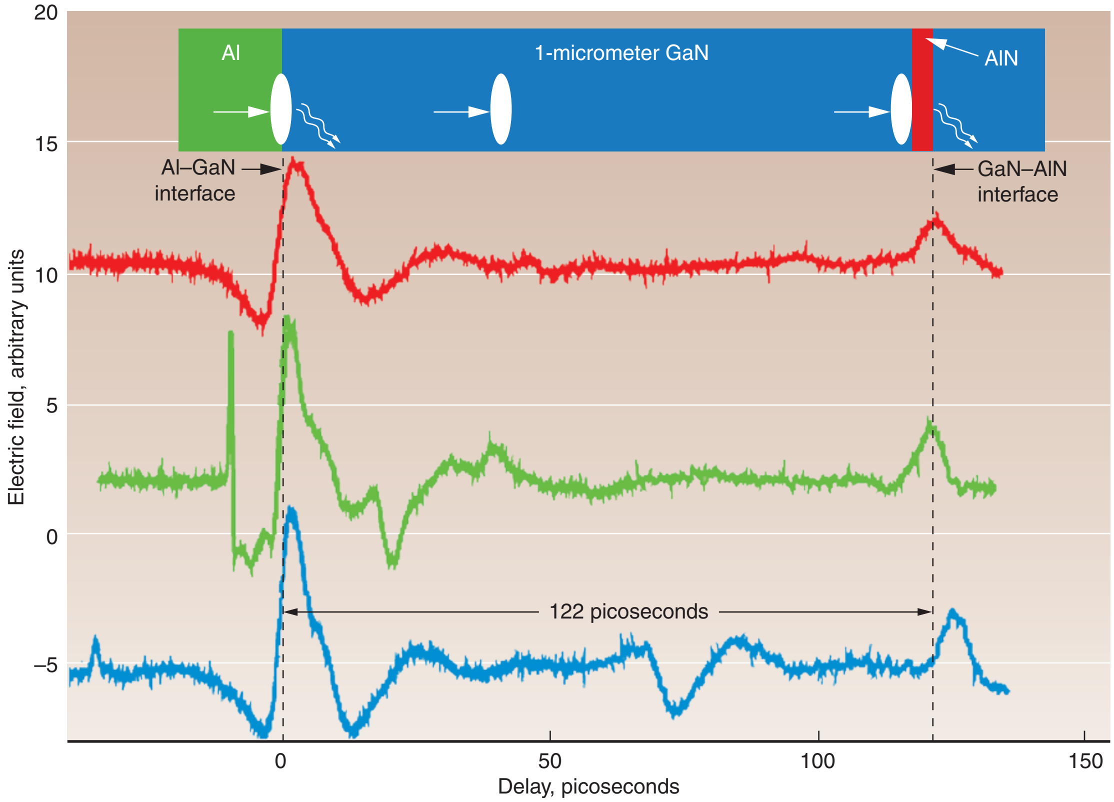
The team applied a standard technique known as electro-optic sampling to detect the radiation from a distance of a few millimeters. "Basically, we use a nonlinear optical process in which we write the terahertz radiation onto an optical pulse and then read the wave off the pulse," says Reed. A brief terahertz signal produced by fast, nonlinear processes that occur when the laser pulse hits the aluminum layer denotes the time the acoustic wave was generated. After this wave transits the aluminum layer, it travels through the interface, generating terahertz radiation that provides the wave's time history.

The laser pulse power is set low enough to be nondestructive to the material. Thus, to obtain an accurate estimate of time history, Reed and Armstrong had to average the signals produced by many pulses hitting one substrate. "Ultimately, we want the same results using a single shot," says Armstrong.

Applications Abound

Terahertz signals have wavelengths approaching the atomic scale—about 0.5 nanometers—allowing them to form and propagate through extremely small material thicknesses. As a result, the semiconductor industry is interested in adapting the Livermore technique to measure the thickness of substrate layers in computer chips. To test the feasibility of this application, Reed and Armstrong experimented with substrates containing a layer of aluminum nitride (AlN) beneath the GaN layer. They then analyzed three samples, measuring the time it took the acoustic wave to travel through the GaN layer to the GaN–AlN interface. The slight time delay between the first and second terahertz signal produced by one substrate indicated that its GaN layer was thicker than those layers in the other samples.

A subpicosecond laser pulse fired onto a piezoelectric sample produced a compressive shock wave that propagated through the material, generating terahertz radiation. Light was measured on the other side of the sample.



The Livermore team conducted experiments with substrates containing multiple layers of piezoelectric materials: aluminum (Al), gallium nitride (GaN), and aluminum nitride (AlN). Results showed a slight time delay in the terahertz signal generated at the GaN–AlN interface of the 260-nanometer film (blue curve) compared with the signals for the 70- (green curve) and 560-nanometer (red curve) films. This delay indicates that the GaN layer is thicker in the 260-nanometer substrate.

X-ray ellipsometry, a technique that measures the polarization of light reflected from a surface, is a prominent method in the semiconductor industry for characterizing thin films. According to Armstrong, ellipsometry is an indirect method that models a thin film's optical properties and then compares the results to actual data. Reed and Armstrong's approach is a more direct way to determine layer thickness. "Characterizing thin films is just one application for this type of acoustic wave measurement," says Armstrong.

Although the characterization method has promise for the semiconductor industry, it is first and foremost applicable to mission-related research at the Laboratory. It may enable scientists to better understand how materials act under extremely high pressures and how much pressure can be applied before a material is damaged. It may also provide a better way to evaluate strain and stress in materials used in shock and ramp-compression laser experiments, where pressure is applied incrementally to a sample. (See *S&TR*, June 2009, pp. 22–23.)

Beefing Up Security

The recent work performed by Reed and Armstrong is a testament to how breakthroughs in scientific research can have a broad range of applications. In addition to serving as the basis for new diagnostic and characterization tools, terahertz generation and detection technologies may help improve security applications, such as airport scanners and handheld, high-power devices for detecting explosives in the field. "High-power terahertz sources have the potential to be very compact," says Armstrong. "Our current experiment fits on a small table. With further development, it could eventually fit in the palm of a hand."

Reed and Armstrong already have future experiments planned. "We tested this process using piezoelectric materials," says Reed, "but we want to evaluate it with other materials as well." By further exploring their technique, the researchers may find other applications for their research, demonstrating that "probing" into basic science can sometimes yield unexpected and fruitful results.

—Caryn Meissner

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