# Surface Acoustic Waves in Materials Science

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# SURFACE ACOUSTIC WAVES IN MATERIALS SCIENCE

**Laser-generated surface waves provide new tools for studying material properties, from linear elastic behavior to fracture.**

Peter Hess

Surface waves take many forms in nature, science, and technology. They include, for example, water waves propagating along the interface between water and air, seismic waves traveling along Earth's crust, and ultrasonic surface waves at the interface between a solid on one hand and vacuum, gas, liquid, or another solid on the other. A common feature of all kinds of surface waves is that most of the energy is localized near the surface, within a depth of about one wavelength. Instead of propagating throughout the whole three-dimensional medium, the energy remains localized at the surface and spreads out primarily in the two-dimensional (2D) interface region.

Water waves illustrate the principal features of elastic surface waves. The particle motion can be easily visualized when a water wave passes a leaf floating on the water surface. The leaf moves to and fro, but also up and down around its original position. The radius of the particle orbit is equal to the wave amplitude. Below the surface, the radius of particle orbits decreases exponentially with depth.

Elastic surface waves, usually called surface acoustic waves (SAWs), were discovered in 1885 by Lord Rayleigh.[1] Unlike water waves, for which gravitational forces determine the behavior, SAWs depend on the elastic forces acting between the constituent atoms. The internal forces of the medium, or stress, are assumed to depend only on the deformation of the material, or strain, measured relative to the undisturbed state. In the bulk of an elastic material, the longitudinal and transverse wave modes are independent and propagate with different velocities, but in surface waves the two modes are coupled. Due to the asymmetry of the elastic forces at the surface, the motion normal to the surface may be different from that in the direction of wave propagation along the surface. Consequently, in the elastic medium, the particle motion is elliptically polarized. The depth dependence of the particle displacement and polarization are illustrated in figure 1. Surface waves also differ from bulk waves in their propagation speed: Because particles are less constrained at a free surface than in the interior of the material, the velocity of SAWs—the Rayleigh velocity—is about 5 to 13% smaller than that of shear waves, the slowest bulk waves.

Surface waves exist in an extremely wide frequency range extending over more than 10 orders of magnitude (figure 2). At the low-frequency infrasound end are seismic surface waves, with wavelengths of kilometers (other seismic waves such as shear bulk waves are also in the infrasound regime). Following the discovery of SAWs, only seismic waves were studied for many years. The development of interdigital transducers (IDTs) around 1960 extended the frequency range for the study and application of SAWs into the ultrasound region.[2] These very small devices, consisting of a series of thin metal lines on a piezoelectric material, can be used both to excite and to detect SAWs. Another important breakthrough in SAW research, especially for materials science, was the excitation of broadband SAW pulses in any absorbing material in the ultrasound region with focused short laser pulses, introduced by Robert Lee and Richard White in 1968 and developed in the following years.[3] Lasers can also be used to excite and detect narrowband SAW trains by writing an interference pattern onto the surface, as reported by Tsuguo Sawada and coworkers in 1990.[4] The motion at even higher frequencies, in the hypersound region, is described as quantized lattice vibrations or surface phonons, which extend typically to $10^{13}$ Hz.

SAWs produced by IDTs have wavelengths about $10^5$ times smaller than electromagnetic waves at comparable frequencies, and have therefore found application in tiny signal processing devices, such as delay lines, resonators, convolvers, and high-frequency filters currently used in mobile phones. The application of lasers, on the other hand, has opened the door to systematic studies of linear and nonlinear elastic properties of thin films and bulk materials not limited to piezoelectric materials.[5] The dispersion that occurs in graded or layered materials allows the determination of linear elastic properties using laser-produced thermoelastic excitation. Strong laser excitation based on ablative or explosive evaporation mechanisms gives access to strongly nonlinear waves, solitary wave behavior, and formation of shocks. This technique can provide new insights into impulsive fracture and the failure of materials.

## Exciting and detecting SAWs

Presumably every scientist (or at least every experimentalist!) has already launched surface waves. If a stone is thrown into a pond, a water wave is generated by the point-source disturbance. The surface waves can easily be seen propagating radially from the source along the water surface. Similarly, plane surface waves can be launched, for example, by distortions extending over the whole width of a water channel.

In some respects, a similar process can be realized on the mesoscopic scale. Short laser pulses can excite broadband surface waves in solids (for a recent review, see ref. 5). The absorbed laser radiation leads to localized heating and thermoelastic expansion at the solid surface, which launches a 2D surface wave (figure 3a). If the laser pulse is focused to a line by a cylindrical lens, a plane wave will propagate in a well-defined direction.

The smallest laser-excited SAW wavelength is a few micrometers—about twice the minimum laser focal width for sufficiently short laser pulses. Such wavelengths correspond to frequency components approaching 1 GHz and limit the SAW pulse length to the nanosecond range. Thus,

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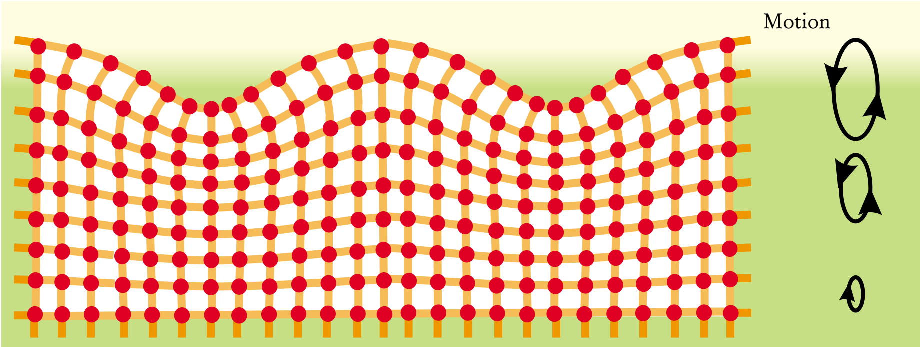



**FIGURE 1. PARTICLES MOVE** in ellipses in a surface acoustic wave, also called a Rayleigh wave, that is propagating in an isotropic half-space. The amplitudes decrease exponentially with depth.

in present state-of-the-art experiments with picosecond laser pulses, the SAW pulse length is determined not by the laser pulse duration but by the spot size. In principle, SAW pulses with shorter wavelengths may be obtained using near-field optics to overcome the diffraction limit of light. For broadband pulses with nanosecond duration, the frequency spectrum extends typically over one to two orders of magnitude.

Propagating SAW pulses can be detected, without contacting the surface, by using continuous-wave (CW) lasers. A Michelson interferometer can measure the absolute surface displacement at two points (figure 3a). With an actively stabilized device, it is possible to monitor subangstrom surface displacements on nanosecond time scales. In a simpler approach, the transient deflection of the CW laser beam by the propagating surface bump is monitored with a position-sensitive detector. The signal depends on the gradient of the surface displacement, and therefore this method measures the surface velocity. An even more straightforward detection device is a piezoelectric transducer in direct contact with the surface. With all these setups, only the vertical or out-of-plane component can be measured; the longitudinal or in-plane component must be calculated by a Hilbert transform.

Short laser pulses can also excite narrowband SAW trains with many periods. In this case, the frequency spread scales inversely with the number of periods. To obtain periodic waves with many cycles, the laser source must possess a periodic spatial intensity distribution at the surface. Such a periodic source can be produced by causing two coherent laser beams, tilted with respect to each other, to overlap in space and time at the surface, creating a 1D interference pattern with light and dark regions (figure 3b). The transient laser grating launches two counterpropagating narrowband SAW trains.[4] Since the SAW generation efficiency increases as laser intensity grows, intense picosecond laser pulses are typically used to excite these so-called transient laser gratings.

A narrowband surface wave is a long train of 1D periodic corrugation, and so it behaves like a diffraction grid when probed by a laser beam. If the probe diameter is much larger than the SAW period, a pronounced diffraction effect is observed, which can be used for time-resolved detection of the transient surface grating, as indicated in figure 3b. A commercial implementation of a narrowband SAW analyzer is shown in figure 3c.

The nature and behavior of surface waves depend on the properties of the underlying material, such as its anisotropy and homogeneity. In addition, elastic waves can be found not only at the interface between a solid and air or vacuum, but also at solid–liquid and solid–solid interfaces. The characteristics of several important kinds of surface and interface waves are summarized in the box on page 45.

## What can be learned

Of great importance in materials science are layered structures, for example, solids with an oxide layer or with films deliberately added to modify the surface properties or protect the material. A layer introduces a characteristic length scale, and the layered medium becomes dispersive. SAWs in homogeneous media, in contrast, show no dispersion. Since the penetration depth of SAWs varies with their wavelength, different depths are probed simultaneously with a broadband pulse containing a wide spectral distribution of wavelengths. The partial waves with different wavelengths originating from a coherent SAW pulse

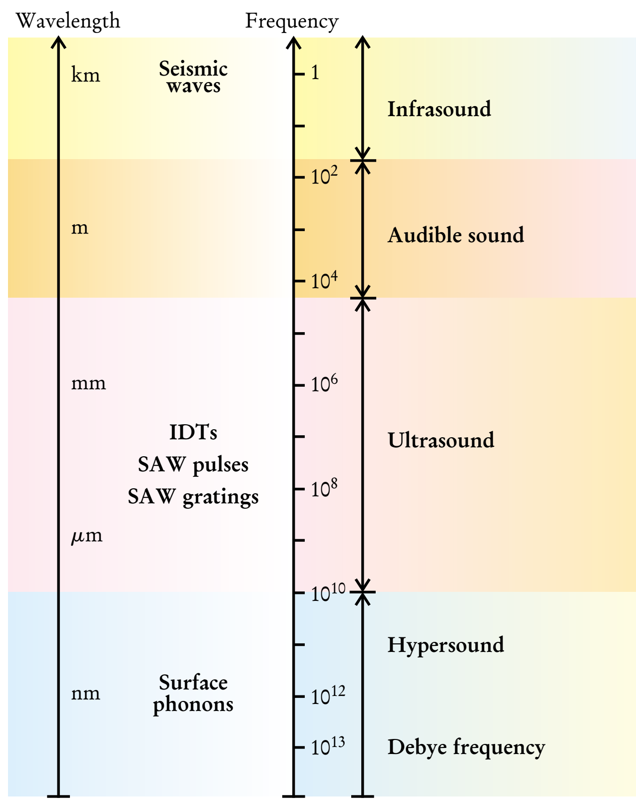



**FIGURE 2. SURFACE ACOUSTIC WAVES** can be found over a broad frequency spectrum. Current research extends from seismic waves in the infrasound region to interdigital transducers (IDTs) and to laser-generated SAW pulses and transient gratings in the ultrasound region.

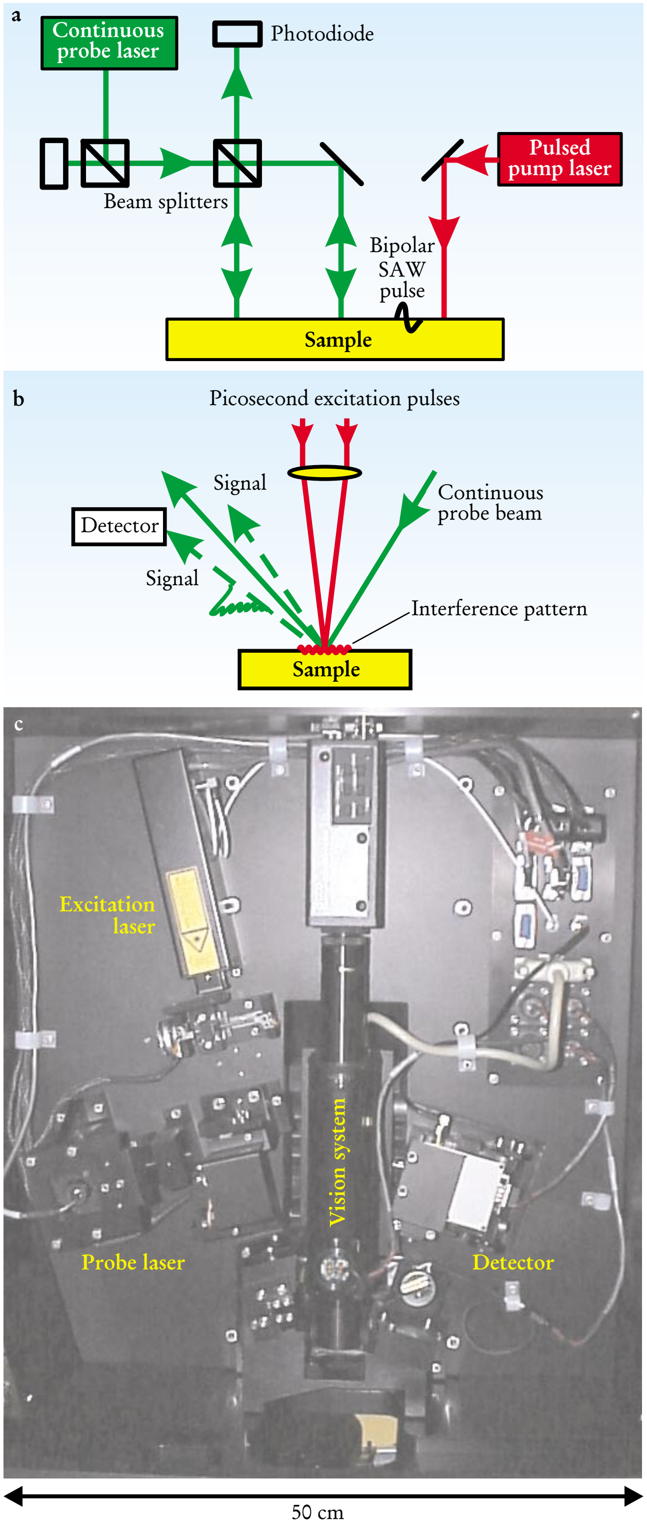



**Figure 3. Laser techniques** for exciting and detecting surface acoustic waves (SAWs). **(a)** A picosecond pulsed laser launches a coherent broadband SAW pulse. The transient displacement caused by the propagating surface wave is monitored with a continuous wave probe laser using a Michelson interferometer. **(b)** If two temporally coincident picosecond laser pulses are crossed at the surface, the resulting interference pattern excites a transient laser grating that generates two narrowband counterpropagating SAW trains by thermoelastic excitation. Diffraction of a probe laser is used to detect the temporal evolution of the grating. **(c)** An inside view of a commercially available SAW analysis system that uses narrowband wave trains. (Courtesy of Philips Analytical Inc.)

interfere during propagation in a dispersive medium, generating a characteristic oscillatory pulse shape (figure 4a).

These dispersive oscillatory waveforms contain specific information about the mechanical and elastic properties of the layer and substrate material. For example, monitoring the pulse profiles at two distances from the excitation source allows the frequency dependence of the phase velocity to be determined. If the high-frequency components of the acoustic pulse travel more slowly than the low-frequency components—so-called normal dispersion—the layer material is softer than the underlying solid. The opposite case, occurring for harder film material, is called anomalous dispersion.

The amount of information that can be extracted from the signal spectrum depends on the thickness of the film and the minimum wavelength of the pulse. If the ratio of the thickness $d$ to the minimum wavelength $\lambda$ is $d/\lambda < 0.1$, only one film property, such as the Young's modulus, can be determined by fitting the linear dispersion to theory; for $d/\lambda > 1$, generating nonlinear dispersion, two or even three film properties, such as the density, Young's modulus, and Poisson ratio, may be accessible.

Figure 5 illustrates the usefulness of SAW analysis. The plot presents the stiffness versus density of micrometer-thick polycrystalline diamond films made through chemical vapor deposition (CVD) with varying concentrations of methane in the source gas.[6] Both properties, which provide important information on the quality of materials, were obtained by SAW analysis. Extrapolation of the Young's modulus to zero methane partial pressure yields 1140 GPa, the ideal stiffness of polycrystalline diamond. Thus the highest quality is expected when the growth rate approaches zero. In addition, figure 5 contains data on free-standing diamond plates. These plates range from black to transparent, depending on the extent of amorphous or graphitic grain boundaries. Interestingly, CVD-diamond plates exhibit SAW dispersion even though there's no substrate backing them. This surprising effect arises from the deposition of the synthetic material, which is neither isotropic nor homogeneous. During diamond growth, properties such as texture and grain size change, generating gradients in the mechanical and elastic properties. This variation in the materials properties from the nucleation side to the growth side of the plates causes dispersion. The figure also includes results for nanocrystalline diamond films, which are much smoother than polycrystalline diamond, but the mechanical properties depend strongly on the grain size.

Also displayed are recent results for polycrystalline plates and thin films of nanocrystalline cubic boron nitride (cBN).[5,6] The values obtained for the nanocrystalline films are substantially lower than the single-crystal properties. Because of its higher oxidation resistance and greater chemical resistance to ferrous alloys such as steel, cBN, with the second highest Young's modulus, is superior to diamond for many applications. SAW analysis can provide crucial information about the material properties of cBN samples.

Narrowband transient gratings have also been widely applied in investigations of elastic, mechanical, and thermoelastic properties of thin films by Keith Nelson's group at MIT. In such experiments, the dependence of the SAW velocity on the frequency can be measured point by point, by changing the grating period with the angle between the

## Types of Surface and Interface Waves

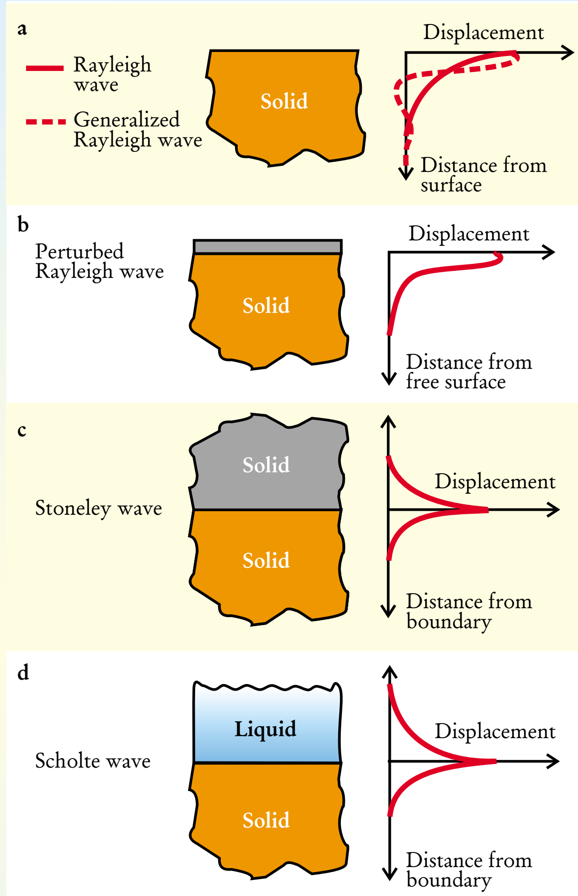
Surface waves can be found in a wide variety of geometries and are given a wide variety of names. The following is an overview of the most important surface and interface waves.

Rayleigh waves propagate on the stress-free planar surface of a semi-infinite isotropic half-space. The particle displacement decays exponentially with depth and becomes negligible for a penetration of more than a few wavelengths (panel a). The particle motion can be decomposed into two orthogonal components, one in the direction of surface acoustic wave (SAW) propagation and one perpendicular to the free surface. These two directions define the so-called sagittal plane. Rayleigh waves are nondispersive, and therefore their phase velocity is independent of the frequency.

Generalized Rayleigh waves propagate in an anisotropic half-space. A feature often found in anisotropic solids is the appearance of oscillations in the depth dependence of the displacement (panel a). The SAW velocity depends on both the direction of propagation and the crystal plane along which it propagates. The group velocity, which describes the direction of propagation of elastic energy, is not in general collinear with the phase velocity or wavevector. This leads to new effects such as "phonon focusing," in which amplification is observed in certain directions due to the anisotropy of the elastic forces. The investigation of this effect for surface waves was pioneered by Alexandre Kolomenskii and Alexei Maznev in 1991.[15] In the so-called pure mode directions, the phase and group velocity are parallel. In the generalized Rayleigh waves, the particle displacement generally has components in the longitudinal, vertical, and transverse directions.

When there is a layer of isotropic material on top of an isotropic half-space, perturbed Rayleigh waves propagate at the surface (panel b). They are polarized in the sagittal plane, but due to the existence of a length scale, they are dispersive: The phase velocity depends on frequency. At long wavelengths, as compared with the film thickness, the particle displacements extend far into the underlying solid and the phase velocity approaches the value of the bare substrate. At short wavelengths (high frequencies), the motion is concentrated more in the vicinity of the film, and the velocity approaches the value of the layer material. Additional modes may also appear in the case of a thin film supported by a substrate. The shear-horizontal waves (with only a transverse displacement) decouple from the sagittal motion, and so-called Love waves are observed in the film system if the shear velocity of the layer is less than the shear velocity of the substrate. For an isotropic half-space with a layer, more than one solution is found, and the system becomes a multimode waveguide with higher-order modes termed Sezawa modes.

Elastic waves may also propagate along the plane interface between two condensed elastic media. So-called Stoneley waves are confined to the interface between two solids and decay exponentially into both solids (panel c). At the liquid–solid interface are Scholte waves, which are guided along the interface (panel d), and leaky Rayleigh waves, which dissipate the energy into the liquid. The group of Jan Thoen at the Katholieke Universiteit Leuven, in Belgium, recently demonstrated the all-optical thermoelastic excitation and detection of Scholte waves on mercury–Plexiglas and mercury–fused silica interfaces.[16] The shape of the Scholte pulse in the time domain and the measured velocity as well as the attenuation of leaky Rayleigh waves matched well with the theoretical predictions by Vitalyi Gusev.[16] This work opens the door to study the linear and nonlinear mechanical properties of such systems.




two exciting laser beams (figure 3b). In this way, the group has studied a polyimide coating tightly bound to silicon, examining the dispersion of the phase velocity of the waves in a large range of film thicknesses and wavelengths.[7] Strongly nonlinear dispersion curves were observed, from which the density, Young's modulus, and Poisson ratio could be extracted.

## Nonlinear waves, shocks, and cracking

At the beach, water waves pass into a region where the depth becomes smaller than their wavelengths. Because the energy becomes concentrated in a smaller depth, the amplitude of the surface wave increases. The fluid particle motion changes from circular to elliptical, because in shallow water no vertical motion exists at the bottom and the contribution to this component decreases. Consequently, the motion of the particles becomes predominantly backward and forward, as readily experienced at the beach. Because crests travel faster than troughs, the waves will change their shape on entering shallow water. The front of the wave will steepen until finally the crests overtake the troughs and the wave breaks. This is the most spectacular phenomenon connected with strongly nonlinear water waves, but it is also extremely destructive.

The dramatic process of wave breaking cannot be observed in solids with SAWs, since solids usually break under strain as soon as a certain degree of bond extension (typically 10–20%) has been reached. During propagation of finite-amplitude waves in a nonlinear medium, energy is transferred from lower to higher harmonics, a process called frequency-up conversion. When this process occurs, the energy also becomes concentrated nearer the surface due to

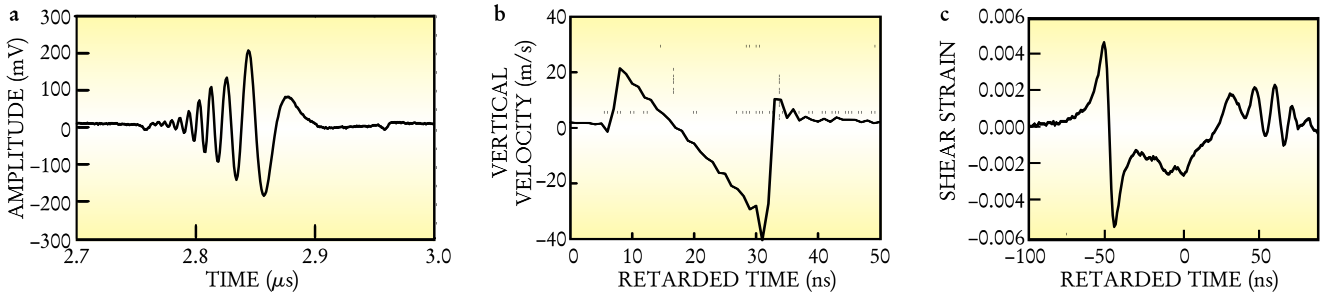



**FIGURE 4. SHAPES OF SAW PULSES. (a)** For a silicon surface covered by a 200-nm cubic boron nitride film, dispersion effects make an initially bipolar pulse evolve into this characteristically oscillatory waveform after traveling about 14 mm from the source. Details of the oscillation contain information about material properties. **(b)** Nonlinearities turned an initially bipolar pulse into this shape with steep shocks after it traveled 18 mm across a silicon surface. In the retarded time frame, $t = 0$ corresponds to the phase point that propagates with the linear Rayleigh velocity of the substrate. A negative retarded time describes the faster part of the wave, and a positive time the slower part. **(c)** This solitary pulse kept its shape essentially unchanged as it traveled about 17 mm across isotropic fused silica covered with a nickel–chromium layer 300 nm thick.

reduced penetration of the high-frequency components. The opposite nonlinear effect, frequency-down conversion, also takes place. It is characterized by the generation of lower frequencies and a lengthening of the SAW pulse.

The nonlinear behavior of ultrasonic waves stems from nonlinearities in the stress–strain relationship. With increasing amplitude of the lattice vibrations, the nonlinear part of the interaction potential is sampled. The shape of an intense surface pulse changes steadily during propagation due to elastic nonlinearity, and the resulting waveform develops shockfronts connected with the formation of steep parts in the wave profile (see figure 4b).[8] Nonlinear SAWs can be excited by focusing pulsed laser radiation onto a highly absorbing carbon layer, which is explosively evaporated. With this technique, Mach numbers—the ratio of the surface velocity to the phase velocity of the SAW—between $10^{-3}$ and $10^{-2}$ have been realized. (For comparison, the Mach number of thermoelastic excitation is roughly $10^{-5}$ and that of ablative excitation around $10^{-4}$.) Such nonlinear SAWs will find use in the study of the elastic nonlinearity of materials and the determination of third-order elastic constants needed for the description when Hooke's law is no longer sufficient.

The theoretical description of nonlinear surface waves has attracted the interest of many theorists. A thorough review of the work performed before 1995 has been given by Andreas Mayer.[9] Two different approaches have been developed recently for the treatment of nonlinear surface and interface waves. The treatment by Evgenia Zabolotskaya and Mark Hamilton uses the Hamiltonian formalism.[10] Vitalyi Gusev derived another set of evolution equations with the assumption that the cumulative effect of weak nonlinear interactions leads to a slow variation of the surface wave in space and time.[11] Surprisingly, both theories, which are not identical, describe current experiments reasonably well. A discrimination between these theories may be possible by improving the detection of the narrow spikes observed in the nonlinear pulse profiles.

## Solitary surface waves

Solitons are permanently localized nonlinear wave entities that propagate with essentially no change of their waveform or speed. The name "soliton" is reminiscent of particles and, indeed, during collisions and interactions, solitons behave like particles. Since a soliton's wave amplitude and speed are coupled to each other, a narrow, high-amplitude soliton may overtake a broad, small one.

Solitons were first discovered in 1834 by John Scott Russell in surface waves.[12] He observed water waves in the Edinburgh–Glasgow canal that consisted of a single isolated crest with no disturbance before or after it. In fact, such water waves can be studied in a simple tank using a paddle that matches the cross section to generate these exotic wave entities.

The celebrated theoretical treatment published by Korteveg and de Vries in 1895 made clear that solitons form in nonlinear dispersive media. For solitons to be stable, the trend of nonlinearities to make the pulse shorter must be exactly canceled by dispersion, which tends to make pulses longer.

Today, optical solitons, in which chromatic dispersion and nonlinear refraction work against and cancel each other, are much better understood than elastic surface solitons (see the article by Mordechai Segev and George Stegeman in PHYSICS TODAY, August 1998, page 42). Indeed, although solitons were discovered in the form of surface waves, our understanding of elastic surface solitons is still developing. A specific problem is that SAWs have no intrinsic dispersion. Therefore, geometrical dispersion must be artificially introduced, such as by depositing a thin film onto the substrate material. The dispersion should not be too strong, however, since otherwise the wavepackets do not form the necessary shocks.

Laser-induced nonlinear SAW pulses now make it possible to study broadband elastic surface solitons. In recent experiments with fused silica coated with an appropriate thin metal film, we have observed the formation of a stable pulse (figure 4c) that propagated faster than the linear phase velocity—a feature expected for normal dispersion.[5] Studies with anisotropic silicon crystals covered by a thin, thermally grown silicon oxide layer clearly showed that the normal dispersion effect could be essentially canceled in a nonlinear pulse.[8] The characteristic oscillatory behavior disappeared and the waveform resembled two Mexican hats, as predicted by Mayer's group.[13] These observations are the first promising steps on the way to realizing elastic surface solitons. But solitary surface waves shouldn't be called solitons until their particlelike behavior has been demonstrated when they collide.

## Fracture of materials

An important property of materials that must be determined experimentally is their mechanical strength. Except for a very few materials, such as carefully prepared

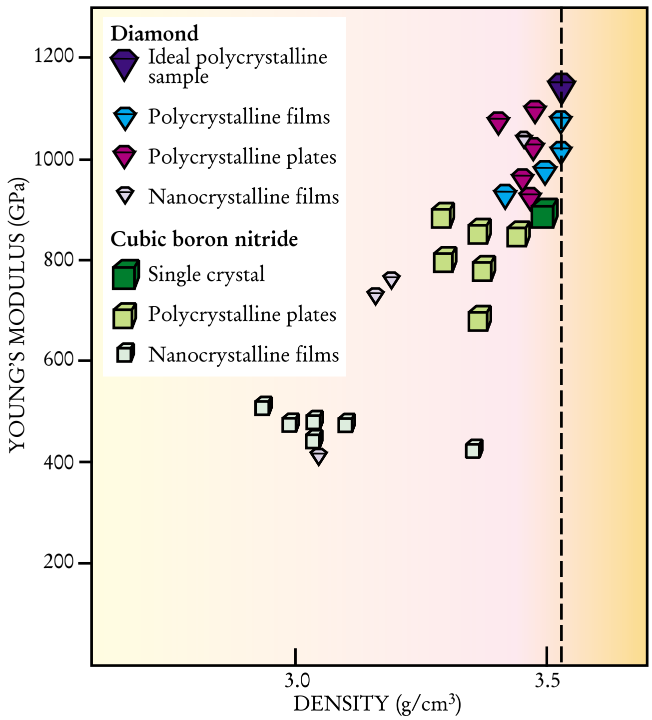



**FIGURE 5. ELASTIC AND MECHANICAL PROPERTIES** of materials can be determined using surface acoustic waves. Here are shown the Young's modulus (stiffness) and the density, both extracted from SAW experiments, for diamond and cubic boron nitride samples. The films and plates were grown using chemical vapor deposition with differing amounts of methane gas, and hence different growth rates. The most slowly grown diamond samples were closest to the stiffness and density (dashed line) of a statistically averaged ideal polycrystalline sample.

glass fibers, the theoretical strength may be orders of magnitude higher than the measured value. Brittle fracture, for example, may occur at stresses well below the designed values. A reason for this behavior may be the microstructure: Flaws, microcracks, grain boundaries, or dislocations may determine the actual strength (see the article by Michael Marder and Jay Fineberg, PHYSICS TODAY, September 1996, page 24). The microchemistry of the material may also be important. It has been postulated that the *Titanic* sank because of brittle failure (instead of ductile behavior) of the steel rivets due to the presence of a fraction of a percent too much sulfur.

Up to now, investigations of mechanical strength have mainly been performed through quasi-static fracture experiments, in which the material is loaded with a constant force. This tensile loading geometry generates a running crack starting at a preformed seed crack. But not everything in these experiments is understood. For example, in experiments on the brittle fracture of silicon single crystals, continuum theories predict that cracks will propagate at the Rayleigh velocity, but the crack velocity observed for different loadings is only 50–85% of that value.[14]

With laser-excited nonlinear SAW pulses, it is possible to generate steep shocks with stresses that exceed the mechanical strength of covalent brittle materials such as silicon. These stresses lead to transient fracture by impulsive loading, similar to the catastrophic failure of the *Titanic*. The influence of rapidly rising stress pulses of very short duration on the dynamics of fracture is currently not well understood. It is not surprising that no detailed theoretical models for impulsive fracture are available, since the theoretical treatment of quasi-static cracking already turns out to be extremely difficult.

Nonlinear SAW pulses provide a new tool to study transient fracture dynamics without seed cracks. For a nonlinear SAW pulse propagating along the ⟨112⟩ direction on the Si(111) plane, a series of cracks, extending at the surface in the ⟨110⟩ direction perpendicular to SAW propagation, could be seen by scanning force microscopy.[8] Investigation of the depth penetration shows that impulsive fracture occurs spontaneously along weak Si(111) planes with the lowest bond density—that is, the lowest cleavage energy. In fact, a whole series of cracks is generated due to the recovery of the shockfronts during SAW propagation in the nonlinear medium.

While the investigation of linear mechanical properties with SAWs is already in widespread use in practical applications, the use of nonlinear SAWs is still in the initial stages. Since the modified excitation process is not very complicated, new, exciting results can be expected in the near future from the application of nonlinear SAWs to such diverse fields as nonlinear elastic properties, surface solitons, and fracture.

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