Correspondence

Electromechanical Properties of Bismuth Germanate $Bi_4(GeO_4)_3$

As is known from the literature, single crystals of bismuth germanate have been grown [1], [2], and the electrooptical properties have been investigated. This correspondence describes the electromechanical properties, i.e., the elastic, dielectric, and piezoelectric behavior. All constants given in this paper were measured at 20°C. Bismuth germanate belongs to the crystal class ($\bar{4}3m$) and thus shows cubic symmetry. We measured the elastic constants dynamically using the pulse–echo method and a resonance method. Measurements of the sound velocities on several specimens in various crystallographic directions yielded the elastic constants c_{ij} and s_{ij} as given in Table I. Since the piezoelectric coupling is low, no distinction was made between c^D and c^E or s^D and s^E, respectively. The temperature coefficients γ_{ij} of the constants c_{ij} and δ_{ij} of the constants s_{ij} are also summarized in Table I.

TABLE I
ELASTIC CONSTANTS c_{ij} AND s_{ij} AND THEIR TEMPERATURE COEFFICIENTS γ_{ij} AND δ_{ij} OF BISMUTH GERMANATE

$c_{11} = 11.58 \times 10^{10}$ N/m² ± 1%	$s_{11} = 9.4 \times 10^{-12}$ m²/N ± 3%
$c_{44} = 4.36 \times 10^{10}$ N/m² ± 1%	$s_{44} = 23 \times 10^{-12}$ m²/N ± 1%
$c_{12} = 2.70 \times 10^{10}$ N/m² ± 8%	$s_{12} = 1.8 \times 10^{-12}$ m²/N ± 8%
$\gamma_{11} = -1.13 \times 10^{-4}$/°C	$\delta_{11} = 1.23 \times 10^{-4}$/°C
$\gamma_{44} = -1.17 \times 10^{-4}$/°C	$\delta_{44} = 1.17 \times 10^{-4}$/°C
$\gamma_{12} = -0.44 \times 10^{-4}$/°C	$\delta_{12} = 1.78 \times 10^{-4}$/°C

The low-frequency dielectric constant ϵ_{11}, the coefficient of thermal expansion α_{11}, and the density ρ are

$$\epsilon_{11} = 16,$$
$$\alpha_{11} = 5 \times 10^{-6}/°\text{C},$$
$$\rho = 7.095 \times 10^3 \text{ kg/m}^3.$$

The piezoelectric coupling coefficient k was evaluated from measurements of the resonance and antiresonance frequencies. Using shear-wave propagation in the ⟨110⟩ direction with polarization in the ⟨001⟩ direction, a coupling coefficient k of $1.5 \times 10^{-2} \pm 25$ percent was obtained. This coupling coefficient k is defined by $k^2 = h_{14}^2/\beta_{11}^S c_{44}^D$, where h_{14} is the piezoelectric constant and β_{11}^s the dielectric impermeability. The complete set of nonvanishing piezoelectric constants is given in Table II.

TABLE II
PIEZOELECTRIC CONSTANTS OF BISMUTH GERMANATE

$\lvert h_{14}\rvert = 2.6 \times 10^8$ N/C	$\lvert d_{14}\rvert = 0.87 \times 10^{-12}$ C/N
$\lvert e_{14}\rvert = 3.76 \times 10^{-2}$ C/m²	$\lvert g_{14}\rvert = 6.0 \times 10^{-3}$ m²/C

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The results of acoustical attenuation measurements for some types of waves are listed in Table III.

TABLE III
ACOUSTICAL ATTENUATION OF SOME SPECIAL TYPES OF WAVES

Direction of Propagation	Effective Elastic Constant	Direction of Particle Displacement	Frequency (MHz)	Attenuation (dB/cm)
⟨100⟩	c_{11}	⟨100⟩	15	0.15
⟨100⟩	c_{44}	⟨001⟩	10	0.3
⟨110⟩	$\frac{1}{2}(c_{11}-c_{12})$	⟨1$\bar{1}$0⟩	10	2.26

H. SCHWEPPE
Philips Zentrallaboratorium GmbH
Laboratorium Aachen
Aachen, Germany

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Velocity Measurements of Lateral Beam Displacement Upon Reflection

***Abstract*—The velocity of the ultrasonic beam displacement at a liquid–solid interface was determined electronically and optically. A stroboscopic technique utilizing light and sound interaction was developed to observe ultrasonic pulses reflecting from metals immersed in water. It was shown that when the beam is displaced it propagates along the surface at the Rayleigh wave velocity before it is reradiated into the water.**

When a plane-longitudinal ultrasonic wave is incident at the plane interface formed by a liquid and a solid, part of the wave is reflected and part is refracted. The directions of the various waves are given in accordance with Snell's law. If one includes mode conversion to Rayleigh waves, Snell's law reads [1]

$$C_f/\sin\theta_R = C_R, \tag{1}$$

where C_f is the longitudinal wave velocity in the fluid, C_R the Rayleigh wave velocity on the solid, and θ_R the Rayleigh angle.

When a bounded beam is incident at a liquid–solid interface at the Rayleigh angle, the beam is displaced along the interface before it is reradiated. Schoch [2] derived an expression for the displacement

$$\Delta = \frac{2\lambda\rho_2}{\pi\rho_1}\left[\frac{a(a-b)}{b(b-1)}\right]^{1/2}\frac{1+6b^2(1-c)-2b(3-2c)}{b-c}, \tag{2}$$

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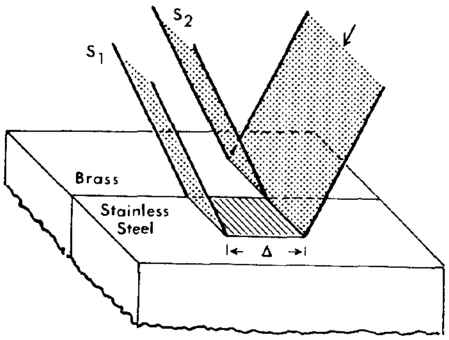


Fig. 1. Separation of reflected beam. Part S_2 is reflected normally, S_1 is displaced if the angle of incidence equals the Rayleigh angle.

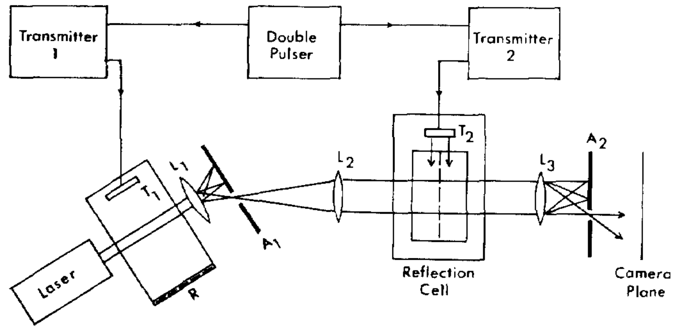


Fig. 2. Schematic diagram of stroboscopic schlieren arrangement. Angles and distances not to scale.

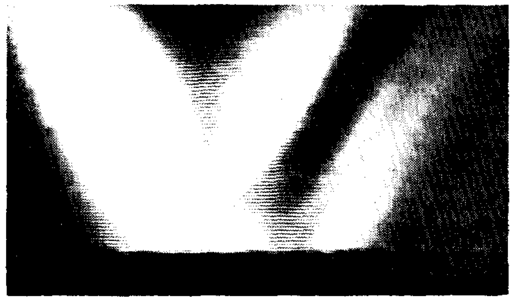
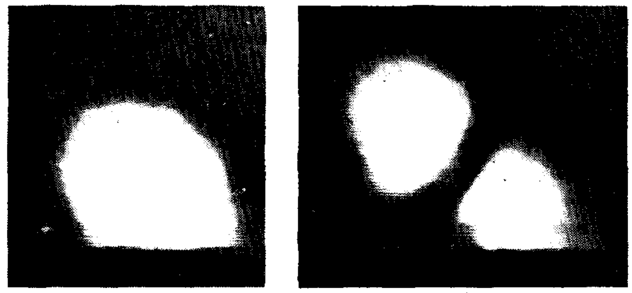


Fig. 3. Schlieren photograph of continuous wave incident from the left and partly reflected from brass (center beam) and partly displaced and subsequently reflected from stainless steel.



(a) (b)

Fig. 4. (a) Stroboscopic schlieren image of incident pulse at time it reaches interface. (b) Reflected pulse split into normally reflected signal from brass (upper image) and laterally displaced and subsequently reflected from stainless steel (lower image).

where λ is the wavelength in the liquid, $a = (C_{S2}/C_{L1})^2$, $b = (C_{S2}/C_R)^2$, $c = (C_{S2}/C_{L2})^2$, and ρ is the density. The subscripts R, S, and L refer to Rayleigh, shear, and longitudinal waves, respectively, and the subscripts 1 and 2 to liquid and solid, respectively.

This relationship, which was verified experimentally by Schoch [3] and others [4], has to be taken into consideration in experimental studies of reflection problems [5], particularly at low frequencies. For stainless steel immersed in water (2) predicts a displacement of 61 wavelengths. However, (2) does not reveal the velocity with which the signal propagates along the surface through the displacement distance before being reradiated into the liquid. In order to determine this velocity two experiments were performed.

Experiment 1

Blocks of stainless steel and brass were silver-soldered together and machined to form adjacent coplanar reflecting surfaces. This sample was placed in water so that one half of the incident ultrasonic beam was reflected from the stainless-steel surface (signal S_1) and the other half from the brass surface (signal S_2) as indicated in Fig. 1. The transmitting transducer was driven by an Arenberg pulsed oscillator and emitted a 5-MHz $\frac{3}{4}$-inch-diameter beam. The reflected signals S_1 and S_2 were received by a 3-inch-diameter transducer, amplified and displayed on an oscilloscope.

The received signal was observed as a function of angle of incidence. When this angle was 30°, which is the Rayleigh angle for stainless steel in water, the signal reflected from stainless steel S_1 would be expected to be displaced by a distance given by (2) while S_2 should be reflected normally at 30° (i.e., $\Delta = 0$) since the Rayleigh angle for brass in water is 49.8°. The receiving transducer was large enough to intercept both reflected signals.

One can show quite readily that the time difference between the arrivals of S_1 and S_2 at the receiving transducer is

$$t = \frac{\Delta}{C_x} - \frac{\Delta}{C_f} \sin \theta_R, \tag{3}$$

where C_x is the velocity with which S_1 travels along the stainless-steel surface. If $t = 0$, it follows from (1) that $C_x = C_R$.

The results of this experiment showed that the time difference t was zero, i.e., only one pulse was displayed on the oscilloscope regardless of the angle of incidence, including the respective Rayleigh angles for both metals. This indicates that the velocity with which the signal is displaced along the surface is identical to the Rayleigh wave velocity.

Experiment 2

The object of this experiment was to present a pictorial representation of the result found in the first experiment. To accomplish this a stroboscopic technique was devised as shown schematically in Fig. 2. The light source was a 10-mW He-Ne laser. The light interacted normally with a 7-MHz ultrasonic beam produced by transducer T_1 driven by Arenberg transmitter 1, which in turn was triggered by a Beckman double pulser at 10^3 pps. Pulse duration was 1 μs. The sound cell was filled with water and ρc rubber R absorbed the signal at one end of the cell. Lens L_1 focused the light beam at aperture plane A_1 where a Raman–Nath diffraction pattern [6] appeared whenever a sound pulse interacted with the laser beam. The apperture A_1 allowed only the first diffraction order to pass. The pulsed light emerging from this aperture was collimated by lens L_2 into a 2-inch-diameter beam.

The entire reflection cell described in Experiment 1 was placed in the path of the pulsed light beam such that the entire region of ultrasonic reflection from the metals was illuminated. The sound propagation directions were normal to the propagation direction of the pulsed light passing through A_1. Transducer T_2

in the reflection cell was driven by Arenberg transmitter 2, which in turn was pulsed by the Beckman double pulser. The two pulses leaving the double pulser had the same repetition rate; the delay time between the two pulses could be varied over a 10-μs range. It was thus possible to adjust the time of pulsed illumination (through A_1) with respect to the position of the ultrasonic pulse in the reflection cell.

Lens L_3 focused the light to aperture A_2 where only the first diffraction order was allowed to pass. This arrangement produced a schlieren image of the sound in the camera plane, specifically an image of the ultrasonic pulse before, during, or after reflection from the brass-stainless-steel sample as determined by the time delay between the two pulses leaving the double pulser.

Fig. 3 shows a schlieren image formed by a continuous ultrasonic wave. The beam is incident from the left at 30°, which is the Rayleigh angle for stainless steel. Half the reflection is from brass and half from stainless steel. It is evident that upon reaching the interface the beam separates; part is reflected normally from brass and part moves along the stainless-steel surface before it is reradiated in the same direction.

Fig. 4(a) shows a stroboscopic schlieren image of the incident pulse as it reaches the metal-water interface. The pulse length was 4 μs. The geometry was the same as that used to obtain Fig. 3. Fig. 4(b) shows a stroboscopic schlieren image of the reflected pulse. One notes that the leading edges of the two pulses are in the same plane normal to their respective propagation directions. This illustrates the observation made in Experiment 1 that the time difference $t = 0$ and thus $C_x = C_R$.

Conclusion

From the measurements of the angle of incidence and the knowledge of the velocities in both media, both experiments indicate that the velocity with which the ultrasonic signal is displaced along the solid is the Rayleigh wave velocity. Hence, phenomenologically one may consider the beam displacement in terms of Rayleigh-type [1] wave propagation along the surface metal.

Orest I. Diachok
Walter G. Mayer
Dept. of Physics
Georgetown University
Washington, D. C. 20007

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Contributors

Noriyoshi Chubachi was born in Kokura, Japan, on October 5, 1933. He received the B.S., M.S., and Ph.D. degrees in electrical engineering from Tohoku University, Sendai, in 1956, 1962, and 1965, respectively.

In 1965, he became a Research Associate at the Research Institute of Electrical Communication, Tohoku University. Since 1966, he has been an Assistant Professor at Tohoku University. He has worked on acoustoelectronics, ultrasonic transducers and delay lines, piezoelectric semiconducting materials, and related problems.

Dr. Chubachi is a member of the Institute of Electronics and Communication Engineers of Japan, the Society of Japanese Applied Physics, and the Acoustical Society of Japan.

Errol P. EerNisse (S '61–M '62) was born in Rapid City, S. Dak., on February 15, 1940. He received the B.S.E.E. degree from South Dakota State University, Brookings, in 1962, and the M.S.E.E. and Ph.D. degrees from Purdue University, Lafayette, Ind., in 1963 and 1965, respectively. While at Purdue, he was supported by a Phi Kappa Phi fellowship and National Science Foundation fellowship.

In 1965 he joined Sandia Laboratories, Albuquerque, N. Mex., where he has done research on semiconductor devices and linear and nonlinear ferroelectric devices. Presently he supervises the Device Physics Research Division in the Radiation Effects in Solids Research Department.

Arthur H. Fitch was born in Arkansas City, Kans., on September 24, 1927. He received the B.S. degree in engineering physics and the M.S. degree in physics from the University of Kansas, Lawrence, in 1949 and 1952, respectively. He received the Ph.D. degree in physics from Johns Hopkins University, Baltimore, Md., in 1957.

From 1950 to 1952 he was employed by the Perkin-Elmer Corporation, Norwalk, Conn., where he worked on the development of infrared process control instrumentation. Since 1957, he has been a member of the technical staff at the Bell Telephone Laboratories, Inc., Whippany, N. J., where he has worked on ferroelectric and ultrasonic devices. He is currently a member of