ACOUSTOELECTRIC EFFECT OF MICROWAVE PHONONS IN GaAs

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An acoustoelectric current induced by a 9-Gc/sec acoustic wave has been observed in GaAs. The dependence of the current on acoustic power, illumination level and temperature has been measured and is in fair agreement with theory. These are the first reported measurements of acoustoelectric currents produced by microwave phonons.

The experiments are part of an investigation of a theory of acoustoelectric effects produced by hypersonic waves of large amplitude.[1] For sufficiently large acoustic amplitudes unusual effects are predicted. The results of the present experiments, which involve low-amplitude waves, can be analyzed in terms of the theory given in reference 1 by taking the limit $e\varphi_0 \ll kT$ where φ_0 is the amplitude of the potential wave. This is equivalent to the small-signal theory given by Weinreich.[2]

The experiments were performed on GaAs containing ~10^8 electrons/cc at room temperature (semi-insulating). The electron concentration was controlled by illuminating the crystal with penetrating light to liberate electrons from deep traps. The electron mobility was about 2×10^4 cm^2/volt sec at 77°K. The acoustic wave train was generated in the GaAs bar by placing one end of the sample in the electric field region of a re-entrant microwave cavity resonant at 9 kMc/sec. The cavity was driven by a magnetron delivering a 0.5-μsec pulse. The sample was cut so that a shear wave polarized in the ⟨001⟩ direction was excited piezoelectrically and traveled along the bar in the ⟨110⟩ direction. The acoustoelectric current was picked up by a pair of contacts near the opposite end of the bar, whose separation was less than the length of the wave train. The contacts were capacitive but their impedance was low enough that the measured current was nearly equal to the total acoustoelectric current. The effect of lead capacitance was minimized by providing an emitter-follower amplifier close to the contacts.

The signals consist of a negative pulse as the wave train passes the contacts in one direction followed by a positive pulse which results from the wave train passing the contacts in the opposite direction after reflection from the end of the bar. We refer to the sum of the measured magnitudes of the negative and positive current pulses as I_{pp}. This pair of electrical pulses is repeated (with diminishing amplitude) as the wave train is successively reflected from the ends of the bar. As many as three pairs of pulses have been observed. The spacing of the pulses is appropriate to the velocity of a ⟨001⟩ shear wave propagating in the ⟨110⟩ direction in GaAs.[3]

The maximum strain that could be obtained was limited by dielectric breakdown in the cavity. The best results so far have been obtained by placing a Teflon spacer in the cavity and filling the gaps with liquified propane at about 90°K. Propane solidifies at about 80°K and forms a high-breakdown dielectric. Since not much contraction takes place below 80°K, there is little strain on the sample due to the propane.

The dependence of the amplitude of the first pair of pulses on microwave power (which should be proportional to the acoustic power in the GaAs) is shown in Fig. 1. Theory predicts a

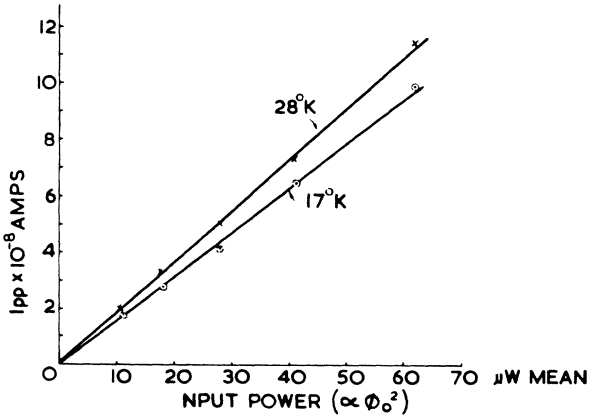

FIG. 1. Peak-to-peak amplitude of acoustoelectric current versus mean microwave power.

linear dependence of acoustoelectric current on acoustic power until $e\varphi_0$ becomes a substantial fraction of kT. Assuming the crystal does not disturb the electric field in the cavity, the maximum value of $e\varphi_0/kT$ at 17°K was about 0.13, which would not give a significant deviation from linearity. In practice, the disturbance of the electric field and also the imperfect polishing of the crystal would result in a rather smaller value than 0.13.

The dependence of the amplitude of the pulses on illumination level is shown in Fig. 2. The results can be explained in terms of an increasing electron concentration with illumination causing a greater current for a given strain but a greater attenuation of the sound. Weinreich[2] has given the relation between the acoustoelectric current density (i_{ae}) and the attenuation constant for the sound due to the electrons (α_n)

$$i_{ae}(x) = (\mu/v_s)\alpha_n Q(x), \qquad (1)$$

where v_s is the sound velocity and Q is the acoustic power per unit area. [Equation (1) shows that if the sound is significantly attenuated through the crystal i_{ae} is a function of x. However, in a region of crystal with no contacts the total current must be continuous and, in the absence of an applied field, it must correspond to some average value of i_{ae}. The electric field distribution required to maintain the current constant and the deviations from the equilibrium electron concentration (N_0) that produce this field would cause α to be a function of x, but this effect would be negligible when $e\varphi_0 \ll kT$.]

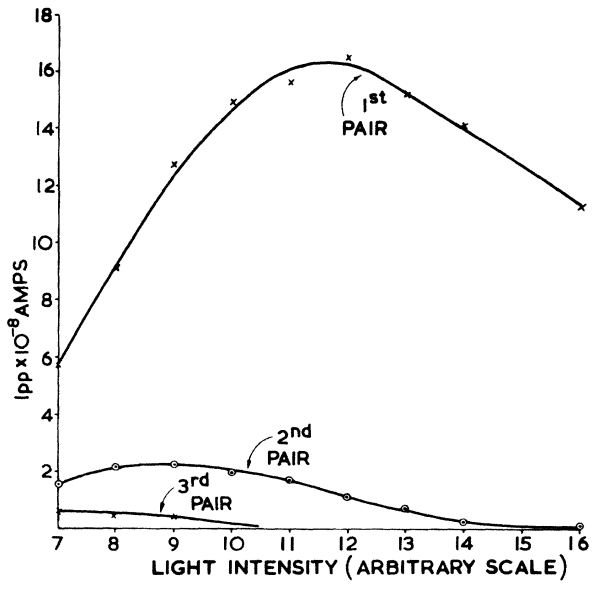

FIG. 2. Peak-to-peak amplitude of acoustoelectric current at 23°K versus light intensity (arbitrary scale).

Writing $Q(0)$ for the incident acoustic power, α_L as the attenuation constant due to the lattice, and $\alpha_n = \beta N_0$, Eq. (1) becomes

$$i_{ae}(x) = \frac{\mu\beta N_0}{v_s} Q(0)\exp[-(\beta N_0 + \alpha_L)x]. \qquad (2)$$

By differentiating with respect to N_0 one finds that the electron concentration for maximum current at a distance x is given by

$$N_0 = (\beta x)^{1/2}. \qquad (3)$$

x is about 0.8 cm for the first pair of pulses and effectively about 2.8 cm for the second pair. Therefore the light intensity (or N_0) for maximum current is higher for the first pair than for the second.

This calculation also indicates that the attenuation due to the electrons at the light intensity for maximum current in the first pair of pulses is about 4 dB/cm. This value can be compared with the value calculated directly from the measured current using the Eq. (1), which is about 0.17 dB/cm. The value of $Q(0) = 740$ watts/meter^2 was obtained by an approximate calculation and the mobility at 20°K was estimated to be 0.5 meters^2/V sec. There is an order of magnitude discrepancy between these two determinations of α_n. This may be due in part to an overestimate of $Q(0)$ because of the uncertainty of the field configuration in the cavity with the sample in it and the loss of acoustic power due to scattering from material near the surface that was damaged by the cutting of the sample. It is expected that this discrepancy can be reduced by improved sample preparation. In view of the uncertainties in the values of $Q(0)$, μ, and I_{ae}, we consider the agreement to be reasonable.

The temperature dependence of the peak-to-peak current of the first pair of pulses at constant illumination is shown in Fig. 3. The interpretation of this curve is difficult at present owing to the uncertainty in the temperature variation of some of the parameters, but it can be given in general terms.

Region 1 (below 15°K).—In this temperature range, the concentration and mobility of the electrons is falling drastically with temperature as shown by photoconductivity measurements. The electrons are apparently falling into donor states.

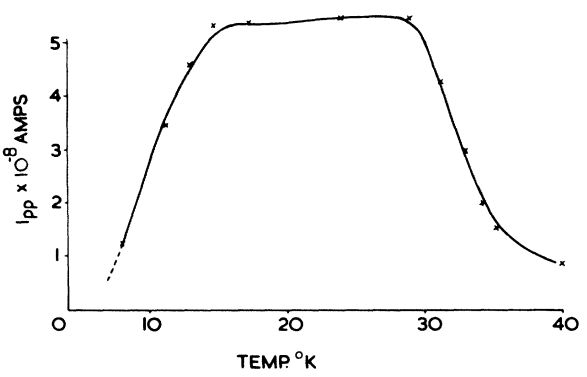

FIG. 3. Temperature dependence of acousto-electric current.

Region 2 (15°K to 30°K).—The remarkably constant current in this range presumably results from a balance between $e\varphi_0/kT$ decreasing with increasing temperature and the mobility increasing.

Region 3 (above 30°K).—The decrease in current is caused largely by an increase in α_L due to the attenuation of the sound by thermal phonons.[4]

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RECOILLESS GAMMA-RAY EMISSION AFTER ALPHA DECAY*

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Recoilless gamma rays are emitted after α decay. We report the results of Mössbauer absorption experiments with the 59.6-keV gamma ray of Np^{237} following both α decay of Am^{241} and β decay of U^{237}.

The 59.6-keV gamma transition in Np^{237} was chosen as a promising first candidate for Mössbauer absorption studies in the actinide region. The 59.6-keV nuclear level,[1] which has spin $\frac{5}{2}^-$ and a half-life of 6.3×10^{-8} sec, decays by an $E1$ gamma transition to the ground state, which has spin $\frac{5}{2}^+$. The total internal conversion coefficient[2] for the transition is 1.0. The maximum resonance cross section,[3] σ_0, is 0.34×10^{-18} cm^2. The 59.6-keV level and the ground state of Np^{237} are described by the same collective-model quantum numbers[4] as are the 26-keV level and the ground state of Dy^{161}, for which the Mössbauer effect is known.[5]

In our experiments cubic NpO_2 was used both as the absorber and as the host lattice for the sources. A single thick polycrystalline absorber (250 mg/cm^2) and two polycrystalline sources, each about 20 mg/cm^2, were prepared. The sources consisted of Am^{241} and U^{237} as 1% solid solutions of AmO_2 and UO_2, respectively, in isomorphous[6] NpO_2. The 6.75-day U^{237} activity was obtained by neutron irradiation and subsequent ion-exchange separation of U_3O_8 highly enriched in U^{236}.

Experiments were performed with a loudspeaker-type velocity spectrometer similar to that reported by Lynch and Baumgardner,[7] modified for cryogenic work. The system was calibrated with the Fe^{57} Mössbauer effect. A Xe-filled proportional counter was used as the gamma-ray detector. Best resolution was obtained by counting the Xe escape peak of the 59.6-keV gamma radiation.

The velocity spectrum obtained for the absorber and Am^{241} source at 77°K is shown in Fig. 1(a). The resonance-absorption effect obtained after α decay may be compared with the larger effects observed after β decay of U^{237} with the source and absorber at 77°K [Fig. 1(b)] and at 4.2°K [Fig. 1(c)]. An experiment was also performed with the absorber and Am^{241} source at 4.2°K; a broad velocity spectrum similar to that of Fig. 1(c) was obtained, but with only a 1% change in count rate at zero velocity. In each case the