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AMPLIFICATION OF MICROWAVE PHONONS IN GERMANIUM

M. Pomerantz
IBM Watson Research Center, Yorktown Heights, New York
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We report the results of some theoretical calculations and experiments on the interaction between an electronic current and a hypersonic wave at a frequency of 9 Gc/sec in germanium. The theory predicts that amplification of the acoustic waves should be possible and we have experimentally observed this amplification in the presence of suitable drift currents.

Acoustic amplification was first observed by Hutson, McFee, and White,[1] who amplified radio-frequency ultrasound in CdS. Amplification was achieved by virtue of the strong piezoelectric coupling between electrons and particular elastic waves in CdS. Subsequent experimental work has been confined to the piezoelectric semiconductors, except for experiments on Bi.[2] The coupling between electrons and phonons in nonpiezoelectric semiconductors can be described by a deformation-potential coupling, which is usually weaker than the piezoelectric coupling, and hence such deformation-potential semiconductors have received less attention. Experiments[3] have shown, however, that particular modes of 9-Gc/sec phonons are strongly attenuated in heavily doped n-Ge although the electron-phonon coupling is via the deformation potential. The relatively strong interaction in this case is a consequence of the multivalley nature of the conduction bands of Ge.

Weinreich, Sanders, and White[4] (called WSW hereafter) pointed out that for many-valley semiconductors the bunching of electrons in particular acoustic waves occurred without attendant space-charge repulsion. This absence of repulsion means that the effects of the electrons on the phonons increases monotonically with increases in the density of electrons. Thus, for many-valley semiconductors the relative weakness of the deformation-potential coupling compared to piezoelectric coupling can be compensated by an increase of electron density.

Previous calculations[5] of the amplification of phonons in deformation-potential semiconductors did not explicitly consider the case of many-valley semiconductors. The present calculation takes account of this crucial property. We consider the shear wave propagating in the (100) direction in Ge. This wave is one for which bunching is not accompanied by space-charge repulsion. This occurs because the shear increases the energy of two of the four equivalent (in zero strain) conduction-band minima while decreasing the energy of the other two by the same amount. This creates two classes of conduction minima (denoted by $\pm$) for which the sum of the space charges in real space is a uniform density.

We calculate the attenuation of this shear wave, extending the theory[4] of the acoustic-electric effect in n-Ge by including the effects of an applied electric field. To WSW's Eq. (3.4) for the current density $j_\pm$ in the two sets of valleys, we add a drift current density. Thus

$$j_\pm = -D[\partial n_\pm/\partial x \pm (\beta q n_\pm)\partial\varphi/\partial x - n_\pm e\beta E], \qquad (1)$$

where D = diffusion constant for the electrons; $n_\pm$ are the electron densities for the two classes of electrons; $\beta = 1/kT$, k = Boltzmann's constant; and $q\varphi$ is the potential energy of an electron in an acoustic wave whose amplitude is proportional to φ. The reader is referred to WSW for a complete discussion of the significance of these terms.

Equation (1), solved in conjunction with the equation for charge conservation [WSW's Eq. (3.3)], gives the space-charge densities accompanying the $\pm$ potential waves. Following the analysis of Weinreich, Sanders, and White,[4] and Weinreich,[6] the attenuation constant is found to

be[7]

$$\alpha = \frac{N\Xi^2\beta}{9S^3\rho} \frac{\omega^2\tau_R(1-V/S)}{[1+(1-V/S)^2\omega^2\tau_R{}^2]}, \qquad (2)$$

where N = electron density, Ξ = shear deformation-potential constant, τ_R is a relaxation time ($\tau_R{}^{-1} = \tau_{i.v.}{}^{-1} + DQ^2$), $\tau_{i.v.}$ = intervalley relaxation time, Q = acoustic wave vector, V = electron drift velocity, S = velocity of the acoustic wave, ω = circular frequency of the acoustic wave, and ρ = density of Ge.

Note that when $V > S$ the attenuation becomes negative, i.e., acoustic gain results when the electronic velocity exceeds the sonic velocity. Values of τ_R as a function of N and T are known for Ge from acoustoelectric measurements.[5] We can use these values to estimate the amplification, using (2), if it is assumed that the electron parameters are not much affected by the presence of the E field. At $\omega \approx 10^{11}$/sec, $N \approx 10^{16}$/cc, $\tau_R \approx 10^{-11}$ sec at 10°K, and for $V \approx 3S$, the calculated gain is $\alpha \approx 800$ dB/cm, a very large gain indeed for microwave phonons.

Experiments have been performed to investigate the predicted phonon amplification in Ge. The samples were bars of single-crystal Ge, oriented in the (100) direction [sometimes the (110) direction], with end faces polished flat and parallel. The samples were 1 cm long and ≈ 0.01 cm^2 in area. Pulses of up to 20 amperes of current were applied to Ohmic contacts near the ends of the samples. The phonons were generated by ferromagnetic film transducers.[3] The samples were cooled in liquid helium. Figure 1 shows some experimental results obtained in a sample containing 10^{16} As donors/cc. The trace in the center of the graticule shows the pulsed current. The lower trace in each exposure shows a large pulse which indicates when the phonons are being generated. (The pulse is electromagnetic leakage from the magnetron that is picked up by the receiver.) The second pulse after 6 μsec (divisions) is the phonon echo. The phonons are generated and detected at the same end of the crystal; hence they travel in two directions before a phonon echo is observed. A traveling wave interaction will be most effective if the electrons and phonons travel in the same direction; hence the electric pulse is applied either during the time the phonons are propagating away from the transducer or when they are returning to the transducer. The relative direction of the electrons can be changed by reversing the polarity of the pulse.

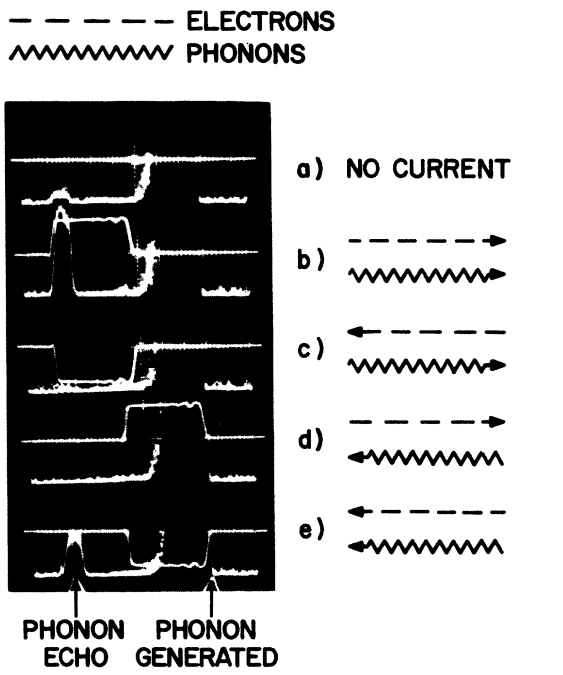

FIG. 1. Phonon amplification in germanium. The times at which the phonon pulse is generated and its echo is received are indicated. The dashed arrows indicate the direction of the electronic current. The wavy arrows show the direction of propagation of the phonons during the time the current is applied. Details are given in the text.

In exposure (a) of Fig. 1 is seen the phonon echo in the absence of electronic current. In (b) a pulsed current, in which the electron drift velocity is about twice the phonon velocity, is applied such that the electrons flow in the same direction as the phonons. An acoustic power gain of 20 dB is observed. The electric field pulse acts both to liberate electrons by impact ionization of the donors and to impart a drift velocity to the electrons. In (c) the direction of the current is reversed, and the phonons are attenuated into the noise. In (d) the current pulse is advanced in time so that the current is now applied when the phonons are propagating away from the transducer. The positive current pulse now means that the electrons are flowing opposite to the phonon direction; attenuation is observed. In (e) the negative pulse now produces gain. The gain in (e) is less than that in (b) because the current produces some lingering lossiness (probably heating and thermal ionization) which attenuates the phonons during their return trip. These pictures show that the phonon power depends on

the electron direction and velocity as expected for a traveling wave interaction.

Precise comparison of these experimental results with the theory, Eq. (2), is difficult because of experimental uncertainties about the area of the sample and the number of carriers present. The influence of impact ionization and the effect of the magnetic field (needed for the transducer) are not yet completely understood. It seems clear, however, that the observed amplification is less, by at least an order of magnitude, than the value predicted by Eq. (2). A suggested cause of this discrepancy is a breakdown of the assumption that the electronic properties are not affected by the applied electric field.[7] It is known that the electrons can be "heated" by the electric field and that this heating changes the electronic transport properties. This possibility has been examined in more detail by Conwell,[8] who estimated that the amplification may be reduced by a factor of order 50 by hot-electron effects. The experimental results are in order-of-magnitude agreement with these estimates.

In addition to offering a solution to the problem of the low intensity of microwave phonons, experiments on the amplification of phonons provide an interesting means of studying the properties of semiconductors, including hot-electron effects, intervalley scattering at low temperatures, and magnetic field effects. Some of these problems are under investigation and will be reported on later.

We wish to acknowledge the considerable technical help provided by many people at this laboratory. Conversations with R. W. Keyes have been useful. We are grateful to E. Conwell for informing us of her work prior to publication. The success of the experiments was due in large measure to the skillful work of J. P. Anderson.

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FAR-INFRARED RESONANCE STATES IN SILVER-ACTIVATED POTASSIUM HALIDE CRYSTALS*

A. J. Sievers
Laboratory of Atomic and Solid State Physics, Cornell University, Ithaca, New York
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The absorption of electromagnetic radiation by localized impurity lattice modes has been used as a lattice probe for a number of years.[1,2] Because the impurity levels lie outside the phonon quasicontinuum,[3] direct energy transfer to band states is not possible. Long lifetimes are predicted[4] and narrow absorption lines have been observed.[1] Recently, the possibility of impurity-induced resonance states within the phonon spectrum has been suggested.[5,6] If the impurity mass is larger than the host mass or if the impurity force constants are less than the host force constants, an approximate localized mode is expected in the continuum. The lifetime of this state increases as the mode frequency decreases.

At this time we wish to report the observation of impurity-induced absorption in silver-activated potassium halide crystals in the frequency region 100 cm^{-1} to 10 cm^{-1} (3×10^{12} cps to 3×10^{11} cps). Strong absorption lines appear at frequencies within the acoustic phonon continuum. An identification of these absorptions with pseudo-localized impurity modes is compatible with our experimental results.

The absorption measurements were made using a 12-inch grating monochromator with a liquid-helium cooled bolometer detector.[7] All crystals were studied at 2°K to minimize host lattice absorption. With a five-position sample holder, the transmission of a doped crystal was compared with the transmission of a pure crystal. The potassium halide single crystals investigated were grown by the Kyropoulos technique in an argon atmosphere. Silver chloride, bromide, and io-

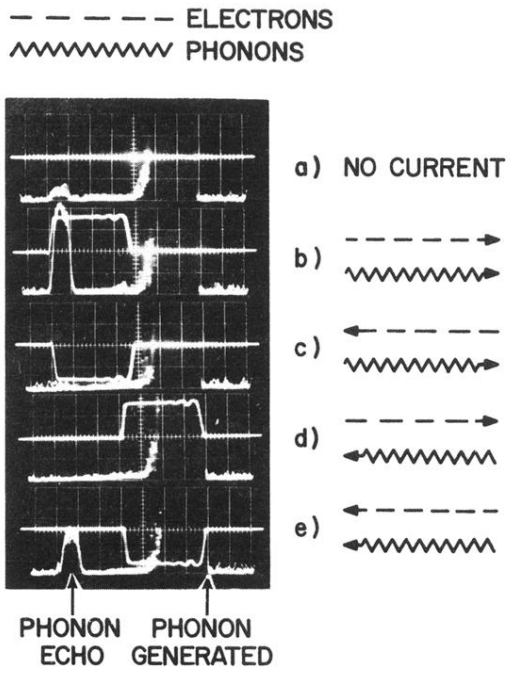

FIG. 1. Phonon amplification in germanium. The times at which the phonon pulse is generated and its echo is received are indicated. The dashed arrows indicate the direction of the electronic current. The wavy arrows show the direction of propagation of the phonons during the time the current is applied. Details are given in the text.