[18]I. Eisele and G. Dorda, Phys. Rev. Lett. 32, 1360 (1974).
[19]S. Kawaji, T. Igarashi, and J. Wakabayashi, Prog. Theor. Phys. Suppl. 57, 176 (1975).
[20]J. P. Kotthaus, G. Abstreiter, J. F. Koch, and P. Ranvaud, Phys. Rev. Lett. 34, 151 (1975).

Effect of Screening of Piezoelectric Phonon Fields on Absorption-Edge Broadening in GaAs†

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(Received 13 August 1976)

The broadening of the intrinsic absorption edge by intense, acoustoelectrically amplified phonon flux in piezoelectric semiconductors is well established. A definitive test is presented to show that the piezoelectric fields of the phonons in GaAs are predominantly responsible for this effect. The test consists of using intense extrinsic generation of excess electrons by a Q-switched, Nd-doped yttrium-aluminium-garnet laser to screen out the piezoelectric fields without affecting the acoustic intensity.

The intrinsic absorption edge in piezoelectric semiconductors (GaAs,[1] GaSb,[2] CdS[3,4]) is broadened by intense, acoustoelectrically amplified beams of phonons. Theoretical interest in this effect stems from its similarity to the Urbach tail and from the possibility that the microelectric fields[1,4-6] associated with piezoelectric phonons are responsible for the strong modulation of the absorption edge. Calculations[7] based on a Franz-Keldysh, exciton-broadening theory have shown that fields of the order of 50 000 V/cm are required to produce the observed modulation. Such fields are indeed consistent with estimates of amplified phonon intensity in GaAs (~1 J/cm^3) and strain (~5×10^{-3}) derived from Brillouin scattering measurements.[1,8] In this Letter, we present a direct experimental test of the predominant role of the piezoelectric fields of the phonons, based on the development of a technique for "switching off" these fields. This is accomplished by generating a large, transient increase in the free-electron concentration which screens out the piezoelectric fields without altering the phonon intensity and strain.

We should note that several other mechanisms may contribute to the modulation of transmission near the band edge, e.g., (1) the voltage applied to the sample, which generates a high dc field in the region or "domain" in which the intense acoustic flux is concentrated, (2) the strain associated with the intense flux, and (3) the very strong Brillouin scattering, particularly when it is resonantly enhanced near the absorption edge. Early experiments in GaAs [1] and GaSb [2] showed that the dc field produced in the domain (< 10^4 V/cm in these materials) was insufficient to account for the observed broadening. In the present experiment, the relative contribution of the dc field is quantitatively established. Recent experiments[9] in GaAs demonstrated that the modulation of transmission near the edge was much greater than could be accounted for by Brillouin scattering alone for the intensely amplified piezoelectric fast-transverse [110] phonons; only far from the edge did such scattering account for transmission modulation. However, two subsequent experiments in CdS,[10,11] although arriving at somewhat conflicting conclusions, do suggest a much more important role for resonant scattering in that material. The present experiment, which definitively tests the role of piezoelectric fields, was performed only in GaAs, but can also be done in CdS.

We shall make use of the known relationship[12] between the magnitudes of the piezoelectric field E_p and the strain S of the phonons given by

$$E_p=\left(\frac{\omega/\omega_D}{\omega_c/\omega+\omega/\omega_D}\right)\frac{e_{14}}{\epsilon}S,$$

where e_{14} is the piezoelectric tensor and ϵ is the dielectric constant; the term in parentheses represents a frequency-dependent screening of the piezoelectric field. In this term, $\omega/2\pi$ is the acoustic angular frequency, $\omega_D=qv_s^2/\mu kT$ is the diffusion frequency, $\omega_c=nq\mu/\epsilon$ is the conductivity relaxation frequency, n and μ are the electron concentration and mobility, and v_s is the sound velocity. We imposed here the simplifying condition that the gain coefficient $\gamma=v_d/v_s-1=0$, where v_d is the electron drift velocity. The results are not substantially different for $\gamma\lesssim20$. In Fig. 1, several curves of $E_p/(e_{14}S/\epsilon)$ vs $\omega/2\pi$ are plotted with n as a parameter. In a perfect insulator ($n=0$), E_p is unscreened and has a max-

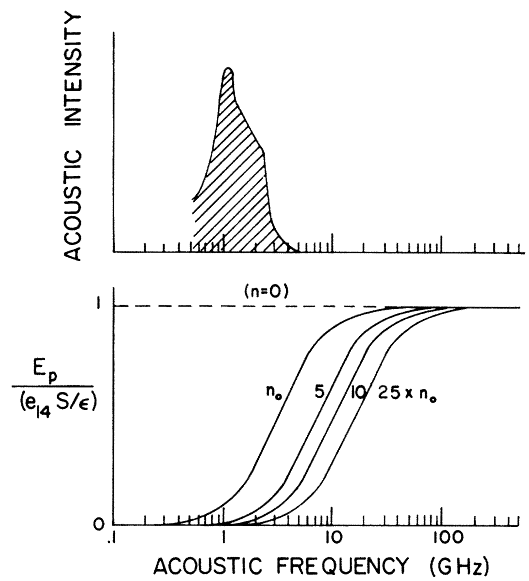

FIG. 1. Top panel: Example of acoustic intensity spectrum in strongly amplified phonon domain in n-GaAs. Bottom panel: Theoretical (small-signal theory) variation of piezoelectric phonon field E_p, for given phonon strain S, as a function of acoustic frequency. The parameter is the electron concentration; $n_0 = 6\times 10^4/\text{cm}^3$ is the equilibrium concentration in the dark in our GaAs sample at 300 K.

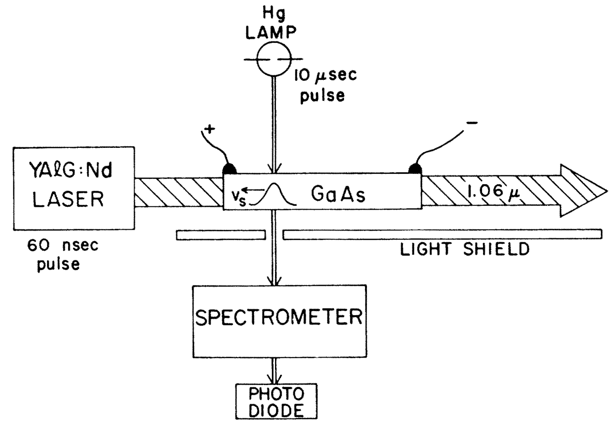

FIG. 2. Experimental setup illustrating interaction of phonon domain with Hg light beam near the intrinsic absorption edge, and modulation of this interaction by intense YAlG laser beam.

imum value which is independent of frequency. In semiconductors, bunching of free electrons by the piezoelectric fields reduces the fields, completely screening them out at the low frequencies $[\omega \ll (\omega_c\omega_D)^{1/2}]$. At high acoustic frequencies $[\omega \gg (\omega_c\omega_D)^{1/2}]$, thermal diffusion of the electrons prevents effective bunching and E_p approaches the same unscreened value as in the insulator. The curve labeled n_0 in Fig. 1 applies to the actual electron density in our GaAs sample, with $6\times 10^{14}/\text{cm}^3$ at room temperature. For higher n, ω_c is increased, which shifts the curves of E_p toward higher frequencies. We also indicated schematically the amplified acoustic spectrum in our sample at $n = n_0$. It has a peak at about 1 GHz and extends beyond 3 GHz.[13] For this spectrum, the piezoelectric fields are appreciable.

In our experiment we could transiently increase n about 25-fold, *after* having built up the acoustic spectrum with the original carrier concentration. The increased carrier concentration produces more effective screening, which greatly reduces the piezoelectric fields for the original acoustic flux distribution. To accomplish this, we exploited the fact that in all our n-GaAs samples, intense pulses from a Q-switched yttrium-aluminum-garnet (YAlG) laser could excite high electron concentrations from deep traps.[14] At laser powers of $\sim 3\ \text{MW/cm}^2$, n can be increased from $n \sim 6\times 10^{14}/\text{cm}^3$ to $n \gtrsim 10^{16}/\text{cm}^3$ at 300 K.

The experimental setup is schematically illustrated in Fig. 2. A light beam from a pulsed Hg arc lamp is transmitted through the GaAs sample, analyzed near the intrinsic absorption edge by a spectrometer, and detected by a Si diode. The transmitted light intensity is labeled I_T^0 in Fig. 3. When an amplified phonon domain containing the flux shown in Fig. 1 passes the focused light spot during a 600-nsec interval, the absorption edge is broadened and the transmission is decreased to I_T, as shown in Fig. 3(a). In order to exclude deliberately the contribution of Brillouin scattering to the modulation of the transmission signal, the light was incident normal to an (001) surface; in this case Brillouin scattering is forbidden[8] for the amplified [110] fast-transverse phonons.

If now a very short (≈ 60 nsec) Q-switched YAlG laser pulse at 1.06 μm is applied when the peak of the domain passes through the Hg light beam, the transmission is briefly, but substantially, restored, as shown in Fig. 3(b). This represents the desired screening out of the piezoelectric fields by the laser-generated excess electrons. We note that, as the laser pulse dies out, the transmission decreases back to its dark value! This result indicates that during the short laser pulse there is no appreciable laser-induced change[15] in the acoustic intensity or strain in the domain. In this experiment, it was essential to ascertain that there was no leakage or scattering of YAlG laser light to the detector. This was

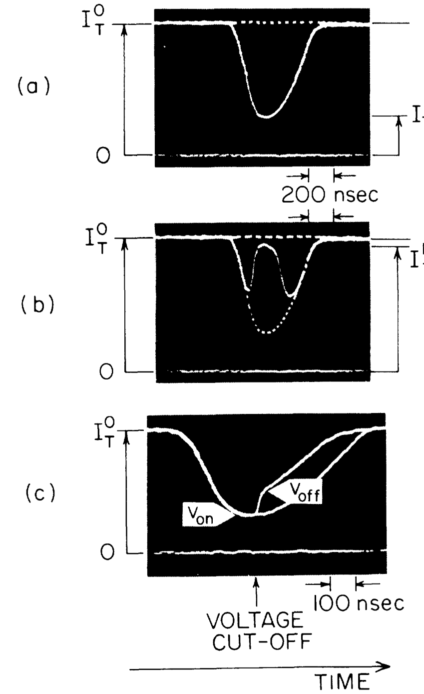

FIG. 3. Superimposed oscilloscope traces. (a) Traveling phonon domain decreases transmission of Hg light, (b) short YAlG laser pulse transiently restores transmission by generating excess electrons, and (c) cutting off the voltage across the sample only modestly decreases domain-induced absorption.

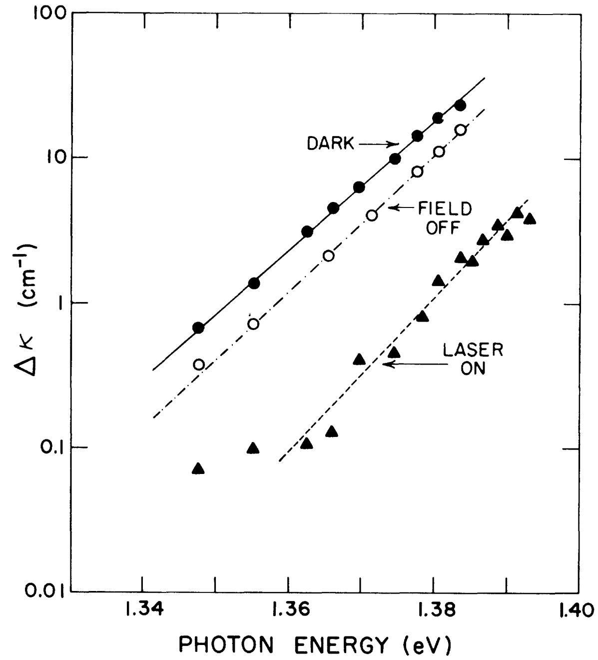

FIG. 4. Increase in absorption coefficient produced by phonon domains: In the dark; with dc voltage across the domain suddenly cut off; and with voltage on, but laser pulse applied.

checked by observing that when the Hg light beam was blocked from passing through the sample, no laser-induced signal was observed.

It is necessary to distinguish between the effect of the piezoelectric fields of the phonons and that of the high dc field produced in the phonon domain by the voltage applied to the sample. The dc field is nearly shorted out by the large increase in electron concentration. This effect can also contribute to the laser modulation of transmission. To determine the maximum contribution of the dc field, we abruptly cut off the external voltage pulse at the peak of the domain modulation signal. As shown in Fig. 3(c), the transmission is increased, but only slightly.[16]

To summarize the data, we show in Fig. 4 the spectral dependence of the change in absorption coefficient, $\Delta\kappa$, produced by the domain for the different conditions of the experiment: In the dark, with the external voltage on; in the dark, just after the external voltage is cut off; and at the peak of the laser excitation. All three curves show the exponential broadening of the absorption edge. During laser illumination, $\Delta\kappa$ is an order of magnitude smaller than in the dark. It is apparent that the dc field, which is in the range of 10^4 V/cm in GaAs at 300 K, is responsible for only a small fraction of the effect. The piezoelectric fields, which must be responsible for the major portion of the absorption-edge broadening, have been estimated[7] to be in the range of 50 000 V/cm.

The significance of this experiment, which unambiguously demonstrates a particular case in which microelectric fields produce an Urbach tail, is that it provides support to the proposal by Dow and Redfield[6] that microelectric fields of *various* origins *may* be fundamental to the *natural* occurrence of Urbach tails in other materials.

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†This work was supported by National Science Foundation Grant No. DMR-7417606A01 and National Science Foundation–Materials Research Laboratory Program No. DMR-7203018A04.

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[1]D. L. Spears and Ralph Bray, Appl. Phys. Lett. 12, 118 (1968).

[2]C. S. Kumar, P. O. Sliva, and Ralph Bray, Phys. Rev. 169, 680 (1968).

[3]C. S. Kumar and W. G. Hutchinson, J. Appl. Phys.

40, 4687 (1969); K. Yamamoto, M. Yamada, and K. Abe, J. Appl. Phys. 41, 450 (1970); K. Yamamoto, F. Murai, and K. Abe, Solid State Commun. 10, 273 (1972).

[4]E. S. Kohn and M. A. Lampert, Phys. Rev. B 4, 4479 (1971).

[5]W. Wonneberger, Z. Naturforsch. 27a, 956 (1972); E. V. Burtsev, Phys. Status Solidi (b) 51, 241 (1972).

[6]J. D. Dow and D. Redfield, Phys. Rev. B 5, 594 (1972).

[7]J. D. Dow, M. Bowen, Ralph Bray, D. L. Spears, and K. Hess, Phys. Rev. B 10, 4305 (1974).

[8]D. L. Spears, Phys. Rev. B 2, 1931 (1970).

[9]D. Garrod and Ralph Bray, in *Proceedings of the Eleventh International Conference on the Physics of Semiconductors, Warsaw, Poland, 1972*, edited by The Polish Academy of Sciences (PWN–Polish Scientific Publishers, Warsaw, Poland, 1972), p. 1167.

[10]R. Berkowicz and B. P. Kietis, Phys. Status Solidi (a) 28, 425 (1975).

[11]T. Hata, T. Hara, M. Ishigaki, and T. Hada, Appl. Phys. Lett. 26, 549 (1975).

[12]D. L. White, J. Appl. Phys. 33, 2547 (1962).

[13]Although the frequency of maximum acoustoelectric gain is near 3 GHz, various nonlinear processes in intense flux produce the transformed spectrum depicted in Fig. 1. A detailed analysis is given by T. E. Parker and Ralph Bray, Phys. Lett. 45A, 347 (1973).

[14]G. K. Celler, S. Mishra, and Ralph Bray, Appl. Phys. Lett. 27, 297 (1975).

[15]Laser-induced modulation of phonon intensity was studied by auxiliary Brillouin scattering measurements for longer laser pulses. See G. K. Celler and Ralph Bray, Phys. Rev. B 13, 5397 (1976).

[16]As a check, we also determined the effect of YAlG laser excitation just *after* the applied voltage was shut off, but while the flux is still very intense. Here too, band-edge transmission was substantially restored. After the laser pulse was over, the transmission did not return fully to its dark value, indicating that some accelerated phonon attenuation took place during the laser pulse.

Voltage-Tunable Far-Infrared Emission from Si Inversion Layers

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We have observed voltage-tunable far-infrared emission from inversion layers of n-channel metal-oxide-simiconductor field-effect transistors fabricated on p-type (100) Si. The radiation is emitted by the electronic transition from the two-dimensional excited-state E_1 sub-band of the inversion layer to its ground-state E_0 sub-band. Population of the excited-state sub-band is realized by heating up the electron distribution with an electric field applied along the channel.

In the inversion layer of a Si-MOS (metal-oxide-semiconductor) structure, the energy levels of the electrons, being discrete for their motion perpendicular to the interface and continuous for their motion parallel to the interface, form two-dimensional sub-bands.[1] There has been great interest in the problem of the sub-band splitting, which is a function of the electron density n_s in the inversion layer and also dependent on the impurity concentration of the Si substrate. Experimentally, far-infrared absorption[2] and photoconductivity experiments[3,4] have been performed to measure the sub-band splitting. We note especially the absorption experiment of Kneschaurek and co-workers[2] and the photoconductivity experiment of Wheeler and Goldberg[3] on the (100) Si inversion layers. The results from these two experiments are in disagreement. While Kneschaurek and co-workers observed one resonance line in their absorption spectra, Wheeler and Goldberg observed two photoresistive peaks: one broad peak at the resonant absorption energy and a sharp peak at a lower energy. The resonance energy and its n_s dependence from either experiment disagree with the energy splitting between the ground-state sub-band E_0 and the first excited-state sub-band E_1 as predicted by the self-consistent field calculations of Stern.[5] Subsequent theoretical work[5-8] has shown that the many-body corrections in this system are sufficiently large to account for such discrepancies between theory and experiment. More recently, however, the importance of screening of the electromagnetic field by the inversion-layer electrons has been recognized.[9,10] It also changes the resonance condition and shifts the resonant energy appreciably above the sub-band splitting.

In view of the complexity of this problem and the great current interest in it, we have performed an experiment to measure the far-infrared radiation emitted by electronic transitions between the sub-bands. We used n-channel Si-MOSFET's (metal-oxide-semiconductor field-effect transitors) on p-type (100) Si and populate

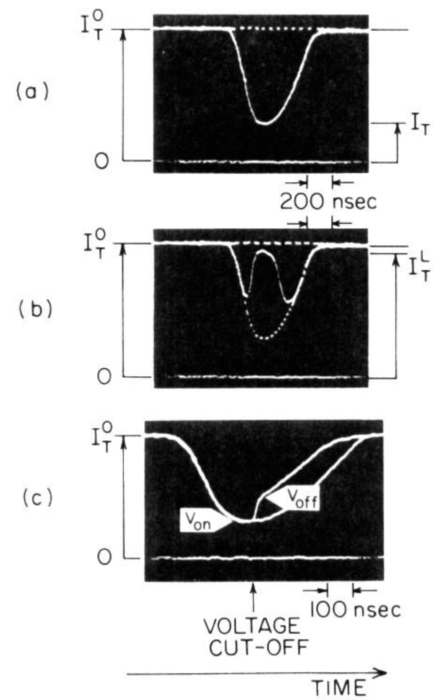

FIG. 3. Superimposed oscilloscope traces. (a) Traveling phonon domain decreases transmission of Hg light, (b) short YAlG laser pulse transiently restores transmission by generating excess electrons, and (c) cutting off the voltage across the sample only modestly decreases domain-induced absorption.