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# Piezo-Urbach rule for acoustoelectric domains in GaAs

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The acoustoelectric-domain-induced changes of the absorption coefficient of GaAs at the fundamental absorption edge have been found to be an exponential function of energy. Such data are analyzed here in terms of the electric microfield model of Urbach's rule. The fit between theory and experiment demonstrates the relevance and importance of the electric microfield model with the electron-hole interaction included and yields values for the piezoelectric microfields in mature domains of $\approx 4\times 10^4$ V/cm.

## I. INTRODUCTION

Propagating regions of intense acoustic flux, called domains, can be produced in piezoelectric semiconductors by acoustoelectric amplification. The modulation of the optical transmission near the intrinsic absorption edge by domains has been observed in GaSb,[1] GaAs,[2] and CdS,[3,4] and has provoked much theoretical interest. The principal purpose of this paper is to show that the excess optical absorption induced by acoustoelectric domains can be accurately described by the electric microfield theory of Urbach's rule.[5] The only adjustable parameter is an effective electric field characterizing the intensely amplified piezoelectric photons in the domain. The electric fields thus obtained agree with values extracted from independent experiments.

## II. DOMAIN-INDUCED ABSORPTION

Acoustoelectric domains are spontaneously generated by the application of sufficiently large electric fields to the semiconductor samples. If the average electron drift velocity exceeds the speed of the appropriate phonons, then stimulated emission of phonons is dominant over phonon absorption, and a portion of the thermal equilibrium phonon population in the crystal is exponentially amplified. The amplified flux generally forms propagating domains.[6]

Evidence accumulated from various experiments indicates that the domain-induced absorption below the band gap is attributable to the large longitudinal piezoelectric fields associated with the amplified piezoelectrically active phonons.[4,7] These fields are believed to become large enough to perturb the energy bands as shown in Fig. 1 and permit Franz-Keldysh-type optical transitions induced by photons with energies $\hbar\omega$ less than the band gap, $E_{gap}$. Various estimates[2,8,9] of the root-mean-square (rms) piezoelectric fields in mature domains in GaAs yield values $F\sim 3\times 10^4$ V/cm. Such large fields compress the conduction electrons into potential valleys where they experience little or no electric fields. Thus the bunched charges involved in current flow experience weak electric fields, whereas the electron-hole pairs that absorb light in the Urbach absorption tail ($\hbar\omega < E_{gap}$) initially reside in the highest-field regions.

Mature domains are relatively thick, $\approx 2\times 10^7$ Å in GaAs,[2,10] and $2\times 10^6$ Å in CdS.[11] Although the piezoelectric fields in the high-flux domains are quite nonuniform, the characteristic lengths of nonuniformity are of the order of an acoustic wavelength. Amplified phonons in a domain are typically in the gigahertz frequency range[12] with wavelengths $\lambda\approx 10^4$ Å. This is a factor of ~100 larger

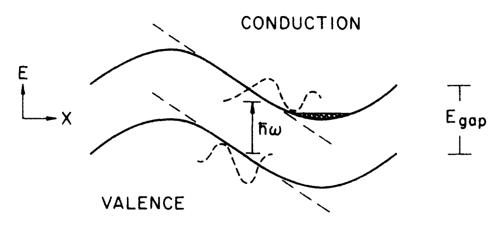


FIG. 1. Band-edge energies as a function of position $x$ in a domain (solid line). The dashed line represents the uniform-field approximation. The electron and hole wave functions (short-dashed lines) are exaggerated in size to demonstrate that a Franz-Keldysh–type optical transition for $\hbar\omega < E_g$ can occur between band tail wave functions. The shaded area of the conduction band minimum indicates that electrons tend to bunch in low-potential regions of the domain.

than either the Bohr radius of an exciton created in the Franz-Keldysh transition ($a \approx 118$ Å for GaAs, $a \approx 23$ Å for CdS), or the electron-hole pairs corresponding electro-optic length $l \equiv (\hbar^2/2m^*|e|F)^{1/3} = 268$ and 98 Å for GaAs and CdS, respectively. Thus, for the optical absorption process, the piezoelectric field can be approximated as uniform (dashed potential in Fig. 1).

The theory of optical absorption in a uniform electric field has been worked out[5] and forms the basis of the electric microfield theory of Urbach's Rule.[13–15] In the Urbach-rule theory, the field-perturbed absorption spectrum is averaged over a distribution of electric microfields. A mature acoustoelectric domain also contains a distribution of microfields, which is, however, very difficult to characterize. Therefore we shall simplify the problem by representing the domain fields by a single field $F \approx \pi\varphi_{max}/\lambda$, where $\phi_{max}$ is the maximum value of the acoustoelectric potential and $\lambda$ is a typical wavelength.

The essence of the microfield theory is that the optical absorption tail is associated with transitions from the ground state to electron-hole pairs in the high-field region of the solid. The relative motion of an electron-hole pair is governed by the reduced-effective-mass Schrödinger equation[5]

$$\left(-\hbar^2\nabla^2/2m^* - e^2/\epsilon_0 r - e\,\vec{F}\cdot\vec{r}\right) U_\nu = E_\nu U_\nu .$$

The optical-absorption coefficient $K_A(\omega)$ is proportional both to the probability $|U_\nu(0)|^2$ that the electron and the hole are created at the same point in space and to the transition density of states[5]

$$K_A(\omega) = C \sum_\nu |U_\nu(0)|^2\, \delta(\hbar\omega - E_{gap} - E_\nu),$$

where the constant $C$ is

$$C = (\pi e^2 a^2/\epsilon_0) K_A^0(\omega_{gap}).$$

Here $e$ is the electrons's charge, $a = \hbar^2\epsilon_0/me^2$ is the exciton Bohr radius, $\epsilon_0$ is the static dielectric constant, and $K_A^0(\omega_{gap})$ is the absorption coefficient of the unperturbed solid at the band gap $E_{gap} = \hbar\omega_{gap}$. We have executed the calculations of $K_A(\omega)$ in a manner similar to the computations of Ref. 5; the present calculations are for much higher fields, however. The results are presented in Fig. 2. The various parameters that enter into the calculations, including the band gap, the exciton Rydberg, and the zero-field absorption coefficient at the band gap are taken from other data.[16] The curvature of the theoretical lines in Fig. 2 is an artifact of the representation of the distribution of domain fields by a single field. Extensive computations[17] using more complicated field distributions reveal that the primary effect of more realistic

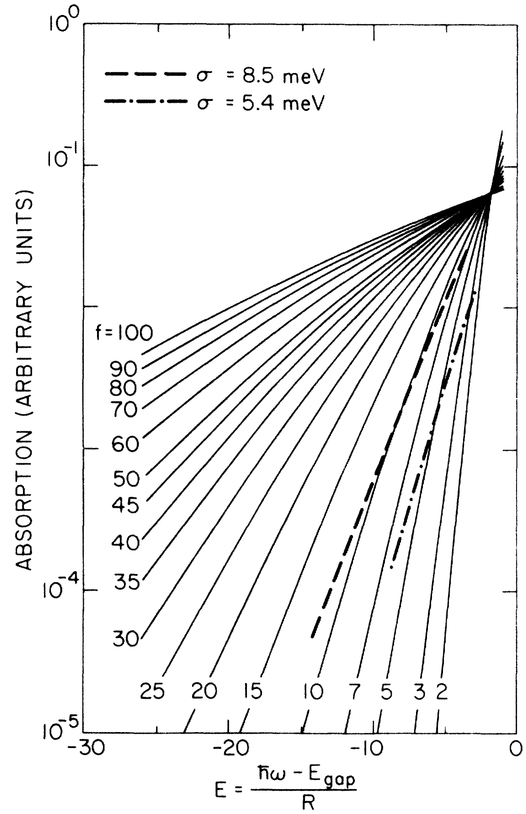


FIG. 2. Absorption by excitions $\sum_\nu |U_\nu(0)|^2 \delta(E - E_\nu)$ vs $E = (\hbar\omega - E_g)/R$. Units $R = 1 = a$, where $a = \hbar^2\epsilon_0/me^2$, $R = e^2/2\epsilon_0 a$. The fields are specified by $f = |e| Fa/R = 3.89 \times 10^{-10}\, \epsilon^3 (m_0/m)^2 F$, with $F$ in V/cm. The solid lines are theoretical curves, identical (except for values of $f$) to those of Ref. 5, Fig. 2a. Dashed line and alternating dashes and dots represent the data of Fig. 4 labeled $\sigma = 8.5$ and 5.4 meV, respectively.

field averaging is to greatly reduce the curvature, with the amount of the reduction depending on the detailed field distribution. Physically, this happens because deep tail absorption is associated with the largest and least probable microfields.

Figure 3 contains corresponding curves for the one-electron Franz-Keldysh limit $e^2/\epsilon_0 \to 0$, which neglects the electron-hole interaction. This limit would be appropriate if the conduction electrons efficiently screened the electric field of the hole.

Note that the theory with final-state electron-hole (exciton) interactions included (Fig. 2) is different in two ways from the one-electron theory (Fig. 3) which omits such effects: (i) the exciton absorption for the same field and energy is larger (by order of magnitude); and (ii) the exciton lines curve less.[18]

Experimental data of the domain-induced change of the absorption coefficient $\Delta K_A(\omega)$ are presented in Fig. 4. The method of measurement has been

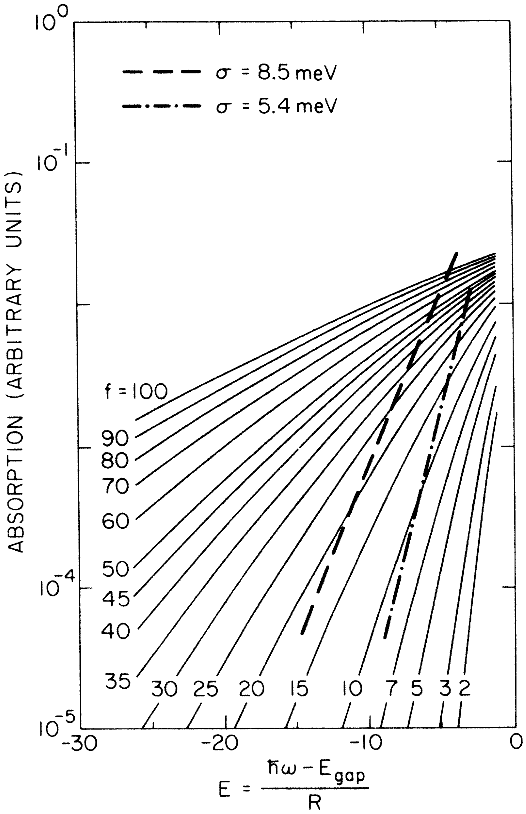


FIG. 3. Absorption vs $E$ in the one-electron Franz-Keldysh limit, neglecting excitons $(e^2/\epsilon_0 \rightarrow 0)$. Note the failure of the theory (solid lines) to fit the data.

$$K_A(\omega) \approx \Delta K_A(\omega) \quad \text{for } \hbar\omega \ll E_{gap}.$$

### III. COMPARISON OF THEORY AND EXPERIMENT

The comparison of the data with the theory is only valid for the most intense domains, in the region where we have

$$K_A(\omega) \approx \Delta K_A(\omega).$$

Note that the data are represented by the dashed and alternating dashed-dotted lines in Figs. 2 and 3. In Fig. 2 the data fit fairly well to theoretical lines corresponding to electric fields $F \approx 5\times10^4$ and $2\times10^4$ V/cm for $\sigma = 8.5$ and 5.4 meV, respectively. The data do not, however, agree with the one-electron theory presented in Fig. 3. We conclude, therefore, the conduction electrons do not efficiently screen the electron-hole interaction and that exciton effects do play an important role in shaping the domain-induced absorption tail. The importance of the electron-hole interaction has been previously demonstrated for optical absorption in a uniform electric field.[20]

Although we have treated the acoustoelectric fields as fitting parameters, it is gratifying to realize that the fields of the order $4\times10^4$ V/cm extracted from our fitting procedure are in agreement with independent estimates of the acoustoelectric potential derived from microwave and Brillouin scattering measurements. The microwave absorption by acoustoelectric domains has been described before.[2] The previously published data[2] for GaAs, on a sample 200 μ thick, showed an exponential tail for $\Delta K$ in the range 1 cm$^{-1} < \Delta K_A(\omega) < 300$ cm$^{-1}$. The present data shown in Fig. 4 are for a sample of similar material, but only 25 μ thick. This sample provides data in the range 3 cm$^{-1} < \Delta K_A(\omega) < 2000$ cm$^{-1}$. The three sets of data, for acoustoelectric domains of different strength, all show an exponential tail over almost three decades in $\Delta K_A$. The various sets of data have a common intercept at an energy $\epsilon_i = 1.512$ eV, which is very close to the band gap $E_{gap} = 1.513$ eV determined by Sturge.[19] The inverse slopes are characterized by the parameter $\sigma$ in the relation for the domain-modulated absorption edge

$$\Delta K_A(\omega) \propto \exp[(\hbar\omega - E_{gap})/\sigma].$$

Data for the unmodulated edge $[K_A^0(\omega)]$ are also shown in the figure. Note that we have $K_A^0 \gtrsim \Delta K_A$ very near the energy gap. However, deep in the absorption tail we have $\Delta K_A \gg K_A^0$ for the most intense acoustic domains; and therefore $K_A(\omega)$, the absorption in the domain, can be specified by

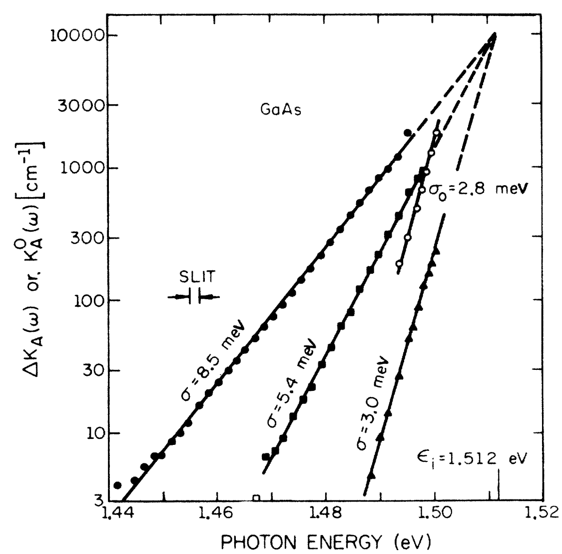


FIG. 4. Experimental data of the domain-induced change of absorption coefficient $\Delta K_A(\omega)$ (▲ ■ ●) and the unmodulated coefficient $K_A^0(\omega)$ (○), for a thin (25 μm) sample of GaAs at 77 °K, at different acoustic-domain intensities.

measured by Bruun[21] and by others,[22] and is described elsewhere; evaluation of these measurements in terms of the models of Tien[23] and of Conwell[24] has been given,[22] treating the microwaves in a small-signal approximation. For mature domains in GaAs, the resulting maximum value of the acoustoelectric potential $\varphi_{max}$ is 0.42 V ± 30%. For an acoustic wavelength[25] of $\lambda = 4500$ Å ± 60%, we find $F = 3\times10^4$ V/cm ± 90%. A Brillouin scattering estimate[2,12] of the excess acoustic energy density in a mature domain yields values of the order 1 J/$cm^3$, which corresponds to an rms piezoelectric field of $\approx 4\times10^4$ V/cm.

In conclusion, we have shown that the large piezoelectric fields in acoustoelectric domains induce broadening of the fundamental absorption edge of GaAs by what can be termed a piezo-Urbach effect, and which can be quantitatively described by the electric microfield model. Thus, we have a piezo-Urbach rule which states that domains of high acoustic flux in piezoelectric semiconductors generate large electric microfields and cause the fundamental absorption edges to be approximately exponential functions of photon energy—much as the electric microfields of optical phonons and impurities cause Urbach's rule in III-V, II-VI, and alkali-halide compounds.[15] Any theory of parametric mixing and acoustoelectric amplification in mature domains must contend with the fact that the piezoelectric fields in the domain are exceedingly large.

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

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

[3]C. S. Kumar and W. G. Hutchinson, J. Appl. Phys. 40, 4687 (1969); K. Yamamoto, M. Yamada, and K. Abe, *ibid.* 41, 450 (1970); J. Phys. Soc. Jpn. 29, 1521 (1970); K. Yamamoto, F. Murai, and K. Abe, Solid State Commun. 10, 273 (1972).

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

[5]J. D. Dow and D. Redfield, Phys. Rev. B 1, 3358 (1970).

[6]For reviews, see J. H. McFee, *Physical Acoustic*, Academic, New York, 1966) Vol. IV, Part A, pp. 1-45; N. I. Meyer and M. H. Jorgensen, Festkörp. 10, 22 (1970).

[7]D. K. Garrod and R. Bray, *Proceedings of the Eleventh International Conference on the Physics of Semiconductors*, PWN-Polish Scientific, Warsaw, 1972), p. 1167.

[8]E. V. Burtsev, Phys. Status Solidi B 51, 241 (1972).

[9]W. Wonneberger, Z. Naturforsch. A 27, 956 (1972).

[10]D. L. Spears and R. Bray, Appl. Phys. Lett. 13, 268 (1968).

[11]A. R. Moore, Appl. Phys. Lett. 13, 126 (1968); A. R. Moore, R. W. Smith, and P. Worcester, IBM J. Res. Develop. 13, 503 (1969).

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

[13]D. Redfield, Phys. Rev. 130, 916 (1963); Trans. N. Y. Acad. Sci. 26, 590 (1964).

[14]D. L. Dexter, Phys. Rev. Lett. 19, 383 (1967).

[15]J. D. Dow and D. Redfield, Phys. Rev. Lett. 26, 862 (1971); Phys. Rev. B 5, 594, (1972).

[16]$E_{gap} = 1.512$ eV, the exciton Rydberg is $R = 5$ meV, $K_A^0(\omega_{gap}) = 8.4\times10^{-3}$ $cm^{-1}$ (see Ref. 19). The dielectric constant is $\epsilon = 12.9$ [S. D. Mahanti and C. M. Varma, Phys. Rev. B 6, 2209 (1971)] and the reduced effective mass is $m/m_0 = 0.06$ [S. F. Pond, Ph.D. thesis (University of Illinois, 1971) (unpublished).

[17]J. D. Dow (unpublished).

[18]In the low-field limit, the exciton curvature apparently vanishes (Ref. 5); in the extreme-high-field limit, $f \gg 100$, the two theories should merge.

[19]M. D. Sturge, Phys. Rev. 127, 768 (1962).

[20]F. C. Weinstein, J. D. Dow, and B. Y. Lao, Phys. Rev. B 4, 3502 (1971); B. Y. Lao, J. D. Dow, and F. C. Weinstein, Phys. Rev. Lett. 26, 499 (1971); Phys. Rev. B 4, 4424 (1971).

[21]M. O. Bruun, Ph.D. thesis (Tech. University of Denmark, 1969) (unpublished); see also, N. I. Meyer and M. H. Jorgensen, Festkörp. 10, 22 (1970).

[22]K. Hess and H. Kuzmany, J. Phys. C 6, 657 (1973).

[23]P. K. Tien, Phys. Rev. 171, 970 (1968).

[24]E. M. Conwell and A. K. Ganguly, Phys. Rev. B 4, 2535 (1971).

[25]The given value of λ corresponds to the frequency of maximum gain.