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A Brillouin Scattering Study of Acoustoelectric Domain Formation in n-GaAs*

Abstract: Brillouin scattering measurements in n-GaAs show (1) that the initial formation of acoustoelectric domains is the consequence of spatially inhomogeneous amplification produced by resistivity inhomogeneities, and (2) that the subsequent stages of domain evolution involve flux-dependent processes which further shape the domain; an important process appears to be parametric frequency conversion.

The question of acoustoelectric domain formation has long been a source of much speculation and controversy. Here we report a Brillouin scattering study of several stages in growth of acoustic flux in n-GaAs at 300°K. The study provides a detailed picture of domain formation and evolution. These measurements were carried out on samples about 2 cm long (orientated along the [110] direction) with $n = 8 \times 10^{14}/\text{cm}^3$ and $\mu = 7{,}000\ \text{cm}^2/\text{V-sec}$.

The application of a high electric field along a [110] direction in GaAs causes the selective amplification of shear waves present in the thermal background. According to small-signal theory,[1] the shear waves grow at a rate given by the expression

$$d\Phi/dt = [\alpha_0(v_d/v_s - 1) - 1/\tau_p]\Phi, \qquad (1)$$

where Φ is the energy density of the sound waves, α_0 is the acoustoelectric gain coefficient, v_d is the drift velocity of the charge carriers, v_s is the sound velocity, and $1/\tau_p$ is the non-electronic lattice attenuation coefficient. This expression has been found valid in n-GaAs up to about 10^8 growth from the thermal background intensity.[2] In Fig. 1 we show the experimental and theoretical frequency distributions of the amplified acoustic energy density at a growth stage just prior to the deviation in current from its ohmic value. The thermal background energy density is shown for reference. The energy density has been normalized to a 1-GHz bandwidth and 10° propagation cone, which are characteristic of the flux at this stage.[2] The close agreement between theory and experiment attests to the applicability of small-signal theory, when the total energy density is less than about 10^{-2}J/cm^3.

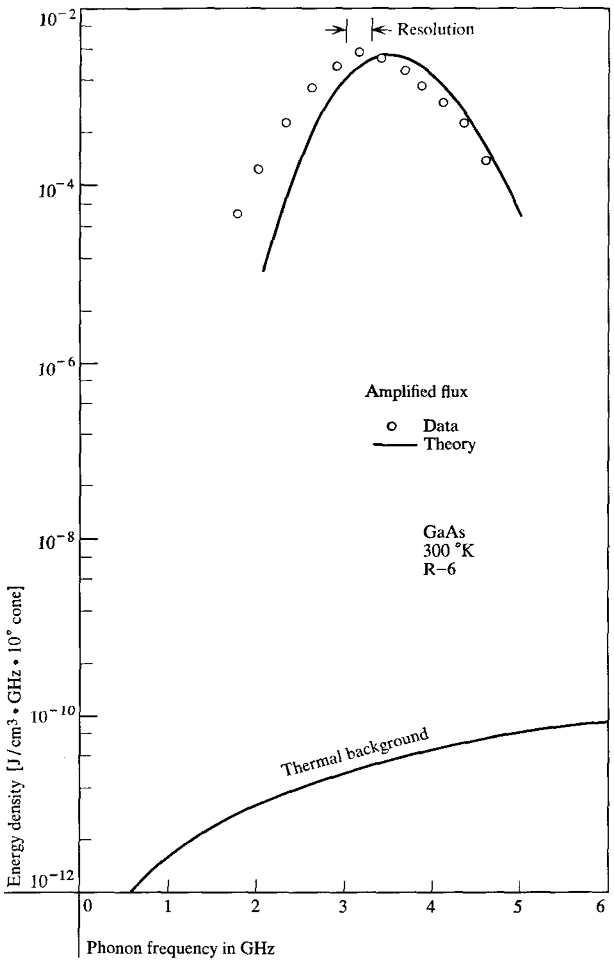

Figure 1 Experimental and theoretical frequency distributions of the amplified acoustic energy density at an early growth stage. The thermal background intensity is shown for reference.

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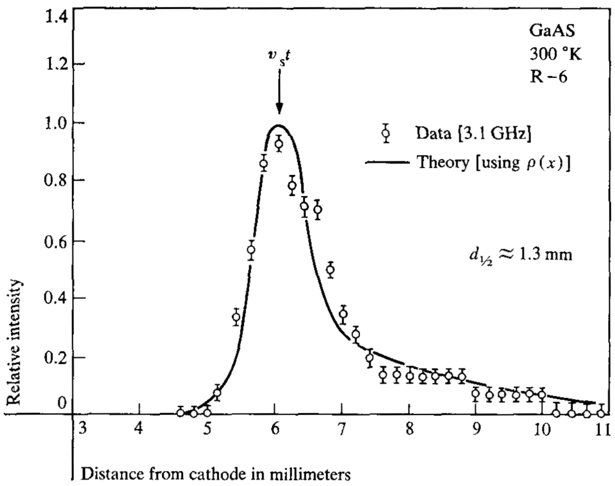


Figure 2 Experimental and theoretical spatial distributions of the 3.1 GHz acoustic flux at the 10^7 growth stage.

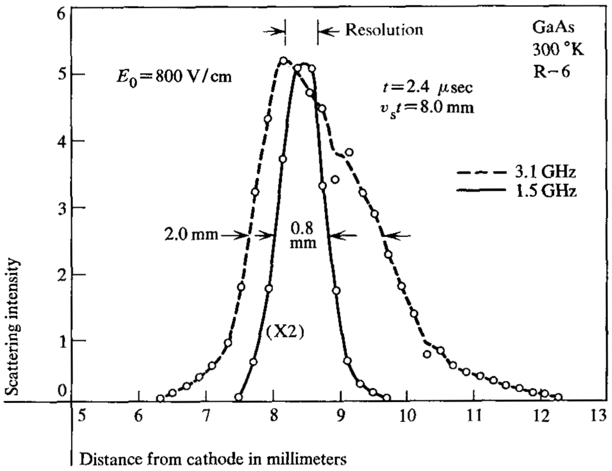


Figure 3 Spatial distributions of the scattering signals at 3.1 GHz and 1.5 GHz, when the 1.5 GHz flux is first detected.

The shape of the acoustoelectric domain in the early growth stage varies considerably from sample to sample.[3] This shape can be correlated with resistivity inhomogeneities present in the particular sample. The important factors to be considered in Eq. (1) are $\alpha_0 \propto 1/\mu$ and $v_d = \mu E_0$, where E_0 is the *ohmic* field. If we assume the thermal background intensity Φ_0 to be uniform throughout the sample, then the amplified intensity $\Phi(x, t)$ at a distance x from the cathode at time t after the voltage pulse is applied, will be given by

$$\Phi(x, t) = \Phi_0 \exp \int_{x_0}^{x} \left\{ \alpha_0(x) \left[\frac{\mu(x) E_0(x)}{v_s} - 1 \right] - 1/\tau_p \right\} dx/v_s, \quad (2)$$

where

$$x_0 = 0 \qquad x < v_s t$$

$$x_0 = x - v_s t \qquad x > v_s t.$$

Since in the ohmic regime, $\mu E_0 = v_d$ is much greater than v_s (usually 5 to 20 times), and since the product $\alpha_0(x)\mu(x)$ is not a function of x, $\Phi(x, t)$ is determined just by $E_0(x)$ and the inherent propagating nature of the flux. The acoustoelectric gain is highest in regions of high electric field, i.e. high resistivity regions of the sample.

We find very good agreement between the observed domain shape in GaAs in the early growth stages and that calculated from Eq. (2) using the resistivity profile $\rho(x)$ obtained from photoconductivity data.[3] An example of this is shown in Fig. 2. The data represents the scattering intensity at 3.1 GHz, the frequency of maximum intensity at this stage ($\Phi = 10^7\Phi_0$). The solid curve is calculated from Eq. (2). The predicted half-width (1.3 mm) of the domain and asymmetry in shape are in good agreement with the data. The domain in this particular sample extrapolates back to the cathode, as indicated by the arrow labeled $v_s t$. However, this is not always the case. When a *low-resistance region* is present near the cathode, the domain extrapolates back in time to some different position in the sample, in accord with Eq. (2). In our most uniform samples we have detected domains as wide as 4 mm in the early growth stages.

Deviations from the predictions of small-signal theory are observed as the flux continues to grow, and the current drops to its saturation value. The most striking effect is a strong downward shift in the frequency of maximum intensity, similar to that observed in CdS.[4] A detailed study[5] of this effect in GaAs has revealed strong evidence for parametric, subharmonic frequency conversion[6]; a second peak in the scattering spectrum appears at about $\frac{1}{2}$ the frequency of the initial peak. Microwave emission data[7] (on the same GaAs samples) reveal not only peaks at f_0 and $f_0/2$, but also peaks which subsequently appear at $f_0/4$, $\frac{3}{2}f_0$, etc., indicating that parametric up-conversion is also occurring.

In the strong flux regime, interesting changes in the spatial distribution of the flux are observed, with the domain shape being a function of acoustic frequency and time. In Fig. 3 we show the spatial distribution of the 3.1 GHz flux and the 1.5 GHz flux, at the stage when the 1.5 GHz scattering was about $\frac{1}{2}$ as intense as that at 3.1 GHz. (In the weak flux regime 1.5 GHz waves were not detectable.) Here the 3.1 GHz domain has a half-width of 2.0 mm and is slightly asymmetric, whereas the 1.5 GHz domain is only 0.8 mm wide (almost the resolution of the light probe, as indicated). Such a late-appearing, narrow domain cannot be explained by small-signal theory and resistivity inhomogeneities.

Let us now examine the shape of 3.1 GHz flux domain in more detail, as shown in Fig. 4(a). The solid line is the calculated distribution at the 2×10^8 growth stage, obtained from an extrapolation [based on the growth rate given by Eq. (2)] of the distribution observed at the 10^7 growth stage shown in Fig. 2. The dashed line is the observed distribution at the 2×10^8 stage. The most obvious feature here is an apparent *broadening* of the 3.1 GHz distribution, from a half-width of 1.3 mm to one of 2.0 mm. Since the intensity in the wings of the domain agrees with the extrapolated intensity, the evolution in shape appears to be a consequence of flux in the center of the domain failing to grow as expected. In other words, a flux-dependent loss process enters which limits the growth at high intensities.

If the missing flux at 3.1 GHz (represented by ΔI_s) has been converted to low frequencies, then the distribution $\Delta I_s(x)$ should be related to the measured spatial distribution of the low frequency flux I_s(1.5 GHz). Such a comparison is presented in Fig. 4(b). The positions and half-widths of these two distributions are well correlated. The magnitudes of the scattering signals are also about the same. To be exact, one should compare the *energy* at 1.5 GHz to that missing at 3.1 GHz. However, one cannot be certain that 3.1 GHz is the only frequency which is instrumental in conversion to 1.5 GHz.

In Fig. 5, we summarize the domain evolution data by showing the domain half-width of various frequency components as a function of time. The amplified energy density grows from about 10^{-2}J/cm^3 at $t = 2$ μsec to about 0.5 J/cm^3 at $t = 5$ μsec, at which stage most of this energy is contained in the frequencies below 1 GHz. The dashed part of the $f_m = 3$ GHz curve is schematically drawn in to represent the initial stage in which the domain arises from the uniform thermal background intensity. As was mentioned above, when the flux at $f_m/2$ was first detected, its spatial distribution was relatively narrow and confined to the center of the f_m domain, with the f_m domain "broadening" at this stage. As the flux at $f_m/2$ grows, its spatial distribution also "broadens" and a narrow domain appears at $f_m/4$. These features are consistent with frequency down-conversion in the intense core of the domain. Note that the f_m domain narrowed in the very strong flux regime, attaining a half-width equal to that at the lower frequencies. This narrowing is a result of the wings of the f_m domain attenuating, rather than the center growing. Such attenuation in the low intensity regions is expected from small-signal theory, since after about 3 μsec, the drop in current lowers the acoustoelectric gain $\alpha_0(v_d/v_s - 1)$, to a value below the nonelectronic attenuation coefficient.

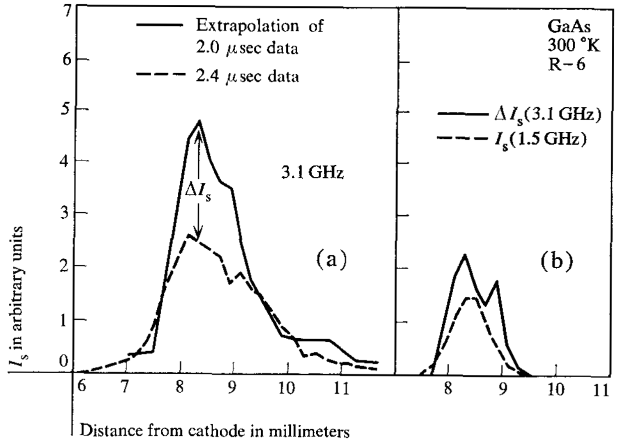
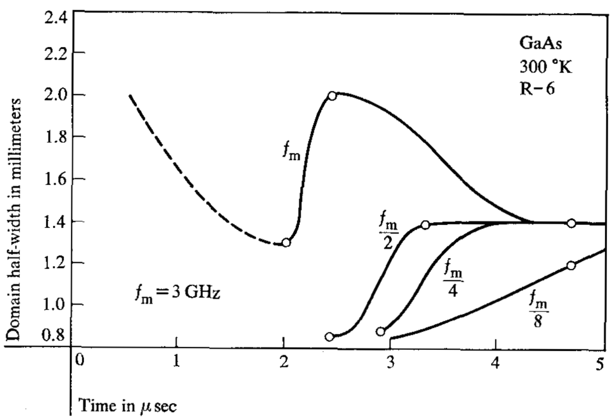


Figure 4 Analysis of the spatial distribution of the 3.1 GHz flux, and comparison with the distribution at 1.5 GHz.

Figure 5 Domain half-width as a function of time for various frequency components in sample R-6. The dashed line represents the initial domain formation at f_m, the frequency of maximum intensity in the early stages.



The sustained intensity in the center of the domain may be the result of frequency up-conversion. We have also found that the acoustoelectric gain coefficient α_0 appears to increase in the strong flux regime.[2] This too would contribute to domain shaping.

Finally, near the anode at $t = 5$ μsec, the domain appears to approach a steady-state condition. Here the half-width is about the same at all frequencies. This half-width increases with applied voltage. Accompanying this broadening is a saturation of the peak field at about 15 kV/cm. The saturation suggests strong nonelectronic losses in the intense core of the domain, possibly as a consequence of parametric up-conversion and mode conversion.

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