R. Bray

A Perspective on Acoustoelectric Instabilities*

Abstract: The acoustoelectric instabilities appear in diverse forms and seem complex because of the large number of factors which influence them. A perspective on the instabilities is provided in terms of experiments on the III-V semiconductors, selected to limit or control the variables. Detailed evidence is presented that the source of the acoustic flux is the thermal equilibrium phonon spectrum. The individual contributions of various factors to the instabilities are identified and discussed; e.g., 1) circuit conditions (constant current or constant voltage) which determine the degree of feedback between buildup of flux and gain everywhere in the sample, 2) boundary conditions, including destruction or reflection of flux, 3) inhomogeneities in resistivity of the samples, to which the current oscillations and initial stages of domain formation are particularly sensitive, and 4) the form of the acoustoelectric gain curve, which determines whether the feedback on the gain is positive or negative when the current is changed by the flux buildup. Also, several aspects of deviation from small signal theory are identified. In strong flux, 1) the peak of the frequency spectrum of the flux is shifted down, 2) the acoustoelectric gain coefficient is changed, and 3) the carrier distribution function may become hot in the high field of the domain. It is concluded that the strong flux effects modify but do not basically determine the form of the resistance instabilities.

Introduction

Acoustoelectric instabilities[1] arise from the strong interaction between a drifted electron distribution and the phonon spectrum in piezoelectrically active semiconductors. Intense phonon beams are created as the electrons amplify a selected portion of the phonon spectrum propagating in a relatively narrow cone. The loss of drift momentum from the electrons to the phonons in this process alters the current and the electric field distribution in the material, which may in turn alter the acoustoelectric gain. The instabilities thereby produced, are most readily observed in the resistance of the sample, and in the spatial distribution of the amplified acoustic flux and the associated electric field; these become concentrated in stationary and/or propagating domains. More subtle forms of the instability are revealed from studies of the frequency spectrum of the amplified flux, which show a very complex evolution during the transition from weak to strong acoustic flux. Finally, in the high-field regions of the domains, hot-carrier instabilities become apparent under certain circumstances.

The acoustoelectric instabilities appear in diverse forms and seem complex because of the large number of factors that influence them. We shall attempt here to provide a perspective on this subject, citing experiments designed to limit or control the variables, thus determining their individual contributions. Most of the illustrations will be drawn from work on the III-V semiconductors, p-GaSb, n-GaAs, n-InSb. The advantage of these materials, over the stronger piezoelectric II–VI compounds, is that the acoustoelectric interactions are weaker, and the instabilities develop more slowly, thus permitting better resolution in space and time of the evolution of the phenomena.

Source and nature of the *acoustic flux*

The acoustic flux whose amplification leads to the instabilities is internally generated in the sample. Possible sources of such flux are (1) the thermal equilibrium phonon distribution, and (2) the shock produced by the onset of the applied voltage pulse. Whereas thermal generation should be uniform throughout the sample and continuous in time, shock generation should be localized at gradients in piezoelectric stress (e.g. at the metal contacts) and be transient in character, occurring only during changes in local field. A still continuing point of contention, both in the past literature[2] and in recent private discussions, is the relative importance of these two mechanisms, particularly in the formation of narrow propagating domains.

The evidence to be presented below supports the thermal source mechanism.

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R. Bray is in the Physics Department, Purdue University, Lafayette, Indiana 47907.

• *Spatial origin*

To determine the spatial extent of the source of acoustic flux, very high voltage pulses were applied (far above the threshold value for acoustoelectric amplification), but of very short duration, $<0.5\ \mu$sec. In this short time, the acoustic flux is amplified to detectable levels before it can propagate more than $\sim$1 mm. Such experiments[3] in p-GaSb at 77°K showed amplified flux to be present throughout the sample (7 mm in length), with no evidence of a predominant source at the contact.

• *Transient vs continuous generation*

To test for the transient character of the flux generation process, pulses of extremely constant current were applied to provide continuous gain. As shown in Fig. 1(a), the voltage produced across the sample is initially ohmic, then rises when the flux buildup becomes sufficient to increase the resistance of the sample, and finally achieves a steady state value after one transit of flux through the length of the sample. The attainment of a steady-state increment in voltage, and the failure to perceive any overshoot are indicative of continuous generation, and the absence of a detectable contribution from a transient generation mechanism.

Adequate constant-current measurements are more difficult to achieve than might be anticipated. We shall cite two examples. The last result contradicts earlier findings[2] in bulk GaAs and GaSb, where transient increases in voltage were observed, with the voltage dropping back close to its ohmic value. Subsequent detailed investigations[4] revealed that strong heating of the sample in constant-current operation can kill the acoustoelectric gain during the flux transit through the sample, thereby causing the transient character of the voltage signal. The more recent successful experiments described above, were carried out on epitaxial n-GaAs where the semiconducting layer is only $\sim$20 μ thick and backed by an insulating GaAs substrate which serves as an excellent heat sink. The thermal quench can also be avoided[5] in pure n-InSb at 77°K.

As a second example, insets (a) to (d) in Fig. 1 show the transition in the voltage and current pulse shapes as the constant-current condition is gradually relaxed. Even slight relaxation from the constant-current condition prevents the achievement of the steady state, and introduces more complicated instabilities, as will be discussed later.

• *Spectral and angular composition of amplified flux*

A most detailed description of the constitution of the amplified acoustic flux and its relation to the thermal source is obtained from Brillouin scattering studies, which yield the frequency spectrum and the angular distribution of the flux. Scattering experiments were carried out[6] at 300°K in n-GaAs with electron density $\sim 8 \times 10^{14}/\mathrm{cm}^3$, where the frequency of maximum gain is about 3 GHz, a range readily accessible to Brillouin scattering. Results obtained at a fairly early stage, before the resistance departs appreciably from its ohmic value, show that both the intensities and the frequency distribution of the acoustic flux are in good agreement with amplification according to small-signal theory, from a thermal flux background given by the Debye theory. Growth by a factor of 10^8 at 3.1 GHz is observed before significant departures from small-signal theory become evident.

Measurements[6] of the angular distribution of the amplified flux show it to achieve a beam-like character, corresponding to a cone of about 10° half-width along the [110] direction of the current. This result is quantitatively consistent with calculations based on the dependence of the gain on the angle between the flux and the current, including the effects of the angular variation of the piezoelectric coupling and sound velocity.

In summary, all the evidence indicates that from the original isotropic thermal source of flux, the amplification process generates a beam with narrow angular cone and narrow frequency bandwidth centered around the frequency of maximum gain.

Instabilities in resistance and flux distribution

Given the source and composition of the acoustic flux, we can now discuss what instabilities may arise, starting with the simplest form of instability, obtained when the current is maintained very constant.

• *Constant current case*

We start at thermal equilibrium with a uniform distribution of acoustic energy density φ_0. It suffices here to consider only the piezoelectrically-active shear waves in a narrow bandwidth near the frequency of maximum gain, propagating with velocity v_s toward the anode (in n-type material), in a narrow cone along the [110] direction of the sample length. Upon application of a current, the energy density φ in a coordinate system moving with the flux, grows at a rate

$$d\varphi/dt = \alpha_n\varphi + c\varphi_0, \qquad (1)$$

where α_n is the net gain, i.e., the difference between the acoustoelectric gain α and the nonelectronic attenuation coefficient $1/\tau_p$. The gain α, for semiconducting material, is given by $\alpha_0(v_d/v_s - 1)$, where α_0 is a material-dependent interaction coefficient, and v_d is the electron drift velocity. The term $c\varphi_0$ is obtainable from detailed balance arguments; for $c = \alpha_0 + 1/\tau_p$, $d\varphi/dt = 0$ as required for $v_d = 0$ and $\varphi = \varphi_0$. The flux at each point along the sample grows as it propagates towards the anode. For constant current, we may assume the gain is constant, at least for small deviations from the ohmic regime, as verified by

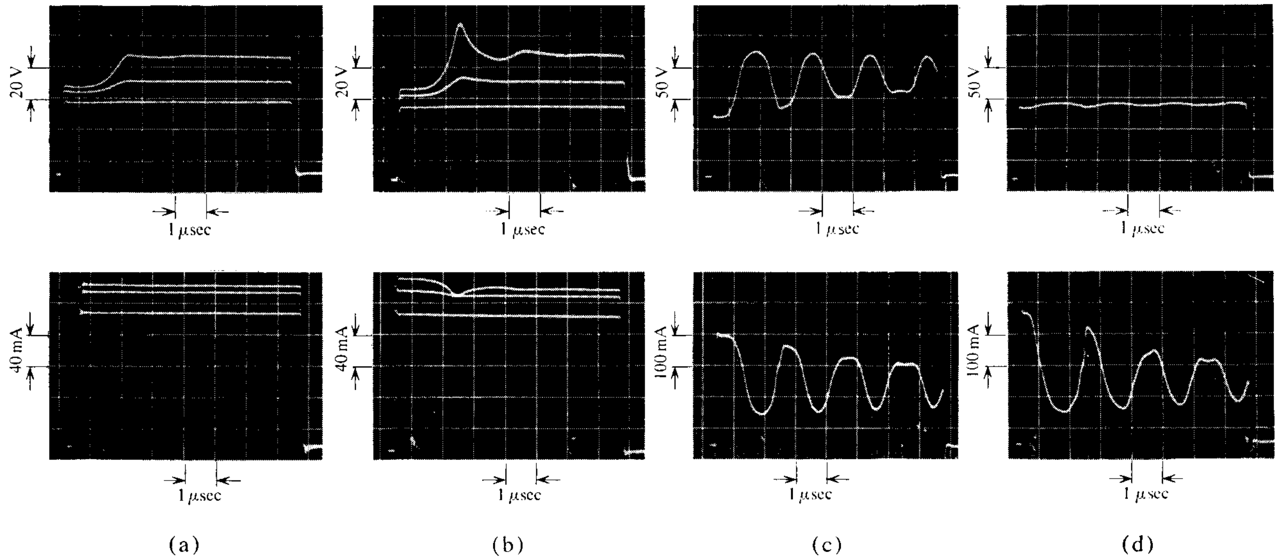

Figure 1 The change in form of the instabilities in current and voltage, with transition from constant current (a) to constant voltage (d) operation for epitaxial n-GaAs at 77°K. Measurements were made by C. Hamaguchi.

Brillouin scattering results in the section above. Then the excess flux at distances $x < v_s t$ from the cathode, is given by

$$\varphi(x) - \varphi_0 = \varphi_0(1 + c/\alpha_n)(e^{\alpha_n x/v_s} - 1), \qquad (2)$$

and at $x > v_s t$, the flux is uniform and given by

$$\varphi(t) - \varphi_0 = \varphi_0(1 + c/\alpha_n)(e^{\alpha_n t} - 1). \qquad (3)$$

When the flux originating at the cathode reaches the anode, at $t = T_p = L/v_s$, a steady state distribution of flux is achieved, varying nearly exponentially over the length of the sample. The amplified flux arriving at the downstream end ($x = L$) is destroyed or reflected, but is continuously replenished from the thermal flux source within the sample. This distribution, peaking strongly at $x = L$, forms a "stationary" domain.

The field distribution $E(x)$ is related to $\varphi(x)$ by the relation based on momentum conservation,

$$E(x) = v_d/\mu + \alpha_0(v_d/v_s - 1)\varphi(x)/nev_s \qquad (4)$$

where μ is the local ohmic mobility, and v_d/μ is the local field E_0, in the ohmic situation. The second term on the right represents the rate of transfer of momentum per electron to the excess acoustic flux. Thus the excess field, $E(x) - E_0$, has the same distribution as the flux. Integrating $E(x)$ over the sample gives the total voltage drop, which rises above the ohmic value only after the momentum losses to the growing flux become appreciable compared to the ohmic term in (4). Thereafter, the voltage rises nearly exponentially, terminating in a steady state value at $t = T_p$, as illustrated in Fig. 1(a). Deviations from pure exponential rise of the voltage are due to the losses at the end of the sample. A more detailed analysis, taking into account the transition from the original thermal flux distribution into the final beam-like distribution concentrated in a narrow frequency range, gives further small deviations from the exponential variation. Such an analysis is presently being applied to experimental data in epitaxial GaAs to obtain the parameters, α_0, $1/\tau_p$, and φ_0, and their variation with transverse and longitudinal magnetic fields.

Several complications can arise even in this very simple case. We have already mentioned the thermal quench of the gain. A second can be obtained in n-InSb at 77°K, if a transverse magnetic field is applied.[5] After the first normal step at $t = T_p$, it is possible to obtain additional steps in the voltage at intervals of $2T_p$, or round-trip transit time through the sample. Here, the acoustic flux is not destroyed at the end contact, but is reflected (at least in part), and enough returns to the cathode at $x = 0$ to supplement the thermal flux source. This build-up of flux within the sample with each successive round trip is the source of the successive steps in the voltage.

The third case is observed in the same material at or near zero magnetic field. When electric fields in the growing domain reach ≈200V/cm, intrinsic impact ionization occurs. Thus, the initial buildup of acoustic flux and domain formation is quickly followed by the hot-carrier quenching of the high-resistance domain. The effect is illustrated in Fig. 2, for a series of increasing constant current pulses. The breakdown becomes visible with the third voltage trace from the bottom, in the failure to

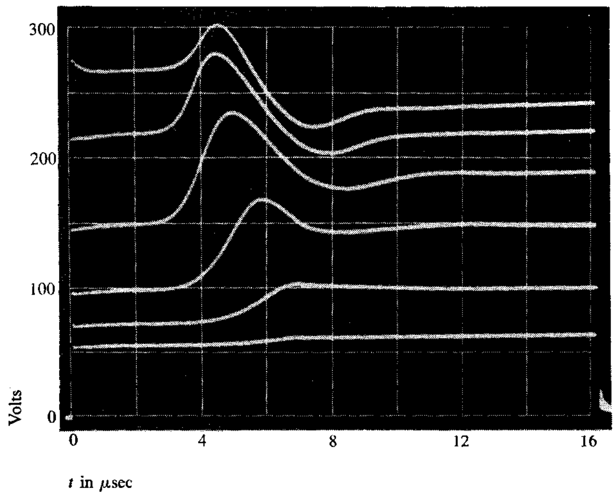

Figure 2 Voltage signals for a series of increasing constant current pulses in n-Insb at 77°K. The normal step in voltage is visible in the bottom two traces. The upper traces show higher voltage increments giving higher fields in the domain, which produce impact ionization and destroy the voltage step. Measurements were made by V. Dolat.

maintain the initial increment in voltage. At low temperatures in CdS, impact ionization of shallow impurity levels during flux buildup has been reported by Moore and Smith[7]. The interesting aspect of these observations of hot-carrier phenomena within the high-field region of the acoustic domain is the indication that the excess power delivered to the electrons in the domain is not all delivered to the amplified phonon beam. This is contrary to the expectation from the simple relation given by Eq. (4). Thus it appears that part of the electrons in the high-field domain do not effectively interact with the intense acoustic flux, but become hot. It is therefore not valid to assume that, in general, the electron distribution function and the ohmic mobility in Eq. (4) are not altered during the intense flux buildup. However, only in the cases cited are the hot-carrier effects so dramatic. Whether the hot-carrier effects should be taken into account at other times requires more detailed analysis than has yet been carried out.

- *The constant-voltage case*

As we have already noted from Fig. 1, oscillatory effects enter as soon as the constant current condition is relaxed. These more complex phenomena are due to a feedback effect between the total amplified acoustic flux and the current which determines the gain everywhere in the sample. This is discussed most simply for the constant-voltage conditions shown in Fig. 1(d).

Equations (1) and (4) apply here as in the constant-current case. The initial flux growth procedes as before until a time when the total flux in the sample becomes sufficient to cause a drop in the current, and hence in the gain factor $(v_d/v_s - 1)$. The relation between the latter and the total flux in the sample, $\Phi = \int_0^L \varphi\, dx$, can be derived from Eq. 4. For constant applied voltage V, integration of Eq. 4 over the length L of the sample gives

$$(v_d/v_s - 1) = (v_0/v_s - 1)/(1 + \beta\Phi) \qquad (5)$$

where $\beta = \alpha_0\mu/nev_s^2L$ and v_0 is the initial ohmic drift velocity at $t = 0$, given by $\mu V/L$. Thus, when $\beta\Phi$ becomes appreciable compared to unity, v_d and hence the gain $\alpha_0(v_d/v_s - 1)$ decrease everywhere in the sample, both for the already amplified flux which has propagated downstream, and for the flux in its wake.

To describe the evolution of the flux distribution and the current oscillation in detail using Eqs. (1) and (5), it is necessary to take into account the losses of flux at the downstream end. A stepwise computer calculation shows that the flux builds up to a peak, as before, at $x = L$, with the current dropping to its minimum value. But as the flux is destroyed at the contact, it is now not continuously replenished because of the decreased gain that had been experienced by the flux following in its wake. As the intense flux is succeeded by a reduced flux, the current rises again, increasing the gain everywhere. Thus, there ensues an oscillatory pattern for the flux buildup and the current in the sample. The flux and current variation can be described by a damped oscillation, such as seen in Fig. 1(d), with period close to one transit time (after the first longer period). Each period sees a different flux distribution.

A fascinating extension of the feedback between current and flux is obtained if we go to the more general form of the acoustoelectric gain expression; at the frequency of maximum gain, $\omega_m = \sqrt{\omega_\sigma\omega_D}$, it is given by[8]

$$\alpha = K^2\omega_\sigma\gamma[\gamma^2 + 4\omega_\sigma/\omega_D]^{-1}\ \mathrm{sec}^{-1}, \qquad (6)$$

where $\gamma = v_d/v_s - 1$, $\omega_\sigma = \sigma/\epsilon$ is the dielectric relaxation frequency and $\omega_D = ev_s^2/\mu kT$ is a carrier diffusion frequency; K^2 is the piezoelectric coupling coefficient. Here the gain increases with v_d, goes through a maximum at $\gamma^2 = 4\omega_\sigma/\omega_D$, and then decreases. In the relatively high conductivity III-V compounds, the ratio ω_σ/ω_D is generally very high, and this "resonant" gain form is not achievable. However, in high-mobility n-InSb at 77°K, in transverse magnetic field, B $\gtrsim$ 2000 gauss, ω_σ/ω_D is greatly decreased through the magnetoresistance effect,[5,9] permitting the resonant gain condition to appear and be controlled by the magnetic field. Here the decrease in current with flux buildup has rather complicated positive and negative feedback effects on the gain. The gain will decrease as before when the current drops, if the γ^2 term in the denominator is small. But at higher current, where $\gamma^2 > 4\omega_\sigma/\omega_D$, the gain increases with drop in current, and the initial flux buildup induces still stronger flux buildup and further drop in current. This effect can not run away, since the situation will eventually reverse when the gain passes over its maximum. A myriad of effects are observed[10] in n-InSb depending on just how much flux buildup and change in current is allowed to take place. This is determined quite sensitively by the sample length, and the magnitude of the gain which can be controlled[11] by transverse magnetic field. Computer studies[12] based on the considerations presented above, can simulate the various instabilities observed.

Effect of inhomogeneities on domain formation

The discussion so far has been based on uniform samples. However, there is an inevitable spatial dependence of the initial amplification related to the inhomogeneity of the ohmic resistivity of the sample. This became particularly evident from a study of the spatial variation of the amplified flux in the *short-pulse experiment* described above. Although flux was present throughout the sample, the intensity profile was highly nonuniform. Its form was extremely well correlated with an independently determined profile of the ohmic resistivity; i.e., positions of maxima, minima and gradients matched very well. However, although the variations in ohmic resistivity from average were no more than $\sim$10% in the samples investigated, the variations in amplified flux were one to two orders of magnitude greater.[3] These results are readily understandable on the basis that the uniformly generated flux is non-uniformly amplified.[13] Because the pulses were so short, we can observe effects of variations in gain in 1 mm intervals in the sample. For the material in question, the acoustoelectric gain is given by $\alpha = \alpha_0(v_d/v_s - 1)$. At the frequency of maximum gain, α_0 is inversely proportional to the local mobility; the local drift velocity varies inversely as the local carrier concentration. Thus, for $v_d/v_s - 1 \gg 0$, the gain varies directly as the local resistivity. Since the flux grows exponentially with growth coefficient α, the amplified flux profile is a grossly exaggerated representation of the ohmic resistivity profile. Thus, in any real sample, the amplified flux distribution will differ considerably from the ideal cases discussed, and in general should be quite dependent on the polarity of the applied voltage for long pulses. This will naturally reflect itself in the current oscillation patterns.

A most important consequence is the production of continuous rather than damped current oscillations in most samples of GaAs and GaSb. These are illustrated in Fig. 3(a) for n-GaAs, In each period, the current drops from ohmic to a low, relatively flat saturation level and then returns to ohmic at the end of each period, which coincides with a single transit time T_p, of a narrow, propagating domain. In addition, it is frequently observed in such cases, that the pattern of flux distribution and current oscillation is quite different if the polarity of the applied voltage is reversed. Fig. 3(b) illustrates the drastically altered current

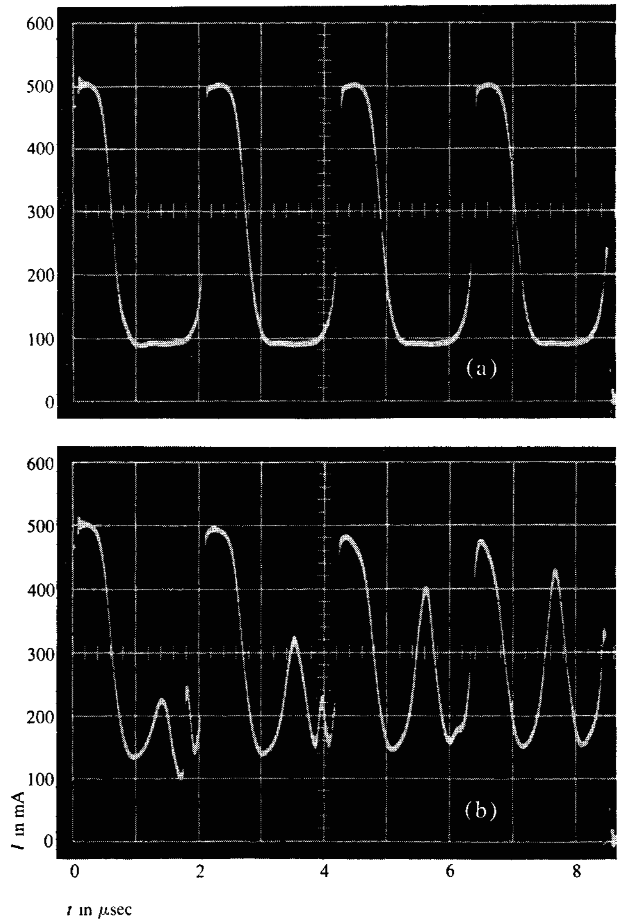

Figure 3 Current oscillations for constant voltage pulses in n-GaAs. Cases (a) and (b) are for the same sample, but with reversed polarity. A computer calculation by J. B. Ross using the simple model, substantially duplicates these observations (except for the smallest pip in (b)), if the resistivity (hence gain) is higher in half of the sample. Case (a) of continuous oscillations corresponds to flux propagation from high to low resistivity end.

oscillation for reversed polarity. The features of asymmetrical response and propagating domain formation can be explained in terms of the simple model, if we take into account the inherent inhomogeneity in the sample. The condition for continuous oscillations and formation of propagating domains is that the resistivity (hence gain) be greater in the upstream portion of the sample. Obviously, reversal of polarity in such a case completely changes the conditions and yields quite different flux and current patterns. This is verified by simulation calculations.[12] For a sample in which the resistivity is higher in half the sample, the basic features of Fig. 3 (except for the smallest pip in 3(b)) can be reproduced. Also excellent correlation is obtainable[6] of domain shape as determined by Brillouin scattering with predictions based on the simple theory and incorporating the measured inhomogeneity in resistivity in given samples.

Strong flux effects

Effects of strong flux and high field in the domain, beyond the expectations or predictions of the simple model, become apparent in the later stages of flux growth and domain evolution. We have already noted the impact ionization by hot carriers in InSb, and the warning it provides of changes in carrier distribution function in the domain.

The effect of strong flux is most dramatically evident in the evolution of the spectrum of the amplified flux as obtained from Brillouin scattering. As the resistance begins to depart appreciably from ohmic, the spectrum of the amplified acoustic flux shifts from that predicted by small-signal theory. The peak intensity of the flux drops from the expected frequency of maximum gain ω_m to lower frequencies. This is a common feature in both CdS[14] (where it was first observed) and GaAs[15]. In the latter, shifts in the peak intensity from ω_m to $0.1\omega_m$ can be followed in detail. This transition in the spectrum occurs spatially in the most intense region of the domain[6] and is attributed to parametric down-conversion[16] of the flux.

It also appears that the gain is stronger in that region of the domain where the flux is most intense. Evidence is provided from a study[17] of the evolution of the shape of a domain by means of a narrow optical probe, in n-GaAs at 77°K. Such a study shows at an early stage, a specimen-dependent broad distribution of flux. In the later stages, this domain narrows to $\sim$ 1–2 mm width. During this process growth continues in the intense part of the domain while the wings attenuate. This indicates that the net gain is still positive where the flux is most intense, but negative where the acoustic flux is weak.

As the current drops with the growth of the flux, there is evidence that the acoustoelectric gain, α, drops less rapidly than does the gain factor $v_d/v_s - 1$. Thus to the extent that $\alpha = \alpha_0(v_d/v_s - 1)$ is still valid at strong flux, this implies that α_0 increases in strong flux. The evidence is based 1) on the relation given by Eq. (4), between the measured field and the total flux at the peak of the domain[15], and (2) from the fact that the drop in current from ohmic as the flux grows is much greater than is compatible with the magnitudes of the parameters α_0 and τ_p , determined in weak flux conditions[10,15].

In summary, both the flux dependence of the gain and the down-conversion of the acoustic spectrum are features of the intense flux buildup. In part, the changes in gain and loss parameters may reflect the change in the frequency spectrum. However, whether these two effects are related or separate consequences of the strong flux regime, awaits extension of the nonlinear theory.

Conclusions

We have attempted to define the role of the various factors contributing to the acoustoelectric instabilities. The simple model for the acoustoelectric gain (which is essentially a small-signal model) is capable of explaining most of the primary effects, i.e., the various forms of the voltage and current wave forms, from steady state to oscillatory. Here it is necessary to include the effects of circuit conditions (involving feedback between the nonuniform flux buildup, and the current and gain everywhere in the sample), boundary conditions including destruction or reflection of flux, inhomogeneities in the resistivity to which the waveforms and domain formation are particularly sensitive, and the form of the acoustoelectric gain curve which determines the dependence of the gain on local resistivity in the early stages of amplification, and the response of the gain to changes in the current in the later stages.

The more subtle and interesting effects associated with the instabilities, such as the field and flux dependence of the frequency spectrum of the flux, the acoustoelectric gain and losses, and the carrier distribution function do, of course, influence the more readily observable resistance instabilities. However, they serve the role of modifying rather than primary influences, and it is necessary not to attribute everything to them. The major effects of the flux-dependent changes in acoustoelectric parameters are: the enhancement of the amplitude of the current oscillations and the narrowing of the domain, which have the consequence of sharpening both the current drop and its return to ohmic when the narrow domain is destroyed at the downstream end. The polarity dependence of the current oscillations and of the formation of propagating domains is indicative of the importance of the inhomogeneities, whose role cannot be overridden by the intense flux effects. In CdS, strong flux effects appear more precipitously and appear to have more influence on the instabilities. However, this means that the intermediate phases of the instability are easily lost to the observer. The early and intermediate phases are therefore best studied in the weaker piezoelectric materials, where it is possible to follow them in sufficient detail in both space and time.

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