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XI-10. Acoustoelectric Domain Effects in III-V Semiconductors

R. BRAY, C. S. KUMAR, J. B. ROSS, and P. O. SLIVA

Department of Physics, Purdue University, Lafayette, Indiana, U. S. A.

Current oscillatory behavior, acoustoelectric in origin, and similar to that described previously for *p*-GaSb, has been found in Li-diffused *p*-GaSb, *n*-GaAs, *n*- and *p*-InSb, indicating the effect is universal in the III-V group. A new optical probe technique for detecting the space and time distribution of acoustic flux domains is described. The oscillatory behavior is discussed in terms of three basic factors: 1) transient generation, 2) propagation, and 3) amplification—of domains of acoustic flux. A striking new effect is the strong enhancement of acoustoelectric domain formation by transverse magnetic fields.

§ 1. Introduction

Current instabilities, acoustoelectric in origin, have been recently observed in three groups of piezoelectric semiconductors: III-V (*p*-GaSb,[1] *p*-InSb,[2] *n*-GaAs[3]); II-VI (CdS,[4-9] CdSe,[10] CdTe,[10] ZnO[5,11]); VI (Te[12]). Such instabilities are due to the internal generation of acoustic flux, and to its strong amplification by carriers moving with drift velocity exceeding the velocity of sound. The characteristic feature of the instabilities is the transformation in time of the field distribution in the material from a nearly uniform one to a strongly non-uniform one. One form of instability consists of continuous oscillation of the current between an ohmic and a high resistance state. This is related to the development of successive domains of high resistance which propagate through the sample with the velocity of sound in the direction of carrier drift.[1,7-9] A second form consists of the transition of the current from ohmic to a steady, high resistance state, corresponding to the eventual formation of a stationary domain at the downstream electrode.[8,13] Damped oscillations of the current, culminating in a steady, high resistance state, are frequently observed and appear to represent a combination, or perhaps competition, of the two instabilities, with the propagating domains dying out.[8,13] The factors determining which of the various instabilities appears in a given sample have not yet been satisfactorily resolved. We restrict ourselves here to the case of continuous oscillations such as were originally described and analyzed for *p*-GaSb.[1] It has been possible to make a more complete investigation and to observe new effects by extending the work to Li-diffused *p*-GaSb and several other highly conducting III-V semiconductors, *n*-GaAs, and *n*- and *p*-InSb.

§ 2. Oscillatory Current Pattern

Representative current oscillation patterns for constant voltage pulses of varying amplitude are shown in Fig. 1 (a). The corresponding I-V characteristic is shown in Fig. 1 (b). The results are for Li-diffused *p*-GaSb at 77°K, with the field applied in the [110] direction. The oscillations are well defined and heating effects are absent, in contrast to the case for non-diffused GaSb (see ref. 1), Fig. 1). The improvement is

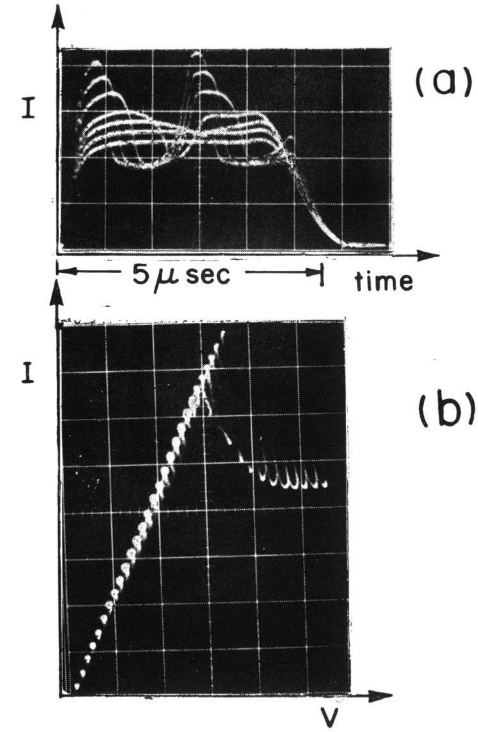

Fig. 1. (a) Current oscillation patterns. (b) Current-voltage characteristic. Li-diffused *p*-GaSb at 77°K; hole concentration $=8.2\times10^{15}/cm^3$; mobility $=3280\ cm^2/V\ sec$.

due to the lithium, which removes deep acceptors by ion-pairing,[14] reduces the hole concentration, and raises the mobility. We note that the current remains ohmic for an incubation time T_i. A transition period T_t follows, during which I drops to a well defined saturation value, if V is sufficiently high. Both T_i and T_t decrease sharply as V is increased. The current finally returns to ohmic after a total time T_p, the oscillation period. The latter equals the one-way transit time -between electrodes- of a piezoelectrically active shear wave. T_p is independent of any variation we have achieved in field strength, carrier concentration, mobility or lattice temperature.

§ 3. Probe Studies and Model

We shall discuss the oscillatory behavior in terms of three basic factors: a) transient generation, b) propagation, and c) amplification of domains of acoustic flux. The interpretation relies heavily on probe measurements of the space and time distribution of the acoustic flux. The previously described *electric field* probe technique[1] has been augmented by an *optical probe* technique[15] which has proved to be extremely useful, as well as interesting for its own sake.

a. Optical probe technique

The probe consists of a narrow beam (0.3 mm) of monochromatic light which is passed *through* the sample. The passage of a domain of flux past the beam produces a pulsed change in the transmitted light intensity. The inset photograph in Fig. 2 shows oscilloscope traces of a sequence of such optical modulation signals, taken at a series of positions along the sample, as the sample is moved normal to the light beam. Each signal was obtained during the application of a constant voltage pulse of 5 μ sec duration to Li-diffused *p*-GaSb at 77°K. The modulation is due to a decrease in transmission, which is restricted to wavelengths at the intrinsic absorption edge. This effect corresponds to a transient shift in the edge to a lower energy. Auxiliary experiments indicate that the shift is not due to the high electric field in the domain, and is therefore attributed to the acoustic flux.

b. Domain characteristics: Origin, propagation and structure-sensitivity

The value of the optical modulation probe signals for determining such domain characteristics as width, propagation velocity, and growth pattern is apparent from inspection of the figure. The arrival time of the peak of the domain at various positions along the sample is plotted in Fig. 2. The domain propagates with velocity close to that of the piezoelectrically

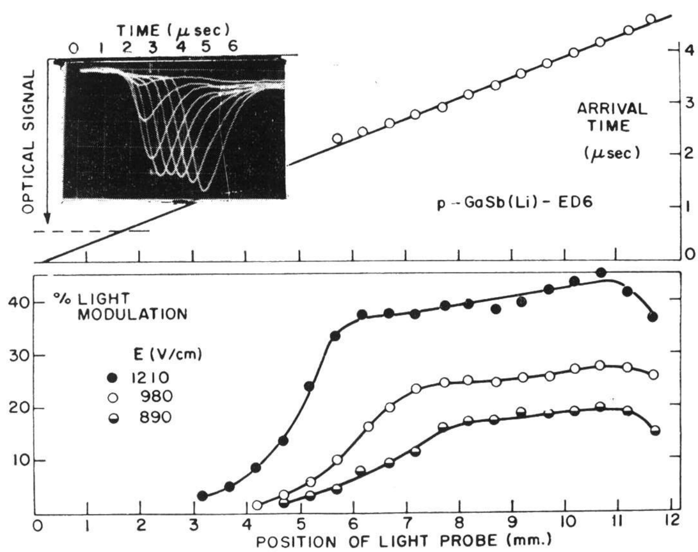

Fig. 2. Results of optical probe study. Li-diffused *p*-GaSb at 77°K. Resistivity=1 Ω·cm. *Inset*: Oscilloscope traces of optical modulation signals at various positions on the sample. *Upper figure*: Arrival time of domain peak as a function of position along the sample. *Lower figure*: Magnitude of modulation signal as a function of position, for several voltages.

active shear wave,[1] $v_s=2.8\times10^5$ cm/sec, in the [110] direction. The domain source can be located by extrapolation. In the present case it appears to originate in a region close to the positive contact, during the rise time ($\approx .5\ \mu$ sec) of the applied voltage pulse. From extensive probe studies on many samples, we have found that several domains may be simultaneously generated at different locations. Each domain can generally be traced back to the contact and/or to regions of resistance gradient which are either accidentally present or deliberately introduced.[1] When high voltage pulses are applied, gradients of piezoelectric stress are established in all such regions. Such a gradient is the source term of the inhomogeneous wave equation for sound and is responsible for the generation of traveling waves.[16]

We picture the generation process to be *transient*, occurring during the adjustment of a boundary or region to a differential piezoelectric stress produced by the application of the electric field. The production of a propagating domain, *i.e.*, a spatially restricted flux pattern, is a consequence of the *transient* generation of the flux at a *localized* source.

The optical modulation signals of Fig. 2 represent a domain that is much wider (several mm) than the resolution of the probe. We have found that the width and shape of the domains in *p*-GaSb are quite variable and highly structure-sensitive quantities. In general, they depend on such factors as the width of the region of resistance gradient, and the number and distribution of such sources in the sample. Accurate determination of the domain velocity is possible only in the selected cases where a single, sharp domain is observed.

c. *Amplification and current instability*

We consider next the flux amplification process and its reaction on the current.[17] We shall attempt a description in the simplest terms to get at the essentials of the problem. Let the net rate of gain of acoustic flux dN/dt, be proportional to $N[K(v_d/v_s-1)-1/\tau]$, where N is a measure of flux intensity, K is a coefficient depending on the carrier concentration and the strength of acoustoelectric coupling, v_d is the drift velocity, v_s the sound velocity and τ is a momentum relaxation time due to non-electronic interactions, for the flux in the propagating domain. The two terms inside the brackets correspond respectively to rate of gain and loss of flux intensity. The gain term is of a form common to any of the theories[18] of acoustic amplification for the case of a highly conducting semiconductor. (Amplification of flux not traveling parallel to the current may be neglected here.)

If $v_d/v_s>(1+1/K\tau)$, the flux will initially grow exponentially with time and with position as the domain propagates downstream from the generation site. The current will remain ohmic for an incubation time T_i, *i.e.*, until the rate of momentum loss by the carriers to the growing flux in the domain becomes comparable to the normal momentum randomizing processes. Thereafter, there is a transition period during which further acoustic gain causes noticeable excess resistance in the domain, and the current decreases for constant voltage across the sample. Excess field appears in the domain at the expense of the ohmic (flux free) regions. Correspondingly, v_d decreases, causing the gain per unit flux to drop everywhere; eventually a steady state situation is achieved when the gain is only sufficient to compensate for the losses in the domain. This steady state is manifested by the saturation of current with time in Fig. 1, and by the saturation in optical modulation signal with position in Fig. 2.

The steady state drift velocity, v_d^*, is given by the relation $v_d^*/v_s=(1+1/K\tau)$. For strong coupling and/or long phonon lifetime, we can expect v_d^* to approach v_s. In *p*-GaSb and also in the other III-V semiconductors, we have generally found that $v_d^*/v_s>2$. The underlying reason may be the relatively weak piezoelectric coupling in these materials, although other factors such as trapping can also contribute in certain cases. Furthermore, v_d^*/v_s increases at $T\gg77°K$, and it becomes difficult to obtain the oscillatory behavior. This may be interpreted in terms of a decrease in the phonon lifetime with increasing temperature, as is shown by attenuation studies[19] at 3 and 9 Gc/sec.

d. *Regeneration and current oscillations*

When the domain reaches the end of the sample, after a time T_p, it is apparently destroyed. There is no evidence of reflected flux. Then the current returns to ohmic value, as seen in Fig. 1 (a). The rise in the current increases the field at the original generating site(s); new domain(s) are created, and the cycle is repeated.[1] The oscillatory form of the instability comes from the *transient* nature of the generation. (By contrast, the non-oscillatory form of the instability is generally attributed to *continuous* generation from the thermal background.) The current oscillation pattern reflects the domain structure in a given sample. The pattern in Fig. 1 (a) represents a relatively simple domain structure. Much more complicated oscillation patterns are possible. In fact, with increase in voltage, even weak sources may begin to generate, thereby causing voltage-dependent oscillation frequency.

We noted in our discussion that domain formation was inherent in the process of generation. It *preceded* amplification and the production of a negative resistance characteristic. This is in contrast to some attempts[3,8,9] to ascribe acoustoelectric domain formation to the Ridley font mechanism,[20] where propagating domains are a *consequence* of a bulk negative resistance characteristic.

e. Voltage dependence of the oscillation pattern

The simple model presented above indicates that the decrease in T_i and T_t with increasing applied voltage, as observed in Fig. 1, is the direct consequence of the increase in v_d and hence in the gain. (However, enhanced generation may be a contributing factor.) The fact that the domain is traveling, imposes a condition for the achievement of a steady state current: $(T_i+T_t)<T_p$, *i.e.*, that the sample be long enough, and/or the applied voltage be high enough.

The fact that the steady state current, and hence v_d^*, saturate with the applied voltage, has interesting implications. From Fig. 2, we note that the steady state optical modulation signal, and hence the acoustic flux intensity, increases with voltage. We can conclude that v_d^* (and hence the $1/K\tau$ term) is independent of the flux intensity. This result suggests that within the range covered by these experiments, the phonon loss term is linear, *i.e.*, that τ is independent of N. A non-linear loss term is therefore not necessary to achieve steady state condition if the decrease in v_d and the acoustic gain term with increasing flux intensity is taken into account. A model presented by Hutson,[21] assuming no decrease in gain, requires non-linear losses to achieve steady state. In materials where very narrow domains may exist with very great flux densities, a non-linear phonon loss term may play a significant role. In such a case, the steady state current should not saturate with increasing voltage.

§ 4. Other III-V Semiconductors

The preceding analysis and our experience with p-GaSb indicated that acoustoelectric domain formation could be optimized by 1) using long samples (≥ 4 mm) with high carrier concentration $\approx 10^{16}/\text{cm}^3$, 2) applying the field in the [110] direction, and 3) operating at $T \leq 77$°K. With these conditions, current oscillatory behavior was obtained in every III-V semiconductor investigated: n-GaAs, n- and p-InSb. The behavior is quite similar in all materials, indicating that the effect is essentially independent of band structure, and apparently universal in the III-V group. The oscillation period in each material corresponds to the appropriate sound velocity in the [110] direction. Critical fields for onset of oscillations were lower in the higher mobility materials.

The case of p-InSb[2] requires special mention. Here intrinsic breakdown and acoustoelectric domain formation occur at a comparable threshold field ≈ 400 V/cm. In this competition, intrinsic breakdown is dominant. The application of transverse magnetic field of even a few kG raises the threshold for intrinsic breakdown[22] and permits unambiguous observation of the acoustic instability. However, if the electric field in the domain rises sufficiently, a delayed transition to intrinsic breakdown ultimately occurs. Thus there is a delicate balance between the two effects, controllable by the transverse magnetic field.

§ 5. Magnetic Field Enhancement

During the course of the experiments with p- and n-InSb, we discovered a more striking role of transverse magnetic field,-its ability to enhance acoustoelectric domain formation. The enhancement has also been obtained in p-GaSb and n-GaAs where there is no intrinsic breakdown. Thus it is present irrespective of the need to suppress intrinsic breakdown.

The magnetic enhancement is illustrated in Fig. 3 by a series of current pulses taken at varying $B_\perp$ for constant applied voltage. In Fig. 3 (a) are shown results for p-InSb, at near-threshold electric field, 340 V/cm, with $B_\perp$ varying from 5–70 kG. The drop in current in the ohmic regime with increasing $B_\perp$ is just the magnetoresistance effect. The stronger, delayed drop in current due to acoustoelectric domain formation is observable only at $B_\perp \geq 40$ kG. The magnetic enhancement effect, which is here

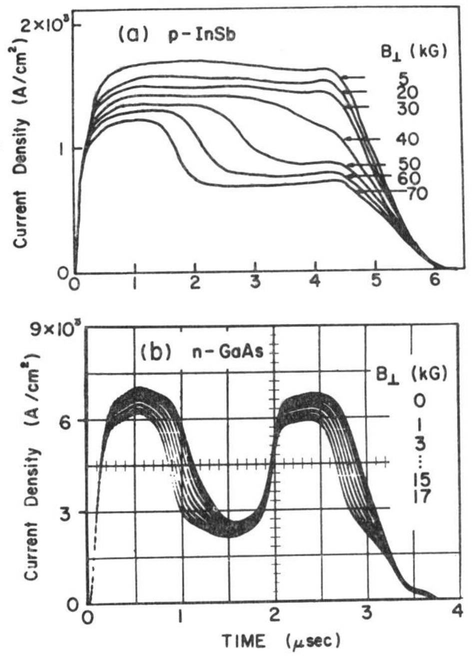

Fig. 3. Acoustoelectric domain enhancement by transverse magnetic field.
(a) p-InSb at 77°K; $\mu=4{,}300\ \mathrm{cm^2/V\ sec}$; $p=1\times10^{16}/\mathrm{cm^3}$.
(b) n-GaAs at 77°K; $\mu=8{,}150\ \mathrm{cm^2/V\ sec}$; $n=1.7\times10^{16}/\mathrm{cm^3}$.

monotonic with $B_\perp$, consists of the decrease in 1) the threshold voltage for domain formation, 2) the incubation time, and 3) the steady state current. (Oscillatory current behavior is not observed here because the pulse duration is less than the transit time T_p.)

Figure 3 (b) shows oscillatory current pulses for n-GaAs at a field of 320 V/cm, well above threshold in this case. $B_\perp$ varies from 0 to 17 kG. Already at $B_\perp \approx 5$ kG, the enhancement is apparent, *i.e.*, the incubation time and steady state current decrease. Extended measurements to 70 kG again give monotonic behavior. Here we note that the transit time T_p is independent of $B_\perp$. The fact that $B_\perp$ does not alter the domain velocity indicates that it does not switch the active mode or change the direction of propagation of amplified flux. Apparently the magnetic field serves directly to increase the acoustoelectric amplification. Qualitative comparison of results in the different materials, indicates that the effectiveness of the magnetic field is greater, the lower the effective mass of the carriers.

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DISCUSSION

Kikuchi, M.: We have been working on n-type InSb at 77°K and found out very drastic reduction in the threshold field to get the acoustoelectric current oscillation when a magnetic field was applied in perpendicular to the current flow. The reduction is almost an order of magnitude for the magnetic field greater than 2 kG.

We also tried to rotate the magnetic field in a plane which is perpendicular to the current, and the effect revealed very interesting dependence on the angle of rotation.

Is it all right for your model to explain such a drastic reduction in the threshold field by applied perpendicular magnetic field?

Bray, R.: We have seen the enhancement of the acoustic amplification by transverse magnetic field in all the III–V compounds studied. The effect is largest in *n*-InSb. A possible mechanism is the decrease in mobility by the magnetic field. This increases ω_D — the diffusion frequency, and prevents outdiffusion of carriers from the sound wave. According to the Hutson—White theory, the gain at frequency of maximum gain is proportional to ω_D.

For weak magnetic fields we can expect that as the magnetic field is rotated away from the transverse fowards the longitudinal direction, the magnetoresistive effect would disappear. We have seen this happens in *n*-InSb at $B < 25$ kG at 77°K. The enhancement of acoustic buidup disappears rapidly as B is rotated away from the transverse direction.