Optical Modulation by Acoustoelectric Domains in p-GaSb†

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Propagating domains of acoustic flux are spontaneously generated and strongly amplified by pulses of high voltage in p-type GaSb. These domains were previously detected by electrical probe measurements of the associated high resistance and high field in the domains. We have found that such domains can also strongly modulate the transmission of infrared light. The passage of a domain past a focused light beam produces a transient change in transmission. This signal contains considerable information about the properties of the domains. However, our main interest in this paper is the nature and mechanism of the modulation. The spectral dependence of the interaction was studied in the purest available as-grown p-GaSb and in Li-diffused material. The primary effect is a strong decrease in transmission which is restricted to wavelengths near the intrinsic absorption edge. The modulation corresponds to a transient shift and/or broadening of the edge towards longer wavelength. This effect is best observed in Li-diffused GaSb. In as-grown material, the tail of the absorption edge is broadened by contributions from impurity transitions. There the modulation is related not only to the shift of the edge, but also to domain-induced increase in electron occupation of deep acceptor impurity levels. Greater heating effects in as-grown material make it much less useful for studying domain-induced modulation effects. Correlations were made between the optical modulation and the local electric field strength in the domain, using both electrical and optical probe measurements. Uniform applied fields, equivalent to those produced locally in the domain, were insufficient to produce optical modulation. It was concluded that the modulation is caused by the intense acoustic flux and not by the electric field established in the domain. Several mechanisms of acoustic modulation are suggested by analogy with known thermal and static strain effects.

I. INTRODUCTION

THE establishment of propagating domains of high resistance and high electric field is a characteristic feature of a variety of current instabilities in semiconductors.[1] In the case of instabilities of acoustoelectric origin in piezoelectric semiconductors, such domains are also regions of intense acoustic flux.[2] We have found that the acoustic domains are capable of strongly modulating the transmission of light near the intrinsic absorption edge.[3] This property has permitted the development of an optical probe technique for following the processes of domain formation, propagation, and growth.[4] However, it is not these aspects of the acoustoelectric instability with which we shall be primarily concerned here, but rather with the investigation of the nature and mechanism of the optical-modulation process itself.

The effect to be discussed consists of the modulation of the optical absorption coefficient; it was first observed in p-GaSb and subsequently also in n-GaAs.[5] It is to be distinguished from domain-induced optical effects observed in CdS, such as Brillouin scattering[6] and rotation of the plane of polarization of the light.[6,7] Our discussion will be restricted to the work on p-GaSb, where the impurity as well as the intrinsic absorption is affected. In material taken directly from grown ingots, the presence of deep impurity levels strongly affects the tail of the intrinsic absorption edge as well as the optical-modulation signals. It was necessary to use Li-diffused GaSb to eliminate the impurity effects and permit observation of the intrinsic edge and its modulation. Since the nature of the material is so important in the observation of the effect, we present in Sec. II a discussion of the impurity structure in as-grown p-GaSb and its modification by Li diffusion. Large and useful optical signals representing acoustic domains are obtainable only in Li-diffused material. The experimental arrangement is described in Sec. III. The form of the optical-modulation signals and the spectral dependence of the effect in Li-diffused and as-grown material are described in Secs. IV and V, respectively. We have also observed that optical emission signals may be obtained when domains arrive at the downstream (negative) contact. A brief description of such effects is given in Sec. VI. In Sec. VII several possible mechanisms of optical modulation are discussed. It is shown that it is the intense acoustic flux and not the associated high electric field in the domain which appears to be responsible for the modulation.

II. MATERIAL

Single crystals of GaSb, grown by the Czochralski technique without intentional doping, are invariably p-type with hole concentrations $\geq 10^{17}/\text{cm}^3$ at room temperature. The large carrier concentration is due to

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[1] A collection of recent work on the various types of instabilities in semiconductors is contained in J. Phys. Soc. Japan Suppl. **21**, 443 (1968); **21**, 505 (1968); **21**, 685 (1968).
[2] P. O. Sliva and R. Bray, Phys. Rev. Letters **14**, 372 (1965).
[3] C. S. Kumar, R. Bray, and P. O. Sliva, Bull. Am. Phys. Soc. **11**, 173 (1966).
[4] R. Bray, C. S. Kumar, J. B. Ross, and P. O. Sliva, J. Phys. Soc. Japan Suppl. **21**, 483 (1966).
[5] D. L. Spears and R. Bray, Appl. Phys. Letters, **12**, 118 (1968).
[6] J. Zucker and S. Zemon, Appl. Phys. Letters **9**, 398 (1966); S. Zemon, J. H. Wasko, L. L. Hope, J. Zucker, *ibid.* **11**, 40 (1967).
[7] J. D. Maines, Appl. Phys. Letters, 8, 67 (1966).

the presence of a large number of deep acceptor levels introduced unintentionally in the growth process.[8,9] Optical-absorption studies[10–12] have shown that there is a large shoulder at the intrinsic absorption edge, which can be attributed to excitation from deep acceptor impurity levels. Diffusion of Li into such material alters the impurity structure, and permits deliberate variation and control of the carrier concentration and of the contribution of impurities to the absorption edge.[9,11]

Diffused Li enters GaSb as a donor.[13] Its primary effect is that of ion pairing[9] with deep double acceptors $A^=$ according to the reaction $Li^+ + A^= \rightarrow Li^+A^=$. The deep double acceptors are replaced by single shallow acceptors $Li^+A^=$ at 0.02 eV.[9] The elimination of the deep impurity levels greatly modifies the optical absorption. The absorption edge becomes much sharper, as shown by our present measurements at 77°K (see Fig. 9) and those of Habegger and Fan[11] at 300°K. A further increase in the Li content of the material produces an additional decrease in the carrier concentration via a second ion-pairing process[9] of Li^+ with the 0.02 eV levels; $Li^+ + Li^+A^= \rightarrow [(Li^+)_2A^=]$. The net effect of these processes is to allow variation of the carrier concentration over a range from 2.6×10^{15} to $1.0\times10^{17}/cm^3$, and of the hole mobility from 1250 to 3280 cm^2/V sec at 77°K.

Note that the Li-diffused samples anneal very easily, even at room temperature. To ensure sample stability it was necessary to store diffused samples in liquid nitrogen. This annealing instability is attributed to the fact that the Li enters the sample interstitially and is therefore very mobile.[9] Deliberate annealing by the rapid out-diffusion of "excess" Li at elevated temperatures (100–200°C) has been useful for controlled increase of the carrier concentration of a diffused sample. The anneal is such as to increase the hole concentration, thus decreasing the resistance. A side effect of annealing is that the resistance near soldered contacts can be appreciably lower than in the interior portions of the sample. This is a result of local heating during the soldering process. This situation may be alleviated by gold plating over the low-resistance end portions of the samples or avoiding soldering techniques altogether. Plated or indium-soldered contacts are generally low resistance and ohmic.

III. EXPERIMENTAL DETAILS

The schematic experimental arrangement for observing optical modulation is shown in Fig. 1. The GaSb sample sits horizontally in a moveable liquid-nitrogen Dewar. Radiation from the monochromator is focused on a particular position on the sample, partially transmitted, and then refocused on a cooled InSb photodetector. The passage of a domain is detected by the change in the transmitted intensity. This produces a transient response in the detector; this signal is amplified and displayed on the scope. For optical probing the sample is moved normal to the incident light beam, along the direction of carrier drift.

For spectral dependence measurements a single-pass, Perkin Elmer Model 98 prism spectrometer was used. The light source was a Sungun lamp. A sodium chloride prism with its low dispersion and hence greater concentration of light on the focused spot (generally, 0.3 mm wide) was suitable for the probe experiments. A flint-glass prism was used for studying the spectral dependence. The requirement of high intensity for measureable domain signals necessitated the use of wide slits and limited the resolution to about 0.04 μ.

The detector was a broad, diffused-junction InSb detector cooled to its operating temperature of 77°K, and biased negatively with the full infrared light intensity incident. The response time of the detector was a few microseconds, due primarily to its high junction resistance and capacitance. The speed of response was increased at the cost of sensitivity by placing a variable resistance of 50–400 Ω in parallel with the detector. For a compromise between the need for fast response and sufficient sensitivity to observe the modulation signal, a response time ≈ 0.3 μsec was generally used. The output from the detector was amplified by a Tektronix 1121 preamplifier with a bandwidth of 17 mc/sec.

The light intensity I transmitted at zero field is related to the absorption coefficient α_0 by the well-known relation

$$I = I_0 \frac{(1-R)^2 e^{-\alpha_0 w}}{1-R^2 e^{-2\alpha_0 w}}, \qquad (1)$$

where I_0 is the intensity incident on the sample, w is the sample thickness, and R is the reflectivity. I and I_0 are measured with the sample in and out of the beam,

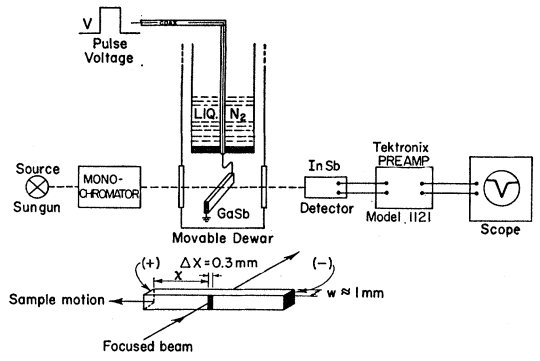

FIG. 1. Schematic arrangement for studying the modulation of infrared transmission by ultrasonic domains.

[8] C. Hilsum and A. C. Rose-Innes, *Semiconducting III–V Compounds* (Pergamon Press, Inc., New York, 1961), p. 137.
[9] R. D. Baxter, R. T. Bates, and F. J. Reid, J. Phys. Chem. Solids **26**, 41 (1965).
[10] W. M. Becker, A. K. Ramdas, and H. Y. Fan, J. Appl. Phys. Suppl. **32**, 2094 (1961).
[11] M. A. Habegger and H. Y. Fan, Phys. Rev. **138**, A598 (1965).
[12] E. J. Johnson and H. Y. Fan, Phys. Rev. **139**, A1991 (1965).
[13] H. J. Hrostowski and C. S. Fuller, J. Phys. Chem. Solids **4**, 155 (1958).

respectively. The flux domain produces a transient change in the transmitted intensity ΔI, from which the change in the absorption coefficient $\Delta\alpha$ was calculated.

IV. OPTICAL MODULATION IN Li-DIFFUSED *p*-GaSb

A. Current Oscillations and Domain Signals

The acoustoelectric instability has been observed in a large variety of piezoelectric semiconductors[4] subjected to voltage pulses above a threshold value. For a constant voltage pulse, the current breaks into oscillations between an ohmic and a high-resistance state. A representative pair of current and voltage pulses in Li-diffused *p*-GaSb at 77°K is shown in Fig. 2. The circuit did not completely maintain constant voltage, and the instability is evident in both pulses. Nearly two cycles of oscillation are observable. During each oscillation period, a domain of high resistance is formed, grows, and propagates through the crystal in the direction of carrier drift.[2,4] These domains are regions of excess acoustic flux, traveling with the velocity characteristic of the constituent sound waves. In the present case, the field is applied along the [110] direction. The velocity of the domain identifies the flux as consisting of the piezoelectrically active, fast shear waves, moving with a velocity of 2.8×10^5 cm/sec. The acoustic flux is internally generated in the piezoelectric semiconductor, and strongly amplified by the carriers when their velocity exceeds the sound velocity. The net transfer of energy and momentum from the carriers to the acoustic flux makes the domain a region of high resistance and hence of high electric field. When the domain reaches the downstream contact, it is destroyed by reflection, absorption, and scattering, whereupon the current returns to its ohmic value. This rise in current triggers the generation of a new domain, and the whole process repeats, thus producing the oscillatory pattern.

A representative optical-modulation signal produced by the motion of domains past a focused beam of light of width 0.3 mm is shown in the bottom half of Fig. 2. The signal shows passage of two successive domains corresponding to the two oscillations in the current. Whereas the modulation of the current is produced by the total excess flux in the crystal, the optical signal represents only the local flux as it passes the position of the light beam. The sensitivity of the system was such that the optical modulation could be observed only after the flux had grown enough to appreciably decrease the current. It is generally sufficient to confine probe studies to short pulses which produce only the first oscillation and the first domain. Figure 3 shows a sequence of traces for such a case, taken at a series of positions along the sample, as the sample is moved normal to the incident light and along the carrier-drift direction. The time at which modulation is observed varies with the probe position. The propagation velocity of the domain can be determined from the variation of the arrival time of the peak of the signal with probe position. This is best done after the domain signal reaches a steady-state value; otherwise the growth of the signal while it is being observed distorts the determination of the peak of the signal.

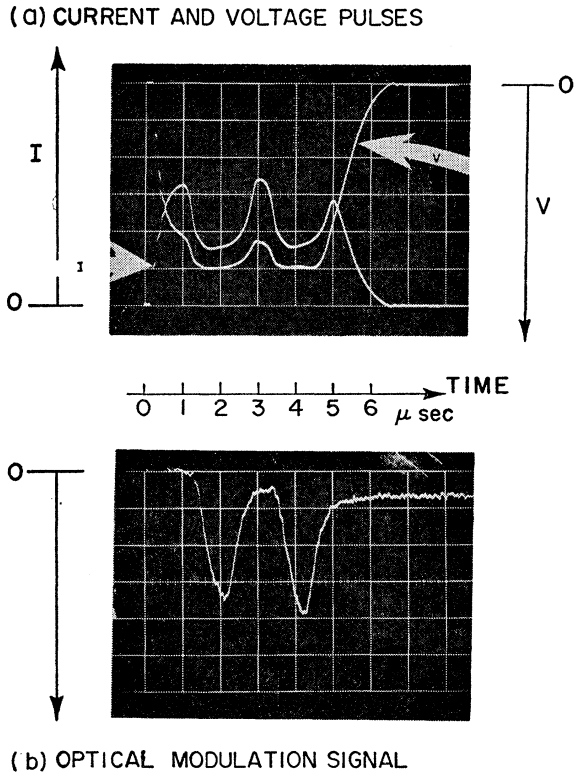

FIG. 2. Upper half: Traces of the voltage and the current pulses showing two periods of oscillation. Lower half: A representative optical signal produced by the passage of two domains past the light beam.

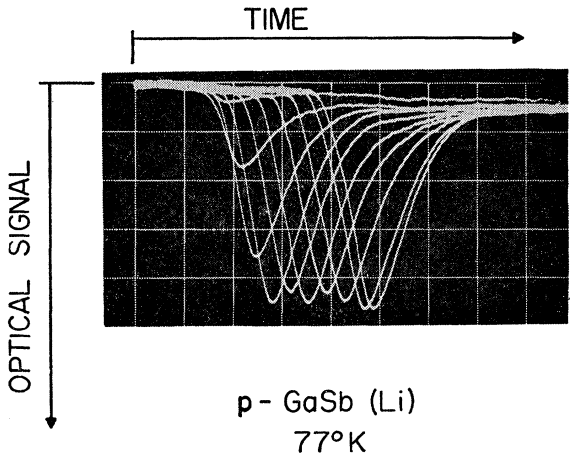

FIG. 3. A sequence of optical-modulation traces taken at an advancing series of positions along the sample, as the sample is moved normal to the incident light.

As further examples of the type of information obtainable from optical probe studies, we note several other aspects of the optical signals. The signals are broad, reflecting the fact that the domains themselves are rather broad ($\approx$5 mm) in this particular case. Domain shape and width are specimen-dependent properties. These characteristics vary with the uniformity of the samples, and with the nature of the contacts. The rapid growth and approach to steady state of the amplitude of the domains can also be noted from Fig. 3. Not shown here is the fact[4] that with increasing applied voltage, the initial growth becomes more rapid, and the steady-state amplitude is increased and attained earlier in time.

We notice in Figs. 2 and 3 that there is a small residual signal after the domain passes the probe. This lasts for several milliseconds after the voltage pulse is over and can be attributed to the heating of the sample. At 77°K, such heating effects are fairly small in Li-diffused samples, but very large in the as-grown materials, as we shall see later. The heating is due to two effects. Ordinary Joule heating occurs throughout the duration of the pulse. There is additional heating at the instantaneous site of the domain. Lattice interactions cause the scattering and randomizing of part of the *propagating* acoustic flux in the domain. That part of the flux which is scattered out of the domain and remains behind is manifested simply as an increase in lattice temperature.

We see that the optical probing technique readily provides a great amount of information about the acoustoelectric instability. The results of a more detailed study and analysis will be presented elsewhere.

B. Spectral Dependence

In order to establish the nature and mechanism of the optical modulation we have studied its spectral dependence. The results at 77°K are shown in Fig. 4.

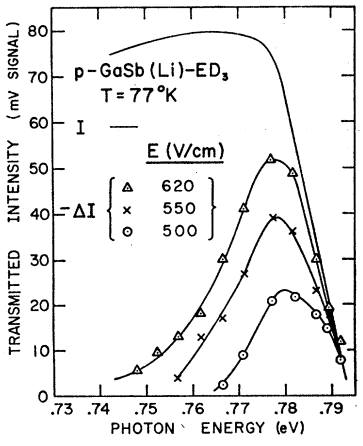

FIG. 4. Spectral dependence of the transmitted intensity I, at zero field, and the change in transmission ($-\Delta I$) for the indicated average fields across the sample.

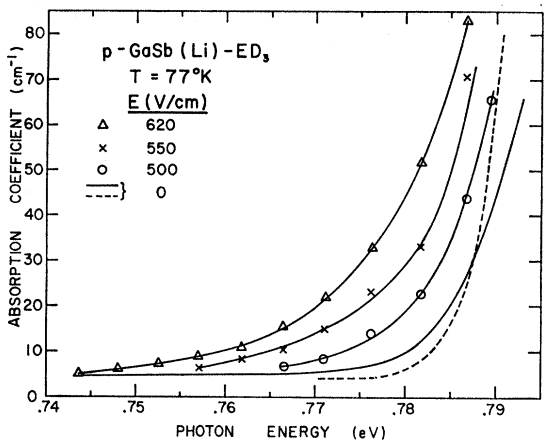

FIG. 5. The four solid curves show the zero-field and the three high-field absorption characteristics, all taken with the same low resolution (0.02 eV). The dashed curve shows the zero-field absorption with higher resolution (0.005 eV).

The transmitted intensity I (solid curve) at zero field, and the peak modulation signals $-\Delta I$ for three applied fields are plotted as a function of the photon energy $h\nu$. In the Li-diffused material the domains cause only a *decrease* in transmission through the sample. The modulation signals were corrected for the small heating effect. The field specified is the average field in the sample, *not* the field in the domain. The critical field for domain formation for this sample is 400 V/cm. We note that the modulation is restricted to a small range of photon energies close to the intrinsic absorption edge. The maximum modulation $\Delta I/I$ approaches 100%. The minimum observable value of ΔI (corresponding to an oscilloscope signal of $\approx$3 mV) is determined by the noise of the preamplifier. The wavelength at which the maximum optical modulation signal ΔI is observed depends upon the thickness of the sample, which was 440 μ in the present case.

In Fig. 5, the absorption coefficient is shown as a function of photon energy. The four solid curves show the zero field and the three high-field absorption characteristics, all taken with the same resolution (0.02 eV). The dashed curve shows the zero-field absorption with better resolution (0.005 eV). This higher resolution reveals a much sharper absorption edge, but the true absorption edge of Li-diffused material was probably still not observable. With the higher resolution, the intensity was too weak to permit adequate measurement of the domain-induced modulation. It is evident that the modulation due to the domain causes an appreciable shift and/or broadening[14] of the absorption edge toward lower energy. The strength of modulation increases with increasing applied field.

The results of an extension of the optical studies to 195 and 300°K are shown in Fig. 6. The solid curves (without data points) show the low-resolution, zero-field

[14] A recent high-resolution study (0.002 eV) in n-GaAs (Ref. 5) shows predominantly a broadening of the absorption edge.

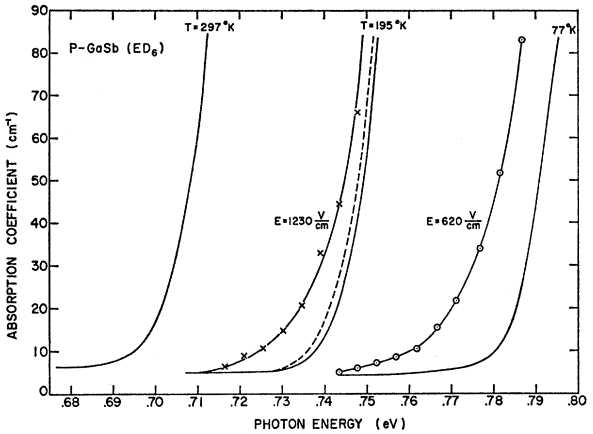

FIG. 6. Absorption characteristics at indicated average field strengths and temperatures. Solid curves: the zero-field absorption characteristics. Data points: the shifted absorption curves due to domains. The 195°K curve at 1230 V/cm includes the Joule heating contribution; the shifted absorption due to heating alone is shown by the dashed curve.

absorption curves at the various temperatures. The shift of the edge due to the domains at 77 and 195°K is also shown at the indicated field strengths. At temperatures significantly greater than 77°K, much higher fields are necessary to obtain domain formation and optical modulation. Thus at 297°K, no shift of the intrinsic edge is shown because even at fields as high as 2000 V/cm neither domain formation nor optical modulation could be observed. At 195°K, a field of 1230 V/cm produces less modulation than does a field of 620 V/cm at 77°K. At such high fields (>1000 V/cm) the Joule heating of the sample becomes quite appreciable and produces a much stronger contribution to the optical signal than is seen in Figs. 2 or 3 at 77°K. However, the contribution to the signal from the domain is still distinguishable. The data in Fig. 6 at 195°K and 1230 V/cm given by the crosses represent the total optical modulation and thus *include* the Joule heating contribution.[15] An estimate of the latter obtained by a linear interpolation of the modulation signal is shown by the dashed curve. Note that most of the modulation is still due to the domain.

It is of interest to compare the change of the edge due to variation in temperature with that due to the domain. In both cases the edge shifts in the same direction. The increase in temperature produces a shift of the zero-field edge with no sign of broadening observable with the given low resolution. The domains at both 77 and 195°K appear to produce both a shift and a broadening effect. Although the shape of the absorption-edge modulation due to the domain is not identical with that produced by the temperature increase, the shift in the edge is in the same direction in both cases. We have estimated what temperature rise gives a modulation equivalent to that produced by the domain at a particular field. By arbitrarily measuring the shift at $\alpha=40$ cm^{-1} and assuming a linear relation[16] for the shift of the energy gap with temperature, $\Delta E_g = -3.5\times10^{-4}$ eV/°K, we find that the modulation produced by domains at a field of 620 V/cm at 77°K is approximately equivalent to a 30°K rise in temperature.[17]

C. Polarization Effect

The magnitude of optical modulation was found to depend on the state of polarization of the infrared light. The modulation $\Delta I/I$ for polarization vector **A** parallel to **E** was larger than for the perpendicular case. Typically the difference was about 17% irrespective of the applied field, as long as the current was in the saturation state. The material was not birefringent at zero field.

V. OPTICAL MODULATION IN AS-GROWN *p*-GaSb

A. Current Oscillations and Domain Signals

The as-grown GaSb material possesses a much broader optical-absorption edge and yields more complicated optical-modulation effects than does Li-diffused material.

Illustrations of the types of optical signals observed are shown in Fig. 7(a). The upper trace (2) at $\lambda=1.7\,\mu$ (close to the absorption edge) represents a *decrease* in transmission; the lower trace (3) at $\lambda=2.1\,\mu$ represents an *increase* in transmission. For comparison, Fig. 7(b) shows a trace (1) for Li-diffused material at $\lambda=1.6\,\mu$.

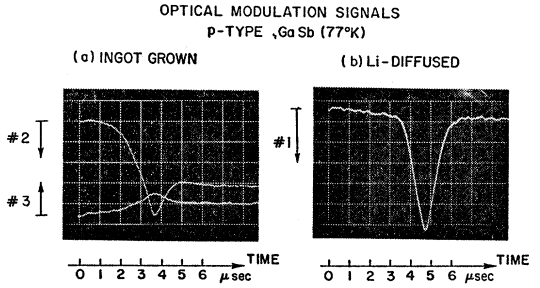

FIG. 7. Comparison of domain-induced modulation signals in as-grown and Li-diffused *p*-GaSb. Signal 1 at 1.6 μ corresponds to a *decrease* in transmission for an intrinsic excitation. Signal 2 at 1.7 μ corresponds to a *decrease* in transmission for a combination of intrinsic excitation, and transition from a deep acceptor impurity level to the conduction band (I–C transition). Signal 3 at 2.1 μ corresponds to an *increase* in transmission for a transition from the valence band to an acceptor impurity (V–I transition). The long-lasting tail on signals 2 and 3 are contributions due to very strong heating effects in the as-grown material, and present in much weaker form in the Li-diffused material.

[15] The data at 195°K were taken only at one field. Although stronger modulation signals could be observed by going to higher fields, these were greatly complicated by heating, contact-injection, and optical-emission effects. These distortions made it difficult to make quantitative measurements.

[16] V. Roberts and J. E. Quarrington, J. Electron. 1, 152 (1955).

[17] We caution however, that the *residual* heating produced by the domain is very much less than 30°K. In no way do we imply that the effect of the domain is *merely* equivalent to an increase in temperature.

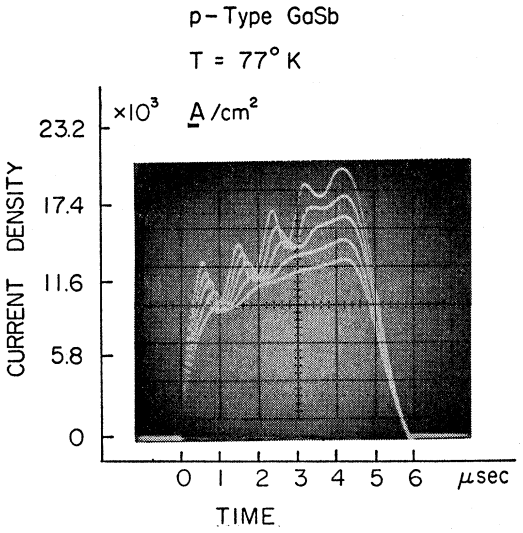

FIG. 8. Multiple current oscillations for as-grown p-GaSb; $T=77°K$, $p=3\times10^{16}/cm^3$, and $\mu=2000$ cm²/V sec. The gradual rise in current level shows the effect of heating in this material.

In contrast to the optical signal for Li-diffused material, the peaks due to the domain in traces 2 and 3 are barely resolvable from the long-lasting Joule heating signals, which are very large in this material. The modulation signals in the as-grown material are found at longer wavelength than in the Li-diffused material. The heating signal and the domain signal generally have the same sign, a fact that will be useful for identifying the optical transitions in the various regions of the spectrum.

The much larger heating in as-grown material is due to the higher carrier concentration and the fact that the fields required for domain formation are appreciably greater than in Li-diffused material. The Joule heating in this material also influences the shape of oscillatory current pulses, as shown in Fig. 8. The ohmic current level increases appreciably during the applied pulse of constant voltage because of an increase in free-carrier concentration, produced by thermal ionization of impurities. Pulsed Hall-effect measurements confirm this interpretation.

The continuous acoustoelectric current oscillations were first reported and interpreted in as-grown p-GaSb.[2] The thermal distortion in the current pattern and the optical modulation signals was a major impetus for the extension of the measurements to Li-diffused p-GaSb and n-GaAs.

B. Spectral Dependence and Nature of Optical Modulation

The results of the spectral study at 77°K of the as-grown GaSb are given in Fig. 9. The dashed curve without data points shows the zero-field, low-energy tail of the absorption curve. For contrast, the solid curve shows the much sharper zero-field absorption curve for a Li-diffused sample, reproduced from Fig. 5 for comparison. The absorption characteristic in the domain at points of peak modulation for an average field of 1075 V/cm across the sample is shown by the dashed curve with circles. The threshold field in this sample was 800 V/cm. The effect of Joule heating is included in this curve. The lower dashed curve (◇) shows only the Joule heating contribution at the time of occurrence of the domain peak. An estimate of the latter was made by a linear interpolation across the base of the optical signal. The data shown are for a more limited range of photon energies than the actual observations. Very close to the absorption edge, the Joule heating completely masks the domain signals, while at much longer wavelengths the signals are so small that a meaningful estimate of the absorption coefficient cannot be made. The signals corresponding to trace 3 in Fig. 7 would show a small *decrease* in absorption far from the intrinsic edge, at $h\nu=0.59$ eV.

The low-energy tail in the absorption curve at zero field has been attributed to transitions involving deep acceptor levels.[10–12] Two types of transitions contribute, one from electron-occupied impurity levels to the conduction band (I-C) at the short wavelengths near the intrinsic edge, and the other from the valence band to empty impurity levels (V-I) at longer wavelengths. This description is confirmed[10,12] by measurements with Te-doped samples. Te is a compensating donor which increases the electron concentration on the deep acceptor impurities. This produces an increase in absorption corresponding to I-C transitions and a decrease in absorption for V-I transitions.

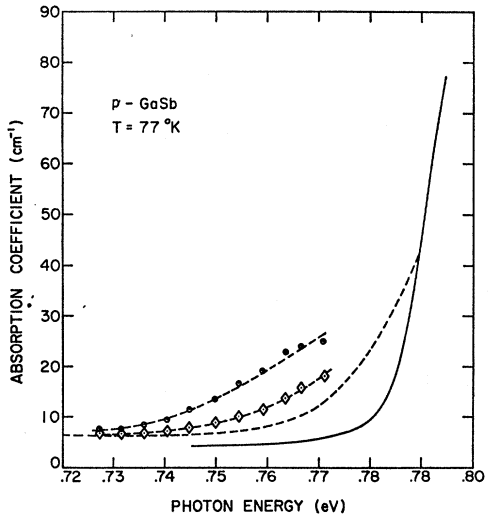

FIG. 9. Modulation of the absorption edge in as-grown p-GaSb. For contrast, the rather sharp (zero-field) absorption edge for Li-diffused material is shown (solid line); the zero-field edge for as-grown material contains the broad tail (dashed line). The shifted absorption for the domain plus heating contribution at an applied field of 1075 V/cm is shown by the circles. The heating contribution alone in the latter case is given by the diamond points.

The effects of an increase in temperature on the absorption curve are also relevant and instructive. First, there is an increase in the free-hole concentration due to enhanced thermal excitation of the acceptors. This produces an increase in electron concentration on the impurities, with consequences for the optical absorption very similar to those described above for compensation by Te. An additional effect is the thermal shift in the intrinsic absorption edge to longer wavelength. Correspondingly, there must be motion of the impurity levels with respect to the band edges which would cause some shift in the I-C and V-I absorption characteristics. Such effects could cause the transition probability at a fixed wavelength to increase for I-C transitions, and to decrease for V-I transitions,[18] thus reenforcing the absorption changes produced by increased electron occupation on the impurity levels. We conclude that the Joule heating contributions to traces 2 and 3 in Fig. 7(a) correspond, respectively, to an increase in I-C and a decrease in V-I transitions.

Analogous modulation of the impurity transitions are expected to be produced by the domains. We know from the results in the Li-diffused material that there is a shift in the absorption edge toward longer wavelength due to the domain itself. Also, pulsed Hall measurements show that there is an increase in free-hole concentration, hence in electron occupation of impurities in the as-grown material. The pulsed Hall voltage signals show a gradual increase in free-hole concentration attributable to Joule heating, and a much larger transient increase in hole concentration when the domain passes the Hall probes. Therefore, we can explain the domain-induced components of traces 2 and 3 in the same way as the heating components.

We still have to consider what produces the observed *transient* increase in free-hole concentration in the domain. Several mechanisms may be considered:

(a) Impact ionization of impurities by the high field in the domain is possible. However, because most of the energy of the free carriers is being used up in the acoustic amplification process, the carriers in the domain may not become sufficiently "hot" to cause impact ionization. Nevertheless, the high field in the domain could decrease the ionization energy and cause a change in population via the thermal ionization process.

(b) The domain flux may itself increase the ionization rate of impurities by phonon-assisted transitions.

(c) The shift in the intrinsic absorption edge implies a transient decrease in the intrinsic energy gap. If this also decreases the ionization energy of the acceptor impurities, it would cause a transient increase in the number of free holes.

[18] These conclusions are based on a study of the shift of the absorption curves with temperature in Fig. 10 of Ref. 10.

VI. DOMAIN-INDUCED EMISSION OF LIGHT

In addition to the transmission modulation signals, we have frequently observed transient signals representing emission of light. These signals occur with the same periodicity as the current oscillations and the transmission modulation signals, and are clearly related to the formation and passage of acoustoelectric domains through the sample. Although such signals can be a nuisance for optical probing studies, they do not seriously interfere with the latter. For one thing, the emission signals can be eliminated by various means, described below. When they do occur, they are seen only when the domain is near the negative contact, and hence only interfere with optical modulation signals near that end of the sample. Since the emission signals are independent of the presence of the incident light beam, they can be separately measured and correction for them can be made.

An emission signal is illustrated in Fig. 10. In Fig. 10(a), the emission signal and the applied (almost constant) voltage pulse are shown for a time scale of 1 μsec/cm. The emission signal is shown again in Fig. 10(b) for a compressed time scale of 5 μsec/cm. These results were obtained on a Li-diffused p-GaSb sample, at 77°K. The oscillatory character is quite evident in both the voltage and the emission signals. The emission spike occurs just as the excess voltage returns to the ohmic value, i.e., as the domain is leaving the sample. The fact that the onset of the emission signal coincides in time with the arrival of the domain at the negative contact was confirmed by voltage probe measurements.

The emission signal has an interesting decay structure. It appears to be composed of a fast and a slow component, with the latter lasting long after the voltage pulse has been terminated. Also, the fast component produced by the second domain is much larger than that produced by the first.

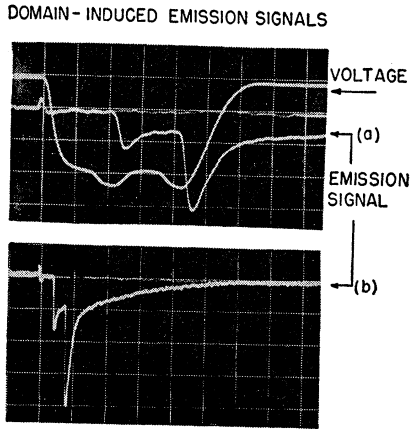

FIG. 10. Emission signals in Li-diffused p-GaSb at 77°K. (a) Superimposed voltage pulse containing two oscillations, and corresponding double emission pulse from two domains. Time scale is 1 μsec/cm. (b) Same emission signal with compressed time scale of 5 μsec/cm.

To interpret these results, it is important to realize that to obtain emission it is essential for the domain to reach the negative contact in appreciable strength. This was demonstrated by the following observations. If the duration of the voltage pulse is decreased, so that the domain does not reach the negative contact before it begins to attenuate, the emission signals are not observed. If L-shaped samples are used, with the large area at the negative end, the high-field domain does not reach the soldered end contact in full strength, and again emission is not observed. On samples where the resistivity is very low near the end contacts (as it frequently is near soldered contacts on Li-diffused samples because of annealing effects), emission is suppressed. In the latter case, the domain attenuates strongly before reaching the end contact.

Thus the emission of light is associated either with the *rapid* destruction of the domain at an end contact, as opposed to gradual attenuation, or to the arrival and presence at the contact of the intense acoustic flux or its associated high electric field. The simplest explanation would seem to be that the high electric field[19] in the domain causes minority carrier injection from the negative contact. The strong emission observed indicates that there is an appreciable radiative component to the recombination of the minority carriers. The presence of the slow component in the emission suggests that part of the minority carriers are trapped, and recombine radiatively either directly from the trap or after delayed excitation to the conduction band. The increase in the fast component in the second emission signal may be due to the fact that the traps are nearly saturated by the first injection; then all additionally injected carriers would be free and would recombine directly. Although the emission phenomenon appears interesting for its own sake, the effect does not appear to be directly related to the acoustic effects (except insofar as the domain provides a high localized field) nor to the optical-modulation process.

VII. MECHANISM OF MODULATION OF INTRINSIC ABSORPTION EDGE

The traveling domains are associated with (a) a strong acoustic intensity, (b) high electrical resistance, and (c) a high local electric field as determined by electrical probe measurements. In this section we wish to examine the possible role of each of these factors in producing the optical modulation.

A. Effect of High Field in Domain

It is known that the absorption edge of various solids can be altered by the application of high electric fields; the best known mechanism for this is the Franz-Keldysh effect.[20] This shows up at low absorption levels as primarily a broadening of the edge, toward longer wavelengths. Thus, although no experimental or theoretical analyses of the magnitude of the Franz-Keldysh effect have been made for GaSb, it is conceivable that the optical modulation observed in our present experiment could be caused by the Franz-Keldysh effect.[21] However, a number of specific tests indicates that the optical modulation is associated with the acoustic flux in the domains, rather than with high electric field *per se*. Fields as high as those measured in the domain, if deliberately applied to the sample without the formation of a domain, do not produce observable optical modulation. Several experiments supporting this view are presented below.

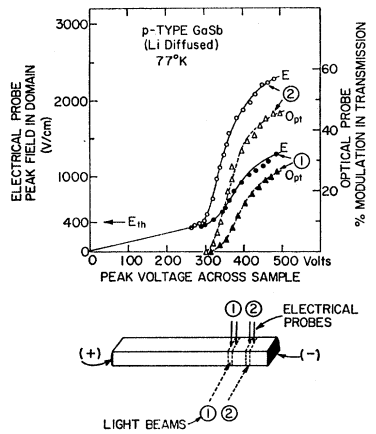

FIG. 11. Comparison of the variations of optical-modulation signal and electric field in domain for increasing voltage applied across the sample. The electric-field curves and the optical-modulation curves are labelled by E and Opt, respectively. Two sets of data are shown for probe positions (1) and (2) on the sample. The threshold field for domain formation is $E_{th}=400$ V/cm.

(i) In Fig. 11 we show plots of optical modulation ($\Delta I/I$) and the electrical field, measured at the peak in the domain as a function of the voltage applied across the whole sample at 77°K. The electric field was measured in the domain with two closely spaced (0.66 mm) electrical probes. A sample was chosen in which the spatial extent of the domain was very broad ($\approx$6 mm) compared with the optical and electrical probe. Thus we believe that the field in the domain was determined with quite sufficient accuracy. Measurements were made at two positions on the sample, giving

[19] A measure of the fields in the domain is given in Sec. VII. Similar emission signals on *n*-GaAs have been observed by D. L. Spears in our laboratory. Emission signals in *n*-GaAs related to sudden attenuation of the domain in I-shaped samples, and apparently not involving contact injection, have been recently discussed by A. Bonnot, Phys. Status Solidi **21**, 525 (1967).

[20] W. Franz, Z. Naturforsch. **130**, 484 (1958); I. V. Keldysh, Zh. Eksperim. i Teor. Fiz. **34**, 1138 (1958) [English transl.: Soviet Phys.—JETP **6**, 788 (1958)].

[21] Domains of high field in CdS have been followed by optical modulation by K. W. Böer *et al.* See, e.g., K. W. Böer, Phys. Rev. **139**, A1949 (1965). However, the domains were not acoustoelectric in origin, but were rather attributed to a decrease in free-electron density or mobility with increasing field strength. The optical modulation in this case was attributed to a Franz-Keldysh effect.

the data curves marked (1) and (2) in Fig. 11. The local electric field rises linearly till about 300 V is applied across the sample. At a threshold field of about 400 V/cm, the peak local field begins to deviate from ohmic behavior, as domains become detectable. At the same threshold voltage we note the appearance of the optical signal. No optical modulation is observed until an electrical domain is also observed. As the voltage across the sample is increased, the field in the domain rises very rapidly, as does the optical modulation. Thus there appears to be a strong correlation between the increase in the field in the domain and the increase in magnitude of the optical signal. However, on the same sample the threshold field is about 1000 V/cm at 195°K, and over 2000 V/cm at 297°K. Yet no optical modulation is observed in those cases until a domain is formed. Assuming there is *no* strong temperature dependence of the threshold[22] for observing the Franz-Keldysh effect in GaSb, we can conclude that at least at fields $\approx$2000 V/cm in the domain there is *no* contribution of the Franz-Keldysh effect to the optical modulation.

(ii) By using very short pulses it is possible to go to very high fields without allowing enough time for domain formation to occur. By applying a pulse of 0.25-μsec instead of 5-μsec duration, the threshold field at 77°K was found to increase from 400 to 900 V/cm. Again no optical modulation was observed until domain formation occurred.

(iii) For a given pulse length, the threshold field is a function not only of temperature but also of mobility and carrier concentration. In various Li-diffused samples, the threshold field at 77°K varied between 200 and 800 V/cm. Again no optical modulation is observed as long as the field in the observed region is ohmic and no domain has formed.

We conclude that both optical modulation and high domain field are consequences of the high acoustic intensity in the domain. Let us therefore consider the possible effects of the flux.

B. Effect of Intense Acoustic Flux

First, we shall briefly summarize the present state of our knowledge about the acoustic flux in the domain. Electrical and optical probe measurements show that the flux is spatially concentrated in a domain; it travels as a beam along a [110] direction. The orientation and the velocity of the domain ($\approx 2.8\times10^5$ cm/sec) identify the flux as consisting of piezoelectrically active fast shear waves. Our knowledge of the frequency spectrum is less direct. As a first approximation we assume the flux to have a central frequency corresponding to that for which the net gain is a maximum. From White's[23] linear theory of acoustic gain, the frequency of maximum gain is given as $\omega_m=(\omega_c\omega_D)^{\frac{1}{2}}$, where $\omega_c=\sigma/\epsilon$, σ is the conductivity and ϵ the dielectric constant of the material; $\omega_D=v_s^2/D$, where v_s is the velocity of sound and $D=\mu kT/e$ is the diffusion constant of the material. Using numbers appropriate to our material we obtain a value of $\omega_m\simeq10^{11}$ rad/sec. The above choice of ω_m is made without consideration of acoustic-attenuation processes. Since such losses increase with frequency, the frequency of maximum net gain is expected to be lower than ω_m. Therefore, we may take the frequency of maximum net gain to be roughly in the range of 10^{10}–10^{11} rad/sec. The theory used for estimating ω_m is valid for small flux signals, but we are dealing here with very strongly amplified flux. However, recent Brillouin-scattering measurements[6] of strongly amplified flux in CdS indicate that the frequency spectrum in an amplified domain is within the order-of-magnitude estimate made here from the linear theory. Thus the domain consists of a beam of acoustic waves, in a relatively restricted range of frequencies in a specified branch of the acoustic spectrum.

Next, we consider to what extent the flux is coherent. The amplification process, whether according to the traveling-wave picture or the stimulated phonon-emission picture, is inherently a coherent one. However, we know less about the nature of the starting flux. This is possibly quite noisy, and surely contains waves of various initial phases. Thus the amplified flux consists of a noisy superposition of waves of different frequencies and phases. It is evident that the flux can *not* be regarded simply as a "hot" phonon gas, such as would correspond to a local increase in lattice temperature, *nor* as a simple plane wave of very large amplitude.

Having established a picture of the flux, we turn now to a discussion of possible mechanisms for the modulation of the absorption edge. We first look for guidance from the known processes which determine the temperature dependence of the absorption edge. Two temperature-dependent processes are generally held to be important: lattice dilatation and lattice vibrations. The lattice dilatation can either decrease or increase the band gap. For GaSb it is known from hydrostatic pressure experiments[24] that the gap increases with increasing pressure; hence thermal expansion must produce a decrease in the band gap. Lattice vibrations also decrease the band gap. The latter effect arises from the fact that in the presence of lattice vibrations a transition producing an electron-hole pair requires an additional energy equal to the lattice interaction energies of the electron and the hole.[25] The sign of the lattice interaction energies or the so-called "self-energy" terms is such as to decrease

[22] The fact that these comparisons are made at different temperatures should not affect the validity of the argument. It would be very fortuitous if the critical field for observing the Franz-Keldysh effect just coincided with the threshold field for domain formation.

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

[24] A. J. Edwards and H. J. Drickamer, Phys. Rev. 122, 1149 (1961).

[25] H. Y. Fan, Phys. Rev. 82, 900 (1951); also E. J. Johnson, in *Semiconductors and Semimetals*, edited by R. K. Willardson and A. C. Beer (Academic Press Inc., New York, 1967), Vol. 3, p. 153.

the band gap. The self-energy term depends upon the specific nature of the scattering mechanism. In polar material such as III-V compounds, one would expect the dominant contribution to come from polar optical scattering. Experimental evidence indicates that the self-energy contribution to the thermal shift in the edge may be dominant. Thus, lattice dilatation accounts for only $\frac{1}{3}$ of the total variation of the energy gap with temperature in InSb, and only $\frac{1}{4}$ in InAs.[26]

We now consider the analogous effects for a domain of acoustic flux with the previously specified differences kept in mind. With regard to the self-energy term, the dominant contribution for the flux domain would have to arise from the piezoelectrical interaction with shear waves, which causes the very large drop of the current from ohmic value.[27] An additional contribution to the self-energy term from the shear phonons may be due to deformation potential interaction. The latter interaction is not expected for the spherical conduction band with minimum at $\mathbf{k}=0$, but is expected in the valence band where shear causes the splitting of the degeneracy at $\mathbf{k}=0$. Since the self-energy contributions to the shift in the edge would appear to be due to different scattering mechanisms for the domain and for increase in temperature, it is surely not meaningful to compare the edge shift due to temperature with that due to the domain.

A lattice-dilatation contribution in the domain is not to be expected for the long-wavelength shear waves. However, if the flux is very large, higher-order effects might produce lattice dilatation.

Another aspect of the lattice-vibration picture is that strong interaction of the carriers with phonons, resulting in very short collision times, could produce uncertainty broadening[28] of the energy states of the carriers and thus modify the absorption edge. The high resistance in the domain may be looked upon as representing a strong decrease in the carrier-momentum relaxation time due to stimulated emission of phonons. The resistance in the domain is observed to increase over the ohmic value by an order of magnitude. The corresponding energy-level broadening is compatible with the observed changes of 0.01–0.02 eV in the absorption edge.

So far we have concentrated on the electron-phonon interactions, and disregarded the coherent-wave aspects of the flux. From the latter point of view we should examine the effects of an ac shear strain and ac longitudinal piezoelectric field. As mentioned before, static shear lifts the degeneracy at the top of the valence band.[29] One of the bands moves up, the other down, the over-all effect being a decrease in the intrinsic gap. Should the shear strain in the domain be large enough to cause modulation by this mechanism, only a time and space average of the effect would be seen, not an ac modulation of the light. The ac aspects of the acoustic waves would be suppressed for several reasons: (a) The light beam passing through the crystal would encounter the superposition of the various frequencies and phases of the acoustic waves; (b) the width of the light beam is much larger than the acoustic wavelength (0.1–1 μ); (c) the optical-detection system is much too slow to see fluctuations in the 10^{10} cps range.

We have shown that the high electric field in the domain can not account for the optical modulation. However, the evidence presented did not preclude the possibility that the piezoelectric fields associated with the shear waves may be larger than the measured macroscopic field in the domain, hence capable of modulating the absorption edge. If the flux could be approximated by a single plane wave, it would not be unreasonable that the maximum piezoelectric field might be much larger than the measured field. However, in terms of our picture of the flux as a superposition of waves, it is very difficult to see how the piezoelectric field could be very much larger than the measured fields in a substantial portion of the domain.

In conclusion, there appear to be several mechanisms which can contribute in principle to the modulation of the intrinsic absorption edge by the intense acoustic flux in the domain. However, the task of distinguishing between these mechanisms and arriving at a quantitative description appears to be quite formidable, especially since the precise nature of the flux in the domain can not yet be specified. Another prerequisite for elucidation of the effect is the experimental determination of the modulated absorption edge with better resolution. In this respect, we have noted that a recent high-resolution study[5] in n-GaAs gives primarily a broadening rather than a pure shift in the edge. It remains to be determined whether such a result is common to the different III-V direct-gap semiconductors, or whether material- and specimen-dependent effects obscure the picture. The latter difficulties are present even in analyses of the ordinary, unmodulated absorption edge.

ACKNOWLEDGMENTS

We are indebted to Miss L. Roth for growing the p-GaSb ingots, to T. O. Yep and W. M. Becker for advice on the techniques of lithium diffusion, and to D. L. Spears for assistance with the spectral dependence measurements and for discussions of the mechanisms of optical modulation.

[26] J. R. Dixon and J. M. Ellis, Phys. Rev. 123, 1560 (1961).

[27] Although we attribute the optical modulation to the very strong shear waves that must be present, we can not exclude the possibility that it is really due to a byproduct component of the amplified waves, produced by nonlinear interactions among the intense shear acoustical waves. In view of the transient nature of the modulation signal, and its propagation with the velocity of the shear waves, any such byproduct flux would have to die very rapidly in the wake of the domain, or move along with it.

[28] A. Radkowsky, Phys. Rev. 73, 749 (1948); and also Ref. 25.

[29] G. L. Bir and G. E. Pikus, Fiz. Tverd. Tela 3, 3050 (1961) [English transl.: Soviet Phys.—Solid State 3, 2221 (1962)].

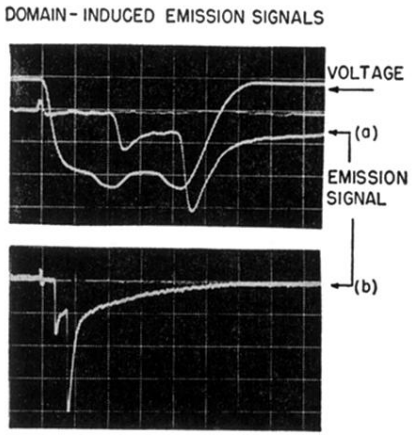

FIG. 10. Emission signals in Li-diffused p-GaSb at 77°K. (a) Superimposed voltage pulse containing two oscillations, and corresponding double emission pulse from two domains. Time scale is 1 μsec/cm. (b) Same emission signal with compressed time scale of 5 μsec/cm.

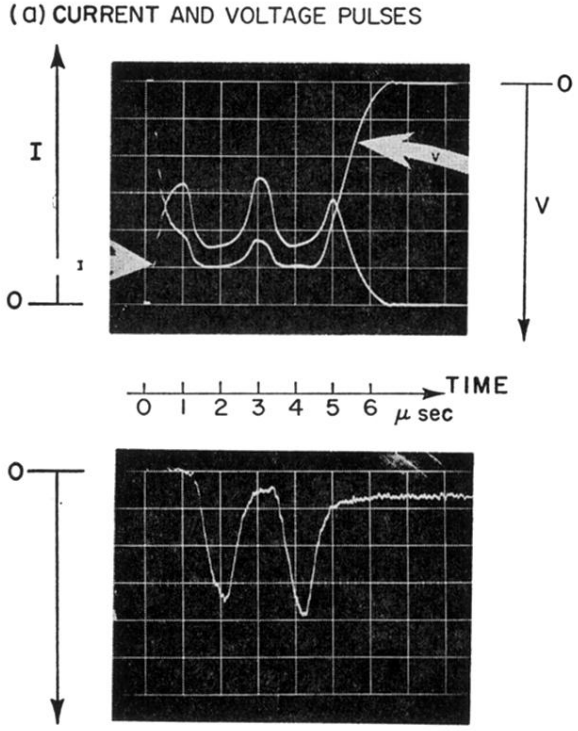

FIG. 2. Upper half: Traces of the voltage and the current pulses showing two periods of oscillation. Lower half: A representative optical signal produced by the passage of two domains past the light beam.

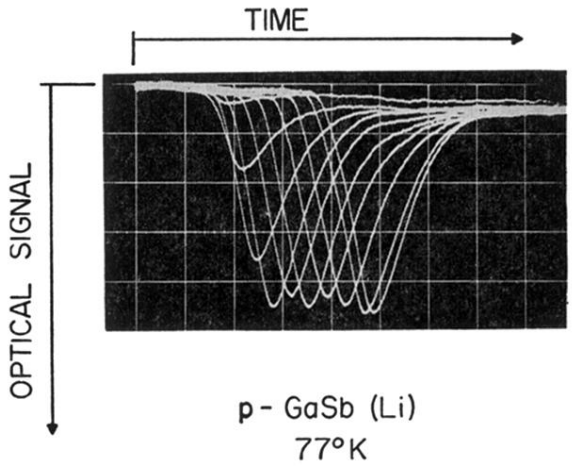

FIG. 3. A sequence of optical-modulation traces taken at an advancing series of positions along the sample, as the sample is moved normal to the incident light.

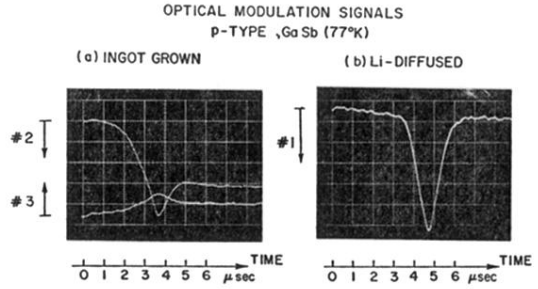

FIG. 7. Comparison of domain-induced modulation signals in as-grown and Li-diffused p-GaSb. Signal 1 at 1.6 μ corresponds to a *decrease* in transmission for an intrinsic excitation. Signal 2 at 1.7 μ corresponds to a *decrease* in transmission for a combination of intrinsic excitation, and transition from a deep acceptor impurity level to the conduction band (I–C transition). Signal 3 at 2.1 μ corresponds to an *increase* in transmission for a transition from the valence band to an acceptor impurity (V–I transition). The long-lasting tail on signals 2 and 3 are contributions due to very strong heating effects in the as-grown material, and present in much weaker form in the Li-diffused material.

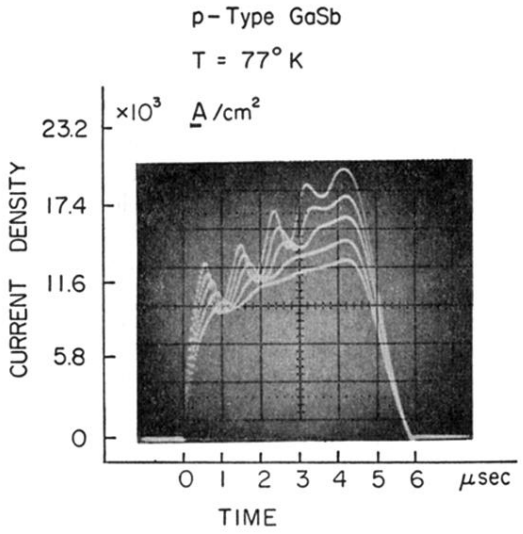

FIG. 8. Multiple current oscillations for as-grown p-GaSb; $T=77°K$, $p=3\times10^{16}/cm^3$, and $\mu=2000$ cm²/V sec. The gradual rise in current level shows the effect of heating in this material.