

background α_2 ;

$$r(E) = f(E) + \alpha_2. \quad (\text{A5})$$

$r(E)$ is obtained by putting in place of the scatterer a piece of the same material as the x-ray-tube target, and exciting it to fluorescence. From (A4) and (A5) one obtains

$$\frac{R(E) - \alpha_1}{r(E) - \alpha_2} = \beta + \frac{F(E)}{f(E)}, \quad (\text{A6})$$

and from (A6),

$$\frac{R(E) - \alpha_1}{r(E) - \alpha_2} = \beta, \quad (\text{A7})$$

for the intervals of values of E in which $F(E) = 0$. Therefore, from (A7) and the observed spectra $R(E)$

and $r(E)$, $F(E)$ is determined as well as $f(E)$ by (A4) and (A5) (see dashed line in Figs. 3, 4, 5), even in the case in which the scattering angle is only a few degrees and the components overlap.

From (A1), (A2), and (A3) one finds

$$F(E) = \int_{-\infty}^{+\infty} f(E_0) g(E - E_0) dE_0. \quad (\text{A8})$$

This result is of considerable importance because $f(E)$ and $F(E)$ are known functions, obtained from direct measurements. From the solution of (A8) for $g(E)$ one gets the ideal Compton spectrum without knowing $\sigma(E)$ and $\varphi(E)$, the apparatus profile and the true profile of the primary line, respectively.

Oscillatory Photoconductivity in InSb†

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The oscillations in the low-temperature photoconductive spectral response of p -type InSb are found to be strongly dependent on electric field strength in both intrinsic and extrinsic photoconductivity. The oscillatory structure gradually disappears at electric fields higher than ~ 20 V/cm. As a function of increasing temperature, the position of the minima of the oscillations shifts towards lower energies and the size of the oscillations decreases. A qualitative interpretation, consistent with all observations, shows that the primary reasons for oscillatory photoconductivity are: (a) the preferential momentum losses of carriers due to longitudinal optic phonon emission in the direction of the electrical potential gradient; (b) the fact that the steady-state distribution of carriers generated by photon absorption is drastically different from equilibrium.

I. INTRODUCTION

OSCILLATIONS in photoconductive spectral response have recently been observed in many semiconductors.¹ In this paper we report the main results of an extensive investigation of both the intrinsic and extrinsic oscillatory photoconductivity in InSb. In particular the dependence of the shape of the oscillations on electric field strength and on temperature have not been reported elsewhere. Partly because of these experiments, we present an interpretation of the phenomenon of oscillatory photoconductivity which differs in important respects from those given earlier. Our qualitative interpretation is borne out by a theo-

retical calculation of the photoconductive response with the help of the Boltzmann equation.²

II. EXPERIMENTAL

The preparation of InSb single crystals used in this work has been described elsewhere.^{3,4} Our samples generally contained 10^{13} to 10^{15} cm⁻³ excess acceptor impurities.

The photoconductive spectral response was measured with a Perkin-Elmer model 13 monochromator whose light beam was chopped at ~ 200 cps. A dc voltage was applied across the sample in series with a load resistor. The ac voltage across the load resistor was amplified and recorded. In this way, only the light-induced change in current is measured, i.e., the dc "dark current" is suppressed. For measurements of the extrinsic photo-

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¹ Table I summarizes the materials and types of optical transitions in which oscillatory photoconductivity has been observed.

² H. J. Stocker and H. Kaplan, following paper, Phys. Rev. **150**, 619 (1966); hereafter referred to as II.

³ We acknowledge the use of one high-purity single crystal of InSb supplied by Texas Instruments.

⁴ W. Engeler, H. Levinstein, and C. R. Stannard, Jr., J. Phys. Chem. Solids **22**, 249 (1961).

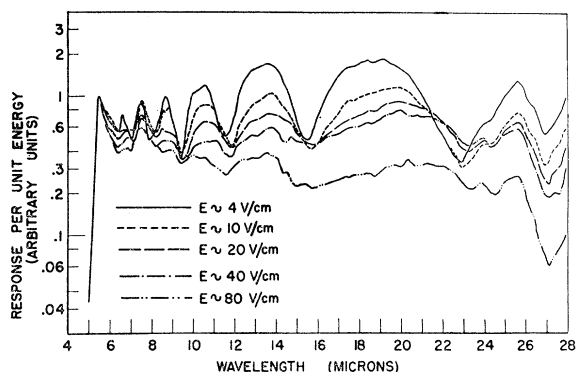


FIG. 1. Extrinsic photoconductive spectral response of a sample of Ag-doped InSb at $T \sim 7^\circ\text{K}$, for various electric field strengths. The relative magnitudes have been adjusted to unity at 5.6μ . The separation of the minima of the oscillations is equal to 0.0244 eV . The dip at 27μ is due to lattice absorption.

conductivity, it was generally necessary to eliminate higher energy scattered radiation, to which the sample would be much more sensitive. This was accomplished with an InSb filter, cooled to near liquid-helium temperature.

III. RESULTS

A. Extrinsic Photoconductivity

The main feature of the extrinsic spectral response in InSb and other materials is the occurrence of oscillations with minima at photon energies

$$E_n = E_i + n\hbar\omega_0, \quad (1)$$

where E_i is the ionization energy of the impurity in question and $\hbar\omega_0$ is the long-wavelength longitudinal

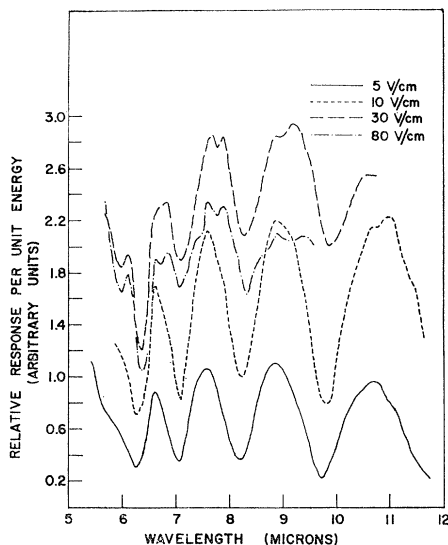


FIG. 2. Extrinsic photoconductive spectral response of a Ag-doped sample at $T \sim 7^\circ\text{K}$; with relative magnitudes for various electric field strengths maintained. Note that the photosignal at 80 V/cm is smaller than at 30 V/cm .

TABLE I. Experimental observations of oscillatory photoconductivity.

Material	Temperature range	Reference
(A) Extrinsic transitions		
InSb:Cu	$T < 12^\circ\text{K}$	a,b,c,d
InSb:Ag	$T < 12^\circ\text{K}$	b,c,d
InSb:Au	$T < 12^\circ\text{K}$	b,c,d
InAs:Mn	$T < 10^\circ\text{K}$	e
Ge:Cu	$T \sim 5^\circ\text{K}$	f,g
Ge:Zn	$5^\circ\text{K} < T < 27^\circ\text{K}$	f,h,g
Ge:Au	$T \sim 7^\circ\text{K}$	h,g
Ge:Ga	$T \sim 7^\circ\text{K}$	h
Ge:Be	$T \sim 5^\circ\text{K}$	i
Ge:Cd	$T \sim 5^\circ\text{K}$	i
Si <i>n</i> -type	$T \sim 78^\circ\text{K}$	j
(B) Intrinsic transitions		
InSb <i>p</i> -type	$4^\circ\text{K} \leq T \leq 50^\circ\text{K}$	k,l,d
InSb <i>n</i> -type	$T \sim 8^\circ\text{K}$	m
GaSb	$T \sim 4^\circ\text{K}$	l
CdS	$T \sim 4^\circ\text{K}$	n

a R. F. Blunt, Proc. IRIS 3, 2, 31 (1958).

b W. E. Engeler, H. Levinstein, and C. R. Stannard, Jr., Phys. Rev. Letters 7, 62 (1961).

c W. E. Engeler, H. Levinstein, and C. R. Stannard, Jr., J. Phys. Chem. Solids 22, 249 (1961).

d C. R. Stannard, Jr., Ph.D. thesis, Syracuse University, 1963 (unpublished).

e M. Schultz, RCA (private communication).

f C. Benoit a la Guillaume and J. Cernogora, J. Phys. Chem. Solids 24 383 (1963).

g V. A. Besfamil'Naya, I. A. Kurova, N. N. Ormont, and V. V. Ostroborodova, Zh. Eksperim. i Teor. Fiz. 48, 1588 (1965) [English transl.: Soviet Phys.—JETP 21, 1065 (1965)].

h J. A. Kurova and N. N. Ormont, Fiz. Tverd. Tela 6, 3708 (1964) [English transl.: Soviet Phys.—Solid State 6, 2970 (1965)].

i N. D. Tyapkina and V. S. Vavilov, Fiz. Tverd. Tela 17, 1252 (1964) [English transl.: Soviet Phys.—Solid State 7, 1010 (1965)].

j I. V. Kryukova, Fiz. Tverd. Tela 17, 2551 (1965) [English transl.: Soviet Phys.—Solid State 7, 2060 (1966)].

k H. J. Stocker, C. R. Stannard, Jr., H. Kaplan, and H. Levinstein, Phys. Rev. Letters 12, 163 (1964).

l M. A. Habegger and H. Y. Fan, Phys. Rev. Letters 12, 99 (1964).

m D. N. Nasledov, Yu. G. Popov, and Yu. S. Smetanikova, Fiz. Tverd. Tela 6, 3728 (1964) [English transl.: Soviet Phys.—Solid State 6, 2989 (1965)].

n Y. S. Park and D. W. Langer, Phys. Rev. Letters 13, 392 (1964).

optical phonon energy of the host lattice. Table I summarizes the published data. We have studied the dependence of the shape of the oscillations on electric field strength for a number of samples of InSb doped with Ag, Au, and Cu. Both the magnitude of the photocurrent and the spectral response depend nonlinearly on electric field strength. At fields of the order of 20 V/cm the oscillations are noticeably reduced in relative magnitude and disappear completely, if the field is increased further. We illustrate the typical behavior found in Figs. 1 and 2 for two samples of InSb:Ag. Figure 1 shows the dependence of the shape of the spectral response, plotted versus wavelength in the $5\text{--}28 \mu$ region. The relative magnitudes have been adjusted to unity at 5.5μ in order to emphasize the change in shape. The minimum at 23μ corresponds to $n=1$ in Eq. (1), the minimum at 16μ to $n=2$, etc. The dip at 27μ is due to lattice absorption. Figure 2 shows the spectral response in the $5.5\text{--}12\text{-}\mu$ region, with relative magnitudes maintained. Note that the photocurrent for an applied field of 80 V/cm is actually lower than the photocurrent at 30 V/cm over most of the spectrum. Because of the low signal-to-noise ratio encountered at the higher field strengths, not much

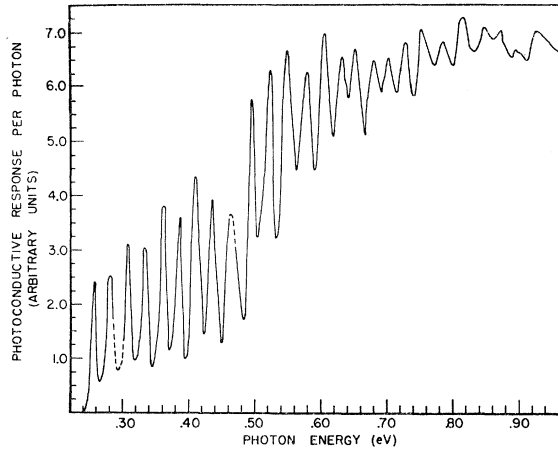


FIG. 3. Intrinsic photoconductive spectral response of a sample of *p*-type InSb at $T \sim 8^\circ\text{K}$. The separation between minima of the oscillations increases slightly at higher photon energies because of the curvature of valence and conduction bands.

significance should be attached to some of the smaller bumps in the curves of Figs. 1 and 2, but the decrease in photocurrent at higher fields has definitely been established. We return to the interpretation of these observations in Sec. IV B.

B. Intrinsic Photoconductivity

Figure 3 shows the spectral response for a *p*-type⁵ sample of InSb at liquid helium temperature. No less than 25 oscillations can be identified. The spacing between minima in the intrinsic response, in contrast to the extrinsic case, is not exactly equal to the LO phonon energy of InSb at $q=0$ ($\hbar\omega_0=0.0244$ eV). If, however, the data were plotted versus initial excitation energy of the electron in the conduction band (i.e., excitation energy immediately after the optical transition) rather than versus photon energy the spacing would be exactly equal to $\hbar\omega_0$. This can be seen from Fig. 4, where we have plotted the photon energy of each minimum versus the number of that minimum. If the valence and conduction bands, separated by an energy gap E_g , were both assumed to be exactly parabolic with respective effective masses m_h and m_e , the electronic excitation energy E_e due to a direct optical transition with photon energy $h\nu$ would be given by

$$E_e = (h\nu - E_g) / (1 + m_e/m_h). \quad (2)$$

At photon energies higher than 0.7 eV, the non-parabolic nature of the bands should, according to the band structure calculation of Kane,⁶ become important. From our results, which are of course subject to the

⁵ All samples in which intrinsic oscillatory photoconductivity was observed were *p* type, with excess acceptor concentrations in the range 10^{13} to 10^{15} cm^{-3} . Two *n*-type samples with approximately 10^{15} electrons per cm^3 were measured, but no oscillatory structure was found. Nasledov *et al.* have recently found oscillatory structure in *n*-type InSb, with $n \leq 10^{14}$ cm^{-3} .

⁶ E. O. Kane, J. Phys. Chem. Solids **1**, 249 (1957).

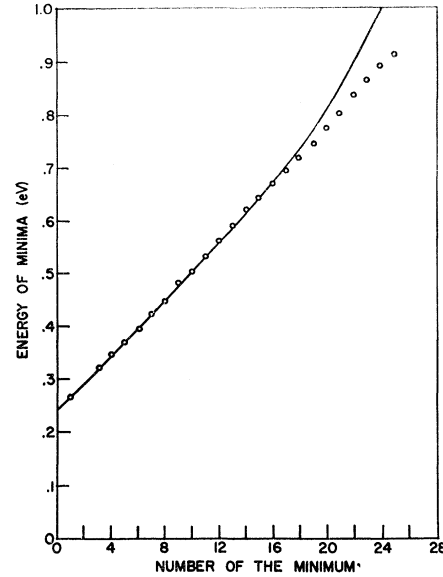


FIG. 4. Photon energy of the minima of the intrinsic oscillations of Fig. 3 versus number of minimum. The solid line was calculated from Kane's band structure and the model proposed in this paper. The deviation at large photon energies is within the bounds of the experimental uncertainty of the band structure parameters.

correctness of our interpretation of the oscillations, it appears that these nonparabolic effects are somewhat less important.

Our "experimental" value of the factor $1 + (m_e/m_h)$ from Fig. 4 is 1.078 ± 0.003 , in agreement with what is known about electron and heavy hole effective masses.

The shape of the intrinsic oscillations is dependent on electric field strength in a manner similar to the extrinsic case. Figure 5 shows the first two oscillations

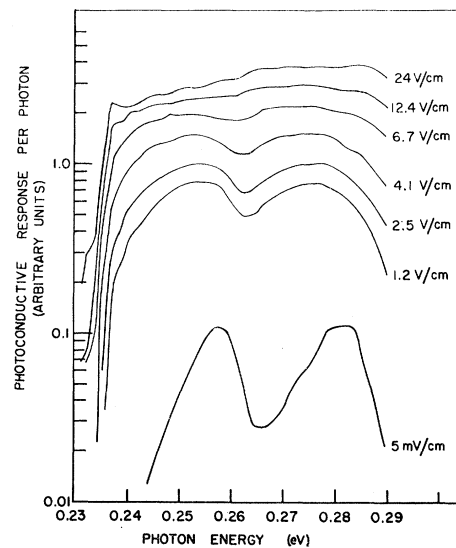


FIG. 5. Electric field dependence of the intrinsic photoconductive spectral response of InSb at $T \sim 8^\circ\text{K}$. Only the first two oscillations are included. At large electric fields, the oscillations disappear completely.

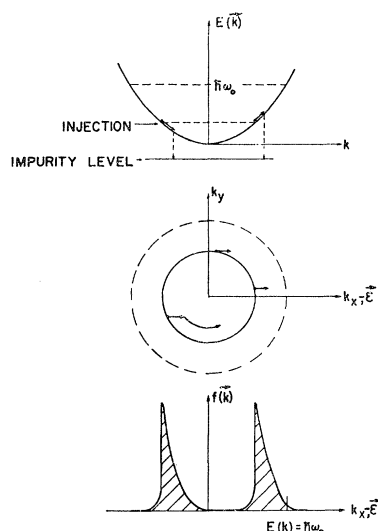


FIG. 6. Illustration of the basic mechanism responsible for oscillatory photoconductivity. Explanation in text, Sec. IV A. Case (a), injection at $0.4\hbar\omega_0$. Top graph: conventional picture of the conduction band. Middle graph: plane section in momentum space parallel to electric field. Bottom graph: distribution function along a direction parallel to the electric field.

(between 0.23 and 0.29 eV) of a *p*-type InSb sample for various electric field strengths.

C. Temperature Dependence

The temperature dependence of the intrinsic spectral response was measured for several samples in the range $T=4^\circ\text{K}$ to $T\cong 70^\circ\text{K}$. The shape of the oscillations remains relatively unchanged in the range $4^\circ\text{K} \leq T \leq 30^\circ\text{K}$. Above $T=30^\circ\text{K}$ the magnitude of the oscillations decreases rapidly and for $T \geq 60^\circ\text{K}$ no oscillatory structure can be detected. The position of the minima and maxima of the oscillations is observed to shift continuously towards lower photon energies as the temperature is increased. This shift is due to the gradual change of the energy gap in InSb, which decreases from 0.235 eV at $T=4^\circ\text{K}$ to about 0.210 eV at $T\cong 70^\circ\text{K}$.

D. Magnetic Field Measurements

The photoconductive spectral response was measured in the presence of magnetic fields of varying magnitude and orientation of the sample relative to the field. Measurements up to 8.5 kG gave no indication of any displacement of the oscillations, although the magnitude of the photocurrent was affected in a manner to be expected on the basis of simple magnetoresistance effects.

E. Absorption Spectrum

An earlier interpretation⁷ of the oscillations in the photoresponse assumed that similar structure existed in the absorption spectrum. We have investigated the optical absorption spectrum for both intrinsic and extrinsic transitions and found no evidence of any oscillatory structure.

⁷ W. E. Engeler, H. Levinstein, and C. R. Stannard, Jr., Phys. Rev. Letters **7**, 62 (1961).

IV. DISCUSSION

Among the many factors influencing the photoconductivity in a solid, the following are the most important ones for our consideration:

(1) The initial distribution of electrons in the conduction band (or holes in the valence band) immediately after absorption. In the extrinsic case the impurity energy level is discrete, and the initial distribution is therefore expected to be nearly monoenergetic. (The optical transition is likely to be direct one, i.e., involving no phonons.) In the case of intrinsic transitions, the initial distribution depends on the structure of both valence and conduction bands. If both bands are spherical, and the transition again a direct one, the initial distribution of electrons or holes will also be monoenergetic. In InSb the conduction band is spherical, and the heavy hole band is nearly spherical. At photon energies higher than about 0.8 eV the anisotropy of the heavy hole band causes the injection energy in the conduction band to spread considerably. This is one of the factors responsible for the "flattening" of the oscillations at higher photon energies. The density of states available for light-hole-band-to-conduction-band transitions is only about 30% of the total and will be neglected for the purpose of this discussion.

(2) The steady-state distribution of electrons (holes) in the conduction (valence) band. One is used to thinking that carriers injected into an energy band relax very quickly, by various mechanisms, to a near equilibrium distribution. However, this is not the case in semiconductors at low temperatures, and this is the main clue to the understanding of oscillatory photo-

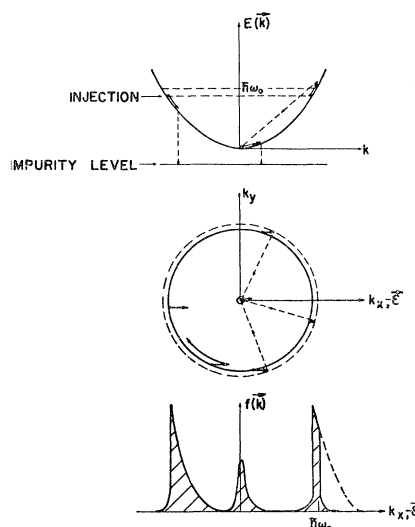


FIG. 7. Illustration of the basic mechanism responsible for oscillatory photoconductivity. Explanation in text, Sec. IV A. Case (b), injection at $0.9\hbar\omega_0$. Top graph: conventional picture of the conduction band. Middle graph: plane section in momentum space parallel to electric field. Bottom graph: distribution function along a direction parallel to the electric field.

conductivity. The processes which determine the establishment of the steady-state distribution are:⁸

(a) Longitudinal optic (LO) phonon emission. Interaction of electrons with LO phonons is strong, causing rapid emission of LO phonons if electrons have energies larger than one LO phonon energy ($\hbar\omega_0$) above the bottom of the conduction band. In InSb, the time for emission of one LO phonon is $\tau_0 \sim 10^{-12}$ sec, much shorter than any other time of importance. An electron injected at energy $(n+0.5)\hbar\omega_0$ rapidly emits n LO phonons of energy $\hbar\omega_0$, and therefore is found at energy $0.5\hbar\omega_0$ after a time of $n \times 10^{-12}$ sec. We can call this a "cascade" process. The contribution to the current the electrons make while "cascading" down in energy is negligible, and it is therefore sufficient to look at what happens in the range between 0 and $1 \hbar\omega_0$.

(b) Acoustical phonon emission and absorption. At low temperatures ($T < \sim 40^\circ\text{K}$), energy losses due to acoustical phonon interaction are small compared to the rate of removal by recombination.

(c) Recombination. The lifetime τ_l of carriers in semiconductors can be quite short because of the efficiency of impurities as capturing centers. For electrons in InSb, τ_l is of the order 10^{-10} sec. A short lifetime tends to prevent the establishment of an equilibrium distribution.

(d) Impurity scattering. Elastic scattering by impurities tends to keep carriers on the same energy shell; i.e., to keep the distribution from spreading over a wider energy range.

(e) Electron-electron interaction. The steady-state densities of electrons (holes) generated are small (less than 10^{11} cm^{-3}), so that this factor is negligible.

A. Primary Mechanism Responsible for Oscillatory Photoconductivity

A simple physical picture of the basic mechanism responsible for the oscillations is illustrated in Figs. 6, 7, and 8. The "life history" of electrons injected into the conduction band is schematically indicated for injection: (a) at $\sim 0.4\hbar\omega_0$, well below one LO phonon energy (Fig. 6), (b) at $\sim 0.9\hbar\omega_0$, close to the LO phonon energy (Fig. 7), and (c) at $\sim 1.4\hbar\omega_0$, above the LO phonon emission threshold (Fig. 8).

In the top graph for each case we indicate what happens to the conventional picture of a parabolic energy band. In the middle graph a plane section of momentum space parallel to the electric field is shown. In momentum space, injection occurs on a sphere of constant energy; in our two dimensional picture it occurs on a circle. In the bottom graph, we plot the distribution function $f(k)$ along a direction parallel to the electric field \mathbf{F} [where $f(k)$ measures the probability of an electron with momentum k].

⁸ For more detailed and quantitative discussion, see II.

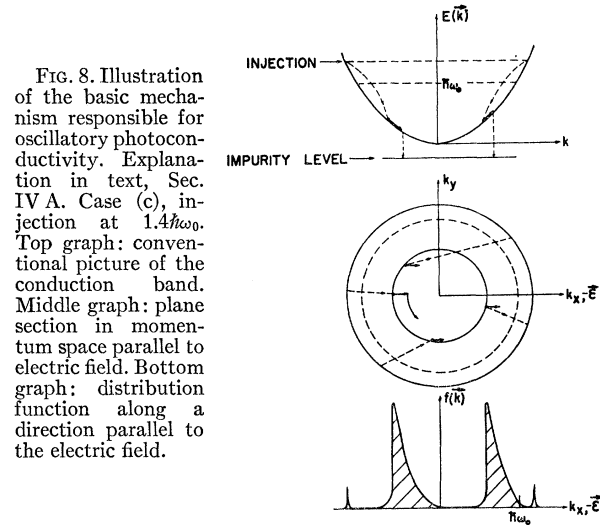


FIG. 8. Illustration of the basic mechanism responsible for oscillatory photoconductivity. Explanation in text, Sec. IV A. Case (c), injection at $1.4\hbar\omega_0$. Top graph: conventional picture of the conduction band. Middle graph: plane section in momentum space parallel to electric field. Bottom graph: distribution function along a direction parallel to the electric field.

Electrons gain or lose energy due to the electric field, depending on whether the initial momentum is in the same direction as or opposite to the electric field.

In Fig. 6, case (a), nearly all electrons make a transition out of the conduction band (e.g., a transition to shallow donor states with emission of acoustical phonons) before they reach one LO phonon energy. The distribution is sharply centered near the points of injection and thus drastically different from an equilibrium distribution. The fact that the electron distribution is sharply peaked is essentially due to the relative inefficiency of the acoustical phonon scattering, which would quickly establish a near equilibrium distribution at high temperatures. In addition, shallow impurity states are known to be efficient capturing centers, so that electrons cannot drift very far before they get removed from the conduction band.

In Fig. 7, case (b), some of the electrons on the right-hand side reach $E = \hbar\omega_0$, rapidly emit one LO phonon, and reappear at the bottom of the conduction band before they finally also get captured by an impurity. It is evident that the electrons lose momentum to the lattice by this LO phonon emission process and since the net momentum lost is in the direction of the electric potential gradient, the electric current is reduced; the spectral response will show a dip at this point.⁹

In Fig. 8, case (c), the electrons are injected at energies above the emission threshold. They immediately (within 10^{-12} sec in InSb) emit an optical phonon and make a transition to a state with energy $\hbar\omega_0$ smaller. The distribution is identical to case (a), except for an additional small spike at the injection

⁹ One might ask whether it would not be possible for the electron distribution to become such that the net momentum would be in the direction of the electric field. In that case the net electrical charge flow would be opposite to the electric potential gradient, i.e., the photoconductor would have a "total negative resistance." The calculations in II show that such an unusual behavior might indeed be expected under certain conditions, but it is at present not clear whether these conditions are experimentally realizable.

energy. The photocurrent, of course, is also (within less than a few percent) the same as in (a). The reason that in this case LO phonon emission does not reduce the current is that momentum is lost *equally* in all directions with net effect zero, not preferentially in the $-\mathbf{F}$ direction as in case (b).

It should be apparent that injection at $E = (N+0.4)\hbar\omega_0$ produces the same distribution (and hence the same photocurrent) as injection at $E = (n-1+0.4)\hbar\omega_0, \dots, E=0.4\hbar\omega_0$ apart from small additional spikes. Thus, the spectral response will show a repetition of the pattern between $E=0$ and $1\hbar\omega_0$, i.e., oscillations. The primary reason for the occurrence of oscillatory photoconductivity is thus the preferential loss of momentum due to LO phonon emission. An energy dependence of lifetime and/or scattering, to which the oscillations were attributed in earlier work,^{10,11} is thus not necessary for their existence, although it will influence their shape. This is shown rigorously in II.

B. Detailed Shape of the Spectral Response

If injection is exactly monoenergetic (as in the extrinsic case), the exact shape of the oscillations depends on: (1) the variation with energy of the electron lifetime due to recombination, (2) the energy dependence of the elastic scattering probability, (3) the electric field strength. If the electric field is small, the distribution is sharply peaked as shown in Figs. 6 to 8. The spectral response therefore reflects the energy dependence of both lifetime, $\tau_l(E)$ and elastic scattering time, $\tau_1(E)$. It can be shown¹² that the photocurrent for a nearly monoenergetic distribution is given by

$$\mathbf{J} = (e^2/m^*)\mathbf{F}N\tau_l(E)\tau_1(E) = e\mathbf{F}N\tau_l(E)\mu(E), \quad (3)$$

where N is the number of carriers injected per second and $\mu(E) = e\tau_1(E)/m^*$ the mobility. The fact that both τ_l and τ_1 are strongly increasing functions of energy explains the rather large width of the dips in the spectral response at nearly vanishing electric field strengths. On the basis of the primary mechanism

¹⁰ H. J. Stocker, C. R. Stannard, Jr., H. Kaplan, and H. Levinstein, Phys. Rev. Letters **12**, 163 (1964).

¹¹ M. A. Habegger and H. Y. Fan, Phys. Rev. Letters **12**, 99 (1964).

¹² H. J. Stocker, Ph.D. thesis, Syracuse University, 1965 (unpublished). Copies available on request.

alone, one would expect the dip to be much narrower, as can be seen from the theoretical curves in II.

At higher fields, the distribution is more spread out. A significant fraction of electrons therefore reaches the energy of one LO phonon, even if injection is at $0.4\hbar\omega_0$ [case (a)]. The effects of LO phonon emission are thus seen over a wider range of injection energies at higher fields than at low fields. The dip in the spectral response near $E=\hbar\omega_0$ thus widens as the electric field is increased, and its magnitude decreases. The effects due to energy variation of lifetime and mobility are, of course, also gradually smeared out as the electric field is increased.

In the intrinsic case the shape of the spectral response may be further affected by a non-monoenergetic injection. In InSb, in particular, electrons transferred from the light hole band are injected at a lower energy than those from the heavy hole band. The expected position of the minima of the oscillations due to light-hole-conduction-band transitions, which can be estimated from the known band structure of InSb,⁶ very nearly coincide with minimas due to heavy-hole-conduction-band transitions and are thus not directly visible.¹³ It should further be pointed out that part of the photoconductive signal is contributed by holes "generated" by the band to band transitions. The percentage contribution can vary greatly from sample to sample, because lifetime and impurity scattering time for both electrons and holes are sensitive to the types and concentration of impurities present. This probably accounts for the experimental observations that in some samples the amplitude of the oscillations can be as large as 70% of the total photosignal, while in others only 20% or less. The photocurrent due to heavy holes alone should also show oscillatory structure, but because of the relatively small curvature of the heavy hole band, it would have a much larger period than the component due to electronic current.¹⁴

ACKNOWLEDGMENTS

We would like to thank J. Wright for technical assistance and Professor H. Kaplan for many discussions.

¹³ See Fig. 1 in Ref. 7.

¹⁴ The first minima, based on our model, would occur at a photon energy of about 0.48 eV.