larger perturbation on the lattice dynamics are accompanied, instead, by perfect-crystal phonons since their spatial extension is such as to cover a larger region which is not appreciably perturbed by the exciton. The two cases examined here may in a way be analogous to the interconfigurational and intraconfigurational transitions of Sm^{++} ions in alkali halides.[11] We note also that the Huang-Rhys factor, i.e., the average number of phonons which accompany the electronic transitions, a measure of the linear coupling between electron and phonons, is larger for $n = 2$ excitons in agreement with a similar observation in CuCl.[12,13] In fact the estimated values of the Huang-Rhys factor, i.e., the ratio of the first to the zeroth line, are approximately 0.1 for NaBr, 0.2 for LiI,[2] and 1 for KI, $n = 2$.

A comparison with the projected densities of states relative to the lattice vibrations of KI and LiI[6] shows that the phonons emitted during the exciton (LiI, $n = 1$ and KI, $n = 2$) creation are of symmetry Γ_1. It is found that the peaks of the Γ_1 distribution, relative to the negative site, occur at ~16 meV for KI and ~36 meV for LiI in very close agreement with the values of the splitting reported above.

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DYNAMIC MEASUREMENT OF ELECTRON ENERGY RELAXATION IN InSb†

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We have measured the time dependence of the hot-electron current following a step variation in the applied electric field in n-InSb at 4.2°K. We obtain the average electron energy as a function of electric field, as well as the energy dependence of both the mobility and the energy relaxation rate.

Transport phenomena in strong electric fields are dependent on the details of the electron-phonon coupling. In this Letter, we report dynamic measurements of the electron-phonon relaxation in n-type InSb at helium temperatures. Our method[1] allows the direct determination of the electric field dependence of the mean electron energy ϵ, and consequently the energy dependence of both the mobility μ and the electron-phonon interaction.

One of the first studies of low-temperature transport phenomena in InSb was that of Sladek,[2] who estimated the electron-phonon coupling constants from the field dependence of the electron mobility. Preliminary dynamic measurements were carried out by several authors,[3,4] while more detailed results were reported by Kinch[5] and Lifshits, Oleinikov, and Shulman.[6] These measurements present conflicting views of the dominant energy exchange mechanism and are subject to certain experimental and theoretical difficulties which we shall discuss further on.

In the present work, we study the electron dynamics in the transition between one steady state and another. More specifically, we measure the time dependence of the current density j following a small step variation ΔE in the electric field E (see Fig. 1). The average energy satisfies the usual energy-balance equation

$$n\,d\epsilon/dt = \vec{E}\cdot\vec{j} - nP, \qquad (1)$$

where n is the electron density and P is the pow-

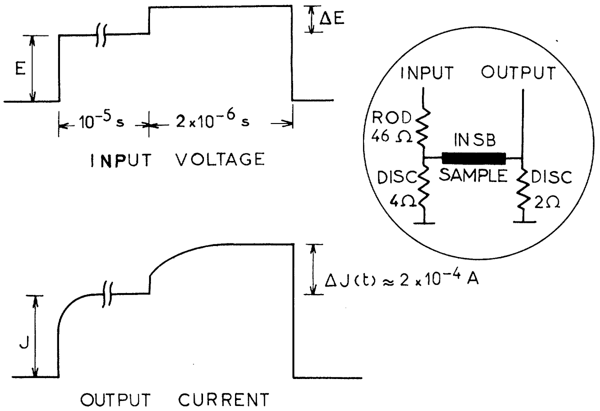

FIG. 1. Pulse configuration and current response. Inset shows sample circuit.

er transferred to the lattice per electron.

A step variation ΔE in the field results in an essentially instantaneous current jump, since the momentum relaxation time is short (10^{-13} to 10^{-12} sec) compared with times of experimental interest. This initial jump is followed by a slow variation of the energy towards its steady-state value corresponding to the field $E+\Delta E$, and is accompanied by a current variation, since the mobility is energy dependent.

We construct a simple physical model by assuming that, for the time scale of interest, the physical parameters depend only on the instantaneous average energy $\epsilon(t)$. Thus the current density, at constant concentration n, is given by $j = ne\mu(\epsilon)E$, where μ is the energy-dependent mobility. Inserting this into Eq. (1) gives for the energy variation $\Delta\epsilon(t)$, in the linear approximation,

$$\Delta\epsilon(t) = 2e\mu E\Delta E\tau(1-e^{-t/\tau}),$$

where

$$\tau^{-1} = P(d/d\epsilon)\ln(P/\mu).$$

The time dependence of the current is given by the same exponential, whose time constant we measured. Once τ is known as a function of E, the average energy is simply calculated from

$$\epsilon(E)-\epsilon(0) = (2/n)\int_0^E j(E)\tau(E)dE \qquad (2)$$

which allows us to determine the energy dependence of μ and P.

In our experiments, the "steady-state" field E and the incremental field ΔE are pulses provided, respectively, by a 214B Hewlett-Packard pulse generator and by the synchronized output of a Hewlett-Packard 188A sampling oscilloscope. The pulses, after appropriate attenuation, are superimposed through a matched tee and are applied to the sample holder through a 50-Ω coaxial system. A schematic of the sample circuit is shown in the inset of Fig. 1. For reasons of compactness, both the sample and resistors are immersed in the helium bath. This arrangement provides us with an essentially constant-voltage source, with an ultimate capability of 0.15-nsec rise time. The current is measured as a voltage drop across the 2-Ω disk resistor (see inset of Fig. 1), which after amplification by a Keithley 104 wide-band amplifier is fed into the sampling oscilloscope, equipped with a 185 B plug-in unit. Since we work with small ΔE's, the corresponding currents are small and so is the signal-to-noise ratio.

The signal is extracted from the noise by a Nuclear Data 801 multichannel analyzer at the rear output of the sampling oscilloscope, and is displayed on an X-Y recorder. Very clean exponential behavior was observed, and the τ's were determined from semilog plots after corrections for the finite source impedance. The bias field E was in the range 40-400 mV/cm while ΔE was typically 5% of E and the output signal was a fraction of a millivolt. The measured times τ were in the range 10-500 nsec.

The measurements were performed on a series of n-type InSb samples with carrier concentrations in the range 2×10^{13}-3.6×10^{14} cm^{-3}. The samples are rectangular parallelepipeds, whose dimensions are typically $1\times1\times10$ mm^3, and are provided with indium alloyed contacts. Hall effect measurements at saturating magnetic fields (up to 3 kG) were carried out throughout the electric field range in order to verify that the electron density is indeed constant, within 1.5%.

Severe experimental difficulties were encountered with all samples in the concentration range 2×10^{13}-8×10^{13}. The τ measured in these samples depends on the time interval between the application of the bias field E and the incremental field ΔE. In fact, a continuous increase of τ is observed, a saturation value being finally reached after delays of the order of milliseconds.[7] This slow variation is accompanied by a conductivity change on the same time scale. However, we have not studied this process in detail, and since an unambiguous determination of τ in these samples is impossible, they were discarded.

In Fig. 2 is shown the electric field dependence of τ as well as that of the electron temperature T_e. Here T_e is defined as the temperature appearing in the Fermi distribution and is chosen to reproduce the average energy ϵ, as deduced

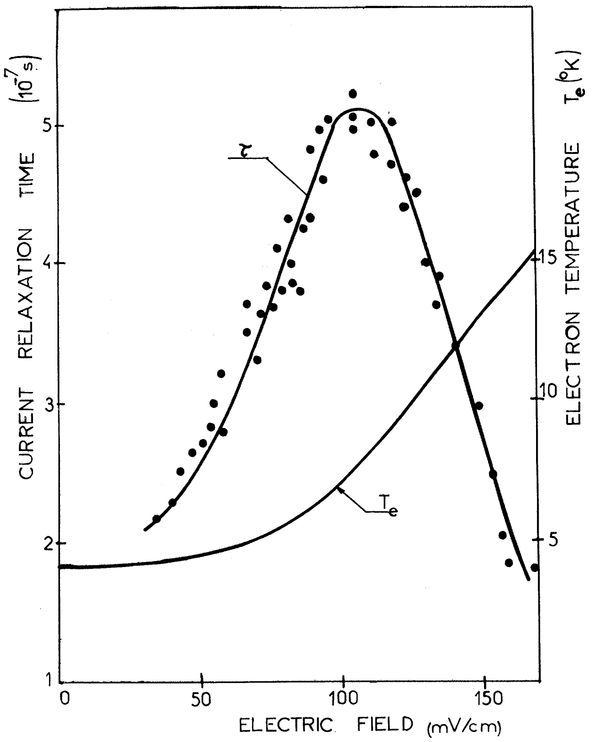

FIG. 2. Measured relaxation time and electron temperature as functions of the electric field, for a sample with $n = 1.19 \times 10^{14}$ cm^{-3} and at a lattice temperature of 4.2°K

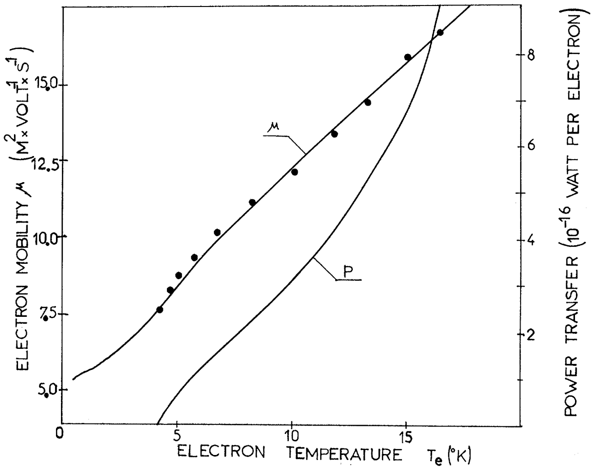

FIG. 3. Comparison of dynamic (closed circles) and static (solid curve) determinations of mobility μ as a function of the electron temperature. Also shown is the energy dependence of the power P transferred to the lattice.

from Eq. (2). Its role here is simply that of a convenient parameter for characterizing the average electron energy.

An independent, although indirect, method for determining the field dependence of ϵ is also possible in the range where impurity scattering dominates the mobility. In this case, the momentum relaxation time depends only on the average electron energy and has no explicit lattice-temperature dependence. If one then assumes that the electron distribution function in the presence of a strong electric field is adequately represented by a displaced thermal equilibrium distribution with an effective temperature T_e, one can simply deduce the field dependence of T_e by equating the mobility in a given field E with the Ohmic mobility measured at lattice temperature T_e.

An important aspect of the present work is to verify the validity of this latter procedure by comparing it with our dynamic measurements. We see indeed from Fig. 3 that these two independent experiments are in very good agreement, which suggests in addition that our analysis based on an average energy is a justified approximation in this range. Here again, no agreement between the two methods was obtained for samples in the range 2×10^{13}-8×10^{13} cm^{-3}.

Also shown in Fig. 3 is the average energy relaxation rate per electron as a function of electron temperature. A knowledge of this quantity is in principle sufficient for the determination of the details of the electron-phonon interaction. The most straightforward analysis of the latter result would consist in calculating the power transfer via both piezoelectric and deformation-potential interactions, as a function of mean electron energy, and comparing with experimental results. This had indeed been done by several authors.[5,6]

We feel however that the problem is far more complicated than this, and would require a significant theoretical advance in order to take adequately into account some of the following difficulties. First of all, the usual phonon-induced transition rates completely neglect impurity scattering, while in InSb, $\omega\tau_I \ll 1$, where ω is the relevant phonon frequency and τ_I is the impurity relaxation time. Momentum and energy conservation imply that the typical phonon wave vectors of importance are of the order of the average electron wave vector and therefore $\hbar\omega \simeq (\epsilon m_e s^2)^{1/2}$ with m_e the effective mass and s the sound velocity. For InSb, $\omega\tau_I < 0.1$, and therefore impurity scattering cannot be neglected in the electron-phonon interaction. Even worse is the fact that $kl_I \simeq \epsilon\tau_I\hbar^{-1} \sim 1$, where k is the electron wave vector and l_I the electron mean free path for impurity scattering. We emphasize that even for degenerate samples in the 10^{14}-cm^{-3} range, $kl_I \sim 1$.

This raises serious questions as to the validity of the Boltzmann equation and the nearly-free-electron description of the electronic states. Several attempts have been made to bypass some of these problems by explicitly introducing relaxation effects in the electron-phonon interaction. Gunn,[8] for example, has replaced the usual Fermi "golden rule" by a Wigner-Breit type theory, which attributes a certain lifetime broadening to the electronic states. It is also possible to introduce these effects phenomenologically by adding a relaxation term to the usual density-matrix kinetic equation. It would be desirable to treat the electron states in the presence of impurities by methods similar to those employed in Green's-function theory of the multiple scattering problem,[9] but here again most of these results are invalid for $kl_t \sim 1$. We are presently studying this problem. Finally we wish to stress that all determinations of the deformation-potential constant in InSb are subject to the same criticism, since these problems have not been dealt with adequately. This might explain the rather large spread in the deformation potential values reported in the literature.[10-13]

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ABSORPTION OF OXYGEN IN SILICON IN THE FAR INFRARED

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An absorption line of oxygen in silicon has been observed at 29.3 cm^{-1} at 1.8°K. Assignment to oxygen has been confirmed by observation of the oxygen isotope effect. Effects of uniaxial stress on the line have been measured. Additional lines observed at 37.7, 43.5, and 48.9 cm^{-1} when the crystals are heated to 35°K are assigned to a bending vibrational mode of Si_2O.

Many investigations have been made in the past of the absorption of oxygen in silicon in the near infrared.[1-4] It has been proposed[1] that oxygen dissolves interstitially in silicon forming a complex which may be approximately described as Si_2O. The intense 9-μ absorption has been ascribed[2,3] to the antisymmetric stretching mode of the nonlinear Si_2O complex. There is also the possibility of motion of the oxygen in the plane perpendicular to the Si-Si axis; structure observed on the 9-μ band[2,3] suggests the presence of low-lying quantized states associated with such motion.

We have extended the investigation of oxygen in silicon into the far infrared where we have observed absorption features associated with an in-plane A_1 bending motion of the Si_2O complex. These new observations and their interpretation will enable a resolution of most of the outstanding problems[2-4] concerning the motion of oxygen in silicon.

The dominant far-infrared line due to the ^{16}O isotope appears at 29.3 ± 0.1 cm^{-1} at 1.8°K. The linewidth at 1.8°K is less than 0.2 cm^{-1}. We have confirmed that the line is due to oxygen by measuring the isotope shift in a crystal containing 75% of ^{18}O and 25% of ^{16}O [Fig. 1(a)]. The ^{18}O line occurs at 27.2 cm^{-1}. Measurements of