impurity levels in the IIb's lie a few tenths of a volt above the valence band.[4] An estimate of the spin-orbit splitting Δ of the order of 0.005 volt from atomic data suggests that possibly the constant-energy surfaces cannot be simply expressed by[5]

$$E(k)=Ak^2 \pm [B^2k^4+C^2(k_x^2k_y^2+k_y^2k_z^2+k_z^2k_x^2)]^{1/2},$$

which is good for the valence band of germanium[6] and silicon,[7] but that higher order terms must be taken into account in the secular determinant for diamond. It has been suggested[8] that the low-mass line is due to the light hole, and that the high-mass line, being isotropic, is a spherical energy surface which goes with the split-off band, and that the heavy hole should be anisotropic and have a mass of $\sim 3m_0$. Further experiments are in progress to clarify the data.

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ELECTRIC-FIELD-INDUCED MODULATION OF THE ABSORPTION DUE TO INTERBAND TRANSITIONS OF FREE HOLES IN GERMANIUM

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Provided the structure of the valence band of Ge in the vicinity of $\vec{k}=0$ is independent of temperature, then the absorption due to direct interband transitions[1-3] depends on temperature only through the distribution function of the free holes. The distribution function is of prime importance in determining the absorption, and any agency which changes the energy distribution of holes in $\vec{k}$ space will produce a corresponding change in absorption. It is possible, therefore, to study the effect of a high electric field (E) on the distribution function in a direct manner. In principle, if the details of the band structure are known, it is possible to relate a photon energy with a range (because of warping) of $\vec{k}$ for both types of hole and hence to obtain the distribution function in $\vec{k}$ space of both light and heavy holes. Such a relationship is shown in Fig. 1 for transitions to the split-off band, for a band structure calculated as described below. The arrows indicate the value of k^2 at which the energy of the hole (light or heavy according to band) is $\frac{3}{2}kT$.

In practice the change in absorption was observed due to a change in distribution produced by the high field; such a differential method is inherently more sensitive than a method measuring the total absorption. In a subsidiary experiment performed for the purpose of comparison, the distribution function was changed in a known way by raising the lattice temperature a small amount and the change in absorption observed (to be referred to as the δT effect). The change in absorption can be calculated from Kane's[3] theory. Taking the spin-orbit splitting as 0.290 ev, and the other band-structure parameters as given by Kane—but modifying the energy dependence on $\vec{k}$ of the split-off band by 30%, as Kane suggests, crudely to allow for higher order perturbation terms not rigorously included—the change in absorption due to a 13.5% increase of temperature of a Maxwellian distribution at 93°K (Fig. 1, curve 1) and 293°K (Fig. 2, curve 1) has

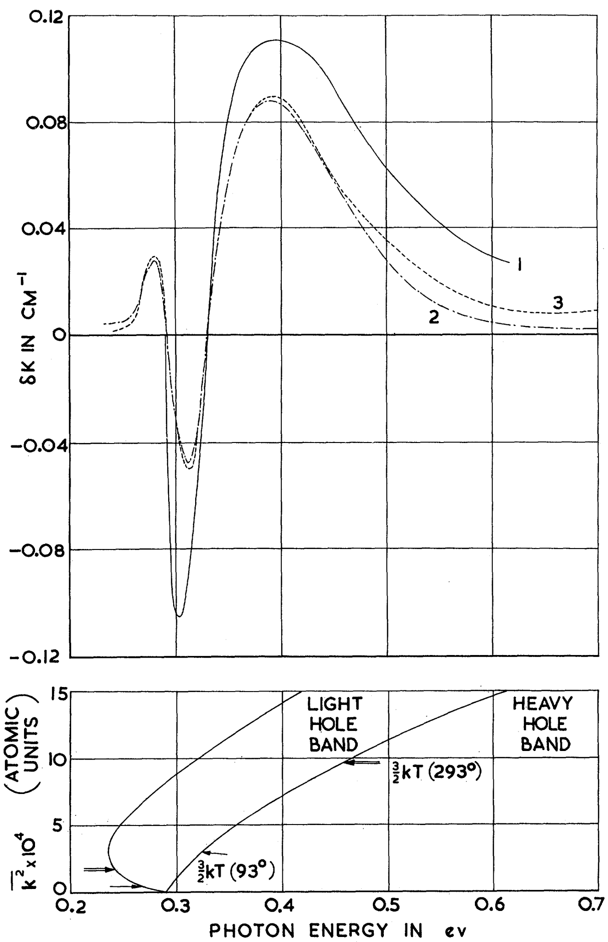

FIG. 1. Change in absorption with photon energy for a lattice temperature of 93°K. Curve 1, theoretical δK for transitions between heavy-hole and split-off band ($\delta T/T = 0.135$). Curve 2, field effect for $E = 170$ v cm^{-1}. Curve 3, δT effect for $\delta T = 12.6$°K. Below, the relationship between k^2 and photon energy.

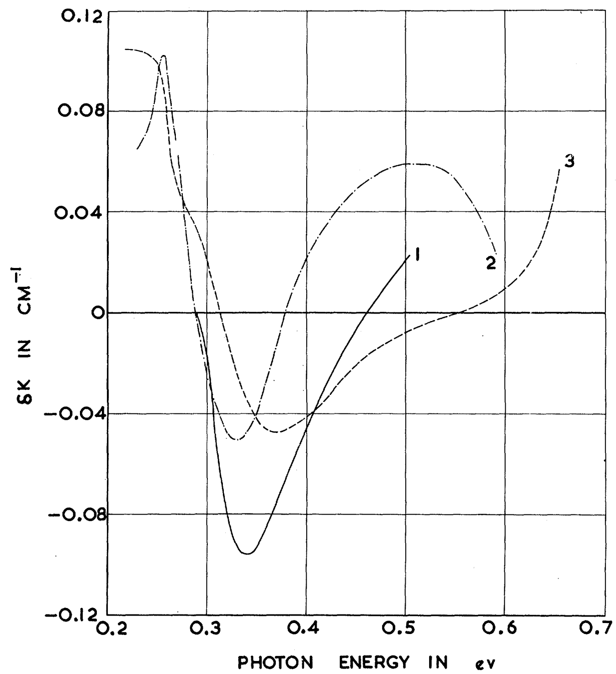

FIG. 2. Change in absorption with photon energy for a lattice temperature of 293°K. Curve 1, theoretical δK for transitions between heavy-hole and split-off band ($\delta T/T = 0.135$). Curve 2, $\delta K \times 5$ for field effect at $E = 1480$ v cm^{-1}. Curve 3, $\delta K \times 3$ for δT effect, $\delta T = 13$°K.

been calculated for transitions from the heavy-hole band to the split-off band. (The free carrier concentration was chosen to be 4.4×10^{15} cm^{-3}.)

In the experimental arrangement for measuring the field effect, light from a tungsten filament lamp was passed through a germanium filter (to prevent optical excitation of carriers in the specimen) and focussed on the optically polished germanium specimen mounted in a low-temperature cell. After being passed through a Leiss spectrometer, the light was finally focussed on a cooled (77°K) InSb detector. High-field pulses of 5-μsec duration and of repetition frequency 1.3 sec^{-1} were applied to the dumbbell-ended specimen. Though it caused a significant rise in lattice temperature, a pulse of 5-μsec duration was necessary to enable a saturation of the field effect to be observed since the time constant of the detector was 1 μsec. However, it was always possible to distinguish and eliminate thermal effects because of the relatively long thermal time constant of the specimen. Determination of the total intensity of the light transmitted enable the change in absorption (δK) to be calculated.

The subsidiary experiment was performed using the same optical arrangement. The change in lattice temperature was produced by passing a direct current through the specimen for 2 sec. A steady state was reached during this period, the temperature increase being indicated by a thermocouple of suitable response time and in good thermal contact with the specimen. The beam was stopped down so that only a volume of the crystal close to the thermocouple was "active."

Measurements have been made at various lattice temperatures between 90°K and 320°K on a p-type Ge sample containing 4.4×10^{15} cm^{-3} free carriers. Curve 2 of Fig. 1 shows δK for a field of 170 v cm^{-1} and curve 3 shows the δT effect for

$\delta T/T = 0.135$, both measured with the lattice at 93°K. A similar pair of results are shown in Fig. 2 for a lattice temperature of 293°K. The change of absorption due to transitions of heavy holes to the split-off band can readily be identified by comparison with the calculated curve; a maximum at about 0.27 ev is associated with transition of the light holes.

Some of the salient points which emerge from these results and from the velocity field curves for the same sample are:

(1) At a lattice temperature of 93°K, a comparison between the field effect and the δT effect shows that in electric fields up to 350 v cm^{-1} the distribution remains Maxwellian, within the accuracy of the measurement. Figure 3 shows the relationship between δT and E obtained from the comparison. The calculated change in absorption of heavy holes is in reasonable agreement with the observed values both with regard to shape and magnitude.

(2) At a lattice temperature of 293°K there is a marked difference between the field effect, the δT effect, and the computed δK. If the low-temperature band-structure parameters are correct, then it is possible that the discrepancy between the predicted curve and the δT effect may be due (a) to changes of the band structure with temperature to which the calculated and observed results are sensitive, or (b) to indirect transitions. Alternative (a) is favored since for indirect transitions $\delta K_{ind}/\delta T$ is always positive, and δK_{ind} has been estimated to be less than 20% of the value for direct transitions. In an electric field the departure of the distribution from Maxwellian at this higher lattice temperature can be understood since the cross section for hole-hole scattering falls[4] while the cross section for phonon scattering rises with increasing temperature.

(3) For given scattering mechanisms, Fig. 3 enables the field dependence of the mobility to be predicted and, from the energy balance equation, a value of $(\Xi_{lop}/\Xi_{lac})^2$ can be determined if the same value is assumed for all transitions. Taking Brown and Bray's[5] values of the parameters, which occur in the mobility formula, we find (i) that the calculated ratio of zero-field mobilities at 93°K and 293°K agrees with the observed ratio to within 4%; (ii) that a dependence of lattice mobility, μ_L, on the hole temperature, T_h, of $\mu_L \propto T_h^{-\delta}$, $\delta \sim 1.3$, has to be assumed to account for the observed dependence of mobility on field; and (iii) that the mean value of $(\Xi_{lop}/\Xi_{lac})^2$ is 1.6 ± 0.3, which is approximately half the value required if optical and acoustical phonon scattering are responsible for the $\mu_L \propto T^{-2.3}$ law, and implies that the normal form of optical and acoustical phonon scattering is not entirely responsible for the high value of δ. (Calculations we have made show that the nonparabolic shape of the light-hole band[3] makes an insignificant contribution to the temperature dependence of μ_L.)

In conclusion we should like to point out that the theoretical response time of the modulation is the energy relaxation time τ_ϵ of the free holes. At room temperature $\tau_\epsilon \sim 10^{-11}$ sec,[6] and is not more than 10^{-10} sec at 93°K. Since substantial depths of modulation (>10%) can be achieved with the lattice at 93°K, the field effect we observe could form the basis of a modulator capable of modulating a light beam at very high frequencies.

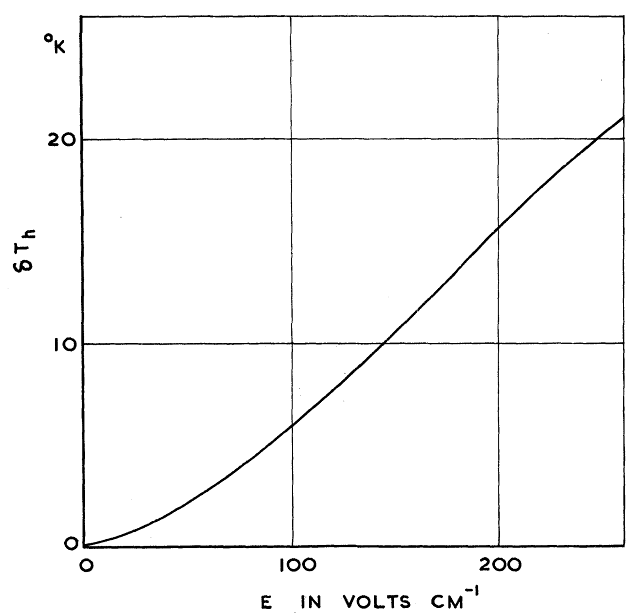

FIG. 3. The increment of hole temperature with electric field strength for a lattice temperature of 93°K. Maximum error in δT is ±15%.

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