in the band. Such an increase is predicted by the theories of Lax[5] and of Cohen.[6] Both of these theories, however, predict a stronger curvature than is actually observed. Because of the curvature of these lines, a linear extrapolation of the data to zero field yields a value for the energy gap which is too high. This error is reduced when lower energy transitions are used. The absorption data should then yield a better estimate of the energy gap than the higher energy reflection data. A systematic increase of the intercept value for transitions of higher quantum number can be seen in both sets of data. An estimate of the actual energy gap can be obtained by extrapolating these values to zero number. This yields a value of 0.024 eV. A similar estimate of the effective mass at the band minima for this orientation yields a value of 0.0065 m_0 as compared to a value of 0.01 m_0 for this mass when measured at the Fermi surface.

This value of 0.024 eV for the edge energy and the value for the Fermi energy of 0.022 eV[7] yields 0.068 eV for the position of the optical absorption edge ($\hbar\omega_0$) which is in reasonable agreement with the observed transmission of the sample.

The fact that the even transitions are not observed for energies below the absorption edge indicates that the selection rule $\Delta l=0$ is obeyed. This implies that the valence band is located directly below the conduction band,[8] which lends further support to the current contention that only three conduction band ellipsoids exist.[9]

The material used for this investigation came from two crystals of Bi, one grown by pulling from the melt, and the other grown by a horizontal zone technique. Both showed identical magneto-optical effects. One end of the samples was mounted onto the cold finger of an optical cryostat in order to minimize strain. An enclosure filled with helium as an exchange gas was used to keep the sample temperature close to the bath temperature.

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Lifetime of *d*-Band Holes in InSb†

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Profiles of the In $L\beta_2$ x-ray emission in metallic indium and in InSb have been recorded by means of a vacuum two-crystal instrument. According to the usual term assignments, the final state for this transition contains a hole in the 4*d* band. With suitable assumptions regarding both this state and the initial state, an approximate measure of the decay width of the 4*d* hole is obtained.

RECENT analysis of the optical properties of 3–5 semiconductors[1] has demonstrated the effect of interband absorption from the *d* bands of several of these semiconductors. In order to obtain a satisfactory fit with the data, the final state for optical absorption must be assigned an extremely short relaxation time.[1a] This final state may be considered to include a *d*-band hole and a "conduction band" electron; the coupling of these may, of course, be significant. The required short relaxation time may, in principle, arise from (1) a short lifetime for the *d*-band hole, or (2) a short lifetime for the electron state.

It is the purpose of this note to report the results of a measurement which tends to exclude the first alternative above. This measurement is of the line shape of the indium $L\beta_2$ x-ray transition. The initial state for this transition includes a hole in the In 2*p* band (L_{III} state)

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[1a] *Note added in proof*. In reference 1, the broad optical structure was discussed in terms of lifetime broadening of an otherwise narrow interband transition. This report is written accordingly. It was brought to the author's attention that, in more recent work, other possibilities have been considered by Philip and Ehrenreich (Physical Review, this issue). They now consider also the possibility that the broad optical structure may arise from superposition of transitions at different points in the zone. Such a view is not inconsistent with the results reported here.

and the final state includes a hole in the 4d band ($N_{IV,V}$ state).[2] This emission will exhibit lifetime broadening due to the decay of both the initial and final states. Since independent estimates (discussed in detail below) of the L_{III} level width indicate that it is roughly half as large as alternative (1) above would require for $N_{IV,V}$, the latter should be quite apparent from a study of the line shape.

EXPERIMENTAL PROCEDURE

The transition In $L\beta_2$ is well known. Its mean wavelength is 2744.9 xu.[3] The present measurements were carried out by means of a vacuum two-crystal spectrometer using calcite crystals. The specimen was excited to x-ray fluorescence by primary radiation from a Ti target operated at 20 kV, 200 mA. Data were stored in paper tape and reduced by means of a computer.[4] Spectra from metallic indium and InSb were recorded. The metallic indium specimen was prepared by rolling indium wire to a sheet approximately 0.002 in. thick. The InSb specimen was prepared by pulverizing a fragment of single-crystal material into a relatively coarse grained powder (~100 mesh).[5] This was mixed with a polystyrene-benzene solution and spread on a thin aluminum sheet.

RESULTS AND DISCUSSION

Spectra obtained from metallic indium and from InSb are shown in Fig. 1. Relative intensity measurements were made at intervals of 0.22 eV (16 sec of arc) with 400-sec counting time at each point. Each point is the average of four measurements. In no case does the statistical uncertainty exceed 1% of the peak height. There is no difference between the contours observed for metallic indium and for InSb which exceeds experimental error.

The observed spectrum contains the effect of finite instrumental resolution as a smearing aberration. It was assumed that the instrumental window is given by the $(1, -1)$ rocking curve[6] and the spectra corrected for its effect by the method of Burger and van Cittert.[7] In this correction procedure, the unfolding operator was taken as its third approximation. The results are indicated by the solid curves in Fig. 1.

[2] This discussion makes use of the usual assumption that, if interactions with the photoelectron are neglected, the system containing an inner shell vacancy has a unique energy (except for lifetime broadening). The possibility that this may not be the case is advanced in reference 8.

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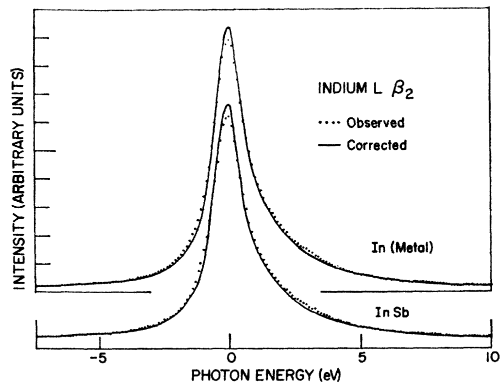

FIG. 1. Emission contours associated with the hole transition $L_{III} \rightarrow N_{IV,V}$ in metallic indium and in indium antimonide. The curves have been displaced vertically for clarity. The zero of energy is placed at the position of maximum intensity.

The width for the L_{III} state may be estimated. Parratt's empirical numbers[8] for such widths may be interpolated to give 2.5±0.1 eV. Recent measurements of the In L_{III} absorption edge[9] appear consistent with this estimate.

To proceed further, we need to make some assumption about the d-band hole relaxation time and the origin of pronounced asymmetry of the contours in Fig. 1. The simplest assumptions regarding these points are that (1) the lifetime of a d-band hole is independent of its energy within the band, and (2) the asymmetry arises either from a splitting of the N_{IV} and N_V levels in the solid or that the asymmetry arises from satellite processes or a combination of these effects. Under these assumptions, a "natural band profile" is obtained by reflecting the low-energy part of the contours of Fig. 1 in a line drawn through the maximum ordinate. The full width at half maximum of this "natural band profile" is 2.7±0.1 eV. This presumably results from a composition of an L_{III} state width of 2.5 eV and the lifetime broadening of a d-band hole which is what we seek to estimate. If the line shapes are presented to be Lorentzian, then the width of the $N_{IV,V}$ state is 0.2±0.2 eV.

This result suggests that the very short relaxation time which is required from the optical data should not be attributed to fast processes leading to the destruction of d-band holes. This leaves alternative (2) mentioned above. Thus the optical data together with the present results suggest either (1) that the conduction band is quite broad or (2) that electron-electron scattering leads to a very short lifetime for the optical photoelectron.

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