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VII-4. Piezoemission of Indium Antimonide

C. BENOIT à la GUILLAUME and P. LAVALLARD

Laboratoire de Physique de l'Ecole Normale Supérieure
24, rue Lhomond, Paris 5°, France

The shift of the intrinsic recombination line of InSb under a uniaxial stress σ along ⟨100⟩, ⟨111⟩ and ⟨110⟩ direction has been measured at low temperature for light with $E//\sigma$ and $E\perp\sigma$. From the variation of the splitting of the valence bands with the orientation of σ we obtain the two deformation potentials of the valence band: $b=-2$ eV and $d=-5$ eV. We try to explain a small difference between the position of the line for $E//\sigma$ or $E\perp\sigma$ at high stress, by the existence of a linear k term in the valence band, and a stress induced linear k term in the conduction band.

§ 1. Introduction

Piezoabsorption with polarized light seems to be the most direct method to get the deformation potentials of the valence band of diamond or zinc blend type semiconductors including their sign. Such a method is useful in the case of indirect gap material, like Ge and Si[1] hence in that case samples of about 1 mm thickness are used. In the case of direct gap material it is very difficult to use this method hence we need very thin samples. If the transition is strong enough the reflectivity method can be used (CdTe).[2] In the case of InSb, we used the piezoemission technique; we measure the change in the spectrum of the intrinsic recombination of photoexcited carriers in InSb at low temperature under the action of a known uniaxial stress. But in n type material, as soon as the splitting of the valence band is larger than kT, we have excited holes only in the upper valence sub-band, and we have no information on the lower one.

§ 2. Theory

G. E. Pikus and G. L. Bir have calculated the effect of a deformation ε on the valence band of Ge[3] and III-V compounds.[4] In the case of III-V compounds, the degeneracy of the valence band at $k=0$ is removed by a uniaxial stress because the cubic symmetry is destroyed. They obtain the following expressions for the two split bands near $k=0$: (according to the notations of ref. 4).

a) stress along the ⟨100⟩ axis

$$E^{\pm}_{1/2}(k)=-a\varepsilon+\frac{b\varepsilon_{zz}}{|b\varepsilon_{zz}|}\sqrt{\mathscr{E}_\varepsilon}-\left[\left(A+\frac{B}{2}\right)(k_\perp\pm k_{0\perp})^2+(A-B)k_z^2\right],$$

$$E^{\pm}_{3/2}(k)=-a\varepsilon-\frac{b\varepsilon_{zz}}{|b\varepsilon_{zz}|}\sqrt{\mathscr{E}_\varepsilon}-\left[\left(A-\frac{B}{2}\right)(k_\perp\pm k_{0\perp})^2+(A+B)k_z^2\right];$$

b) stress along the ⟨111⟩ axis

$$E^{\pm}_{1/2}(k)=-a\varepsilon+\frac{d\varepsilon_{ij}}{|d\varepsilon_{ij}|}\sqrt{\mathscr{E}_\varepsilon}-\left[\left(A+\frac{D}{2\sqrt{3}}\right)(k_\perp\pm k_{0\perp})^2+\left(A-\frac{D}{\sqrt{3}}\right)k_z^2\right],$$

$$E^{\pm}_{3/2}(k)=-a\varepsilon-\frac{d\varepsilon_{ij}}{|d\varepsilon_{ij}|}\sqrt{\mathscr{E}_\varepsilon}-\left[\left(A-\frac{D}{2\sqrt{3}}\right)(k_\perp{}^2+\left(A+\frac{D}{\sqrt{3}}\right)(k_z\pm k_z{}^0)^2\right],$$

$-a\varepsilon$ is the shift of the whole valence band due to the dilatation $\varepsilon=\sum_i \varepsilon_{ii}$, $\sqrt{\mathscr{E}_\varepsilon}$ is one half the valence band splitting at $k=0$.

$$\mathscr{E}_\varepsilon=\frac{b^2}{2}\sum_{i>j}(\varepsilon_{ii}-\varepsilon_{jj})^2+d^2\sum_{i>j}\varepsilon_{ij}^2\,.$$

In a first step, $k_{0\perp}$ is neglected, *i.e.* the linear k term of the valence band is neglected. We take for the bottom of the conduction band:

$$E_c(k)=E_g+c\varepsilon\,.$$

Effects related to linear k terms will be considered in part IV.

For compression along the ⟨100⟩ and ⟨111⟩ axes, the angular momentum is a good quantum number, and we may speak of $M=\pm1/2$ and $M=\pm3/2$ bands. Transitions from the $M=\pm1/2$ valence band to the conduction band $M=\pm1/2$ satisfy selection rules $\Delta M=0,\ -1,\ +1$ and so occur for light polarized both parallel and perpendicular to the stress direction. Transitions from the $M=\pm3/2$ valence band can only satisfy the selection rule $\Delta M = \pm 1$ and so can only occur for light polarized perpendicular to the stress. For other directions of σ (*i.e.* $\langle 110 \rangle$) M is no longer a good quantum number and we have no more simple selection rules.

§ 3. Experimental Set-up

The experiments were done on n type InSb kindly supplied to us by S. A. T., Paris ($n \sim 2 \times 10^{14}\ \mathrm{cm}^{-3}$, $\mu \sim 600{,}000\ \mathrm{V}^{-1}\mathrm{cm}^2\mathrm{sec}^{-1}$ at 77°K). The samples are 6-7 mm in height and have square cross-section 1 to 10 mm². They are oriented with their long dimension oriented within a few degrees.

The excess carriers are excited by a high pressure mercury arc HBO 100. We used two different stress apparatus. In one case, the sample in vacuum was cooled by contact. A force up to 50 kg is applied to the sample at a temperature around 30°K or 80°K. In the second apparatus, the sample was immersed in superfluid helium at 2°K, and a force up to 20 kg could be applied.

The spectrum of the recombination radiation which is under these conditions the band to band one[5] was recorded in polarized light with equivalent slit width of about 0.25 meV at 2°K, and 0.5 meV at 30°K and 80°K. In fact, the precision on the peak position of the line was limited by the atmospheric absorption.

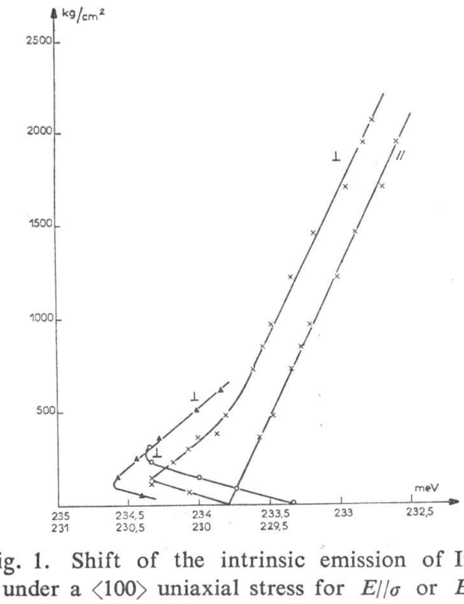

Fig. 1. Shift of the intrinsic emission of InSb under a $\langle 100 \rangle$ uniaxial stress for $E // \sigma$ or $E \perp \sigma$. ▲▲▲ at 2°K. ××× at 30°K. ○○○ at 80°K (the energy scale is the lower one).

§ 4. Results

Figures 1, 2 and 3 give the shifts of the intrinsic line at 2°K and 30°K for $E // \sigma$ and $E \perp \sigma$ for the three directions of applied stress, versus

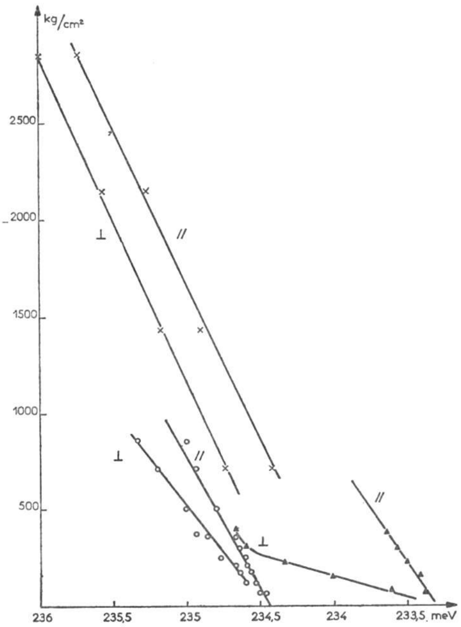

Fig. 2. Shift of the intrinsic emission of InSb under a $\langle 111 \rangle$ stress for $E // \sigma$ or $E \perp \sigma$. ○○○ at 2°K. ▲▲▲ ××× at 30°K.

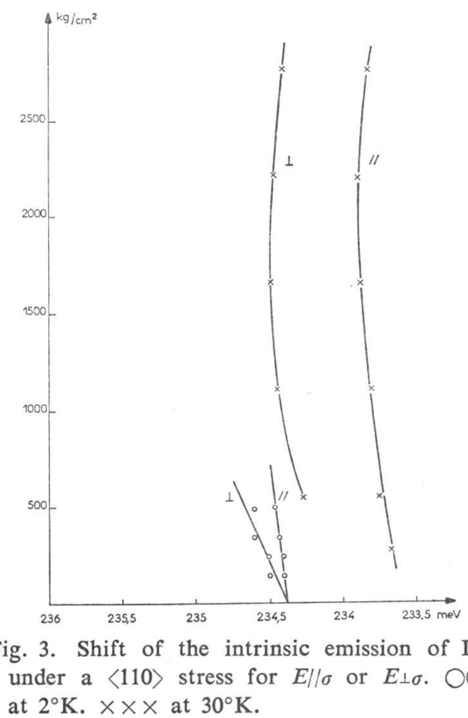

Fig. 3. Shift of the intrinsic emission of InSb under a $\langle 110 \rangle$ stress for $E // \sigma$ or $E \perp \sigma$. ○○○ at 2°K. ××× at 30°K.

the intensity of the stress. For the ⟨100⟩ and ⟨111⟩ stresses, the $E//\sigma$ curve is linear and the $E\perp\sigma$ curve exhibits a change in slope at a pressure which goes down with temperature. Such a behaviour is understood as follows: at low pressure, *i.e.* when the valence band splitting $2\sqrt{\mathscr{E}_\varepsilon}$ is less than kT, we get contributions from both sub-bands with $E\perp\sigma$ (no selection rule), and the slope at the beginning 5 to 5.5× 10^{-6} eV kg^{-1} cm^2 corresponds to $(a+c)\varepsilon/\sigma$ and is equal to 1/3 of the shift due to a hydrostatic pressure. The signs of b and d are obtained from the following remarks:

1) At low pressure for $\sigma//\langle 100\rangle$ and ⟨111⟩ the line $E\perp\sigma$ is at higher energy than the $E//\sigma$ line.

2) In the same pressure range the $E\perp\sigma$ line is broader, indicating two components unresolved.

3) At high pressure, when $kT\ll 2\sqrt{\mathscr{E}_\varepsilon}$ we have holes only in the upper sub-band and we observe lines of the same order of magnitude for $E\perp\sigma$ and $E//\sigma$ and for $\sigma//\langle 100\rangle$ and $\sigma//\langle 111\rangle$. Thus for compression the $M=\pm 1/2$ bands move up, and the $M=\pm 3/2$ move down and we conclude b and d are negative.

From the slopes at high pressure, we get:
from the ⟨100⟩ case

$$(a+c)\varepsilon/\sigma-|b|(s_{11}-s_{12})=-0.75\times 10^{-6}\,\text{eV kg}^{-1}\text{cm}^2\,,$$

from the ⟨111⟩ case

$$(a+c)\varepsilon/\sigma-\frac{1}{2\sqrt{3}}|d|s_{44}=+0.8\times 10^{-6}\,\text{eV kg}^{-1}\,\text{cm}^2\,,$$

from the ⟨110⟩ case

$$(a+c)\varepsilon/\sigma-\frac{1}{2}\left[b^2(s_{11}-s_{12})^2+3\left(\frac{1}{2\sqrt{3}}ds_{44}\right)^2\right]^{1/2}\sim 0\,.$$

The errors on the slopes are estimated to $\pm 0.15\times 10^{-6}$ eV kg^{-1} cm^2

The value of $(a+c)\varepsilon/\sigma=5.35\pm 0.3$ 10^{-6} eV kg^{-1} cm^2 has been taken from the change of band gap with pressure.[6] A value of the order of 5×10^{-6} eV kg^{-1} cm^2 is also obtained from our data on the slope of the $E\perp\sigma$ emission at low pressure. But our precision is not good.

$$s_{11}=2.22\times 10^{-6}\,\text{cm}^2\,\text{kg}^{-1}$$
$$-s_{12}=0.745\times 10^{-6}\,\text{cm}^2\,\text{kg}^{-1}$$
$$s_{44}=3.12\times 10^{-6}\,\text{cm}^2\,\text{kg}^{-1}$$

from the work of R. F. Potter.[7]

From the ⟨100⟩ and ⟨111⟩ slopes, one gets the two deformation potentials of the valence band:

$$b=-2.05\pm 0.15\,\text{eV}\qquad d=-5\pm 0.5\,\text{eV}$$

From these values, a slope of $(0.3\pm 0.15)\times 10^{-6}$ eV kg^{-1} cm^2 is computed for the ⟨110⟩ case in rough agreement with the experiment.

§5. Discussion

1) In their theory of piezoresistance in p type InSb Pikus and Bir[3,4] found $b\sim -0.6$ eV and $d=-5$ eV, from the experimental data of Tuzzolino and Potter,[8] and the theoretical calculation of the valence band constants B and D by Kane.[9] Our result for $|b|$ is greater, but the value of b obtained from the piezoresistance is not accurate. Our values of b and d in InSb are quite similar to those of Si.[1]

2) At high stress, in the case where the splitting is much larger than kT, we still have a difference of about 0.3 meV between the $E//\sigma$ and $E\perp\sigma$ emissions but in that case we have only excited holes in the upper sub-band. We try to explain this effect by the existence of linear k terms in the valence band, and stress induced linear k term in the conduction band.

For example, in the case of ⟨100⟩ stress, the group theory gives two representations of dimension one which are in correspondence by a time-reversal operation for k vectors on the main crystallographic axis for the conduction band, and for both valence sub-bands. Then, new selection rules appear, shown in Fig. 4. To get

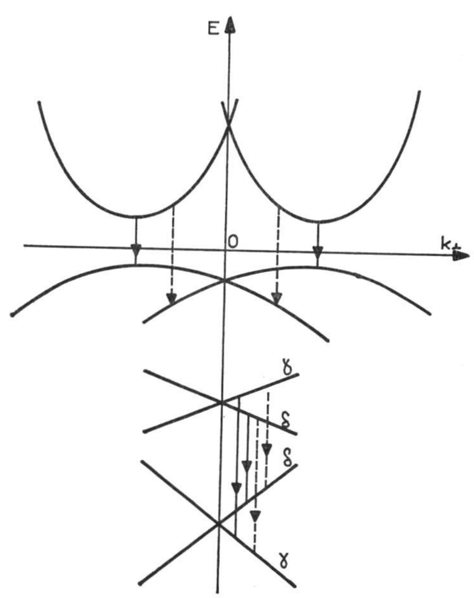

Fig. 4. Band scheme of InSb near $k=0$ including linear k terms. Minimum energies for photon emitted $E//\sigma$ and $E\perp\sigma$ are shown.

a different value between $E // \sigma$ and $E \perp \sigma$ for the minimum energy of a photon, we need a stress induced linear k term in the conduction band. Such a term arises from mixing S states with Γ_4 and Γ_5 levels.

The matrix element between $|iS\uparrow\rangle$ and $|iS\downarrow\rangle$ is:

$$\sum_{\substack{m \\ \neq iS}} \sum_{n} \frac{1}{E-E_m} \frac{1}{E-E_n} \left\langle iS\uparrow | \hbar\vec{k}.\frac{\vec{p}}{m} | \Gamma_4(m)\uparrow \right\rangle$$
$$\cdot \left\langle \Gamma_4(m)\uparrow | D(\Gamma) | \Gamma_5(n)\uparrow \right\rangle$$
$$\cdot \left\langle \Gamma_5(n)\uparrow | \frac{\hbar}{4m^2c^2} (\vec{\nabla} V \times \vec{p})_- \cdot \vec{\sigma}_+ | iS\downarrow \right\rangle ,$$

where

$$D = \frac{\hbar^2}{m} \sum_{ij} \varepsilon_{ij} \frac{\partial^2}{\partial x_i \partial x_y} + \sum_{ij} V_{ij} \varepsilon_{ij}$$

and Γ may be Γ_3, Γ_4 and Γ_5.

The first matrix element is important for p levels and its value is of the order of $\hbar k P / E_G$ with P defined as Kane does.[9)]

It is difficult to evaluate the order of magnitude of these linear k terms in order to justify our explanation.

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