4457/87

IC/87/79
INTERNAL REPORT
(Limited distribution)

International Atomic Energy Agency
and
United Nations Educational Scientific and Cultural Organization
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS

FINE STRUCTURE AND ENERGY SPECTRUM OF EXCITON IN DIRECT BAND GAP CUBIC SEMICONDUCTORS WITH DEGENERATE VALENCE BANDS *

Nguyen Toan Thang ** and Nguyen Ai Viet **
International Centre for Theoretical Physics, Trieste, Italy

and

Nguyen Que Huong
Institute of Theoretical Physics, Hanoi, Vietnam.

ABSTRACT

The influence of the cubic structure on the energy spectrum of direct exciton is investigated, using the new method suggested by Nguyen Van Hieu and co-workers. Explicit expressions of the exciton energy levels 1S, 2S and 2P are derived. A comparison with the experiments and the other theory is done for ZnSe.

MIRAMARE - TRIESTE
June 1987

* To be submitted for publication.

** Permanent address: Institute of Theoretical Physics, Nghia Do, Tu Liem, Hanoi, Vietnam.

I. INTRODUCTION

Most of the cubic semiconductors have the upper valence band fourfold degenerate at the extremum. Therefore the problem of the exciton spectra in these crystals is not so readily solved. It has been studied in many theoretical works [1]-[10]. Recently, Nguyen Van Hieu and co-workers [10] presented a new simple method for calculating the exciton states in semiconductors for the case, when the hole band is parabolic. In this case the hole masses do not depend on the direction in the momentum space, so one could choose perturbative parameter to be proportional to the difference between the heavy and light hole masses. In this work we study the exciton energy spectrum, taking into account the contribution of the cubic structure of crystals, using the method suggested in Ref. 10.

We shall use the unit system with $\hbar = c = 1$.

II. PERTURBATION THEORY

We consider a direct band gap cubic semiconductor with an upper valence band fourfold degenerate at the Γ point. In the neighbourhood of this point the valence band is nearly decoupled into light and heavy-hole bands, characterized by the different effective mass: heavy and light one. In general the band structure of the upper valence band of cubic semiconductors can be described by three parameters (for example, Luttinger parameter $\gamma_1, \gamma_2, \gamma_3$ or Dresselhaus-Kip-Kittel A, B, C...). Following [10] we characterized the valence Γ_8 by the masses of the heavy and the light hole (m_H and m_L) along one of the cubic axes <100> . The third parameter is taken to be the heavy hole mass $m_{H'}$, in the direction <111> . Then in our treatment the perturbation parameter due to cubic structure θ can be given by:

$$\theta = m_0 \left(\frac{1}{m_H} - \frac{1}{m_{H'}} \right) , \tag{1}$$

with

$$\frac{1}{m_0} = \frac{1}{2} \left(\frac{1}{m_H} + \frac{1}{m_L} \right) , \tag{2}$$

As shown in [10], if the heavy and light hole masses m_H, m_L are replaced by the common value m_0, defined above, then the Schrödinger equation for the exciton has exact analytical solution with eigenvalues $E_\nu^{(0)}$ and eigenvectors $|\psi_N^{(0)}\rangle$.

For the discrete energy states ν is the set of three quantum numbers (n,l,m) while for those in the continuous energy spectrum ν is the asymptotic relative momentum of the electron-hole pair:

$$E_\nu^{(0)} = -\frac{R_y^*}{n^2} \quad \text{for} \quad \nu = \{n,l,m\}\,, \qquad = \frac{p^2}{2m_2} \quad \text{for} \quad \nu = \{\vec{p}\}\,. \tag{3}$$

where

$$R_y^* = \frac{e^4 m_2}{2\varepsilon_0^2}\,, \qquad \frac{1}{m_2} = \frac{1}{m_0} + \frac{1}{m_e}\,. \tag{4}$$

m_e being the effective mass of the conduction electron, ε_0 being the background dielectric constant.

The full set N of quantum numbers of the exciton state consists of the total momentum $\vec{P}$, the electron spin projection μ, the hole spin projection M $\left(M = \pm\frac{1}{2}\right.$ for light hole, $M = \pm\frac{3}{2}$ $\left.\text{for heavy one}\right)$, and the set ν. We denote:

$$|\Psi_N^{(0)}\rangle = |\vec{P};\mu M;\nu\rangle\,. \tag{5}$$

In the manner of Ref.[10], it is easy to express the matrix element $\widetilde{H}_{N'N}$ of the nonparabolic perturbation term $\widetilde{H}$ of the exciton Hamiltonian between the unperturbed exciton state vectors in the form:

$$\widetilde{H}_{N'N} = \langle \vec{P}',\mu' M';\nu' | \widetilde{H} | \vec{P};\mu M;\nu\rangle = -\frac{\theta}{2m_0}\delta_{\mu'\mu}\,\delta(\vec{P}'-\vec{P})\sum_{\vec{p}}\mathcal{Y}^*_{\nu'}(\beta\vec{P}-\vec{p})\mathcal{Y}_\nu(\beta\vec{P}-\vec{p})\,\widetilde{L}_{M'M}(\vec{p})\,. \tag{6}$$

where

$$\widetilde{L}_{M'M}(\vec{p}) = \begin{pmatrix} 0 & \widetilde{G}(\vec{p}) & \widetilde{F}(\vec{p}) & 0 \\ \widetilde{G}^*(\vec{p}) & 0 & 0 & -\widetilde{F}(\vec{p}) \\ \widetilde{F}(\vec{p})^* & 0 & 0 & \widetilde{G}(\vec{p}) \\ 0 & -\widetilde{F}^*(\vec{p}) & \widetilde{G}(\vec{p})^* & 0 \end{pmatrix}. \tag{7}$$

$$\widetilde{G}(\vec{p}) = \sqrt{3}\,(p_x - ip_y)p_z\,, \qquad \widetilde{F}(\vec{p}) = i\sqrt{3}\,p_x p_y\,; \quad \beta = \frac{m_0}{m_e + m_0}\,. \tag{8}$$

$\mathcal{Y}_\nu(\vec{p})$ is the wave function in the momentum space of hydrogen-like system with the reduced mass m_r.

In the spirit of Ref.[10] we can separate the relative motion of the electron-hole pair from the motion of its center of mass and write $\widetilde{H}_{N'N}$ in the form

$$\widetilde{H}_{N'N} = \widetilde{H}^{(0)}_{N'N} + \widetilde{H}^{(1)}_{N'N} + \widetilde{H}^{(2)}_{N'N}\,. \tag{9}$$

where

$$\widetilde{H}^{(0)}_{N'N} = -\frac{\theta}{2m_0}\delta_{\mu'\mu}\,\delta(\vec{P}'-\vec{P})\,\widetilde{O}_{M'M}(\vec{P})\,. \tag{10}$$

$$\widetilde{H}^{(1)}_{N'N} = -\frac{\theta}{2m_0}\delta_{\mu'\mu}\,\delta(\vec{P}'-\vec{P})\sum_{\vec{p}}\mathcal{Y}_{\nu'}(\vec{p})^*\mathcal{Y}_\nu(\vec{p})\,\widetilde{T}_{M'M}(\vec{p})\,. \tag{11}$$

$$\widetilde{H}^{(2)}_{N'N} = -\frac{\theta}{2m_0}\delta_{\mu'\mu}\,\delta(\vec{P}'-\vec{P})\sum_{\vec{p}}\mathcal{Y}_{\nu'}(\vec{p})^*\mathcal{Y}_\nu(\vec{p})\,\widetilde{Q}_{M'M}(\vec{P},\vec{p})\,. \tag{12}$$

with

$$\widetilde{O}_{M'M}(\vec{P}) = \begin{pmatrix} 0 & \widetilde{G}(\vec{P}) & \widetilde{F}(\vec{P}) & 0 \\ \widetilde{G}^*(\vec{P}) & 0 & 0 & -\widetilde{F}(\vec{P}) \\ \widetilde{F}(\vec{P})^* & 0 & 0 & \widetilde{G}(\vec{P}) \\ 0 & -\widetilde{F}^*(\vec{P}) & \widetilde{G}(\vec{P})^* & 0 \end{pmatrix}. \tag{13}$$

$$\widetilde{T}_{M'M}(\vec{p}) = \begin{pmatrix} 0 & D(\vec{p}) & E(\vec{p}) & 0 \\ D(\vec{p}) & 0 & 0 & -E(\vec{p}) \\ E(\vec{p}) & 0 & 0 & D(\vec{p}) \\ 0 & -E(\vec{p}) & D(\vec{p}) & 0 \end{pmatrix}. \tag{14}$$

$$\widetilde{Q}_{M'M}(P p) = \sqrt{6}\,\beta P p \begin{pmatrix} 0 & \mathcal{f}_{1-1} & 0 & 0 \\ \mathcal{f}_{1-1} & 0 & 0 & 0 \\ 0 & 0 & 0 & \mathcal{f}_{1-1} \\ 0 & 0 & \mathcal{f}_{1-1} & 0 \end{pmatrix}. \tag{15}$$

$$D(\vec{p}) = \sqrt{2}\, p^2 \mathcal{f}_{2-1}\,,$$
$$E(\vec{p}) = \frac{\sqrt{2}}{2} p^2 (\mathcal{f}_{2-2} - \mathcal{f}_{22}). \tag{16}$$

$\mathcal{f}_{ij}$ being the rank i spherical tensors in the reference frame with $O_z \parallel \vec{P}$:

$$\mathcal{f}_{10} = z, \quad \mathcal{f}_{1\pm1} = \mp \frac{1}{\sqrt{2}} (x \pm iy). \tag{17}$$

$$\mathcal{f}_{20} = \frac{1}{2}(2z^2 - x^2 - y^2),$$
$$\mathcal{f}_{2\pm1} = \mp\sqrt{\frac{3}{2}}\,(x \pm iy) z\,,$$
$$\mathcal{f}_{2\pm2} = \frac{\sqrt{3}}{2\sqrt{2}}(x \pm iy)^2,$$
$$x = \frac{p_x}{p}, \quad y = \frac{p_y}{p}; \quad z = \frac{p_z}{p}. \tag{18}$$

$\widetilde{H}^{0}_{N'N}$, $\widetilde{H}^{(1)}_{N'N}$ and $\widetilde{H}^{(2)}_{N'N}$ are the cubic corrections of the center-of-mass motion, the relative motion and their mixed correction, respectively, to the exciton Hamiltonian.

From (10) and the formula (28) of Ref. [10], the total term of the center-of-mass motion of the exciton Hamiltonian is given by:

$$H^{P}_{N'N} = \delta_{\mu'\mu}\,\delta(P'-P)\, O_{M'M}(\vec{P}). \tag{19}$$

where

$$O_{M'M}(\vec{P}) = \begin{pmatrix} A(\vec{P}) & B(\vec{P}) & C(\vec{P}) & 0 \\ B(\vec{P})^* & -A(\vec{P}) & 0 & -C(\vec{P}) \\ C(\vec{P}) & 0 & -A(\vec{P}) & B(\vec{P}) \\ 0 & -C(\vec{P})^* & B(\vec{P})^* & A(\vec{P}) \end{pmatrix}. \tag{20}$$

$$A(\vec{P}) = \frac{1}{4}\frac{\varkappa}{m_0}\beta^2(2P_z^2 - P_x^2 - P_y^2),$$
$$B(\vec{P}) = \frac{\sqrt{3}}{2}\frac{\beta^2}{m_0}(\varkappa - \theta)(P_x - iP_y)P_z\,,$$
$$C(P) = \frac{\sqrt{3}}{4}\frac{\beta^2}{m_0}\left[\varkappa(P_x - iP_y)^2 - 2i\theta P_x P_y\right]. \tag{21}$$

$$\varkappa = \frac{m_H - m_L}{m_H + m_L}. \tag{22}$$

It is easy to diagonalize (19) to obtain the energy E^P due to the center-of-mass motion of the exciton:

$$E^{P} = \pm \frac{\beta P^2}{2m_0^2}\left[\varkappa + 3(\theta^2 - 2\varkappa\theta)\,\eta\!\left(\frac{\vec{P}}{P}\right)\right]^{1/2}. \tag{23}$$

where

$$\eta\!\left(\frac{\vec{P}}{P}\right) = \frac{1}{P^4}\left(\vec{P}_x^2\vec{P}_y^2 + \vec{P}_y^2\vec{P}_z^2 + \vec{P}_x^2\vec{P}_z^2\right). \tag{24}$$

So the moving exciton $\vec{P} \neq 0$ splits into the "light" and "heavy" excitons with the corresponding energy:

$$E_L^{(0)}(P,\nu) = E_\nu^{(0)} + \frac{P^2}{2}\left(\frac{1}{M_L} + \frac{1}{\Delta M_L}\right). \tag{25}$$

$$E_H^{(0)}(P,\nu) = E_\nu^{(0)} + \frac{P^2}{2}\left(\frac{1}{M_H} + \frac{1}{\Delta M_H}\right). \tag{26}$$

The masses M_L and M_H of the light- and heavy exciton in the parabolic approximation are given by [10]:

$$\frac{1}{M_L} = \frac{1}{M_0} + \frac{\chi\beta^2}{m_0},$$
$$\frac{1}{M_H} = \frac{1}{M_0} - \frac{\chi\beta^2}{m_0},$$
$$M_0 \equiv m_0 + m_e. \tag{27}$$

The cubic correction to the exciton masses are

$$\frac{1}{\Delta M_L} = \frac{\beta^2}{m_0}\left\{-\chi + \left[\chi^2 + 3(\theta^2 - 2\chi\theta)\eta\left(\frac{\vec{P}}{P}\right)\right]^{1/2}\right\},$$
$$\frac{1}{\Delta M_H} = \frac{\beta^2}{m_0}\left\{\chi - \left[\chi^2 + 3(\theta^2 - 2\chi\theta)\eta\left(\frac{\vec{P}}{P}\right)\right]^{1/2}\right\}. \tag{28}$$

To study the corrections to the energies levels (25), (26) due to the terms $\tilde{H}^{(1)}_{N'N}$ and $\tilde{H}^{(2)}_{N'N}$ we can use the perturbation theory. The calculations are quite similar to those for the case of the spherical approximation [10] and will not be developed in the following.

III. FINE STRUCTURE OF EXCITON AT REST

For the exciton at rest ($\vec{P} = 0$) only the term $H^{(1)}_{N'N}$ gives the contribution to the exciton energy. For the 1S exciton the second order correction due to this term equals:

$$\Delta E(\vec{P}=0, 1S) = -\frac{32}{5} S_{1S} \frac{m_z^2}{m_0^2} R_y^* \theta^2,$$
$$S_{1S} \simeq 0{,}2246. \tag{29}$$

Similarly, for the 2S-exciton:

$$\Delta E(\vec{P}=0, 2S) = -\frac{32}{5} S_{2S} \frac{m_z^2}{m_0^2} R_y^* \theta^2,$$
$$S_{2S} \approx 0{,}7029. \tag{30}$$

The 2P-exciton can be described by the total angular momentum F $\left(F = \frac{1}{2}, \frac{3}{2} \text{ and } \frac{5}{2}\right)$ and its projection F_z on the quantization direction $\left(F_z = \pm\frac{5}{2}, \pm\frac{3}{2}, \pm\frac{1}{2} \text{ for } F = \frac{5}{2};\ F_z = \pm\frac{3}{2}, \pm\frac{1}{2} \text{ for } F = \frac{3}{2} \text{ and } F_z = \pm\frac{1}{2} \text{ for } F = \frac{1}{2}\right)$. Using the second order perturbation theory we have obtained for 2P-exciton the following:

$$\Delta E\left(P=0, 2P, F=\tfrac{1}{2}, F_z=\pm\tfrac{1}{2}\right) = \frac{3\sqrt{6}}{20}\frac{m_z}{m_0}\theta\frac{R_y^*}{4},$$

$$\Delta E\left(P=0, 2P, F=\tfrac{3}{2}, F_z=\pm\tfrac{1}{2}, \pm\tfrac{3}{2}\right) = \frac{\chi m_z}{5 m_0}\frac{R_y^*}{4} \times \left\{\frac{5}{2} - \frac{3\sqrt{6}}{\gamma}\frac{\theta}{\chi} - \frac{1}{2}\left[25 + \frac{27}{\gamma}\frac{\theta^2}{\chi^2} + \frac{9\sqrt{6}}{\chi}\theta\right]^{1/2}\right\}$$

$$\Delta E\left(P=0, 2P, F=\tfrac{5}{2}, F_z=\pm\tfrac{3}{2}, \pm\tfrac{1}{2}\right) = \frac{\chi m_z}{5 m_0}\frac{R_y^*}{4} \times \left\{-\frac{5}{2} - \frac{3\sqrt{6}}{\gamma}\frac{\theta}{\chi} + \frac{1}{2}\left[25 + \frac{27}{\gamma}\frac{\theta^2}{\chi^2} + \frac{9\sqrt{6}}{\chi}\theta\right]^{1/2}\right\}.$$

$$\Delta E\left(P=0, 2P, F=\tfrac{5}{2}, F_z=\pm\tfrac{5}{2}\right) = \frac{3\sqrt{6}}{20}\frac{m_z}{m_0}\theta\frac{R_y^*}{4}. \tag{31}$$

From (31) we can see that because of the energy splitting of the exciton level with $F = \frac{5}{2}$ into two sublevels we have four sublevels of the 2P-exciton energy instead of three obtained in the parabolic model.

IV. FINE STRUCTURE OF MOVING EXCITON

Taking into account the cubic correction term $\widetilde{H}_{N'N}$ we have obtained for the energy of the light and heavy 1S exciton the following

$$E_L(\vec{p}, 1S) = E(P=0, 1S) + \frac{p^2}{2M_{L1S}} ,$$
$$E_H(\vec{P}, 1S) = E(P=0, 1S) + \frac{p^2}{2M_{H1S}} . \qquad (32)$$

$E(\vec{P} = 0, 1S)$ being the binding energy

$$E(P=0, 1S) = E_{1S}^{*} + \Delta E(P=0, 1S) . \qquad (33)$$

The binding energy in the spherical model is given by formula (59) in [10]:

$$E_{nS}^{*} = -\frac{R_y^{*}}{n^2} - 2\chi^2\left(\frac{m_2}{m_0}\right)^2 R_y^{*} \cdot S_{nS} . \qquad (34)$$

M_{L1S} and M_{H2S} respectively are the effective masses of the light and heavy exciton:

$$\frac{1}{M_{L1S}} = \frac{1}{M_{L1S}^{*}} + \frac{1}{\Delta M'_{L1S}} ,$$
$$\frac{1}{M_{H1S}} = \frac{1}{M_{H1S}^{*}} + \frac{1}{\Delta M'_{H1S}} . \qquad (35)$$

where M_{L1S}^{*} and M_{H1S}^{*} are the exciton masses in the spherical model and given by formula (60) in [10]

$$\frac{1}{M_{HnS}^{*}} = \frac{1}{M_H} - \frac{20}{3}\chi^2\beta^2\frac{m_2}{m_0^2}\widetilde{R}_{nS} ,$$
$$\frac{1}{M_{LnS}^{*}} = \frac{1}{m_L} - \frac{20}{3}\chi^2\beta^2\frac{m_2}{m_0^2}\widetilde{R}_{nS} ,$$
$$\widetilde{R}_{1S} = \widetilde{R}_{2S} = 0.1875 . \qquad (36)$$

The total cubic corrections $\Delta M'_{L1S}$ and $\Delta M'_{L2S}$ resulting from the $\widetilde{H}^{(0)}_{N'N}$ and $\widetilde{H}^{(2)}_{N'N}$ terms are given by

$$\frac{1}{\Delta M'_{L1S}} = \frac{1}{\Delta M_L} - 4\beta^2\frac{m_2}{m_0^2}\theta^2\widetilde{R}_{1S} ,$$
$$\frac{1}{\Delta M'_{L2S}} = \frac{1}{\Delta M_H} - 4\beta^2\frac{m_2}{m_0^2}\theta^2\widetilde{R}_{1S} . \qquad (37)$$

Similarly for the 2S-exciton we have obtained:

$$E_L(\vec{P}, 2S) = E(\vec{P}=0, 2S) + \frac{P^2}{2M_{L1S}} ,$$
$$E_H(\vec{P}, 2S) = E(\vec{P}=0, 2S) + \frac{P^2}{2M_{H1S}} .$$
$$E(\vec{P}=0, 2S) = E_{2S}^{*} + \Delta E(P=0, 2S) \qquad (38)$$

E_{2S}^{*} is given by (34) and $\Delta E\ (P = 0,\ 2S)$ by (30).

Note that as in the spherical model the effective masses of the exciton 1S and 2S are still equal, but due to the cubic structure they depend on the momentum direction.

For the 2P exciton the analogous calculations showed that its energy splits into six levels:

$$E(\vec{P}, 2P, F=\tfrac{5}{2}, F_z=\pm\tfrac{5}{2}) = \gamma(\vec{P}) + \omega\,(r_1 \cos\frac{\varphi_1}{3} - \frac{2}{3}) ,$$
$$E(\vec{P}, 2P, F=\tfrac{5}{2}; F_z=\pm\tfrac{3}{2}) = \gamma(\vec{P}) + \omega\left[r_1 \cos(\frac{\varphi_1}{3} - \frac{\pi}{3}) - \frac{2}{3}\right] ,$$
$$E(\vec{P}, 2P, F=\tfrac{5}{2}; F_z=\pm\tfrac{1}{2}) = \lambda(\vec{P}) + \omega\left[r_2 \cos(\frac{\varphi_2}{3} - \frac{\pi}{3}) + \frac{2}{3}\right] ,$$
$$E(\vec{P}, 2P, F=\tfrac{3}{2}, F_z=\pm\tfrac{3}{2}) = \gamma(\vec{P}) + \omega\left[r_1 \cos(\frac{\varphi_1}{3} + \frac{\pi}{3}) - \frac{2}{3}\right] ,$$
$$E(\vec{P}, 2P, F=\tfrac{3}{2}, F_z=\pm\tfrac{1}{2}) = \lambda(\vec{P}) + \omega\left[r_2 \cos(\frac{\varphi_2}{3} + \frac{\pi}{3}) + \frac{2}{3}\right] ,$$
$$E(\vec{P}, 2P, F=\tfrac{1}{2}, F_z=\pm\tfrac{1}{2}) = \lambda(\vec{P}) + \omega\left[r_2 \cos\frac{\varphi_2}{3} + \frac{2}{3}\right] . \qquad (39)$$

where

$$\omega = \frac{\chi}{5}\,\frac{m_2}{m_0}\,\frac{R_y^*}{4} . \qquad (40)$$

$$\varphi_i = \arccos\left(-\frac{u}{r_i^3}\right) . \qquad (41)$$

$$r_1 = 2\left[h + h^2 + 18\sqrt{6}\,\frac{\theta}{\chi} + \frac{81}{8}\,\frac{\theta^2}{\chi^2} + 61\right]^{1/2} ,$$
$$r_2 = 2\left[h + h^2 - 9\sqrt{6}\,\frac{\theta}{\chi} + \frac{81}{8}\,\frac{\theta^2}{\chi^2} + 25\right]^{1/2} . \qquad (42)$$

$$h = \frac{P^2}{2\omega}\left(\frac{1}{M_L} - \frac{1}{M_H}\right) . \qquad (43)$$

$$\gamma(\vec{P}) = -\frac{R_y^*}{4} + \frac{P^2}{6}\left(\frac{1}{M_H} + \frac{2}{M_L}\right) ,$$

$$\lambda(\vec{P}) = -\frac{R_y^*}{4} + \frac{P^2}{6}\left(\frac{2}{M_H} + \frac{1}{M_L}\right) . \qquad (44)$$

The spherical exciton masses M_H and M_L are given by (27).

We give the scheme of the energy splitting of the 2P exciton in Fig. 1.

V. NUMERICAL RESULTS FOR ZnSe

We illustrate the above results by calculating numerical values for the case of ZnSe. The following parameters are used:

$$m_e = 0.17; \quad m_L\langle 100\rangle = 0{,}2; \quad m_H\langle 100\rangle = 0{,}65; \quad m_H\langle 111\rangle = 1{,}09.$$

(All masses are in units of the free electron mass.) The exciton masses in the principal directions <100> and <111> are given in Table 1. The binding energies of the 2P-exciton are given in Table 2, where all energies are given in meV.

From Tables 1 and 2 it is obvious that the agreement with the experimental data is quite good. The above results show that the accuracy of the method presented in [10] and applied here is the same as that of the previously used variational [8] and perturbation approaches [3].

ACKNOWLEDGMENTS

Two of the authors (N.T.T. and N.A.V.) would like to thank Professor Abdus Salam, the International Atomic Energy Agency and UNESCO for hospitality at the International Centre for Theoretical Physics, Trieste. The authors would also like to thank Professor Nguyen Van Hieu for suggesting the problem, and for continuous support.

REFERENCES

[1] G. Dresselhaus, J. Phys. Chem Solids 1 (1956) 14.

[2] A. Baldereschi and N.O. Lipari, Phys.Rev. B3 (1971) 439.

[3] N.O. Lipari and A. Baldereschi, Phys. Rev. B6 (1972) 3746.

[4] O. Kane, Phys. Rev. B11 (1975) 3850.

[5] N.O. Lipari and M. Altarelli, Solid State Commun. 18 (1976) 951.

[6] N.O. Lipari and M. Altarelli, Phys.Rev. B15 (1977) 4883.

[7] M. Altarelli and N.O. Lipari, Phys. Rev. B15 (1977) 4898.

[8] M. Sondergeld, Phys. Status Solidi (b) 81 (1977) 253.

[9] B. Sermage and G. Fishman, Phys. Rev. Lett. 43 (1979) 1043.

[10] Hoang Ngoc Cam, Nguyen Van Hieu and Nguyen Ai Viet, Ann. Phys. 164 (1985) 172.

TABLE CAPTIONS

Table 1 The exciton masses for ZnSe.

Table 2 The binding energies of the 2P-exciton. The first line gives the experimental result of Sondergeld, the second and third ones give the result in the variation and perturbation theory, respectively. The last line gives the result in our work.

TABLE 1

	Exp.[8]	Theory[8]	Theory[10]	This work
M_H 100	1,11 ± 0,10	0,87	0,58	0,72
$M_L<100>$	0,38 ± 0,05	0,42	0,39	0,51
$M_H<110>$	1,95 ± 0,10	1,0	0,79	0,74
$M_L<110>$	0,37 ± 0,05	0,4	0,33	0,43

TABLE 2

	$E_{2P}\left(F=\frac{1}{2}\right)$	$E_{2P}\left(F=\frac{3}{2}\right)$	$E_{2P}\left(F=\frac{5}{2}, F_z=\pm\frac{3}{2}, \pm\frac{1}{2}\right)$	$E_{2P}\left(F=\frac{5}{2}, F_z=\pm\frac{5}{2}\right)$
Exp.[8]	4,19	5,9	4,80	5,15
Theory[8]	4,20	5,92	4,76	5,10
Theory[3]	4,05	5,73	4,57	4,89
This work	4,14	5,62	4,72	4,89

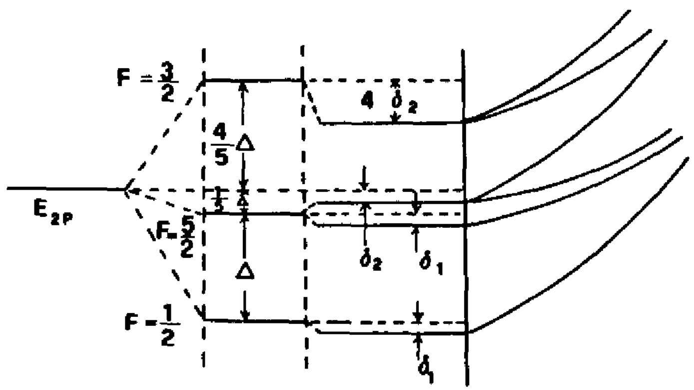

Fig.1

Fig. 1 The scheme of splitting of 2P-exciton energy

$$\Delta = \frac{x\mu}{m_0}\frac{R_y}{4}\ ; \quad \delta_1 = \frac{3\sqrt{6}}{20}\ \frac{\theta_{cub}}{x}\,\Delta; \quad \delta_2 = \frac{3\sqrt{6}}{25}\ \frac{\theta_{cub}}{x}\,\Delta\ .$$