

The investigation of electronic band parameters: obtaining and peculiarities of $\text{InSb}_{1-x}\text{Bi}_x$ crystal structures

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ABSTRACT

$\text{InSb}_{1-x}\text{Bi}_x$ solid solutions monocrystal structures with $\Delta E_{g_{80K}} = 0,12\text{eV}$ were obtained using the modified Czochralski, zone and laser melting methods. A band structure of semiconductor $\text{InSb}_{1-x}\text{Bi}_x$ substitution solid solution is calculated by the empirical pseudopotential method. Spin-orbital interactions are also included in local calculations. Using the virtual-crystal approximation the composition and temperature dependences of energy gap are studied. The results are in good agreement with available experimental data.

Keywords: band structure, semiconductor, solid solution, pseudopotential, virtual-crystal, energy gap.

1. EXPERIMENT

Nowadays detectors of IR-radiation on $\lambda = 9 - 15\mu\text{m}$ spectrum range are elaborated from low-stable CdTe-HgTe solid solutions containing mercury. Solid solution $\text{InSb}_{1-x}\text{Bi}_x$ are expected to be useful for this aim, however there are some technological difficulties in obtaining compounds with energy gap less then 0.15 eV at 80 K^{5,6}. In ⁵ it is shown, that changing of energy gap width depending on InBi content in InSb is $-3,5\text{ eV}/(\text{per mole})$. From which it follows that at 3 – 3,5% InBi content in solid solution it is possible to achieve $\Delta E_{g_{80K}} = 0,1 - 0,12\text{eV}$. From analysis of publication follows that it is not turn out well to obtain crystals of necessary melts with small ΔE_g by generally accepted methods. Therefore we have used technological methods purposeful to obtain InSbBi monocrystals with Bi enlarged content. It were used:

- Czochralski method, where the electric current was put through crystal melt boundary, in order to cool crystallization front at the expense of Peltier effect;

- zone melting at simultaneous translational motion and rotation of ampoule under $\alpha = 45^\circ$ angle relatively to vertical line with magnetic field imposition. This allows to mix melt relatively to the crystal in convection and diffusion regions of melt;
- melting with following impulsive laser radiation of InBiSb solid solution polycrystalline layer, deposited on InSb monocrystal substrate.

The first two methods have allowed to obtain InSb – InBi crystals with $\Delta E_g = 0,13eV$ at 80K. In third case ΔE_g attains $\sim 0,12eV$. In our opinion the third method is the most perspective, since there is now necessity in bulk crystals for IR-photodetectors.

Accounting the achieved experimental data in obtaining of InSbBi solid solutions monocrystal structures, we have carried out calculations of its energy spectrum, represented below.

2. THEORY

The narrow-gap substitutional solid solutions on the basis of compounds $A^{III}B^V$ are promising materials for solid-state electronics engineering. Interest in multicomponent alloys has increased recently. Multicomponent alloys are potentially very important materials for building infrared (IR) detectors, low-noise filters of communication systems, lasers with smooth reorganization of a wavelength^{1,2}. At present the CdHgTe alloys are the most available semiconductor materials for manufacturing far-infrared devices ($\lambda > 8$ microns). However, the properties of these crystals largely depend on technological process, which is not as perfect as, for example, for connections $A^{III}B^V$. Many unforeseen factors strongly influence the band gap, and the processes of degradation result in instability of the physical and ecological characteristics³.

The conventional alloys $A^{III}B^V$ do not allow the possibility to expand a wave range beyond the boundary of 7.5 microns (InAsSb). Therefore, two alternate ways of solving this problem have appeared now. The former involves obtaining new multicomponent materials on the basis of $A^{III}B^V$. The idea of changing the band gap at the expense of voltage, which arises in appropriate superlattices and heterostructures is the basis of the latter⁴. Both of approaches are characterized by strong and weak legs.

The experimental study of the InSb - InBi systems has begun about 30 years ago in the classical works of Jean-Louis⁵⁻⁷. Technological difficulties of cultivating an indicated substitutional solid solution were decelerating its broad practical introduction until recently. However, recent achievements in the given field^{8,9} open new possibilities of constructing the solution and its applications. Increasing interest has been noticed in fundamental properties, such as an

electronic band structure, relation of the band gap to a composition of an alloy and temperature, optical and photo-electric characteristics of indicated materials.

InBi crystallizes in tetragonal (B10) structure and is a semimetal – which is not characteristic of majority of compounds $A^{III}B^V$, which are cubic semiconductors. That fact has stimulated the research of the correlation between an anomalous crystalline structure and physical properties¹⁰. The relation of the lattice constants in InBi is $c/a = 0.9545^9$. Physical properties of the solid solution $\text{InSb}_{1-x}\text{Bi}_x$ ($x < 3\%$) were studied in a number of papers. It was shown that substitution solid solution of a zinc-blende structure with a direct band gap forms in a given range of change of composition. The first estimated calculations of the band structure $\text{InSb}_{1-x}\text{Bi}_x$ were developed through three methods; the Hermann relativistic corrections; the empirical pseudo-potential method; the Van-Vehten semiconductor model⁷. These methods have not allowed quantitative explanation of concentration and temperature dependence of the band gap, and, thus, optical properties were not properly explained. Though the electrical and optical properties of the examined solid solution are of great practical interest, detailed calculations of the electronic band structure have not been performed till now. The electronic energy spectrum $\text{InSb}_{1-x}\text{Bi}_x$ was calculated in the essay with the help of the empirical pseudo-potential method taking into account spin-orbit interaction in virtual crystal approximation. Concentration and temperature dependence of the band gap was theoretically investigated in the essay.

It is necessary to solve the Schredinger wave equation for calculation of the electronic band structure, where one-electronic pseudo-potential Hamiltonian is written in atomic units as:

$$H = -\nabla^2 + V_p(\vec{r}). \quad (1)$$

Where

$$V_p(\vec{r}) = V(\vec{r}) + \sum_t (E - E_t) |b_t\rangle \langle b_t|, \quad (2)$$

— the crystal pseudo-potential, $V(\mathbf{r})$ — the true crystal potential, $|b_t\rangle$ — the wave function of the fundamental state with the energy E_t . The Fourier transform of the pseudo-potential $V_p(\mathbf{r})$, disregarding its nonlocal part, is written as

$$V_p(\vec{r}) = \sum_{\vec{G}} V_L(\vec{G}) \cdot e^{i(\vec{G}\cdot\vec{r})}, \quad (3)$$

Where

$$V_L(\vec{G}) = \sum_{\alpha} S_{\alpha}(\vec{G}) \cdot v_{\alpha}(\vec{G}), \quad (4)$$

$$S_{\alpha}(\vec{G}) = \frac{1}{N_{\alpha}} \sum_j e^{i(\vec{G}\cdot\vec{R}_j^{\alpha})}, \quad (5)$$

\mathbf{G} is the reciprocal lattice vector, $v_\alpha(\mathbf{G})$ is the atomic pseudo-potential form-factors, N_α is the quantity of α atoms in the primitive unit cell, \mathbf{R}_j^α defines the position of the j^{th} α atom. In the case of compounds $A^{\text{NB}}B^{\text{N}}$ with zinc-blende structure, middle point of AB was chosen as origin. These equations can be reduced to:

$$V_L(\vec{G}) = v^s(\vec{G}) \cdot \cos(\vec{G} \cdot \vec{\tau}) + i \cdot v^A(\vec{G}) \cdot \sin(\vec{G} \cdot \vec{\tau}), \quad (6)$$

Where

$$\begin{aligned} v^s(\vec{G}) &= \frac{[v_A(\vec{G}) + v_B(\vec{G})]}{2}, \\ v^A(\vec{G}) &= \frac{[v_A(\vec{G}) - v_B(\vec{G})]}{2}, \end{aligned} \quad (7)$$

$\vec{\tau} = (a/8) \cdot (1,1,1)$, a — is the lattice constant.

In the empirical pseudo-potential method we consider only first four v^A and v^S , which can be justified by the effect of truncating the strong spanning potential. The band structure $\text{InSb}_{1-x}\text{Bi}_x$ can be found through solving the secular equation:

$$\det\left\{ \left[K^2 - E_n(\vec{k}) \right] \cdot \delta_{\vec{G}\vec{G}'} \cdot \delta_{ss'} + V_L(\vec{G} - \vec{G}') \cdot \delta_{ss'} + V_{s_0}^{ss'}(\vec{K}, \vec{K}') \right\} = 0 \quad (8)$$

The spin-orbit term is

$$V_{s_0}^{ss'}(\vec{K}, \vec{K}') = (\vec{K} \times \vec{K}') \cdot \sigma_{ss'} \cdot \left\{ -i\lambda^s \cdot \cos(\vec{K} - \vec{K}') \cdot \tau + \lambda^A \cdot \sin(\vec{K} - \vec{K}') \cdot \tau \right\} \quad (9)$$

Here s and s' are the spin states, σ is the Pauli matrix, $\mathbf{K} = \mathbf{k} + \mathbf{G}$, λ^A and λ^S are adjustable parameters. For the substitutional solid solution, in accordance with the virtual crystal approximation (VCA) and the Vegard law, lattice constant and pseudo-potential form-factors $\text{InSb}_{1-x}\text{Bi}_x$ can be constructed as the linear combinations:

$$\begin{aligned} a_{ss} &= a_{\text{InBi}} \cdot x + a_{\text{InSb}} \cdot (1-x), \\ V_{ss} &= V_{\text{InBi}} \cdot x + V_{\text{InSb}} \cdot (1-x), \end{aligned} \quad (10)$$

Where a_{ss} , V_{ss} are lattice constant and form-factors of the substitution solid solution.

Extensive calculations were made along the fundamental symmetrical directions of the Brillouine Zone in the basis of 137 plane waves (the secular determinant with regard to spin states has the dimension 274×274). Figure 1 presents the band structure InSb and InBi , calculated using the theoretical parameters, given in Table 1 in comparison with parameters of the other works^{7,11}. The calculated energy distances between electronic levels in high symmetric points at the boundary cases $x=0$ (InSb) and $x=1$ (InBi) satisfactorily will correlate with known experimental data and results of the pseudo-potential calculations of other authors (Table 2). The s-zone of In-element drops lower than the p-zone of Bi-element at almost 2eV in the Γ point in InBi -alloy than in InSb -alloy^{7,10}.

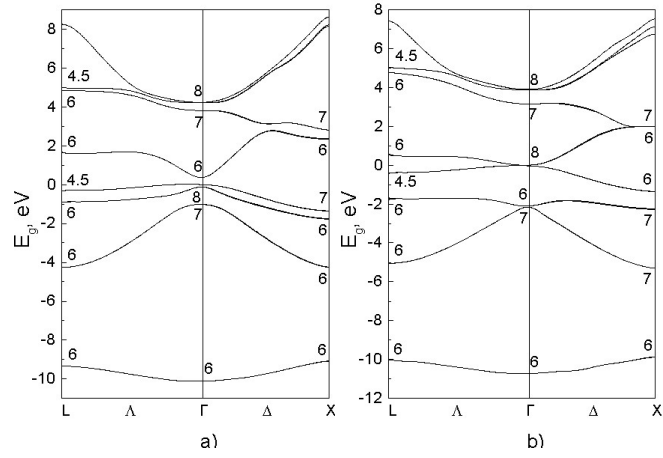


Fig 1 Band structure of InSb (a) and InBi (b)

Table 1. Pseudopotential parameters using in calculations.

	InSb		InBi	
	Ref. ¹¹	Our data	Ref. ⁷	Our data
$v^S(3)$	-0.2547	-0.2285	-0.22	-0.285
$v^S(8)$	0.0188	0	-0.03	-0.0035
$v^S(11)$	0.0452	0.0405	0.02	0.0145
$v^A(3)$	0.0302	0.06	0.08	0.049
$v^A(4)$	0.0012	0.05	0.05	0.035
$v^A(11)$	0.0329	0.01	0.02	0.005
λ^S	0.00231	0.00230	–	0.001693
λ^A	0.00028	0.00028	–	0.003443

Table 2. Interband transitions (eV).

	InSb			InBi	
	Theor. ¹¹	Our calcul.	Exp. ¹²	Theor. ¹⁰	Our calcul.
$\Gamma_{8V} - \Gamma_{6C}$	0.26	0.247	0.2357	1.9	1.97
$\Gamma_{7V} - \Gamma_{6C}$	1.05	1.23	1.216	0	0
$\Gamma_{8V} - \Gamma_{7C}$	3.65	3.6	-	2.56	3.1
$\Gamma_{8V} - \Gamma_{8C}$	3.68	4.21	-	3.10	3.83
$L_{4,5V} - L_{6C}$	2.03	1.89	1.9	1.25	1.18
$L_{6V} - L_{6C}$	2.60	2.48	-	1.75	2.11
$L_{4,5V} - L_{6C}$	5.3	5.71	-	4.12	4.87
$X_{7V} - X_{6C}$	3.95	3.73	-	0.75	0.77
Δ_{CO}	0.82	0.99	0.98	1.9	1.97

The temperature influence on the band structure of the examined solid solutions can be studied with the help of the Brooks-Yu theory¹³. If the zero-temperature electronic energies are calculated as a function of the atomic pseudopotential form-factors:

$$E(\vec{k}) = E(\vec{k}, \{V_j(\vec{G})\}), \quad (11)$$

then at the terminal temperature each Fourier-component of the j^{th} atomic pseudo-potential is corrected by the Debye-Waller factor $M_j(\mathbf{G}, T)$:

$$E(\vec{k}, T) = E\left[\vec{k}, \left\{V_j(\vec{G}) \cdot \exp(-M_j(\vec{G}, T))\right\}\right]. \quad (12)$$

For cubic crystals the Debye-Waller factor is:

$$M_j(\vec{G}, T) = \frac{|\vec{G}|^2}{6} \langle U_j^2(T) \rangle, \quad (13)$$

where the mean square displacement of the j^{th} atom $\langle U_j^2 \rangle$ is described by a Debye relation:

$$\langle U_j^2(T) \rangle = \frac{3\hbar^2}{m_j k_B} \frac{T}{\Theta_j^2} \left[\Phi\left(\frac{\Theta_j}{T}\right) + \frac{1}{4} \frac{\Theta_j}{T} \right] \quad (14)$$

where m_j is the ionic mass, Θ_j is a Debye temperature of each ionic species, Φ_j is a Debye integral of order one. For Debye-temperature calculations we assume $\Theta_{\text{In}} = 112$ K, $\Theta_{\text{Bi}} = 120$ K, $\Theta_{\text{Sb}} = 220$ K¹⁴. Influence of the lattice thermal expansion was taken into account in corresponding dependences of the lattice constants on temperature. Figure 2 presents the calculation results of temperature and concentration dependences of the band gap of the semiconductor solid solutions $\text{InSb}_{1-x}\text{Bi}_x$ in comparison to experimentally measured values in optic absorption experiments⁶. The coefficient change $\gamma = -\Delta E_g / \Delta T$, estimated on the basis of the derived band structure, is shown in Figure 3.

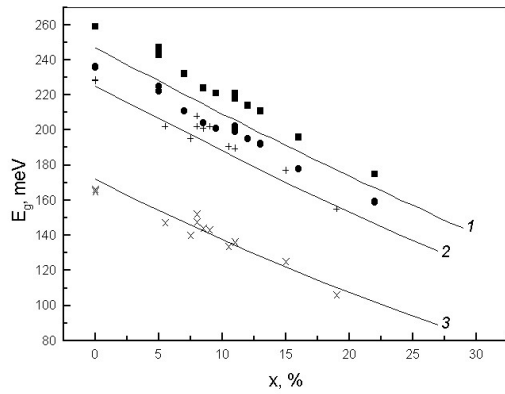


Fig. 2. Variation of energy gap E_g with composition x for $\text{InSb}_{1-x}\text{Bi}_x$.

1 – calculation at 0 K;

2 – calculation at 77 K;

3 – calculation at 300 K;

■, ● – experimental data at 0 K⁶;

+ – experimental data at 77 K⁶;

× – experimental data at 300 K⁶,

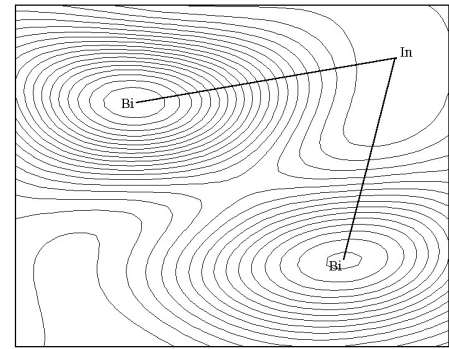


Fig. 3. Electronic charge densities in the (1 1 0) plane of the upper four valence bands.

Satisfactory agreement between the experimental and theoretically derived dependences gives ground to the belief that the chosen model is reasonable for description of the energy band structure of the examined triple semiconductor solid solutions. This can be the reason for further analysis and prediction of optical properties and right method of approach to solving technological problems for obtaining a more perfect material with desired band gap.

3. REFERENCES

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