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Basic Characteristics of Gallium Indium Arsenide Antimonide ($Ga_xIn_{1-x}As_ySb_{1-y}$) Semiconductors Using MATLAB

Abdelkrim Mostefai[1,2,*]

[1] *Department of Electronics, Faculty of Electrical Engineering, University of Sidi Bel Abbes, Algeria*
[2] *Department of Electronics, Faculty of Technology, University of Saida, Algeria*

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Semiconductor materials are categorized by their chemical composition. There are some basic semiconductors, for example silicon (Si) and germanium (Ge), which are part of group IV elements. There are compound semiconductors, binary, ternary and quaternary, and the most common are III-V semiconductors. One of them is a quaternary semiconductor compound $Ga_xIn_{1-x}As_ySb_{1-y}$ (Gallium Indium Arsenide Antimonide) composed of group III elements, for example, gallium (Ga) and indium (In), and group V elements, for example, arsenide (As) and antimonide (Sb). Semiconductors constituted of III-V compounds have great potential for technological applications. They are used in advanced optoelectronic devices, microelectronics and photovoltaic cells due to their properties (robust, high thermal conductivity, direct band gap, etc.). They have been extensively studied over the past decades due to the high quality of these materials and their exceptional optical and electronic characteristics. This work describes the energy gap E_g as a function of x at $T = 300$ K, effective density of states (N_c and N_v) in the conduction and valence bands, intrinsic carrier concentration n_i as a function of temperature T for $Ga_xIn_{1-x}As_ySb_{1-y}$ semiconductors (compositions lattice-matched to GaSb and InAs), and temperature dependence of the energy band gap E_g for GaSb and InAs using MATLAB.

Keywords: III-V Semiconductors, $Ga_xIn_{1-x}As_ySb_{1-y}$, Energy bands, Effective density of states, Intrinsic carrier density, Temperature.

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1. INTRODUCTION

In semiconductor materials, a compound semiconductor is a composite semiconductor material constituted of chemical elements of two or more elements of the periodic table. These semiconductors form groups in the periodic table such as II-VI semiconductors (for example, mercury zinc telluride (HgZnTe) utilized in infrared imaging sensors and infrared detectors), IV semiconductors (for example, silicon germanium ($Si_{1-x}Ge_x$) which facilitates the construction of heterojunction structures) and III-V semiconductors (for example, aluminum gallium arsenide ($Al_xGa_{1-x}As$) [1] utilized in infrared laser diodes and GaAs/AlGaAs solar cells, etc.). III-V semiconductor [2, 3] is a compound material formed by combining one or more group III elements (boron, aluminum, gallium, indium, etc.), and one or more group V elements (nitrogen, phosphorus, arsenic, antimony, etc.). They are mostly employed in microelectronics for integrated circuits, in photovoltaic cells and optoelectronic devices such as light-emitting diodes (LEDs) [3-11]. III-V semiconductor materials are of most interest because of their characteristics, they are durable and resistant, they have high thermal conductivity and a direct band gap, etc.

A quaternary III-V compound semiconductor is a chemical compound including four elements, for example Gallium Indium Arsenide Antimonide ($Ga_xIn_{1-x}As_ySb_{1-y}$) [12-16] ($0 \le x \le 1$ and $0 \le y \le 1$) whose material characteristics have been much discussed [17]. It is a very promising material for optoelectronics such as solar cells, photodiodes and thermophotovoltaic devices. This paper presents the basic characteristics of Gallium Indium Arsenide Antimonide ($Ga_xIn_{1-x}As_ySb_{1-y}$) semiconductors under MATLAB.

2. BASIC CHARACTERISTICS OF GALLIUM INDIUM ARSENIDE ANTIMONIDE ($Ga_xIn_{1-x}As_ySb_{1-y}$)

Gallium Indium Arsenide Antimonide $Ga_xIn_{1-x}As_ySb_{1-y}$ [18] is a quaternary III-V compound semiconductor material. This compound is fundamentally an alloy of gallium antimonide (GaSb, Fig. 1a) and indium arsenide (InAs, Fig. 1b), their energy band gaps E_g are 0.726 eV [19, 20] and 0.354 eV [19] at $T = 300$ K, respectively, they have a zincblende crystal structure.

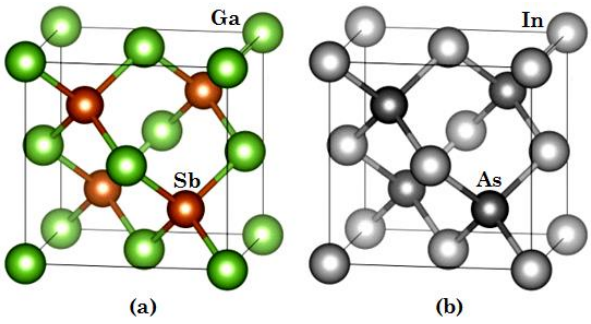

Fig. 1 – Zincblende crystal structure of: a) gallium antimonide (GaSb), b) indium arsenide (InAs)

The following expression presents the energy gap E_g as a function of x for $Ga_xIn_{1-x}As_ySb_{1-y}$ compositions lattice-matched to GaSb (Eq. (1)) and InAs (Eq. (2)) at $T = 300$ K:

* mostakrimo@yahoo.fr

$$E_g \approx 0.29 - 0.165x + 0.6x^2 \quad , \qquad (1)$$

$$E_g \approx 0.36 - 0.23x + 0.54x^2 \quad . \qquad (2)$$

The effective density of states in the conduction band N_c for $Ga_xIn_{1-x}As_ySb_{1-y}$ compositions lattice-matched to GaSb (Eq. (3)) and InAs (Eq. (4)) is given by:

$$N_c = 4.82 \cdot 10^{15} \left(0.022 + 0.03x - 0.012x^2\right)^{3/2} \cdot T^{3/2} \quad , \qquad (3)$$

$$N_c = 4.82 \cdot 10^{15} \left(0.023 + 0.032x - 0.012x^2\right)^{3/2} \cdot T^{3/2} \quad . \qquad (4)$$

The effective density of states in the valence band N_v for $Ga_xIn_{1-x}As_ySb_{1-y}$ compositions lattice-matched to GaSb (Eq. (5)) and InAs (Eq. (6)) is given by:

$$N_v = 4.82 \cdot 10^{15} \left(0.41 + 0.16x + 0.23x^2\right)^{3/2} \cdot T^{3/2} \quad , \qquad (5)$$

$$N_v = 4.82 \cdot 10^{15} \left(0.41 + 0.14x + 0.23x^2\right)^{3/2} \cdot T^{3/2} \quad . \qquad (6)$$

The intrinsic carrier density n_i is given as:

$$n_i = \left(N_c \cdot N_v\right)^{1/2} \exp\left[-\frac{E_g}{2kT}\right] . \qquad (7)$$

The value of y for $Ga_xIn_{1-x}As_ySb_{1-y}$ compositions lattice-matched to GaSb (Eq. (8)) and InAs (Eq. (9)) is given by:

$$y = \frac{0.3835 - 0.3835x}{0.4210 + 0.216x} \quad 0 \le x \le 1 \, , \qquad (8)$$

$$y = \frac{0.4210 - 0.3835x}{0.4210 + 0.0216x} \quad 0 \le x \le 1 \, . \qquad (9)$$

The temperature dependence of the energy band gap E_g for GaSb (Eq. (10), $x = 1$ and $y = 0$) and InAs (Eq. (11), $x = 0$ and $y = 1$) is given by:

$$E_g \approx 0.813 - 3.78 \cdot 10^{-4} \cdot \frac{T^2}{T + 94} \, , \qquad (10)$$

$$E_g \approx 0.415 - 2.76 \cdot 10^{-4} \cdot \frac{T^2}{T + 83} \, . \qquad (11)$$

3. RESULTS AND DISCUSSION

The basic characteristics such as the energy gap E_g as a function of x at $T = 300$ K (Fig. 2), effective density of states N_c and N_v in the conduction and valence bands as a function of x at $T = 300$ K (Fig. 3, Fig. 4), intrinsic carrier concentration n_i as a function of temperature T (Fig. 5, Fig. 6) for $Ga_xIn_{1-x}As_ySb_{1-y}$ compositions lattice-matched to GaSb and InAs, and temperature dependence of the energy band gap E_g for GaSb and InAs (Fig. 7) are treated and analyzed using MATLAB.

Table 1 and Table 2 summarize the results obtained for the energy gap E_g (Fig. 2), effective density of states in the conduction band N_c and effective density of states in the valence band N_v (Fig. 3, Fig. 4), intrinsic carrier density n_i (Fig. 5, Fig. 6) for $Ga_xIn_{1-x}As_ySb_{1-y}$ compositions lattice-matched to GaSb and InAs with different values of x ($0 \le x \le 1$) at room temperature T (300 K).

Table 1 – Results obtained for $Ga_xIn_{1-x}As_ySb_{1-y}$ compositions lattice-matched to GaSb at room temperature T (300 K)

	$x = 0$ $InAs_{0.91}Sb_{0.09}$	$x = 0.2$ $Ga_{0.2}In_{0.8}As_{0.66}Sb_{0.34}$	$x = 0.8$ $Ga_{0.8}In_{0.2}As_{0.13}Sb_{0.87}$	$x = 1$ GaSb
Energy gap E_g (eV)	0.29	0.281	0.542	0.725
Effective density of states N_c (cm^{-3})	$8.172 \cdot 10^{16}$	$1.143 \cdot 10^{17}$	$1.878 \cdot 10^{17}$	$2 \cdot 10^{17}$
Effective density of states N_v (cm^{-3})	$6.575 \cdot 10^{18}$	$7.591 \cdot 10^{18}$	$1.42 \cdot 10^{19}$	$1.792 \cdot 10^{19}$
Intrinsic carrier density n_i (cm^{-3})	$2.691 \cdot 10^{15}$	$4.07 \cdot 10^{15}$	$4.591 \cdot 10^{13}$	$1.547 \cdot 10^{12}$

Table 2 – Results obtained for $Ga_xIn_{1-x}As_ySb_{1-y}$ compositions lattice-matched to InAs at room temperature T (300 K)

	$x = 0$ InAs	$x = 0.2$ $Ga_{0.2}In_{0.8}As_{0.81}Sb_{0.19}$	$x = 0.8$ $Ga_{0.8}In_{0.2}As_{0.26}Sb_{0.74}$	$x = 1$ $GaAs_{0.08}Sb_{0.92}$
Energy gap E_g (eV)	0.36	0.3356	0.5216	0.67
Effective density of states N_c (cm^{-3})	$8.736 \cdot 10^{16}$	$1.231 \cdot 10^{17}$	$2.073 \cdot 10^{17}$	$2.233 \cdot 10^{17}$
Effective density of states N_v (cm^{-3})	$6.575 \cdot 10^{18}$	$7.49 \cdot 10^{18}$	$1.371 \cdot 10^{19}$	$1.725 \cdot 10^{19}$
Intrinsic carrier density n_i (cm^{-3})	$7.189 \cdot 10^{14}$	$1.46 \cdot 10^{15}$	$7.03 \cdot 10^{13}$	$4.644 \cdot 10^{12}$

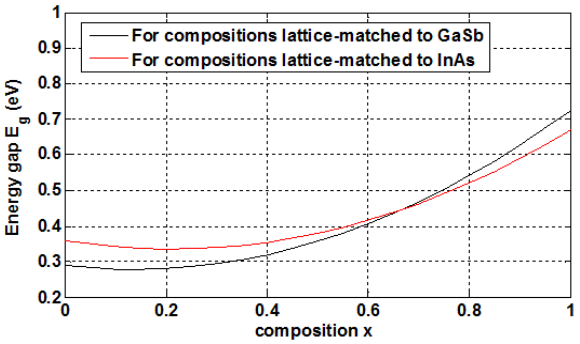

Fig. 2 – Energy gap E_g versus composition x at $T = 300$ K

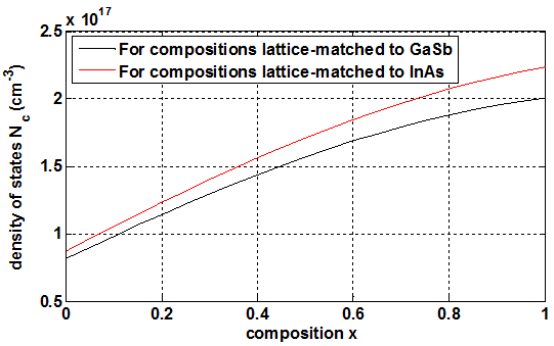

Fig. 3 – Effective density of states N_c versus composition x

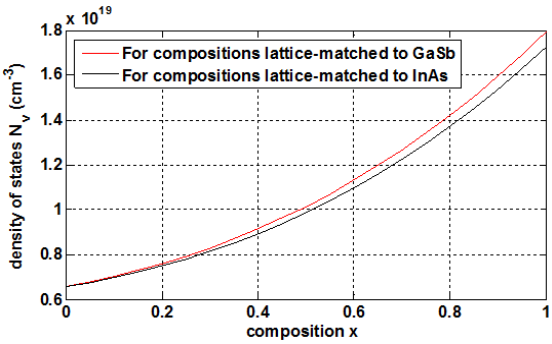

Fig. 4 – Effective density of states N_v versus composition x

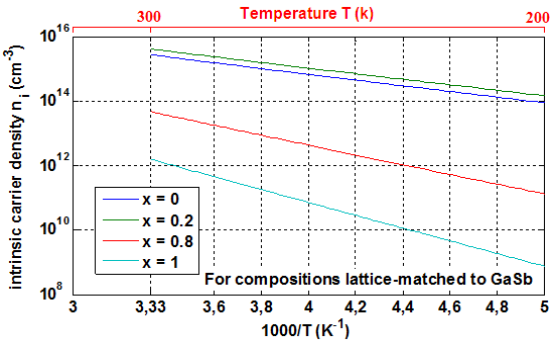

Fig. 5 – Intrinsic carrier density n_i versus $1000/T$ for compositions lattice-matched to GaSb

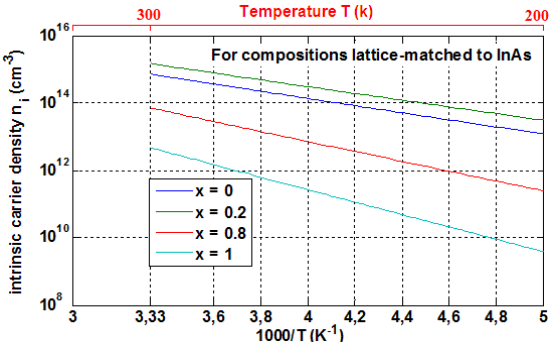

Fig. 6 – Intrinsic carrier density n_i versus $1000/T$ for compositions lattice-matched to InAs

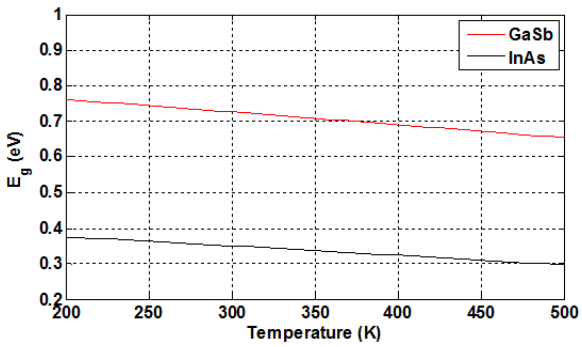

Fig. 7 – Temperature dependence of the energy band gap E_g of gallium antimonide (GaSb) and indium arsenide (InAs)

n_i is the intrinsic carrier density or the intrinsic carrier concentration (Fig. 5 and Fig. 6), the number of broken bonds in an intrinsic semiconductor. To create an electron-hole pair in an intrinsic semiconductor, a bond in the lattice must be broken, and this needs energy. An electron in the valence band needs to accumulate sufficient energy to migrate to the conduction band and leave a hole behind. If the temperature rises, the number of broken bonds (carriers) increases, because the available thermal energy is more important, and the electrons gain sufficient energy to break free. Indeed, any electron that enters the conduction band causes the formation of a hole in the valence band, and the concentration of electrons and holes increases. On the contrary, when the temperature reduces, the electrons do not have sufficient energy to break a bond and stay in the valence band. On the other hand, when the electrons are situated in the conduction band, they rapidly lose energy and return to the valence band, thus annihilating a hole. Consequently, decreasing the temperature leads to a reduction in the intrinsic carrier density, while increasing the temperature leads to an increase in the intrinsic carrier density.

The temperature dependence of the energy band gap is one of the most basic characteristics of semiconductors and has a strong influence on various applications for different semiconductor candidates. From Fig. 7, as the temperature becomes high, the band gap energy reduces due to the expansion of the crystal lattice and the weakening of interatomic bonds. The weakening of bonds indicates that the amount of energy required to break a bond and introduce an electron into the conduction band is less.

4. CONCLUSIONS

III-V semiconductor is a chemical compound material composed of elements included in columns III (group III elements) and V (group V elements) of the periodic table, for example, gallium arsenide GaAs (binary compound), aluminum gallium arsenide AlGaAs (ternary compound) and Gallium Indium Arsenide Antimonide GaInAsSb (quaternary compound).

III-V compound semiconductor materials are the most important due to their features; they have a very high electronic mobility compared to silicon, they are robust and resistant, their thermal conductivity and band gap are higher and direct, respectively, and at very low supply voltage they have ultra-high switching speed, etc. Due to their important characteristics, they are used in the modern electronics manufacturing and technological applications, photovoltaic cells, integrated circuits and advanced optoelectronic devices.

In this context, our paper presents the examination and analysis by simulation under MATLAB of some basic characteristics of Gallium Indium Arsenide Antimonide ($Ga_xIn_{1-x}As_ySb_{1-y}$) semiconductors, for example, the energy gap E_g as a function of x at $T = 300$ K, effective density of states (N_c and N_v) in the conduction and valence bands, intrinsic carrier concentration n_i as a function of temperature T for compositions lattice-matched to GaSb and InAs, and temperature dependence of the energy band gap E_g for GaSb and InAs. For the entire range of compositions, $Ga_xIn_{1-x}As_ySb_{1-y}$ is a direct gap quaternary semiconductor.

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Основні характеристики напівпровідників антимоніду арсеніду галію та індію ($Ga_xIn_{1-x}As_ySb_{1-y}$) за допомогою MATLAB

Abdelkrim Mostefai[1,2]

[1] *Department of Electronics, Faculty of Electrical Engineering, University of Sidi Bel Abbes, Algeria*
[2] *Department of Electronics, Faculty of Technology, University of Saida, Algeria*

Напівпровідникові матеріали класифікуються за їх хімічним складом. Існують деякі основні напівпровідники, наприклад кремній (Si) і германій (Ge), які входять до складу елементів IV групи. Розрізняють складені напівпровідники, подвійні, трійні та четвертинні, а найпоширенішими є напівпровідники III-V груп. Одним з них є четвертинна напівпровідникова сполука $Ga_xIn_{1-x}As_ySb_{1-y}$ (антимонід арсенід галію та індію), що складається з елементів III групи, наприклад, галію (Ga) та індію (In), і елементів V групи, наприклад, арсеніду (As) і антимоніду (Sb). Напівпровідники, що складаються з елементів III-V груп, мають великий потенціал для технологічного застосування. Вони використовуються в передових оптоелектронних пристроях, мікроелектроніці та фотоелектричних елементах завдяки своїм властивостям (міцність, висока теплопровідність, пряма заборонена зона тощо). Протягом останніх десятиліть їх ретельно вивчали завдяки високій якості цих матеріалів та їхнім винятковим оптичним та електронним характеристикам. У роботі описано енергетичну щілину E_g як функцію x при $T = 300$ K, ефективні густини станів (N_c і N_v) у зоні провідності та валентній зоні, власну концентрацію носіїв n_i як функцію температури T для напівпровідників $Ga_xIn_{1-x}As_ySb_{1-y}$ (склади, узгоджені з решіткою GaSb та InAs), і температурну залежність забороненої зони E_g для GaSb та InAs за допомогою MATLAB.

Ключові слова: Напівпровідники III-V груп, $Ga_xIn_{1-x}As_ySb_{1-y}$, Енергетичні зони, Ефективна густина станів, Власна густина носіїв, Температура.