



Laser-induced modulation of optical band-gap parameters in the III–V-type semiconductors from the density-of-state (DOS) calculations

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Abstract. Optical band gap (E_{g0}) is a parameter of paramount importance in describing various transport and optoelectronic properties of the III–V-type low band-gap semiconductors. In the present communication, an attempt has been made to develop an energy–momentum ($E-k$) dispersion relation for studying the density-of-state (DOS) and band-gap-related parameters. The external laser excitation has been treated as a perturbation. It has been shown theoretically that due to such excitation with different intensity (I) and wavelength (λ), the band edge of the conduction band (CB) of the III–V compound semiconductors moves vertically upward, indicating laser modulation (increase) of E_{g0} and related parameters compared to those of the normal ones (unperturbed). Therefore, in the presence of light, the original CB edge forms a pseudo-CB edge above the unperturbed CB edge in the forbidden band (FB) zone. This new development of the ($E-k$) relationship has also been extended for the estimation of exact optical effective mass (OPEM) of an electron in some III–V compound semiconductors. The OPEM variation with carrier concentration showed a continuous decreasing nature, while the corresponding variation of electron effective mass (EEM) (without laser excitation) exhibited an increasing trend. The present theoretical results would be important for the deeper understanding of the variation of OPEM with I and λ . The observed new results will also be beneficial for studying laser-induced effects in semiconductor heterostructures with different applications in optoelectronic devices.

Keywords. Density of state; III–V compound semiconductor; optical band gap; parabolic band; optoelectronics; laser optics.

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1. Introduction

Recently, applications of laser in optical processes in the semiconductor as well as in nanostructured devices are the subjects of substantial interest due to their novelty [1]. The unperturbed band gap (E_{g0}) and the corresponding density-of-state (DOS) function of the carriers in a band are the most important parameters in a semiconductor. When a semiconductor is perturbed using external stimulating agencies [2,3], like heat (or temperature) [4,5], pressure [6], laser [7,8], electric [9] and magnetic fields [10], impurity concentrations [11,12] or other excitations, the values of band-gap parameters of semiconductors are expected to change. Laser dressing effects in low-dimensional semiconductor system

were studied by Pavlov and Zegrya [13] and Brandi *et al* [14,15]. Ghatak and Bhattacharya [16] used Kane three-band model to derive DOS and investigated the optical properties and Einstein relation.

Earlier, optical band gap (E_{g0}) [8] and its variations (ΔE_g) in different compound semiconductors such as $(\text{GaP})_{1-x}(\text{ZnSe})_x$ for $0 \leq x \leq 0.18$ were studied by changing the mole fraction (x) [7]. However, a suitable theory to explain the variation of ΔE_g with laser (or other monochromatic radiation) intensities (I) and wavelength (λ) have not yet been investigated theoretically. In addition, λ and I dependences of the parameters, such as carrier DOS and optical effective mass (OPEM) [17–22] have not been established theoretically. It appears from the previous investigations

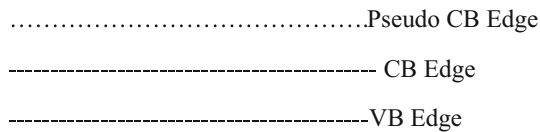


Figure 1. Schematic representation of the formation of pseudo-CB edge in a semiconductor with incident laser perturbation (disappears when the incident light is removed).

[17–21] that the energy–momentum dispersion relations for various band-gap-dependent parameters vary in the context of various perturbing agencies. Therefore, an attempt has been made in the present paper to develop the basic ($E-\bar{k}$) dispersion relations, using the second-order perturbation technique [23] followed by Kane two-band model, for investigating various properties of semiconducting parameters, e.g. changes of the energy band-gap value (ΔE_g), carrier DOS functions, OPEM of electron from the corresponding unperturbed band condition. The said ($E-\bar{k}$) dispersion relation also stimulated us to study variations of OPEM of electrons under externally controlled conditions by doping. Although considerable experimental work had already been made on effective electron mass (EEM) with doping and on the OPEM [22–25] with and without doping, the effects of laser excitations as a perturbation on OPEM in doped semiconductors as a function I and wavelength (λ) were not yet investigated theoretically. In the present paper, such parameters were estimated theoretically and compared with the available experimental results. The influence of a strong constant electric field reduces the width of the forbidden band and the quantising magnetic field increases the optical width of the forbidden band (FB).

It was explored for the first time that with the exposure of laser energy of different I and λ , the conduction band (CB) edge could be moved vertically upward, indicating an increase of band-gap value which led to the formation of a pseudo-CB edge above the original band edge (figure 1).

The organisation of this paper is as follows: §2 provided the theoretical background. Section 2.1 presented the derivation of the dispersion relations. In §2.2, we formulated the energy–momentum dispersion relation, the changes of the energy band-gap value and carrier DOS functions. In §2.3, we developed the model for variations of the OPEM of an electron from the corresponding unperturbed band condition. The results were discussed in §3, regarding the increase of CB-gap value with the intensity and wavelength of the incident laser light considering n-InSb and n-GaAs semiconductors, as examples. The variation of DOS function in the case of n-GaAs as a function of intensity and wavelength of laser light was discussed in §3 along with a brief discussion on the variation of the doping dependence of the

OPEM in n-GaAs. Finally, §4 ended with a conclusion based on the results.

2. Theoretical background

2.1 Presentation on the basis of energy spectrum

The second-order energy eigenvalues, $E_n^{(2)}(\bar{k})$, in the presence of perturbed Hamiltonian, H' , is given by [23]

$$E_n^{(2)}(\bar{k}) = E_n(\bar{k}) + \langle n\bar{k} | H' | n\bar{k} \rangle + \left\{ \frac{|\langle n\bar{k} | H' | m\bar{k} \rangle|^2}{E_n(\bar{k}) - E_m(\bar{k})} \right\}, \quad (1)$$

where

$$H\psi_n(\bar{k}, \bar{r}) = E \cdot \psi_n(\bar{k}, \bar{r}), \quad (2)$$

$$H = H_0 + H', \quad (3)$$

$$H_0 u_n(\bar{k}, \bar{r}) = E_n(\bar{k}) \cdot u_n(\bar{k}, \bar{r}). \quad (4)$$

H is the total Hamiltonian, $\psi_n(\bar{k}, \bar{r})$ is the wave function with $u_n(\bar{k}, \bar{r})$ as its periodic function. H_0 , n , \bar{r} , \bar{k} , E and $E_n(\bar{k})$ are the unperturbed Hamiltonian, the band index, the position vector of the electron, the wave vector of the electron, the total energy of the electron and the energy of an electron in the periodic lattice, respectively.

It is worth remarking that the energy eigenvalue equation determines the dispersion relation for the conduction electron (for $n = c$) in a semiconductor in the presence of an external monochromatic laser excitation as a perturbation (H'). It is to be noted that without the knowledge of the electron energy–momentum ($E-\bar{k}$) dispersion relation, various parameters of a semiconductor (e.g. the DOS) function, which in turn control many other electronic properties, e.g., band-gap variations with intensity of light wave and colours, optical EEM, etc. could not be formulated. Besides, the Boltzmann transport equation, which determines the charge transport properties of a semiconductor device, can be solved if and only if the $E-\bar{k}$ dispersion relation is known [10].

Now, for a monochromatic laser, the light vector \bar{A} , incident on a semiconductor, the perturbed Hamiltonian (H') can be written [26] as

$$H' = \frac{e}{m_0} (\bar{A} \cdot \bar{p}), \quad (5)$$

where \bar{A} is an external electromagnetic field, characterising the light wave (i.e. photon) with \bar{A} as the vector potential and \bar{p} as the momentum vector of the electron, e is the electron charge and m_0 is the free electron mass.

The vector potential $(\bar{A}) = (A_0 \hat{a})$ is considered as a monochromatic plane wave with

$$\bar{A} = A_0 \hat{a} \cos(\bar{s} \cdot \bar{r} - \omega t). \quad (6)$$

Here \hat{a} is the polarisation vector of light, with its amplitude, A_0 , t is the time-scale, ω is the angular frequency of the light wave and \bar{s} is the wave vector.

In eq. (1), the second and the third terms are due to the perturbation factor, H' (eq. (5)) of the first and second order, respectively, to the unperturbed term, $E_n(\bar{k})$.

Using eq. (5) into eq. (1), we get

$$E_n^{(2)}(\bar{k}) = E_n(\bar{k}) + H'_{nn} + \frac{|H'_{nm}|^2}{E_n(\bar{k}) - E_m(\bar{k})}. \quad (7)$$

Using eqs (5) and (6), we find

$$H'_{nm} = \frac{e}{m_0} \langle n\bar{k} | (\bar{A} \cdot \bar{p}) | n\bar{k} \rangle \quad (8)$$

$$= \frac{e}{2m_0} \cdot A_0 \hat{a} \cdot \bar{p}_{nm}(\bar{k}), \quad (9)$$

where

$$\bar{p}_{nm}(k) = \int_{\text{cell}} u_n^*(\bar{k}, \bar{r}) \cdot \bar{p} \cdot u_m(\bar{k}, \bar{r}) d^3r. \quad (10)$$

$\bar{p}_{nm}(\bar{k})$ is known as the \bar{k} -dependence of the optical matrix element (OME) [27,28].

For a semiconductor, whose unperturbed energy band structures are defined for the CB as $n = c$ and the valence band (VB), as $m = v$, we have

$$E_c(\bar{k}) = \frac{\hbar^2 k^2}{2m_c}, \quad (11)$$

where \hbar is the reduced Planck's constant, given by $\hbar = h/2\pi$ and m_c is the EEM at the band edge of the CB.

Using eqs (1) and (7), one can write

$$E_c^{(2)}(\bar{k}) = E_c(\bar{k}) + H'_{cc} + \frac{|H'_{cv}|^2}{\{E_c(\bar{k}) - E_v(\bar{k})\}}, \quad (12)$$

where H'_{cc} and H'_{cv} are, respectively the intraband and interband transition matrix elements due to photoexcitation.

For transition of electrons within the same band, H'_{cc} is neglected because in such a case, when carriers are generated by a photon, it would be lost by recombination in the band, resulting in zero carriers. Hence, we can write

$$H'_{cc} = 0 \quad (13)$$

and

$$H'_{cv} = \left(\frac{eA_0}{2m_0} \right) \cdot [\hat{a} \cdot \bar{p}_{cv}(\bar{k})]. \quad (14)$$

Here, $\bar{p}_{cv}(\bar{k})$ is termed as the \bar{k} -dependence of the OME [28] between CB and VB, and is given as (from eq. (10))

$$\bar{p}_{cv}(k) = \int_{\text{cell}} u_c^*(\bar{k}, \bar{r}) \cdot \bar{p} \cdot u_v(\bar{k}, \bar{r}) d^3r. \quad (15)$$

2.2 Dispersion relation, energy band gap and DOS function in the presence of laser excitation as a perturbation (corresponding unperturbed energy band is given by eq. (11))

From eqs (11) to (14), one gets

$$E_c^{(2)}(\bar{k}) = \frac{\hbar^2 k^2}{2m_c} + \left(\frac{eA_0}{2m_0} \right)^2 \cdot |\hat{a} \cdot \bar{p}_{cv}(\bar{k})|^2 / \{E_c(k) - E_v(k)\}. \quad (16)$$

For the two-band model of Kane with $\bar{k} \cdot \bar{p}$ interaction, due to photoenergy, we find from

$$\hat{a} \cdot \bar{p}_{cv}(k) = -\frac{E_{g0}}{\eta(k)} [\hat{a} \cdot \bar{p}_{cv}(o)], \quad (17)$$

where

$$\eta(k) = E_c(\bar{k}) - E_v(\bar{k}) = \left[E_{g0}^2 + \frac{E_{g0} \hbar^2 k^2}{m_r} \right]^{1/2} \quad (18)$$

and

$$|p_{cv}(o)| = \frac{m_0}{2} \left(\frac{E_{g0}}{m_r} \right)^{1/2}. \quad (19)$$

E_{g0} is the unperturbed band gap of the semiconductor and m_r is the reduced EEM given by

$$m_r^{-1} = m_c^{-1} + m_v^{-1}. \quad (20)$$

Now using eqs (11), (16)–(20) we get

$$E_c^{(2)}(\bar{k}) = \frac{\hbar^2 k^2}{2m_c} + \left(\frac{eA_0}{2m_0} \right)^2 \cdot E_{g0}^3 \cdot \left[E_{g0}^2 + \frac{E_{g0} \hbar^2 k^2}{m_r} \right]^{-3/2}. \quad (21)$$

Equation (21) implies that the total electron energy ($\equiv E_c^{(2)}(\bar{k})$) is the sum of kinetic energy ($\equiv \hbar^2 k^2 / 2m_c$) and the potential energy acquired by the electron generated by the incident light energy:

$$\left(\frac{(eA_0)^2}{16} \cdot \frac{E_{g0}^3}{m_r} \cdot \left[E_{g0}^2 + \frac{E_{g0} \hbar^2 k^2}{m_r} \right]^{-3/2} \right).$$

$E_c^{(2)}(\bar{k}) = E$ is the total electron energy.

We can write eq. (21) as

$$E = \frac{\hbar^2 k^2}{2m_c} + \left(\frac{(eA_0)^2}{16} \cdot \frac{E_{g0}^3}{m_r} \cdot \left[E_{g0}^2 + \frac{E_{g0} \hbar^2 k^2}{m_r} \right]^{-3/2} \right). \quad (21A)$$

Therefore, eq. (21A) is the representation of the perturbed energy–momentum dispersion relation for the parabolic band, whose unperturbed form is given by eq. (11).

In the absence of photon vector, we have $A_0 = 0$, i.e. the amplitude of the electromagnetic wave is zero, which in turn indicates the zero intensity of the light wave. Under this condition, one finds from eq. (21A)

$$\hbar^2 k^2 \approx 2m_c \cdot E. \quad (22)$$

Substituting eq. (22) into the second term of eq. (21), we can write (approximately)

$$E = \frac{\hbar^2 k^2}{2m_c} + \frac{e^2 A_0^2}{16m_r} \cdot \left[1 + \frac{2m_c}{m_r} \cdot \frac{E}{E_{g0}} \right]^{-3/2}. \quad (23)$$

Rewriting eq. (23), we have

$$\gamma(E, A_0) = \frac{\hbar^2 k^2}{2m_c}, \quad (24)$$

where

$$\gamma(E, A_0) = E - \frac{e^2 A_0^2}{16m_r} \cdot \left[1 + \frac{2m_c}{m_r} \cdot \frac{E}{E_{g0}} \right]^{-3/2}. \quad (25)$$

Using [29] we can write

$$A_0^2 = \frac{1}{2\pi^2} \cdot \frac{(I\lambda^2)}{c^3 n_r \cdot \epsilon_0}. \quad (26)$$

I, λ, c, n_r and ϵ_0 are the intensity of light wave, the wavelength or frequency of light, velocity of the perturbing light in vacuum, the refractive index and permittivity of the material in the free space, respectively.

Further, taking $(\vec{k}) \rightarrow 0$ in eq. (24) and using eq. (25), we find $E \neq 0$, which implies that at the band edge of CB, where $k = 0$, the energy of the electron, E , is not equal to zero (unlike eq. (11)), rather it is enhanced by some positive value, ΔE_g , which is approximately given by

$$\Delta E_g = \frac{(e^2 A_0^2 / 16m_r)}{\left[1 + \frac{3}{16} \cdot (e^2 A_0^2 / m_r \cdot E_{g0}) \cdot (m_c / m_r) \right]}. \quad (27)$$

Equation (27) indicated the shift of the band edge from the origin (in the absence of light perturbation) and it varied with A_0^2 , i.e. with I and square of the wavelength. As ΔE_g is a positive value, the band gap of the CB edge increases with I and λ and the band edge moves vertically upward.

From eqs (24) and (25), the expression for DOS function, $N(E, A_0)$, is given by [10]

$$N(E, A_0) = \frac{1}{2\pi^2} \cdot \left(\frac{2m_c}{\hbar^2} \right)^{3/2} \cdot \gamma^{1/2}(E, A_0) \cdot \frac{d\gamma}{dE}(E, A_0), \quad (28)$$

where

$$\frac{d}{dE} \gamma(E, A_0) = 1 + \frac{3}{16} \cdot \frac{e^2 A_0^2}{m_r \cdot E_{g0}} \cdot \left(\frac{m_c}{m_r} \right) \cdot \left[1 + \frac{2m_c}{m_r} \cdot \frac{E}{E_{g0}} \right]^{-5/2}. \quad (29)$$

Combining eqs (27)–(29), the closed form of $N(E, A_0)$ can be written as

$$N(E, A_0) = \frac{1}{2\pi^2} \cdot \left(\frac{2m_c}{\hbar^2} \right)^{3/2} \cdot \left(1 + \frac{3}{16} \cdot \frac{e^2 A_0^2}{m_r \cdot E_{g0}} \cdot \left(\frac{m_c}{m_r} \right) \right)^{3/2} \cdot (E - \Delta E_g)^{1/2}. \quad (30)$$

Thus, the observed DOS (from eq. (30)), i.e. $N(E, A_0)$, is proportional to the square root of $(E - \Delta E_g)$. For a definite value of $N(E, A_0)$, the electron energy E must be greater than ΔE_g .

2.3 OPEM of an electron using the $E - \vec{k}$ dispersion (shown in eq. (21A))

The definition of momentum dependence of electron effective mass, m^* , is given [10] by the relation

$$(m^*)^{-1} = (\hbar^2 k)^{-1} \cdot \frac{dE}{dk}, \quad (31)$$

where E, m_c, k, A_0, E_{g0} and m_r are the total electron energy, CB edge effective mass, wave vector, the amplitude of the light wave, unperturbed band gap and reduced effective mass, respectively.

Writing m_{op}^* as the OPEM of the electron, one gets the relation (using eqs (21A) and (31))

$$\frac{1}{m_{op}^*} = \frac{1}{m_c} - \frac{3}{16} \cdot \frac{(eA_0)^2}{m_r^2 \cdot E_{g0}} \cdot \left[1 + \frac{\hbar^2 k^2}{m_r \cdot E_{g0}} \right]^{-5/2}. \quad (32)$$

From eq. (32), it is clear that m_{op}^* depends on both \vec{k} as well as A_0 . So, writing $m_{op}^* = m_{op}^*(\vec{k}, A_0)$, eq. (32) can be rewritten as

$$\frac{1}{m_{op}^*(\vec{k}, A_0)} = \frac{1}{m_c} - \frac{3}{16} \cdot \frac{(eA_0)^2}{m_r^2 \cdot E_{g0}}$$

$$\cdot \left[1 + \frac{\hbar^2 k^2}{E_{g0} \cdot m_r} \right]^{-5/2}. \quad (33)$$

Equation (33) is the required OPEM of electrons (considering photon or light wave as perturbation). Thus, $m_{op}^*(\bar{k}, A_0)$ is a function of \bar{k} (the momentum vector) as well as A_0 (the light wave amplitude).

Taking $\bar{k} = 0$, in eq. (33), one gets the OPEM at the band edge of CB, as

$$\frac{1}{m_{op}^*(0, A_0)} = \frac{1}{m_c} - \frac{3}{16} \left(\frac{eA_0}{m_r} \right)^2 \cdot \frac{1}{E_{g0}}. \quad (34)$$

Equation (34) can be rewritten as

$$\begin{aligned} \frac{\Delta m}{m_{op}^*(\bar{k} = 0, A_0)} &= 1 - \frac{m_c}{m_{op}^*(\bar{k} = 0, A_0)} \\ &= \frac{3}{16} \cdot \frac{(eA_0)^2}{m_r E_{g0}} \cdot \left(\frac{m_c}{m_r} \right), \end{aligned} \quad (35)$$

where

$$\Delta m = [m_{op}^*(\bar{k} = 0, A_0) - m_c]. \quad (36)$$

For a given value of A_0 (i.e. when intensity (I) and wavelength (λ) of the light wave are given for a monochromatic light), $[\Delta m/m_{op}^*(\bar{k} = 0, A_0)]$ has a fixed value. With the variations of I and λ , $[\Delta m/m_{op}^*(\bar{k} = 0, A_0)]$ will also vary.

It was well known [10,29] earlier that the momentum dependence of EEM also varied with the doping concentration (Ni). Under this condition, one has to replace \bar{k} in eq. (33) by \bar{k}_f , where \bar{k}_f is the momentum wave vector at the Fermi surface. For this case, eq. (33) comes out to be

$$\begin{aligned} \frac{1}{m_{op}^*(\bar{k}_f, A_0)} &= \frac{1}{m_c} - \frac{3}{16} \cdot \left(\frac{eA_0}{m_r} \right)^2 \cdot \frac{1}{E_{g0}} \\ &\cdot \left[1 + \frac{\hbar^2 \bar{k}_f^2}{E_{g0} \cdot m_r} \right]^{-5/2}. \end{aligned} \quad (37)$$

To calculate \bar{k}_f , one has to find the Fermi energy E_f , from the carrier statistical relation, using approximate $E - \bar{k}$ dispersion relation and DOS function, reported in §2.2.

Under degenerately doping conditions, one can write from eq. (24)

$$\hbar^2 \bar{k}_f^2 \approx 2m_c \cdot \gamma(E_f, A_0). \quad (38)$$

Substituting eq. (38) into eq. (37), we get

$$\begin{aligned} \frac{1}{m_{op}^*(E_f, A_0)} &= \frac{1}{m_c} - \frac{3}{16} \cdot \frac{(eA_0)^2}{m_r^2 \cdot E_{g0}} \\ &\cdot \left[1 + \frac{2m_c}{m_r} \cdot \frac{\gamma(E_f, A_0)}{E_{g0}} \right]^{-5/2}. \end{aligned} \quad (39)$$

For a semiconductor to be degenerately doped with a particular carrier concentration (Ni), the Fermi energy, E_f , can be computed from [10] as

$$\gamma(E_f, A_0) = \frac{\hbar^2}{2m_c} \cdot (3\pi^2 \cdot Ni)^{2/3}. \quad (40)$$

Substituting eq. (40) for $\gamma(E_f, A_0)$ into eq. (39), we get

$$\begin{aligned} \frac{1}{m_{op}^*(Ni, A_0)} &= \frac{1}{m_c} - \frac{3}{16} \cdot \frac{(eA_0)^2}{m_r^2 \cdot E_{g0}} \\ &\cdot \left[1 + \frac{\hbar^2}{E_{g0} m_r} \cdot (3\pi^2 \cdot Ni)^{2/3} \right]^{-5/2}. \end{aligned} \quad (41)$$

For a given value of Ni , one can compute $\gamma(E_f, A_0)$ from eq. (40). Knowing $\gamma(E_f, A_0)$ for a given value of A_0 , one obtains $[1/m_{op}^*(Ni, A_0)]$ from eq. (41).

Equation (41) can be rewritten as

$$\frac{\Delta m}{m_{op}^*(Ni, A_0)} = \frac{3}{16} \frac{(eA_0)^2}{m_r \cdot E_{g0}} \cdot \left(\frac{m_c}{m_r} \right) \cdot [Z], \quad (42)$$

where

$$Z = \left[1 + \frac{\hbar^2}{E_{g0} \cdot m_r} \cdot (3\pi^2 Ni)^{2/3} \right]^{-5/2} \quad (43)$$

and

$$\begin{aligned} \frac{\Delta m}{m_{op}^*(Ni, A_0)} &= \frac{m_{op}^*(Ni, A_0) - m_c}{m_{op}^*(Ni, A_0)} \\ &= \left[1 - \frac{m_c}{m_{op}^*(Ni, A_0)} \right]. \end{aligned} \quad (44)$$

Attributing eq. (35) to eq. (42), we get (following eq. (44))

$$m_{op}^*(Ni, A_0) = m_c \cdot [1/(1 - K \cdot Z)], \quad (45)$$

where

$$K = \frac{\Delta m}{m_{op}^*(\bar{k} = 0, A_0)} = \left\{ 1 - \left[\frac{m_c}{m_{op}^*(\bar{k} = 0, A_0)} \right] \right\} \quad (46)$$

and Z is given by eq. (43).

$$m_{op}^*(\bar{k} = 0, A_0)/m_c = 1/(1 - K). \quad (47)$$

3. Results and discussion

Electron energy, E , can be calculated from eq. (21A) as a function of the momentum wave vector, (\bar{k}), by changing A_0 . It is obvious from eq. (21A) that if $A_0 \neq 0$, i.e. in the presence of light wave, the value of $E \neq 0$

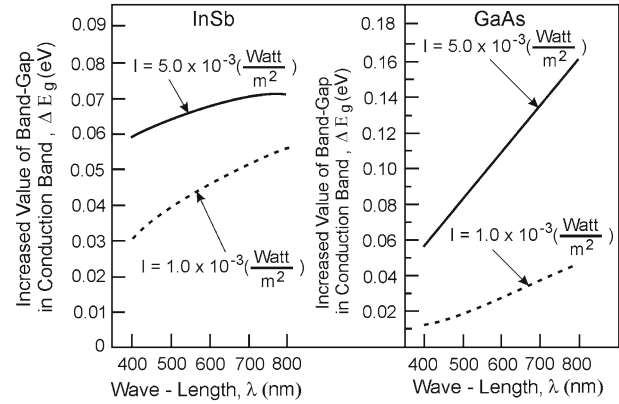
Table 1. Various parameters for n-InSb and n-GaAs at room temperature (300 K).

Sample	E_g (eV)	m_c	m_v	n_r
InSb at 300 K	0.235	$0.0143m_0$	$0.45m_0$	3.5
GaAs at 300 K	1.42	$0.067m_0$	$0.50m_0$	3.27

at $(\vec{k}) = 0$. It implies that in the presence of light wave, the unperturbed parabolic band is perturbed to a new band shape. The new band edge is shifted from the original position and moves vertically upward with the change of A_0^2 , i.e. the square of the light wave amplitude. This shift of the band edge from the original position is denoted by (ΔE_g) , i.e. eq. (27) and may be termed as the ‘increased value of band gap in CB’, taking CB edge as the reference level. Here it would be important to mention that the present observation of broadening of band gap by optical perturbation is quite different from the band-gap narrowing observed when small fractions of N impurities were added to GaAs, GaP or GaSb [19,30–33]. The band gap of GaN, $E_g = 3.30$ eV, in zinc blende structure is much larger than that of any of the conventional III–V compounds. This narrowing is not proportional to the fraction of N , and only at sufficiently high N fractions the band gap starts to widen.

Equation (27) provides the model for ΔE_g coupled along with other semiconductor parameters. Various parameters for n-InSb and n-GaAs type III–V compound semiconductors are depicted in table 1. Table 2 showed the values of ΔE_g (eV) for n-InSb and n-GaAs at room temperature (300 K). The changes ΔE_g (in eV) were calculated and plotted in figure 2, against the variation of wavelength λ (in nm) when the intensities (I) were $I = 1 \times 10^{-3} \text{ W/m}^2$ and $I = 5 \times 10^{-3} \text{ W/m}^2$, respectively, for n-InSb and n-GaAs materials [10].

From figure 2, it is obvious that the value of ΔE_g increases with λ in the visible wavelength range, e.g.

**Figure 2.** Increased band gaps in InSb and GaAs semiconductors as a function of incident laser light wavelength.

$\lambda = 410$ nm corresponding to violet colours and $\lambda = 660$ nm, corresponding to red light.

Figures 3a and 3b show the increase in band gap ΔE_g (eV) values with an intensity I and $\lambda = 660$ and 450 nm, respectively, for n-InSb and n-GaAs samples. It is observed from these figures that the values of ΔE_g are almost zero at the lowest intensity, i.e., $I = 1.0 \times 10^{-4} \text{ W/m}^2$ for both $\lambda = 450$ and 660 nm, respectively. Thereafter, with the increase of I , ΔE_g also increases and finally it reaches the maximum value of 0.36 eV for n-GaAs and 0.07 eV for n-InSb at 300 K for $I = 1.0 \text{ W/m}^2$. For the intermediate values of I , ΔE_g of the two curves in figures 3a and 3b differs widely, with higher values at $\lambda = 660$ nm than that at lower $\lambda = 450$ nm. The usual variation of optical band gap with the change of the mole fraction of the compound semiconductor was already reported [32], whereas from the present study, see figures 2 and 3, we find new observations of the change of band gap with light intensity and wavelength. This behaviour is identical with that observed with a change of impurity concentrations.

Figure 4 showed the plots of DOS function $N(E, A_0)$ ($\equiv N(E, I, \lambda)$ (eq. (30)) against I , for $\lambda = 660$ (solid

Table 2. Various values of ΔE_g (eV) for n-InSb and n-GaAs at room temperature (300 K).

Visible range of colours	ΔE_g (eV) at 300 K			
	$I = 1 \times 10^{-3} \text{ W/m}^2$		$I = 5 \times 10^{-3} \text{ W/m}^2$	
	GaAs $E_{g0} = 1.42 \text{ eV}$	InSb $E_{g0} = 0.235 \text{ eV}$	GaAs $E_{g0} = 1.42 \text{ eV}$	InSb $E_{g0} = 0.235 \text{ eV}$
Violet ($\lambda = 410$ nm)	0.012	0.031	0.06	0.06
Red ($\lambda = 660$ nm)	0.03	0.045	0.12	0.068

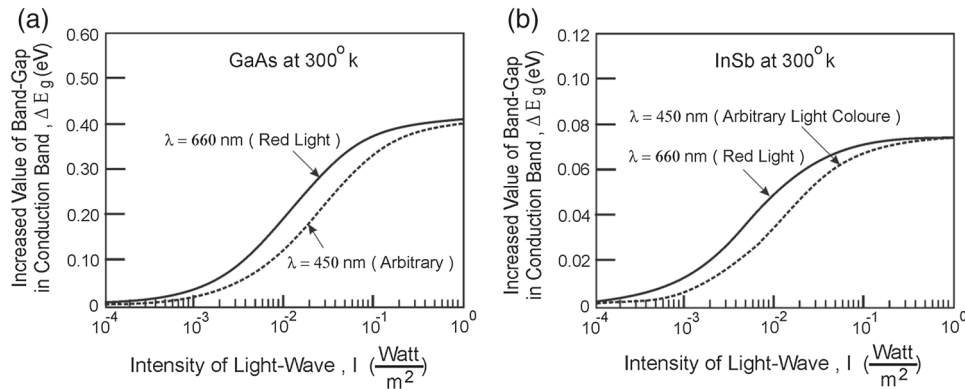


Figure 3. Increased band gap as a function of incident light intensity for (a) GaAs and (b) InSb semiconductors.

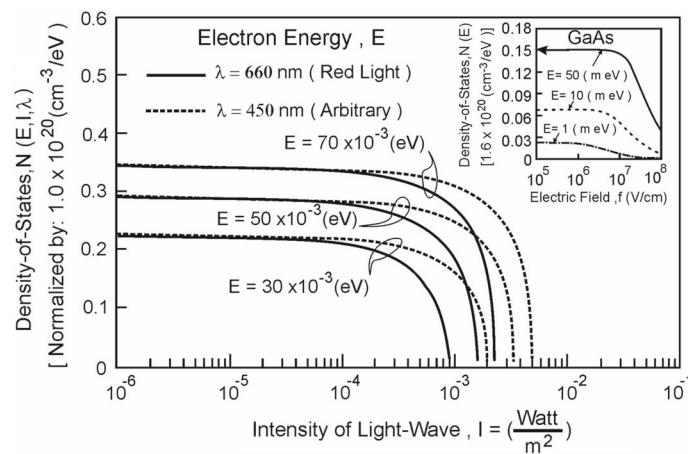


Figure 4. Normalised DOS as a function of incident light wavelength (inset shows the variation of density of states as a function of applied electric field intensity) for GaAs.

curve) and 450 nm (dotted curve) for the sample n-GaAs, for electron energies $E = 30 \times 10^{-3}$, 50×10^{-3} and 70×10^{-3} eV. From figure 4, it is seen that the variation of the carrier (DOS) functions with I for different values of λ as well as E , are almost constant over a wider range of intensity of light: 1×10^{-6} to 1×10^{-4} W/m². Thereafter, the curves slowly fall with an increase in the intensity and finally reach almost zero value. With the increase of E , the DOS curves move upward and fall to zero at higher photon intensity. The effect of λ on DOS curves is also shown in figure 4. It is interesting to see the sharp fall of DOS to zero with an increase of intensity as mentioned earlier.

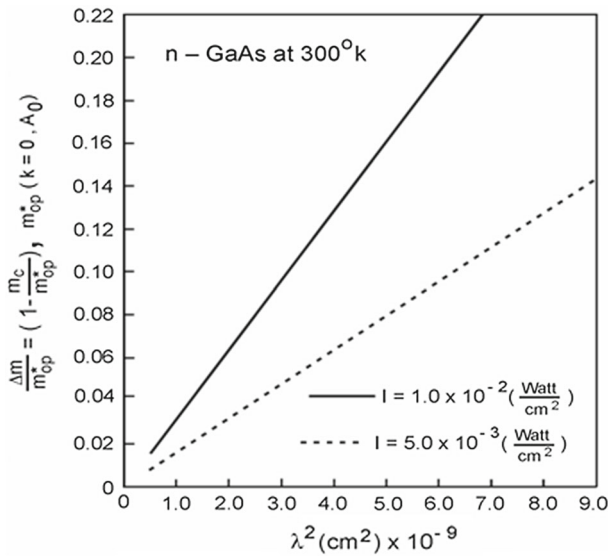
The physical implications of the aforementioned facts are that the DOS represents the probability of the availability of carrier density which tends to fall sharply to zero with the increase in monochromatic light intensity, indicating that the carriers vanish from CB edge. As DOS falls sharply to zero, a quick removal of the carriers from the CB-edge of the semiconductors might happen. Though no experimental evidences of the same are available in the literature [8,10], similar absence of the

carriers from the CB edge had been reported both experimentally [34] and theoretically [9] with applied electric fields as the perturbing agent instead of the present laser excitation. It might be noticed that to perform the fast removal of the carriers from the CB edge, photoexcitation is a better method, rather than the electric field, as in the former case, the fall of DOS with electric field appears to be smoother (as shown in the inset of figure 4 in the case of GaAs semiconductor). A quantitative comparison of the effects of ‘confinement effects’ in ‘electric fields’ and in ‘laser fields’, for GaAs at $T = 300$ K for electron energy, $E = 50$ meV in the literature is shown in table 3.

From eq. (35) variation of OPEM with wave can be studied. In the case of n-GaAs, the results can be discussed from the consideration of figure 5 where $\left[\Delta m / m_{op}^* \left(\vec{k} = 0, \right) \right]$ has been plotted against λ^2 taking $I = 1.0 \times 10^{-3}$ W/cm² (solid curve) and $I = 5.0 \times 10^{-3}$ W/cm² (dotted line). Figure 5 shows that $\left[\Delta m / m_{op}^* \left(\vec{k} = 0, \right) \right]$ is a linear function of λ^2 . Similar

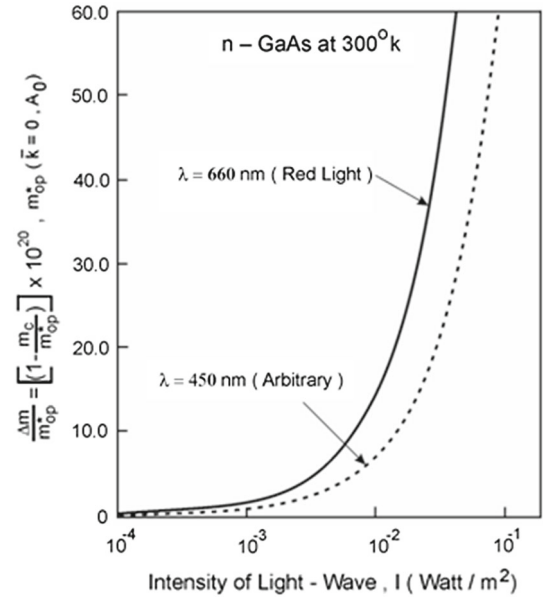
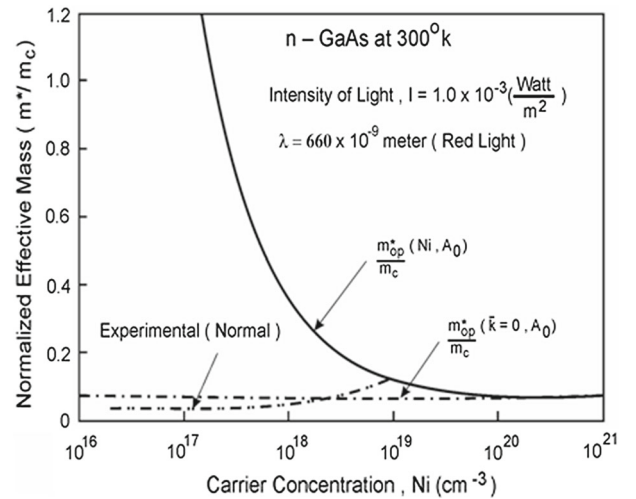
Table 3. Comparison of confinement effects.

Electric field-induced		Laser field-induced	
Electric field strength (eV/cm)	Normalised density of states, $N(E) : 1.6 \times 10^{20} \text{ (cm}^{-3}/\text{eV)}$	Intensity of light wave (W/m^2)	DOS, $N(E, I, \lambda)$: normalised by $1.0 \times 10^{20} \text{ (cm}^{-3}/\text{eV)}$
7×10^6	0.15	1×10^{-4}	0.29
1×10^7	0.12	4×10^{-4}	0.26
5×10^7	0.08	7×10^{-4}	0.23
7×10^7	0.06	1×10^{-3}	0.12
1×10^8	0.035	1.8×10^{-3}	0.05

**Figure 5.** Variation of effective mass ratio $\left[\Delta m/m_{op}^* \left(\vec{k}=0, A_0\right)\right]$ with the square of applied light wavelength λ^2 for n-GaAs at 300 K.

linear curve was also observed by Hodgson [32] who showed variations of dielectric constant (ϵ) to be inversely proportional to OPEM, m_{op}^* for sodium [32]. Like Hodgson, we varied λ^2 from $(1.0-8.0) \times 10^{-9} \text{ (cm}^{-2}\text{)}$, which corresponds to ultraviolet to visible to infrared range of light. Our calculated graph for GaAs shows that $(1 - (m_c/m_{op}^*))$ is an increasing function of λ^2 , where m_c is the unperturbed band edge EEM and m_{op}^* is the perturbed (CB) edge EEM due to light wave. An increasing nature of variation of $(1 - (m_c/m_{op}^*))$ with λ^2 implies that (m_{op}^*/m_c) increases linearly with λ^2 .

Figure 6 shows the plot of $\left[\Delta m/m_{op}^* \left(\vec{k}=0, A_0\right)\right]$ against intensity of light ($I = 1 \text{ W/m}^2$) for n-GaAs taking $\lambda = 660 \text{ nm}$ (red light) (solid curve) and

**Figure 6.** Variation of effective mass ratio $\left[\Delta m/m_{op}^* \left(\vec{k}=0, A_0\right)\right]$, with the intensity of applied light wave (I) for n-GaAs semiconductor at 300 K for two different wavelengths, $\lambda = 660 \text{ nm}$ (red light) (solid curve) and $\lambda = 450 \text{ nm}$ (arbitrary) (dotted curve).**Figure 7.** Variation of normalised effective mass, $(m_{op}^*/m_c) (Ni, A_0)$ (solid curve) for various carrier concentrations (Ni) (cm^{-3}) with optical intensity, $I = 1.0 \times 10^{-3} \text{ W/m}^2$ and $\lambda = 660 \text{ nm}$ (for red light), which correspond to A_0 .

$\lambda = 450 \text{ nm}$ (arbitrary) (dotted curve). Figure 5 shows that with an increase in intensity I , the fraction $(1 - (m_c/m_{op}^*))$ also increases. This also implies a linear increase with the intensity of light. Moreover, for $\lambda = 660 \text{ nm}$, the value of (m_{op}^*/m_c) is higher compared to that for a lower value of $\lambda = 450 \text{ nm}$. At the lowest intensity, $I = 1.0 \times 10^{-4} \text{ W/m}^2$, $(1 - (m_c/m_{op}^*)) \approx 0$,

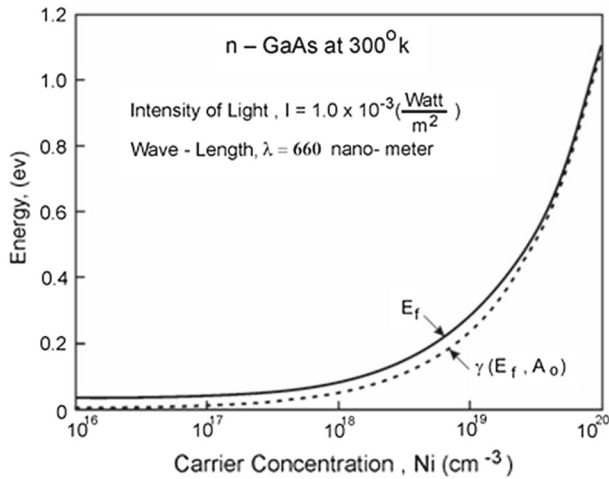


Figure 8. Variation of Fermi energy (E_f) and $\gamma(E_f, A_0)$ (eV) with the carrier concentrations (Ni) (cm^{-3}) for the n-GaAs system at 300 K for optical intensity, $I = 1.0 \times 10^{-3} \text{ W/m}^2$ and $\lambda = 660 \text{ nm}$ (for red light).

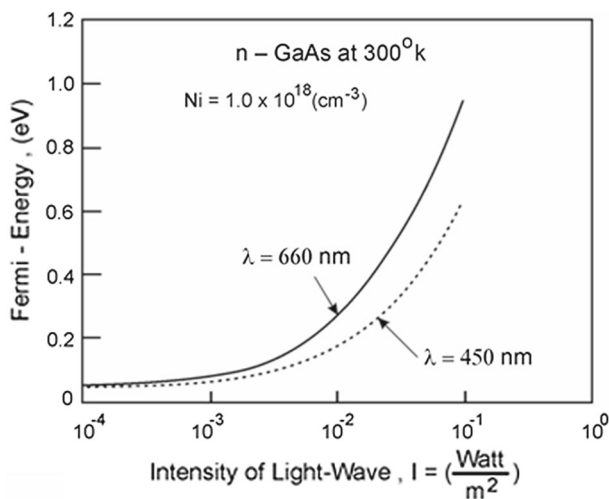


Figure 9. Variation of Fermi energy (E_f) for the carrier concentrations $Ni = 1.0 \times 10^{18} \text{ (cm}^{-3}\text{)}$ against optical intensity, $I = 1.0 \times 10^{18} \text{ W/m}^2$ for $\lambda = 660$ and 450 nm for n-GaAs at 300 K.

$m_{\text{op}}^* \approx m_c$. We have observed earlier that the optical band gap ΔE_g varies almost linearly with the intensity of light as well as λ , and so it is expected that variations of OPEM should be linear with them.

In figure 7, we have plotted OPEM, $(m_{\text{op}}^*/m_c)(Ni, A_0)$ (solid curve), for various values of concentration Ni (cm^{-3}) and a fixed value of A_0 , corresponding to $I = 1.0 \times 10^{-3} \text{ W/m}^2$ and $\lambda = 660 \text{ nm}$. The $(m_{\text{op}}^*/m_c)(\vec{k} = 0, A_0)$ vs. Ni curve shows a fixed line (shown by the arrow). However, the variation of the normalised EEM with Ni shows an increasing trend (corresponding experimental results [30] are indicated

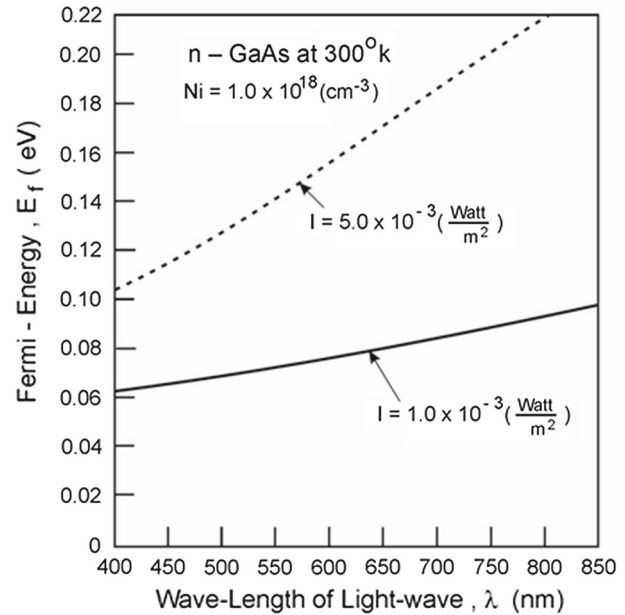


Figure 10. Variation of Fermi energy E_f against the wave-length of the light wave for n-GaAs at 300 K with $Ni = 1.0 \times 10^{18} \text{ (cm}^{-3}\text{)}$ and $I = 5.0 \times 10^{-3} \text{ W/m}^2$ and $I = 1.0 \times 10^{-3} \text{ W/m}^2$.

by an arrow), where the effective mass is measured without photoexcitation. The trend of variation of $[(m_{\text{op}}^*/m_c)(Ni, A_0)]$ possesses a decreasing nature with an increase of Ni value. This is contrary to the aforementioned EEM from the experimental results [33] obtained without optoexcitation. The observed decreasing trend can be physically explained, referring to eqs (42)–(47) where there is an exponent term (i.e. $-5/2$) as indicated in eq. (43), which might be responsible for that. We, therefore, conclude that the decreasing nature of variations of $[(m_{\text{op}}^*/m_c)(Ni, A_0)]$ with Ni would be a new observation when it is measured in the presence of optical excitation.

The variation of Fermi energy E_f (eV) with Ni for $I = 1.0 \times 10^{-3} \text{ W/m}^2$ and $\lambda = 660 \text{ nm}$ is plotted in figure 8 to show the effect of light wave on E_f . The variations of E_f (eV) vs. light intensity I (W/m^2) under $\lambda = 660$ and 450 nm when $Ni = 1.0 \times 10^{18} \text{ (cm}^{-3}\text{)}$ are shown in figure 9. It is noticed that with an increase in I , Fermi energy increases. This increase is also higher for higher wavelength. The variation of E_f (eV) with λ (nm) for $I = 1.0 \times 10^{-3} \text{ W/m}^2$ and $I = 5.0 \times 10^{-3} \text{ W/m}^2$, keeping $Ni = 1.0 \times 10^{18} \text{ (cm}^{-3}\text{)}$ fixed is shown in figure 10. Here also E_f increases almost linearly with an increase in wavelength. This increase is also larger with higher values of intensity. These studies correspond to the case of n-GaAs at room temperature (figure 10).

4. Conclusion

We have used the perturbation theoretical approach to calculate the modulation of the band gap in the presence of laser excitation in some technologically important III–V semiconductors. The gap parameters are found to be dependent on the intensities and wavelengths. Our calculations demonstrated that with photon energies of different wavelengths and intensities, it would be possible to shift the CB edge vertically upward forming a pseudo-CB edge, thereby increasing the optical band-gap value in the presence of laser with different λ and I . It appears, as if, it would be possible to take-off the carrier density from the CB edge (due to shift of the CB edge) vertically upward with the applied photon energy. With the removal of excitation, the pseudo-CB edge disappears. We believe that this new observation might have some important implications.

It was also noticed that the trend of variation of OPEM with λ^2 or I agreed well with the corresponding experimental results (in the case of n-GaAs) when impurity concentration was kept fixed. On the other hand, keeping I as well as λ fixed, the variation of the OPEM with impurity concentration was found to be opposite in nature to that of the normal experimental results (without photoexcitation). The second new theoretical observation could be experimentally verified by performing optical conductivity measurements under monochromatic laser light with different frequencies and intensities. Therefore, further investigation would be interesting to understand the semiconductor properties with excited light wave as perturbation. Present theoretical results might also be interesting to investigate semiconducting heterostructures for applications in optoelectronic devices.

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