Quantum magneto transport properties of nanostructure multi quantum wells short wave Infrared detectors

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Abstract. In this paper, we investigated the band structure and quantum magneto transport properties of the \( \text{In}_{0.53}\text{Ga}_{0.47}\text{As}(d_1=100\text{Å})/\text{InP}(d_2=70\text{Å}) \) type I multi quantum wells (MQWs) at low temperature. These studies were based on the envelope function and effective mass formalisms. We calculated the effect of \( d_1, d_2 \), the band valence offset and temperature on the band gap and the cut-off wavelength of detection. The result of the computed density of states and the position of Fermi level indicate that this sample is quasi two-dimensional system with n-type conductivity. The calculated evolution of the cutoff wavelength with temperature predicts this MQWs can be used as a short-infrared detector. Furthermore, we interpreted theoretically the photoluminescence, the Shubnikov de Haas (SdH) and quantum Hall effects observed by Pusep et al.

1. Introduction
The developments in semiconductors have seen the achievement of structures in which the electronic behavior is two dimensional (2D). One of the major systems where such 2D behavior has been studied is type I multiple quantum wells for their applications in many fields especially in infrared detection [1].

The short wave infrared (SWIR) is the portion of the electromagnetic spectrum that refers to the wavelength range between 1 and 3 micrometers. These detectors served a wide range of applications, include infrared imaging, remote sensing, medical testing, and quality control [2]. The most detectors used to serve these applications are based on the alloy HgCdTe or InGaAs materials [3]. Currently, the ternary alloy variable gap semiconductor \( \text{In}_x\text{Ga}_{1-x}\text{As} \) is widely used due to their highest detectivity, high quantum efficiency and low dark current at room temperature, particularly in lattice matched InGaAs/InP detector structures [4]. Indeed, the \( \text{In}_x\text{Ga}_{1-x}\text{As}/\text{InP} \) heterostructures semiconductor MQWs, have many technological applications, in infrared optoelectronics, THz, superlattice-emitter resonant tunneling bipolar transistor (SE-RTBT) and photodetectors [5]. Moreover, such materials can be used in spintronics and quantum information processing field [6,7]. Their electronics properties can be tuned by varying layers’ thicknesses and indium composition \( x \). Their application in infrared detectors have generated a lot of interest for low cost, low dark current, high speed, and high temperature operation detectors in short wavelength infrared (SWIR) [8].

In general, the \( \text{In}_x\text{Ga}_{1-x}\text{As}/\text{InP} \) structure is grown by molecular beam epitaxy (MBE) technique with different indium fraction \( x \). This periodic MQWs is made from repeated layers of two materials which
have nearly a similar structure, but they have a different electrical property, In$_x$Ga$_{1-x}$As (well) and InP (barrier) [9].

It is well known that the reduction of the dimensionality of a system under extreme conditions like low temperatures and high magnetic field, conduct to the observation of quantum electronic transport effects like Shubnikov-de Haas effect (SdH) and quantum Hall effect (QHE) [10,11].

In the literature the calculation of the energy band structure and the effect of basic parameters on the band gap of this MQWs are very rare or inexistent. So we are attempted to calculated the band structure of the In$_{0.53}$Ga$_{0.47}$As(d$_1$=100Å)/InP(d$_2$=70Å) MQWs based on the envelope function formalism. The aim of this work is to show the correlation between calculated bands structures and magneto-transport properties in In$_{0.53}$Ga$_{0.47}$As/InP nanostructure MQWs. We studied the effects of thickness $d_1$ of well ($d_2$ of barrier), the valence bands offset and temperature on the band gap. These results permit us the interpretation of the photoluminescence, the SDH and QHE Effects observed by Pusep et al. [12] in the same sample.

2. Theoretical formulations and computation

In general, the calculations of electronic band structure for semiconductors based on the k.p theory, it provides a detailed description of a material’s energy [13,14]. For our calculations of the spectra of energy $E(k_z)$ in the direction of growth and $E(k_p)$ in plane of this MQWs, we adopted the envelope function formalism.

The expression of dispersion relation for In$_{x}$Ga$_{1-x}$As/InP, within this formalism and effective mass approximation, is given by [15-17]:

$$\cos[k_z(d_1 + d_2)] = \cos(k_d d_1) \cos(k_d d_2) - \frac{1}{2} \left[ \frac{k^2}{\epsilon_1} + \frac{k^2}{\epsilon_2} \right] \sin(k_d d_1) \sin(k_d d_2)$$

(1)

Where the subscripts 1 and 2 refer to In$_{x}$Ga$_{1-x}$As and InP layers, respectively. With $k_z$ the wave vectors in the growth direction axis and $k_p(k_x,k_y)$ the MQWs wave vector in plane. In our case the origin of energy $E$ has been chosen at the top of InP valence band as shown in Figure 1. With $k_1$ and $k_2$ describe the movement perpendicular to the layer of bulk materials.

At a given energy, the two-band Kane model [18], gives the wave vector ($k_z^2+k_p^2$) in each host material (i=1 or 2) by:

$$\begin{cases}
2\hbar^2 k_z^2 (k_x^2 + k_y^2) = 3(E - \epsilon_1 - \Lambda) (E - \Lambda) \quad \text{for In$_{x}$Ga$_{1-x}$As} \\
2\hbar^2 k_p^2 (k_x^2 + k_y^2) = 3E (E - \epsilon_2) \quad \text{for InP}
\end{cases}
\quad \text{with } k_z = \frac{k_1}{k_2} \text{ and } r = \frac{E - \epsilon_2}{E - \epsilon_1 - \Lambda}

(2)

Here $\epsilon_i (i=1, 2)$ the band gaps of bulk materials and $\Lambda$ is the valence band offset (VBO). The MQWs heavy holes’ mini-bands can be obtained from the equation (1) with the following relations:

$\text{Figure 1.}$ Schematic illustration of band line up between In$_{x}$Ga$_{1-x}$As and InP along the growth direction with different parameters of electronic band structures. ($E_{c,i}$), ($E_{v,i}$), and $\epsilon_i$ where $i=1, 2$ are the conduction, the valence bands edge and band gap of bulks, respectively.
\[-h^2(k^2_1+k^2_2) = 2\left(m^{*}_{hh}\right)_i\left(E-\Lambda\right)\quad \text{for In}_{0.53}\text{Ga}_{0.47}\text{As}\]
\[-h^2(k^2_1+k^2_2) = 2\left(m^{*}_{hh}\right)_iE\quad \text{for InP}\]

with \(\xi = \frac{k_1}{k_2}\) and \(r = \frac{m^{*}_{lh}}{m^{*}_{hh}}\).

Here, \((m^{*}_{hh})_0 = 0.47m_0\) and \((m^{*}_{hh})_1 = 0.6m_0\) are the heavy hole’s effective masses of \(\text{In}_{0.53}\text{Ga}_{0.47}\text{As}\) and \(\text{InP}\) respectively as given in [19,20]. The band gaps parameters \(\epsilon_i(i=1,2)\) used here, are obtained by the empirical expressions of \(\text{In}_{x}\text{Ga}_{1-x}\text{As}\) and \(\text{InP}\) respectively, as a function of alloy composition \(x\) and temperature \(T\) [21].

We use the experimental valence band offset (VBO) \(\Lambda = 346\) meV determined by admittance spectroscopy [22]. We solve the previous relations using the adopted parameters to compute the electronic structure and related properties for the investigated sample.

3. Theoretical results and discussions

The electronic band structure is an efficient tool for describing the electronic and optoelectronic properties of semiconductors materials. Figure 2 (a) shows the energy of conduction (\(E_i\)), light hole (\(lh_i\)) and heavy hole (\(hh_i\)) mini-bands at the center \(\Gamma(k_z=0)\) and the limit (\(k_z=\pi/d)\) of the first Brillouin zone as a function of well thickness \(d_1\) with the ratio \(d_2 = 0.7d_1\). The calculated band gap, from the bottom of the first conduction (\(E_1\)) to the top of the first valence subbands (\(hh_1\)) at \(T=1.7\) K is \(E_g(\Gamma) = E_1 - hh_1 = 852\) meV, as indicated by a vertical dashed line. This value agrees favorably with the direct gap of 820 meV measured by photoluminescence by Y.A. Pusep et al. [12]. The difference of 4\% between two values obtained can be due to the basic parameters adopted here, particularly, the valence band offset (VBO). In Figure 2 (b), we can see the effect of the VBO on the band gap of the investigated MQWs at 1.7 K. The band gap increases to a maximum at 70 meV, then decreases prabolically when the valence band offset increases. As the figure shows the experimental gap is obtained for \(\Lambda\) near of 615 meV. Nevertheless, we used the value \(\Lambda=346\) meV measured by spectroscopy and Xray photoemission spectroscopy for \(x=0.53\) [23]. The difference observed can be due also to the small incertitude on the measured thickness \(d_1\) and \(d_2\) and/or to the strain effects which create a large piezoelectric field in these structures, and modify the band structure due to a large change in their energy band edges [24]. When the well's thickness \(d_1\) increases, the band gap and the subbands widths decrease to discrete energy levels of isolated quantum wells for \(d_1 \geq 170\) Å (Fig. 2a). So the electron gas is bidimensional.

We are interested to explain the effect of some basic parameters on the band gap like the well thickness and temperature. We plotted the evolution of the band gap \(E_{g}^i\) at the center \(\Gamma\) of the first Brillouin zone, as a function of well width \(d_i\) for various temperatures in Figure 3 (a). For a given \(T\), \(E_g\) decreases significantly with increasing \(d_i\), which reflect the formation of thin single quantum well

![Figure 2](image-url)

Figure 2. (a) Energy of both conduction (upper part) and valence (lower part) sub-bands as function of well thickness \(d_1\) at 1.7 K with \(d_1 = 1.43\) \(d_2\). The solid areas show the width of sub-bands in the first Brillouin zone. (b) Width of the band gap as a function of the discontinuity \(\Lambda\) of the valence bands (VBO).
between lattice- matched InP and InGaAs [24]. This phenomenon can be due to the creation of more allowed states in the forbidden bands. Such regions can be occupied by electrons; because of the number of overlapping orbitals between nearest atoms grows with thickness. Thus, the conduction and valence bands starts to get closer, leading to a reduction of the band gap [26]. For a given $d_1$, $E_g(\Gamma)$ decreases when the temperature increases.

Figure 3 (b) shows the variation of the band gap $E_g$ and the cut-off wavelength $\lambda_c$, at the center $\Gamma$ of the first Brillouin zone, as a function of the temperature in the range 1.7 to 300 K. When the temperature increases, $E_g$ decreases from 852 meV at 1.7 K to 780 meV at 300 K, whereas $\lambda_c$ increases following the formula (5). Our results agree well with those of Fernandes dos Santos et al measured by photoluminescence for $T>50$ K [27]. The small difference observed between the calculated and measured band gaps energies decreases from 10 meV to 4meV when $T$ increases from 40 K to 300 K, that can be attributed to the basic parameters of calculations used here. Nevertheless, in the study of Pusep et al. [12], they suppose that the difference between the experimental and the calculated intermini-bands gaps is due particularly to the imprecisely known band offsets of In$_{0.53}$Ga$_{0.47}$As/InP heterostructure. In Figure 3 b, we did the fit of valence band offset $\Lambda$ and the good agreement is achieved for $\Lambda=410$ meV (brown solid line). Moreover, to explain such behavior of band gap as a function of temperature in semiconductors, many theoretical models were developed like Varshni model. Our results were fitted by the empirical Varshni formula [28]:

$$E_g(T) = E_g(0) - \alpha \left( \frac{T^2}{T + \beta} \right)$$

Where $T$ is the temperature in Kelvin, $E_g(0)$ is the energy band gap at 0 K and $\alpha$ and $\beta$ are the Varshni parameters. In this model, the parameter $\beta$ is expected to be comparable to the Debye temperature ($\theta_D$) of the material and $\alpha$ is the slope of $E(\Gamma)$ when $T>\theta_D$. In our case, the best fitting was obtained with $\alpha = 0.49$ meV/K, $\beta = 331$ K and the gap at 0 K $E_g(0) = 851$ meV. These values are consistent with those reported in [25] of $\Gamma$–$\Gamma$ PL peak energies Varshni fitting. From other hand, a novels theoretical models out of fitting parameters, are established based on the authors’ previous temperature dependent modeling thoughts, one was developed by Peiji Geng and al. [29], which relates the band gap energy at the elevated temperature to that at the arbitrary reference temperature and Debye heat capacity. This new model was tested to some binary semiconductors.

In order to explain the effect of temperature on the optical band gap in semi-conductors, Ünlü et al. [30] proposed a thermodynamic model and demonstrate that, the observed behavior of the band gap under temperature is due to the thermal energy and the expansion of the lattice constant with

![Figure 3](image.png)

**Figure 3.** (a) The band gap of the investigated MQWs as a function of well thickness in different temperatures. (b) The band gap energy and the cut-off wavelength as function of temperature of the MQWs, at the centre $\Gamma$ of the first Brillouin zone.
temperature, which cause an increase in the inter-atomic spacing and the potential seen by electrons decreases, leading to a smaller gap.

We calculated the detection cut-off wave length in Figure 5 b, using the formula:

\[ \lambda_c (\mu m) = \frac{1240}{E_g (meV)} \]  

The variation \(1.46 \leq \lambda_c(\mu m) \leq 1.55\) indicated that this sample can be used as short-infrared detector.

Figure 4 (a) shows the band structure of \(\text{In}_{0.53}\text{Ga}_{0.47}\text{As}/\text{InP}\) MQWs, at very low temperature (T=1.7 K) along the growth direction \(k_x\) and in plane \(k_p(k_x, k_y)\), in the first Brillouin zone. Near the forbidden energy gap, two first conduction (\(E_1\) and \(E_2\)), three heavy holes \(h\h_1,2,3\) and light holes \(l\h_1\) mini-bands are observed. The plot of \(E(k_z, k_p)\) shows that all the mini-bands are parabolic in the first Brillouin zone. There is a weak variation following \(k_y\) which can be due to the weak coupling between wells layers. We deduce that the electronic transport is dominated in-plane of this MQWs. We can see also that the top of valence band is dominated by the heavy holes \(h\h_1\).

The electrons and holes effective masse are giving in Figure 4 (b), in the plane \(k_d(k_x, k_y)\), and along the growth direction \(k_p\) of the reciprocal space. We extract the carriers effective mass from the dispersion of the curves in Figure 4 (a), using the following relation given by Kittel [31]:

\[ \left( \frac{1}{m^*} \right)_i = \frac{\hbar^2}{\pi^2 \partial^2} \frac{E_i}{\partial k_i \partial k_j} \]  

Where \(i\) and \(j\) are \(x, y\) or \(z\) axis directions. Along \(k_p\) direction, we remark that the heavy hole’s effective masses still almost constant at \(m_{h1}^* = -0.47m_0\). Whereas, the light holes decrease slightly from \(m_{l1}^*=-0.07m_0\) to \(m_{l1}^*=-0.06m_0\). For the lower subband of electrons \(m_{e1}^*\) increases from 0.093 \(m_0\) to 0.118 \(m_0\) along \(k_p\).

D. Schneider et al. [32] studied the dependence of \(m_{e1}^*\) on the concentration \(n\) in the \(\text{In}_{0.53}\text{Ga}_{0.47}\text{As}(d_1=79 \text{Å})/\text{InP}(d_2=261 \text{Å})\) multi-quantum wells (MQW). In this study, \(m^*\) was determined from Shubnikov–de Haas (SdH) oscillations and \(n\) from SdH and Hall Effect measurements. In the temperature range from 3 to 29.8 K, the effective mass \(m_{e1}^*\) increases from 0.047 \(m_0\) for \(n_{e1} = 5.9 \times 10^{11} \text{cm}^{-2}\) to 0.060 \(m_0\) for \(n_{e1} = 7 \times 10^{11} \text{cm}^{-2}\) respectively. These later results of isolated MQWs \((d_1/d_2=0.30)\) are in agreement with our increase of effective masse in the studied coupled MQWs \((d_1/d_2=1.40)\) with a concentration of \(n_{SdH}=3.973 \times 10^{11} \text{cm}^{-2}\) at 1.7 K.

Figure 5 (a) shows the relation between the longitudinal \(m_{e1}^*(k_y)\) along \(k_p\) and the well thickness \(d_1\) at different temperatures. The carriers’ effective mass marked an important decrease approaching 16 % when \(d_1\) increases from 5 to 100. It is obvious that the thickness \(d_1\) (or \(d_2\)) have a strong impact on \(m_{e1}^*\). Such result can be useful in the widths of materials MQWs to attain the carrier mobility.

**Figure 4 (a)** Calculated band structures of the investigated MQWs along the growth direction \(k_x\) and in-plane \(k_p\). **(b)** Carriers effective mass ratio of the first conduction and valence mini-bands with \(m_0\) the rest mass of an electron.
requested, which can be applied to the design of infrared detector technologically. For a given \(d_1\), \(m^*_{E1}(k_F)\) decreases when the temperature increases. This is due to the increases of electron-phonon interaction with \(T\).

As seen in the Figure 5 (b), we have plotted the evolution of the calculated \(E(k_F)\) energy of heavy holes, light particles bands and the two dimensional (2D) Fermi energy level, as a function of temperature at Fermi wavelength \(k_F\).

When the temperature increases from 1.7 K to 300 K, the energy of the \(hh_i (i=1,2)\) states remain almost constant, that of \(lh_1\) decreases with a small variation and that of \(E_1\) suddenly decreases by 100 meV. The later confirm the decrease of the band gap \(E_F=E_1-hh_1\) in Fig. 3. (b). On the other hand, the Fermi level energy \((E_F)\) does not depend on temperature which is the signature of a two dimensional electrons gas.

In order to determine the Fermi level, we used the measurements of Pusep et al. [12] of the longitudinal magneto-resistance \((\rho_{xx})\) at 1.7 K. The oscillations of \(\rho_{xx}\), at low temperature and under high magnetic fields, are periodic with respect to \(1/B\). The calculated period \(\Delta_{1/B}\) allows us to determine the density of electrons \(n_{2D}\), by the formula:

\[
n_{2D} = \frac{e}{\pi\hbar} \mid \frac{1}{\Delta_{1/B}} \mid
\]

The relation between the inverse of the minima \(1/B_{min}\) and the entire \(N\), Landau level index is given by:

\[
1/B_{min} = \Delta_{1/B} (N + 1/2)
\]

The oscillations period obtained by the straight line slope of (Eq. 8), \(\Delta_{1/B}=0.11985 \text{ T}^{-1}\) and the value of the electrons concentration, is \(n_{2D} = 2.02 \times 10^{11} \text{ cm}^{-2}\). The Fermi wave vector of two-dimensional electron gas was calculated using the formula: \(k_F \approx 2\pi n_{2D}\), which give, \(k_F = 0.0127 \text{ Å}^{-1}\) as indicated in Fig. 4 (a), by blue vertical dashed line. The corresponding electron effective masse at the Fermi energy is \((m^*_{E1})_{EF}=0.097 m_0\).

The Fermi level energy is given by the following relation:

\[
|E_F - E_i| = \hbar^2 \frac{k_F^2}{2m_e^*} \left| \left( \frac{2m_e^*}{\hbar^2} \right)_{E_i} \right| = n_{2D} \pi \hbar^2 \left| \left( m_e^* \right)_{E_i} \right|
\]

Since \(E_c = 1.196 \text{ eV}\), so \(E_F = 1.200 \text{ eV}\) and the half of the band \(E_i(k_F)\) is full (Fig.4 a). This shows that the studied sample has n-type conductivity at 1.7 K. Moreover, we calculated the Fermi level energy using the Fermi–Dirac integral as a function of temperature [33,34]. The resolution of such integrals give the exact value, \(E_F = 1.996 \text{ eV}\).

**Figure 5 (a)** Evolution of effective mass at the bottom of the conduction band at \(k_F\) as a function of \(d_1\) and/or \(d_2\) for \(In_{0.53}Ga_{0.47}As(d_1)/InP(d_2)\) with \(d_1=1.43 \text{ d}_2\). **(b)** Evolution of band energy of light particles and heavy holes, calculated at the Fermi wave vector \(k_F\), as a function of temperature of \(In_{0.53}Ga_{0.47}As(d_1)/InP(d_2)\). \(E_F(2D)\) represents the Fermi level energy.
The density of states (DOS) gives us detailed information about the various electronic states in the band structure of a material. The contributions relating to various electronic states in valence/conduction band are accurately explained by density of states. For the description and explanation of the structure of MQWs with further details, we calculated the DOS.

The DOS of the $i$th mini-band for a finite mini-band energy width $\Delta E^{(i)}=E_{\text{max}}^{(i)}-E_{\text{min}}^{(i)}$, is given by [35]:

$$
\rho_{\text{DOS}}^{(i)}(E) = \begin{cases} 
\left(\frac{m^*}{\pi^2\hbar^2}\right)k_z(E) & \text{for } E_{\text{min}}^{(i)} \leq E \leq E_{\text{max}}^{(i)} \\
0 & \text{otherwise}
\end{cases}
$$

(10)

The generalization of Eq. (10) required a sum over all mini-bands:

$$
\rho_{\text{DOS}}(E) = \sum_{i=1}^{n_{\text{min}}} \rho_{\text{DOS}}^{(i)}(E)
$$

(11)

Figure 6 (a) shows the density of states of the first two conduction subbands of this sample. The density of states is quantified in terms of $m^*/\pi^2\hbar^2d$. The position of the Fermi level energy, indicated by dashed vertical line, show that $E_1$ and all the bands bellow are occupied (as seen in Fig. 4(a)) and the sample had n-type conductivity at 1.7 K. A very weak dispersion of $E_1$ along $k_z$ occurs indicating that the quantum wells are weakly coupled from each other and the system is quasi two-dimensional.

We calculated the Landau levels (LLs) for the conduction band $E_1$ as a function of magnetic field by transposing the quantification rule of the wave vector $k_p$ in plan of the MQWs in $E(k_p)$ as shown Figure 6 (b):

$$
k_p^2 = (2N^{(1)} + 1)\frac{eB}{\hbar}
$$

(12)

where $N^{(1)}$ is the Landau index of $1^{\text{st}}$ mini-band. We have computed the Fermi level energy as a function of $B$, by using the following formula:

$$
n_{2D} = \int_0^\infty \rho_{\text{DOS}}^{(2D)}(E, B) f(E)dE
$$

(13)

with $f(E)=1/(1+\exp(E-E_F/k_BT))$ the Fermi-Dirac distribution.
Table 1. Comparison between experimental observations (ref. 12) and the calculated magnetic field of $R_{xx}$ minima and maxima, labeled here by $B_{\text{min}}$ and $B_{\text{max}}$, respectively.

| $B_{\text{min}}$ (T) | $B_{\text{max}}$ (T) |
|----------------------|----------------------|
| Theoretical (ref.[12]) | Theoretical (ref.[12]) |
| 4.70                | 6.38                |
| 2.97                | 3.63                |
| 2.10                | 2.50                |
| 1.70                | 1.96                |

The expression of the DOS(B) is given:

$$\rho_{\text{DOS}}^{2D}(E, B) = \frac{|e|B}{\hbar} \sum_{r} \sum_{N} \delta(E - E_{u}^{(r)})$$

(14)

When the magnetic field increases, crossovers between the calculated Landau levels (for $N = 0$–4) and Fermi level indicate the same minima of the transverse magnetoresistance $R_{xx}$ oscillations (Shubnikov–de Haas effect), observed in Ref. [12] as shown in table 1, at $B = 6, 2.75$, and $2.21$ T. We calculated the filling factor $\nu$ using the formulate: $R_{xy}(\Omega) = \hbar/\nu N^2$ measured by [12]. At these values of magnetic field, the Hall resistance, $R_{xy}$, shows quantized plateaux. So we interpreted the Shubnikov de Haas oscillations and the Quantum Hall (QHE) plateaux observed by Pusep et al. To observed such oscillations and the QHE, the separation $\omega_c = eB/m^* E_1$ (the cyclotron pulsation) between LL must be superior to activation thermal energy $k_B T$. The magnetic field $B$ must be greater then $0.2$ T ($B > k_B m^* E_1 / e$) with $m^* E_1 = 0.109 m_0$.

We calculated also the transport scattering time $\tau_p = \mu H m^* E_1 / e = 3.22$ ps for the measured Hall mobility $\mu_0 = 5.2 10^3$ cm$^2$/Vs at 1.7 K measured by [12] with our $m^* E_1 = 0.109 m_0$. This value of $\tau_p$ is comparable to the quantum relaxation time $\tau_q = 0.5$ ps and $\tau_q = 2.34$ ps measured in AlGaN/GaN two-dimensional electron gas [36]. The velocity of electrons on the Fermi surface is $v_F = h/\omega_c = 1.35 10^{10}$ m/s. This is a clear demonstration of faster collision between electrons and phonon and high transport performances of this MQWs.

4. Conclusion

We have investigated the electronic transport properties of In$_{0.53}$Ga$_{0.47}$As$(d_1=100\text{Å})$/InP$(d_2=70\text{ Å})$ MQWs at 1.7 K on the basis of the bands structure using the envelop function formalism. The optical band gap $E_g$ and the cut-off wavelength $\lambda_c$, were calculated as a function of $d_1$ and/or $d_2=0.7d_1$ and temperature. In the range of 1.7-300 K, $1.46 \leq \lambda_c(\mu m) \leq 1.55$ shows that the investigated sample can be used for the active zone photodetector in short infrared SWIR atmospheric windows. The position of the Fermi level, on the density of states showed n type conductivity and quasi-two-dimensional electrons gas. The calculated Fermi level energy and LLs as a function of magnetic field permit us the interpretation of the photoluminescence, the Shubnikov de Haas and quantum Hall Effects observed by Pusep et al. These transport parameters results are useful for the design of this nanostructure MQWs as short infrared detector and other applications.

References

[1] Dresselhaus M, Dresselhaus G, Cronin S B and Souza Filho A G 2018 Solid State Properties (Berlin: Springer-Verlag Berlin Heidelberg).
[2] Hansen M P and Malchow D S 2008 International Society for Optics and Photonics 6939 69390I
[3] Rogalski A and Ciupa R 1999 J. Electron. Mater 286 630-636
[4] Kaniewski J and Piotrowski J 2004 Opto-Electron Rev 12 chapter 139-148
[5] Fox M and Ispasoiu R 2017 *Quantum wells, superlattices, and band-gap engineering*. In Springer *Handbook of Electronic and Photonic Materials* (Springer, Cham) pp 1-1
[6] Asar T Özçelik S and Özbay E 2014 *J. Appl. Phys.* 115 104502
[7] Tosi A, Acerbi F, Dalla Mora A, Itzler M A and Jiang X 2010 *IEEE Photonics J.* 3 31-41
[8] Rogalski A 2010 *Infrared detectors*. (Boca Raton: CRC press)
[9] Yerino C D, Liang B, Huffaker D L, Simmonds P J and Lee M L 2017 *J Vac Sci Technol B Nanotechnol Microelectron* 35 010801
[10] Ihn T 2010 *Semiconductor Nanostructures: Quantum states and electronic transport* (Oxford: University Press)
[11] Henriques A B, Hanamoto L K, Oliveira R F, Souza P L, Gonçalves, L C D and Yavich B 1999 *Braz. J. Phys.* 29 707-710
[12] Pusep Y A, Tavares B G M, Tito M A, Dos Santos L F and LaPierre R R 2015 *J. Condens. Matter Phys.* 27 245601
[13] Voon L Y C and Willatzen M 2009 *The kp method: electronic properties of semiconductors* (Berlin: Springer-Verlag Berlin Heidelberg)
[14] Ostromek T E 1996 *Phys. Rev. B* 54 14467
[15] Bastard G 1981 *Phys. Rev* 24 5693
[16] Bastard G 1982 *Phys. Rev. B* 25 7584.
[17] Bouttramine A, Nafidi A, Barkissy D, Bellioua M and Khalal A 2019 *Superlattices Microstruct.* 127 151-156
[18] Kane E O 1957 *J. Phys. Chem. Solids* 4 249-261
[19] Goldberg Y A 1999 *Phys. Rev. B*, 21 1311
[20] Alavi K, Aggarwal R L and Groves S H 1980 *Phys. Rev. B* 21 1311
[21] Paul S, Roy J B and Basu P K 1991 *J. Appl. Phys.* 69 827-829
[22] Lang D V, Panish M B, Capasso F, Allam J, Hamm R A, Sergent A M and Tsang W T 1987 *Appl. Phys. Lett.* 50 736-738
[23] Landesman J P, Garcia J C, Massies J, Maurel P, Jezequel G, Hirtz J P and Alnot P 1992 *Appl. Phys. Lett.* 60 1241-1247
[24] Chen W Q and Hark S K 1995 *J. Appl. Phys.* 77 5747-5750
[25] PECHARAPA W, TECHIDHEERA W, Kraisingdecha P and NUKEAW J 2003 *Journal of Metals, Materials and Minerals* 13 1-5
[26] Gaponenko S V 1998 *Optical properties of semiconductor nanocrystals* Vol. 23 (Cambridge: university press)
[27] Dos Santos L F, Pusep Y, Zanatta A R and LaPierre R R 2015 *J. Phys. D Appl. Phys.* 48 465101
[28] Varshni Y P 1967 *Physica* 34 149-154
[29] Geng P, Li W, Zhang X, Zhang X, Deng Y, and Kou H J. *Phys. D Appl. Phys.* 50 40LT02
[30] Ünlü H 1992 *Solid-state electronics* 35 1343-1352
[31] Kittel C, McEuen P and McEuen P 1996 *Introduction to solid state physics* vol 8 (New York: Wiley) pp. 105-130
[32] Schneider D, Hitzel F, Schlachetzki A and Boensch P 2002 *Physica E Low Dimens. Syst. Nanostruct.* 12 562-565
[33] Kim R, Wang X and Lundstrom M 2008 Notes on fermi-dirac integrals arXiv preprint arXiv:0811.0116
[34] Schubert E F 2015 *Doping in III-V semiconductors* (Cambridge University Press)
[35] Cho H S and Prucnal P R 1989 *J. Vac. Sci. Technol B* 7 1363-1367
[36] Saxler A, Debay P, Perrin R, Elhamri S, Mitchel W C, Elsass C R and Ibbetson J P 2000 *J. Appl. Phys.* 87 369-374