ISSN 1674-1056
http://cpb.iphy.ac.cn
http://iopscience.iop.org/cpb
中国物理 B
Chinese Physics
中国物理 Chinese Physics B

Intersubband optical absorption of electrons in double parabolic quantum wells of $Al_xGa_{1-x}As/Al_yGa_{1-y}As$

Shu-Fang Ma(马淑芳), Yuan Qu(屈媛), Shi-Liang Ban(班士良)
Citation: Chin. Phys. B . 2018, 27(2): 027103. **doi:** 10.1088/1674-1056/27/2/027103

Journal homepage: http://cpb.iphy.ac.cn; http://iopscience.iop.org/cpb

What follows is a list of articles you may be interested in

Effects of post-annealed floating gate on the performance of AlGaN/GaN heterostructure field-effect transistors

Peng Cui(崔鹏), Zhao-Jun Lin(林兆军), Chen Fu(付晨), Yan Liu(刘艳), Yuan-Jie Lv(吕元杰)
Chin. Phys. B . 2017, 26(12): 127102. **doi:** 10.1088/1674-1056/26/12/127102

Parasitic source resistance at different temperatures for AlGaN/AlN/GaN heterostructure field-effect transistors

Yan Liu(刘艳), Zhao-Jun Lin(林兆军), Yuan-Jie Lv(吕元杰), Peng Cui(崔鹏), Chen Fu(付晨), Ruilong Han(韩瑞龙), Yu Huo(霍宇), Ming Yang(杨铭)
Chin. Phys. B . 2017, 26(9): 097104. **doi:** 10.1088/1674-1056/26/9/097104

On the reverse leakage current of Schottky contacts on free-standing GaN at high reverse biases

Yong Lei(雷勇), Jing Su(苏静), Hong-Yan Wu(吴红艳), Cui-Hong Yang(杨翠红), Wei-Feng Rao(饶伟锋)
Chin. Phys. B . 2017, 26(2): 027105. **doi:** 10.1088/1674-1056/26/2/027105

Modified model of gate leakage currents in AlGaN/GaN HEMTs

Yuan-Gang Wang(王元刚), Zhi-Hong Feng(冯志红), Yuan-Jie Lv(吕元杰), Xin Tan(谭鑫), Shao-Bo Dun(敦少博), Yu-Long Fang(房玉龙), Shu-Jun Cai(蔡树军)
Chin. Phys. B . 2016, 25(10): 107106. **doi:** 10.1088/1674-1056/25/10/107106

Improvement of switching characteristics by substrate bias in AlGaN/AlN/GaN heterostructure field effect transistors

Yang Ming, Lin Zhao-Jun, Zhao Jing-Tao, Wang Yu-Tang, Li Zhi-Yuan, Lü Yuan-Jie, Feng Zhi-Hong
Chin. Phys. B . 2015, 24(11): 117103. **doi:** 10.1088/1674-1056/24/11/117103

Intersubband optical absorption of electrons in double parabolic quantum wells of $Al_xGa_{1-x}As/Al_yGa_{1-y}As$*

Shu-Fang Ma(马淑芳), Yuan Qu(屈媛), and Shi-Liang Ban(班士良)†

School of Physical Science and Technology, Inner Mongolia University, Hohhot 010021, *China*

(Received 11 August 2017; revised manuscript received 30 September 2017; published online 5 January 2018)

Some realizable structures of double parabolic quantum wells (DPQWs) consisting of $Al_xGa_{1-x}As$ /$Al_yGa_{1-y}As$ are constructed to discuss theoretically the optical absorption due to the intersubband transition of electrons for both symmetric and asymmetric cases with three energy levels of conduction bands. The electronic states in these structures are obtained using a finite element difference method. Based on a compact density matrix approach, the optical absorption induced by intersubband transition of electrons at room temperature is discussed. The results reveal that the peak positions and heights of intersubband optical absorption coefficients (IOACs) of DPQWs are sensitive to the barrier thickness, depending on Al component. Furthermore, external electric fields result in the decrease of peak, and play an important role in the blue shifts of absorption spectra due to electrons excited from ground state to the first and second excited states. It is found that the peaks of IOACs are smaller in asymmetric DPQWs than in symmetric ones. The results also indicate that the adjustable extent of incident photon energy for DPQW is larger than for a square one of a similar size. Our results are helpful in experiments and device fabrication.

Keywords: double parabolic quantum well, electronic intersubband optical absorption, three energy levels

PACS: 71.55.Eq, 73.20.At, 73.21.Fg, 78.20.Ci **DOI:** 10.1088/1674-1056/27/2/027103

1. Introduction

In recent years, intersubband transition (ISBT) of electrons in a quantum well (QW) consisting of group III–V semiconductors has aroused much interest because of its potential applications in optoelectronic devices such as infrared detectors and all-optical switches.[1–7] Some experiments[8–10] gave optical absorption coefficients for ISBT and their dependence on incident photon energy in QW consisting of III–V group materials at varying temperatures and well widths. As for GaAs/$Al_xGa_{1-x}As$ double quantum wells (DQWs),[11] an early result showed that the frequencies of absorption peaks decrease with increasing well width and temperature. More recently, it was shown that the thin AlAs layer inserted into GaAs/$Al_{0.3}Ga_{0.7}As$ DQWs can improve energy transition of electrons in the mid-infrared frequency range.[12] The transition absorption peaks from the ground states to the first excited states of DQWs showed blue shifts with increasing magnetic field.[13] The optical properties of GaAs/$Al_xGa_{1-x}As$ QWs show prospects both in practical applications and theoretical research.

Several years ago, the ISBTs in square and triangle DQWs with three energy levels for different electric fields were calculated.[14,15] The results showed that intersubband optical absorption coefficients (IOACs) and the energy levels can be modulated by external field strength. Recently, it was found that IOACs and incident photon energies are strongly affected not only by the magnitudes of the electric and magnetic fields but also by the structure parameters of the systems.[16,17] Some results showed that the energy interval decreases whereas the dipole matrix element increases with increasing the barrier width in symmetric double semi-parabolic QWs.[18] On the other hand, linear and nonlinear optical absorptions were discussed for different DQWs (e.g., semi-parabolic, parabolic, inverse parabolic, grade, square ones).[19–23] The results showed that IOACs can be obviously modulated by the size of well width and the middle barrier thickness. Unfortunately, most of these authors considered only optical transition in QWs with two energy levels. It is not sufficient in studies of optical characteristics in DQWs of zincblende $Al_xGa_{1-x}As$ /$Al_yGa_{1-y}As$. Because the parabolic potential can be modulated by changing the Al component x, the composition effects of a system with three energy levels in conduction bands should be discussed in symmetric and asymmetric double parabolic quantum wells (DPQWs). Furthermore, the coupling between the two wells especially for an asymmetric system could indicate novel properties which are helpful in guiding experiments.

In this work, we consider theoretically the effects of well width, middle barrier thickness, Al component and external electric field on optical absorption of electron intersubband transition both in symmetric and asymmetric ($Al_xGa_{1-x}As$ /$Al_yGa_{1-y}As$) DPQWs and compare the results with those of double square quantum wells (DSQWs). The electronic states in these structures are achieved using a finite element difference method. Based on compact density matrix approach, IOACs in these structures are investigated. We organize the

*Project supported by the National Natural Science Foundation of China (Grant No. 61274098).

†Corresponding author. E-mail: slban@imu.edu.cn

© 2018 Chinese Physical Society and IOP Publishing Ltd

rest of our paper as follows. In Section 2, the model and method used in our calculations are described. In Section 3, numerical results and discussion are presented. Finally, in Section 4, some conclusions are drawn from the present study.

2. Theoretical calculation

We consider asymmetric $Al_xGa_{1-x}As/Al_yGa_{1-y}As$ double parabolic quantum wells consisting of two $Al_xGa_{1-x}As$ wells with widths L_{w1} and L_{w2} respectively, between which sandwiched is an $Al_yGa_{1-y}As$ layer with thickness L_{b2}. The outsides of two barriers can be assumed to be finite and with thicknesses L_{b1} and L_{b3}, respectively. The total width of the DQW structure is written as $L = L_{b1} + L_{w1} + L_{b2} + L_{w2} + L_{b3}$ as shown in Fig. 1. The z axis is chosen to be along the crystallographic direction and the x–y plane parallel to the interfaces which are perpendicular to the z direction. The leftmost point of structure is chosen to be the zero point of the z direction.

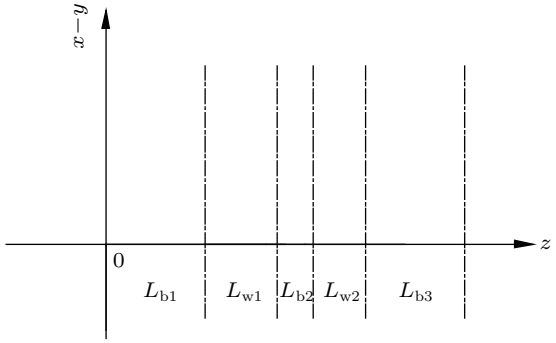


Fig. 1. A schematic diagram of an asymmetric zincblende $Al_yGa_{1-y}As/Al_{x1}Ga_{1-x1}As/Al_yGa_{1-y}As/Al_{x2}Ga_{1-x2}As/Al_yGa_{1-y}As$ DQW. The potential height of every layer is relative to Al component. The parabolic shapes and heights of L_{w1} and L_{w2} are obtained by changing x_1 and x_2.

Since an electron is nearly free in the x–y plane and is confined in the z direction, its wave function can be written as follows:

$$\psi_i(\rho, z) = \left(1/\sqrt{s}\right) \varphi_i(z) \exp \mathrm{i} k_\perp \cdot \rho, \tag{1}$$

where subscripts $i = 1, 2, 3$ indicate the electron at the ground, first and second excited states, respectively; S is the area of a heterojunction interface; $k_\perp$ and ρ are the two-dimensional wave and position vector, respectively. As is well known, electrons can absorb the light with a continuous spectrum in the x–y plane, and with a discrete spectrum in the z direction. Without losing generality, we can consider only wave function in the z direction to understand the optical absorption with discrete spectrum. Within the framework of the effective mass approximation, the one-dimensional Schrödinger equation in the z direction for a confined electron can be given by the following expression

$$\left\{ -\frac{\hbar^2}{2} \frac{\partial}{\partial z} \left(\frac{1}{m^*(z)} \right) \frac{\partial}{\partial z} + V(x_j, y, z) + eF(z) z \right\} \varphi_i(z) = E_i \varphi_i(z), \tag{2}$$

where $\hbar$ is the Planck's constant, $m^*(z)$ and $V(x_j, y, z)$ are the position-dependent effective mass and the height of confinement potential of an electron, respectively, $F(z)$ represents an external electric field, E_i is the energy of an electron at state I, $\varphi_i(z)$ are the corresponding wave functions, and x_j ($j = 1$, 2) denote the different positions of Al component in the two wells. For DPQWs, $V(x_j, y, z)$ can be written as

$$V(x_j, y, z) = \begin{cases} 0.6 \times \left(1155y + 370y^2\right), & 0 < z < L_{b1}, \\ 0.6 \times \left(1155x_1 + 370x_1^2\right), & L_{b1} \le z \le L_{b1} + L_{w1}, \\ 0.6 \times \left(1155y + 370y^2\right), & L_{b1} + L_{w1} < z < L_{b1} + L_{w1} + L_{b2}, \\ 0.6 \times \left(1155x_2 + 370x_2^2\right), & L_{b1} + L_{w1} + L_{b2} \le z \le L - L_{b3}, \\ 0.6 \times \left(1155y + 370y^2\right), & L - L_{b3} < z < L. \end{cases} \tag{3}$$

The relationship between x_j and y can be obtained by the continuous potential at a border

$$x_j = \begin{cases} \dfrac{y}{(L_{w1}/2)^2} \left(z - L_{b1} - (L_{w1}/2)\right)^2, & L_{b1} \le z \le L_{b1} + L_{w1}, \quad j = 1, \\ \dfrac{y}{(L_{w2}/2)^2} \left(z - L_{b1} - L_{w1} - L_{b2} - (L_{w2}/2)\right)^2, & L_{b1} + L_{w1} + L_{b2} \le z \le L - L_{b3}, \quad j = 2. \end{cases} \tag{4}$$

The parabolic potential and electronic effective mass are obtained by changing the aluminum concentration x in the well layers and y in the barrier layers. For ternary mixed crystals (TMCs) $Al_xGa_{1-x}As$ ($Al_yGa_{1-y}As$) with direct band gaps within $0 \le x(y) \le 0.4$, the effective mass of an electron[24] in a conduction band can be expressed as

$$m^*(z) = 0.067 + 0.083x. \tag{5}$$

The eigenenergies and wave functions of electrons can be obtained by solving Eq. (1). Figure 2 shows the DPQW potential profile and wave functions of electrons at the ground, first and

second excited states for symmetric (Fig. 2(a)) and asymmetric (Fig. 2(b)) cases, respectively.

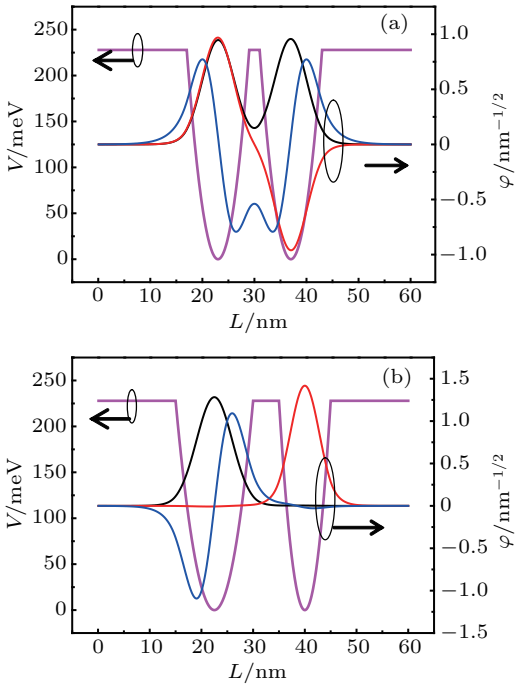


Fig. 2. (color online) Potential profiles of conduction bands in DPQWs (pink curves) and wave functions of electrons at the ground (black curves), first (red curves), and second (blue curves) excited states for (a) symmetric and (b) asymmetric cases, respectively.

It can be seen from Fig. 2(a) that the wave functions of an electron at the ground, first and second excited states have equal probability distributions in two symmetric wells. While the wave functions for ground and the second excited states are mainly distributed in the left well, the first excited states are distributed in the right well in Fig. 2(b) for asymmetric case. Meanwhile, the coupling between the two wells is reduced with the increase of barrier thickness or well width. The enhancement of the parabolic confined potential with increasing x can only influence the energy levels of electrons in the DPQWs. Our result is consistent qualitatively with results of triangle and square DQWs.[25,26]

By the density matrix method,[27] the ISBT absorption coefficients can be calculated using the following formula:

$$\alpha(\omega) = \sum_{n>m} \alpha_{mn} = \omega\sqrt{\frac{\mu_0}{\varepsilon_0\varepsilon_r}} \sum_{n>m} |M_{mn}|^2 \frac{\sigma_v \hbar\tau}{(\Delta E - \hbar\omega)^2 + (\hbar\tau)^2}. \quad (6)$$

Here α_{mn} is the total absorption coefficient of an electron transition along the z direction from states m to n, ω is the angular frequency of an incident photon, ε_0 the static dielectric constant of vacuum, ε_r the relative dielectric constant, μ_0 the permeability of vacuum, M_{mn} the dipole matrix element indicating the intersubband optical transition of the electron by absorbing a photon with energy $\hbar\omega$ and $\Delta E = E_n - E_m$, where E_m and E_n denote the corresponding eigenenergies of the electron, σ_v is the carrier density, and τ the intersubband relaxation time. For an intersubband optical transition along the z-direction, the dipole matrix element M_{mn} can be written as

$$M_{mn} = \int_0^L \varphi_m^*(z)\, ez\, \varphi_n(z)\, \mathrm{d}z. \quad (7)$$

3. Numerical results and discussion

In our numerical computation, these parameters can be adopted as follows:[26] $m^*_{\mathrm{GaAs}} = 0.067m_0$, where m_0 is the mass of a free electron. $\sigma_v = 3.0\times10^{22}$ m^{-3}, $\tau = 0.14$ ps, $\mu = 4\pi\times10^{-7}$ H$\cdot$m^{-1}, the height of three barriers separating the wells is $V(x_j, 0.3, z) \approx 228$ meV for comparison.

3.1. IOACs in symmetric $Al_xGa_{1-x}As/Al_yGa_{1-y}As$ DQWs

Figure 3 shows the variations of absorption coefficient α_{mn} of an electron transition from states m to n with photon energy for different well widths and middle barrier thickness for symmetric $Al_xGa_{1-x}As/Al_yGa_{1-y}As$ DQWs with $L_{w1} = L_{w2}$. It can be seen that α_{12} and α_{23} are observable except the peak corresponding the transition from 1 to 3 since the electron at the second excited state penetrates into the middle barrier while the probabilities in the two wells of an electron at the ground state are nearly equal. This may weaken the interaction between the electron and a photon so that α_{13} approaches to zero. The peaks of IOACs are sensitive to well width L_{w1} and middle barrier value L_{b2}. With increasing L_{w1}, the quantum confinement effect becomes weaker and weaker in symmetry DPQW, the energy difference among the lowest three states in conduction bands decreases, and the corresponding

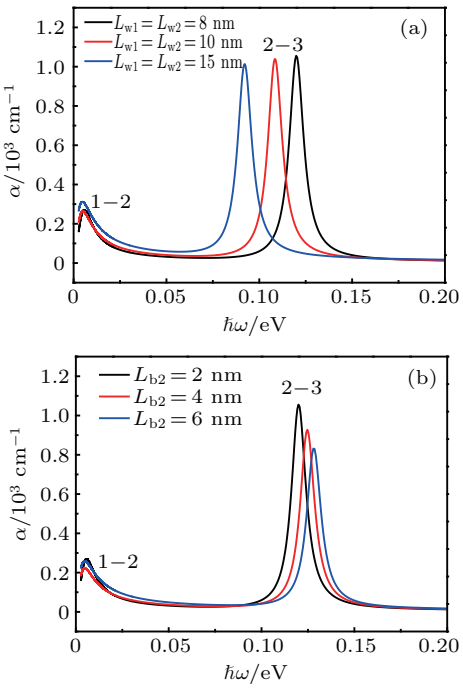


Fig. 3. (color online) Plots of α_{mn} versus photon energy for different (a) well widths and (b) middle barrier thickness. The peak value indicates the main contribution of the transition of an electron from state m to n denoted by m–n in the graphs.

peak shifts toward lower photon energies. It can also be found that the peak of α_{12} moves scarcely due to the almost fixed energy difference between the ground state and the first excited state for a larger side barrier thickness. With increasing L_{b2}, α_{12} decreases first and then increases, and its position has a red shift and then a blue shift but α_{23} decreases and its position moves towards higher photon energies. For a less L_{b2}, the probabilities of an electron in the two wells are nearly the same. When increasing L_{b2}, the wells show a weakened coupling effect and finally become decoupled. The probabilities of the electron in the two wells reveal an increasing difference, and a big probability in turn occurs from the ground to the excited states. This mainly results in the magnitude of α_{23} decreasing with increasing L_{b2}, while the magnitude of α_{12} does not change obviously. When applying an external electric field $F = 20$ kV/cm, the results reveal an increasing energy difference because the external field destroys the symmetry of waves functions. Our results are in qualitative agreement with those of symmetric DSQWs and semi-parabolic ones.[21]

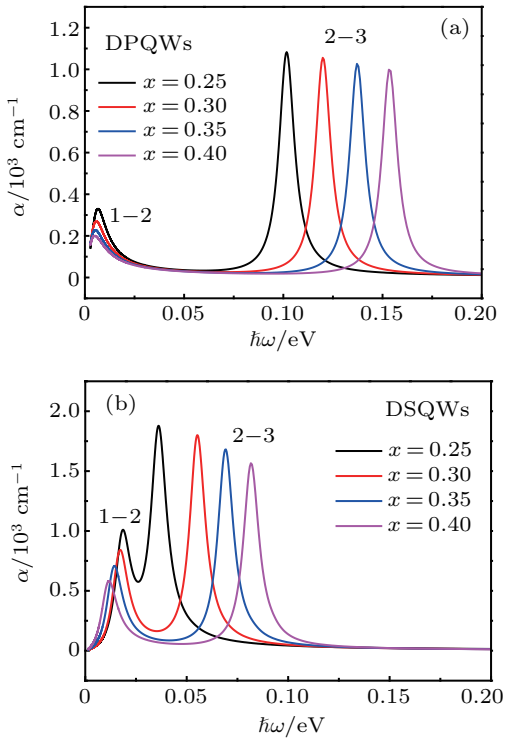


Fig. 4. (color online) Variations of α_{mn} with photon energy of (a) DPQWs and (b) DSQWs for different Al components. The peaks indicate the main contribution of the transition of electron from states m to n denoted by m–n in the panels.

Figure 4 shows the variations of α_{12} and α_{23} with photon energy in DPQWs and DSQWs with different Al components. It can be seen clearly that with increasing x, the absorption peak positions of α_{23} (α_{12}) and α_{13} shift to the higher (lower) photon energies whereas their magnitudes decrease rapidly for both DPQWs and DSQWs. As discussed above, the peaks of α_{13} cannot be demonstrated in the figures. The reason is that the energy differences from the ground (first excited) state to the second excited states increase while those from the ground state to the first excited state decrease due to the enhancement of barrier potential with increasing x. The peaks of IOACs are consistent with those in Fig. 3: $\alpha_{23} > \alpha_{12} > \alpha_{13}$. Consequently, the absorption peaks show a blue shift and a red shift with the x increasing in both of DPQWs and DSQWs. It should be noted that the intervals between the peaks of α_{12} and α_{23} are enlarged in DPQWs compared with those in DSQWs and this property can be used in devices to improve the sensibility of measurement. It can be easily apprehended that the quantum confinement effect of DPQWs turns much weaker than that of DSQWs and leads to an increase of subband energy separation in a similar size and Al component. Meanwhile, the energy levels of ground state and the first excited state vary slightly, but the energy level of second excited state increases quickly with increasing Al component. This results in a blue shift of α_{23} in DPQWs.

3.2. IOACs in the $Al_xGa_{1-x}As$ /$Al_yGa_{1-y}As$ asymmetric DQWs

With the left well width fixed at $L_{w1} = 10$ nm, α_{12}, α_{13}, and α_{23} each as a function of photon energy in asymmetric DPQWs for different values of right well width L_{w2} and middle barrier thickness L_{b2} are shown in Fig. 5. As seen in Figs. 5(a)–5(c), for α_{12}, the intersubband absorption spectra show a red shift and the peak magnitudes decrease with increasing L_{w2}, whereas for α_{13}, the spectra show a red shift but the peak magnitudes increase, as for α_{23},the red and blue shifts appear alternately and the peak magnitude decreases. The peak value contributed from α_{13} is the largest, whereas the peak value of α_{12} is more and more imperceptible as L_{b2} increases. It can also be found that the peak value of α_{23} is less and less until it disappears with increasing L_{b2} and L_{w2}. The reason is that the wave functions of an electron at the ground state and second excited state are distributed in the wide well whereas the wave function of the first excited state is distributed in the narrow well due to the coupling between the wells. Furthermore, the probability of an electron appearing in the narrow well becomes bigger with increasing L_{w2}, which leads to $\alpha_{13} > \alpha_{23} > \alpha_{12}$ in asymmetric DPQWs. With increasing L_{b2} and L_{w2}, the coupling between the two wells becomes weaker and weaker and the eigenenergies of the first excited state in the wide well and the second excited state in the narrow well become close to each other. It can be seen from Eq. (6), IOACs mainly depend on the optical dipole matrix element and the position of energy level, which leads to α_{23} becoming smaller slowly. This property is qualitatively consistent with the result of asymmetric DSQW.[26] It can be seen from Fig. 4(d), with increasing L_{w2}, the intersubband absorption spectrum shows a red shift then a blue shift and the

peak magnitude is the largest for α_{23} when applying an external field $F = 15$ kV/cm, for it tilts the potential and enhances the coupling between the two wells. What is more, the incident photon energy and the peak value of DPQWs are larger than those of DSQWs.

Figure 6 shows the variations of α_{12}, α_{13}, and α_{23} with photon energy with different Al components in asymmetric DPQWs and DSQWs. It can be seen clearly that the intervals of IOACs in DPQWs are larger than those in DSQWs. This characteristic is qualitatively consistent with that of symmetric structures. Meanwhile, the adjustable range of incident photons is equal in asymmetric DPQWs approximately, for quantum confinement effect becomes much weaker than that in DSQWs. Hence, we can construct a parabolic potential to increase the resolution of the absorption peaks in an actual device.

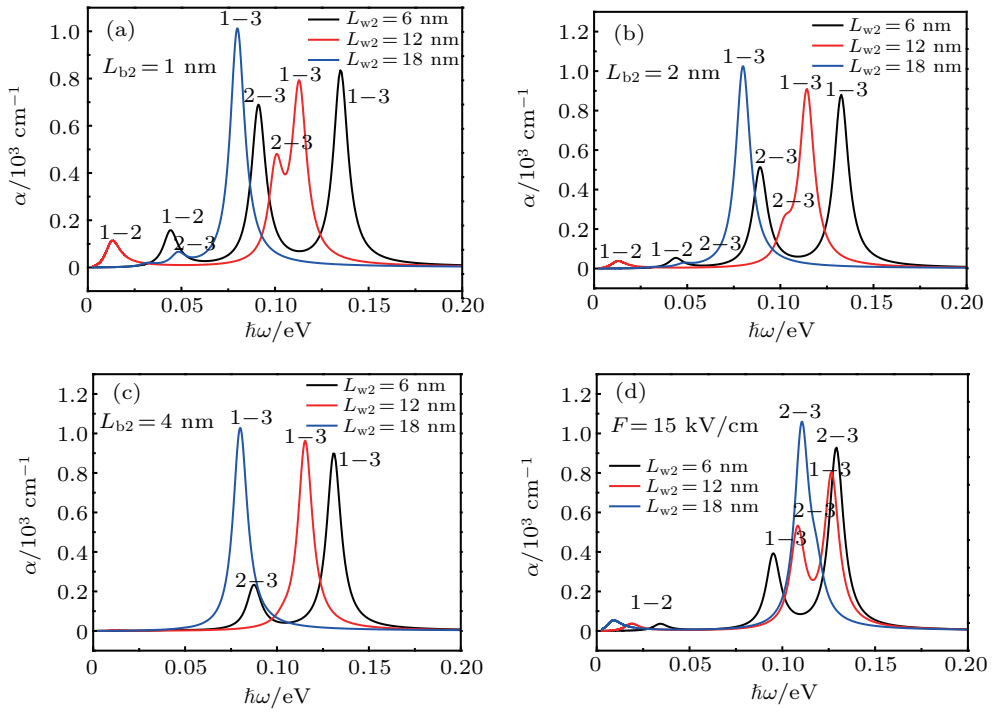


Fig. 5. (color online) Variations of α_{mn} with photon energy for DPQWs with different right well widths L_{w2} and (a) $L_{b2} = 1$ nm, (b) $L_{b2} = 2$ nm, (c) $L_{b2} = 4$ nm, (d) $L_{b2} = 2$ nm and $F = 15$ kV/cm while the left well width $L_{w1} = 10$ nm. The peak values indicate the main contribution of the transition of an electron from states m to n denoted by m–n in the panels.

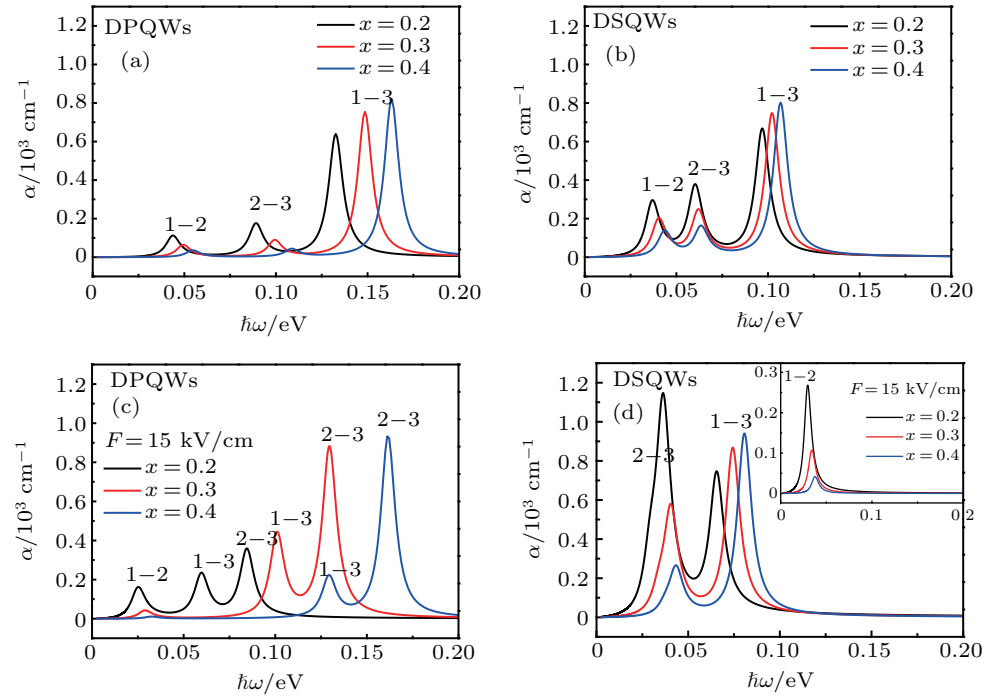


Fig. 6. (color online) Variations of α_{mn} with photon energy for asymmetric (a) DPQWs and (b) DSQWs with $F = 0$ kV/cm; (c) DPQWs and (d) DSQWs with $F = 15$ kV/cm for different Al components. The peak values indicate the main contributions of the transition of an electron from states m to n denoted by m–n in the panels.

All of the intersubband absorption spectra show a blue shift since the energy intervals of eigen-states of an electron in DPQWs and DSQWs increase with increasing x. From Figs. 6(c) and 6(d), it can be seen that the IOAC peaks present $\alpha_{13} > \alpha_{23} > \alpha_{12}$ with $F = 0$ kV/cm, while the values of peaks show $\alpha_{23} > \alpha_{13} > \alpha_{12}$ with $F = 15$ kV/cm. Because a strong external field enforces the electron in the second excited state to move from left well to the right well and leads to the overlap of $\varphi_2(z)$ and $\varphi_3(z)$ being bigger than that of $\varphi_1(z)$ and $\varphi_3(z)$ with increasing x. Hence, external electric fields result in peaks increasing, and play an important role in the blue shifting of absorption spectra due to the electrons excited from the ground state to the first and second excited states for different values of x.

4. Conclusions

We investigate the optical intersubband absorptions for electron transitions of 1–2, 1–3, and 2–3 in DPQWs consisting of $Al_xGa_{1-x}As/Al_yGa_{1-y}As$. Our results show that the absorption coefficient of 1–3 transition is comparatively small and can be increased by reducing L_{b2} and applying an external electric field $F = 15$ kV/cm in an asymmetric structure. Moreover, the width of left well is much more important in an asymmetric structure and the thickness of middle barrier plays an important role in the peak position and height of IOACs in the symmetrical case. The absorption peak positions of $\alpha_{23}(\alpha_{12})$ and α_{13} shift to higher (lower) photon energies whereas their magnitudes decrease rapidly for both DPQWs and DSQWs with increasing x in the symmetrical case. However, all of intersubband absorption spectra shift to higher photon energies with increasing x in asymmetrical DPQWs. This conclusion is consistent with the results of quantum wires and triangle wells.[28–30] What is more, the adjustable extent of incident photon energy is larger in DPQWs than that in DSQWs in a similar size. Our results are important in both experiment and design of optical devices.

References

[1] Tien N T, Hung N N T, Nguyen T T and Thao P T B 2017 *Physica B* **519** 63
[2] Zheng W M, Li S M, Cong W Y, Wang A F, Li B and Huang H B 2016 *Chin. Phys. B* **25** 047302
[3] Restrepo R L, Ungan F, Kasapoglu E, Mora-Ramos M E, Morales A L and Duque C A 2015 *Physica B* **457** 165
[4] Liu D F, Cheng Y and He J F 2015 *Superlatt. Microstruct.* **86** 313
[5] Kuo D M T, Fang A and Chang Y C 2001 *Inf. Phys. Technol.* **42** 433
[6] Someya T, Hoshino K, Harris J C, Tachibana K and Arakawa Y 2000 *Appl. Phys. Lett.* **77** 1336
[7] Campman K L, Maranowski K D, Schmidt H, Imamoglu A and Gossard A C 1999 *Physica E* **5** 16
[8] Kotani T, Arita M, Hoshino K and Arakawa Y 2016 *Appl. Phys. Lett.* **108** 052102
[9] Alves F D P, Karunasiri G, Hanson N, Byloos M, Liu H C, Bezinger A, Buchanan M 2007 *Inf. Phys. Technol.* **50** 182
[10] Li J, Kolokolov K, Ning C Z, Larraber D C, Khodaparast G A, Kono J, Ueda K, Nakajima Y, Sasa S and Inoue M 2003 *Mater. Res. Soc.* **744** M9.2.1
[11] Manasreh M O, Szmulowicz F, Fischer D W, Evans K R and Stutz C E 1990 *Appl. Phys. Lett.* **57** 1790
[12] Liu D F, Wang E X and Guo K X 2017 *Physica E* **86** 64
[13] Ozturk E 2017 *Optik* **139** 256
[14] Zhu J, Ha S H and Ban S L 2013 *Superlatt. Microstruct.* **56** 92
[15] Aziz Aghchegala V L, Mughnetsyan V N and Kirakosyan A A 2011 *Superlatt. Microstruct.* **49** 1
[16] Gu Z, Zhu Z N, Wang M M, Wang Y Q, Wang M S, Qu Y and Ban S L 2017 *Superlatt. Microstruct.* **102** 391
[17] Phuc H V and Tung L V 2014 *Superlatt. Microstruct.* **71** 124
[18] Yu X Q and Yu Y B 2013 *Superlatt. Microstruct.* **62** 225
[19] Li Q, Qu Y and Ban S L 2017 *Acta. Phys. Sin.* **66** 077301 (in Chinese)
[20] B A Ebrahimipour, Askari H R and Ramezani A B 2016 *Superlatt. Microstruct.* **97** 495
[21] Al E B, Ungan F, Yesilgul U, Kasapoglu E, Sari H and Sökmen I 2015 *Opt. Mater.* **47** 1
[22] Solaimani M, Morteza I and Arabshahi H 2013 *J. Lumin.* **134** 699
[23] Karimi M J and Keshavarz A 2011 *Superlatt. Microstruct.* **50** 572
[24] Miranda G L, Mora-Ramos M E and Duque C A 2011 *Physica B* **50** 350
[25] Eseanu N 2010 *Phys. Lett. A* **374** 1278
[26] Chen B, Guo K X, Wang R Z, Zheng Y B and Li B 2008 *Eur. Phys. J. B* **66** 227
[27] Keshavarz A and Karimi M J 2010 *Phys. Lett. A* **374** 2675
[28] Sari H, Kasapoglu E, Sakiroglu S, Yesilgul U, Ungand F and Sökmen I 2017 *Physica E* **90** 214
[29] Safarpour G, Zamani A, Izadi M A and Ganjipour H 2014 *J. Lumin.* **147** 295
[30] Mora-Ramos M E, Duque C A, Kasapoglu E, Sari H and Sökmen I 2013 *J. Lumin.* **135** 301