

Nonlinear optical properties in n-type quadruple δ-doped GaAs quantum wells

Humberto Noverola-Gamas, Luis Manuel Gaggero-Sager, and Outmane Oubram

Citation: Chin. Phys. B, 2022, 31 (**4**): 044203. DOI: 10.1088/1674-1056/ac248e
Journal homepage: http://cpb.iphy.ac.cn; http://iopscience.iop.org/cpb

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

Improving the spectral purity of single photons by a single-interferometer-coupled microring

Yang Wang(王洋), Pingyu Zhu(朱枰谕), Shichuan Xue(薛诗川), Yingwen Liu(刘英文), Junjie Wu(吴俊杰), Xuejun Yang(杨学军), and Ping Xu(徐平)
Chin. Phys. B, 2022, 31 (**3**): 034210. DOI: 10.1088/1674-1056/ac3652

High-sensitive terahertz detection by parametric up-conversion using nanosecond pulsed laser

Yuye Wang(王与烨), Gang Nie(聂港), Changhao Hu(胡常灏), Kai Chen(陈锴), Chao Yan(闫超), Bin Wu(吴斌), Junfeng Zhu(朱军峰), Degang Xu(徐德刚), and Jianquan Yao(姚建铨)
Chin. Phys. B, 2022, 31 (**2**): 024204. DOI: 10.1088/1674-1056/ac2d20

An analytical model for cross-Kerr nonlinearity in a four-level N-type atomic system with Doppler broadening

Dinh Xuan Khoa, Nguyen Huy Bang, Nguyen Le Thuy An, Nguyen Van Phu, and Le Van Doai
Chin. Phys. B, 2022, 31 (**2**): 024201. DOI: 10.1088/1674-1056/ac2d19

Minimum structure of high-harmonic spectrafrom aligned O_2 and N_2 molecules

Bo Yan(闫博), Yi-Chen Wang(王一琛), Qing-Hua Gao(高庆华), Fang-Jing Cheng(程方晶), Qiu-Shuang Jing(景秋霜), Hong-Jing Liang(梁红静), and Ri Ma(马日)
Chin. Phys. B, 2021, 30 (**11**): 114213. DOI: 10.1088/1674-1056/abfbd9

Interlayer distance effects on absorption coefficient and refraction index change in p-type double-δ-doped GaAs quantum wells

H Noverola-Gamas, L M Gaggero-Sager, O Oubram
Chin. Phys. B, 2019, 28 (**12**): 124207. DOI: 10.1088/1674-1056/ab5278

Nonlinear optical properties in n-type quadruple δ-doped GaAs quantum wells

Humberto Noverola-Gamas[1,†], Luis Manuel Gaggero-Sager[2], and Outmane Oubram[3]

[1] *División Académica de Ingeniería y Arquitectura, Universidad Juárez Autónoma de Tabasco, Carretera Cunduacán-Jalpa de Méndez Km. 1 Col. La Esmeralda, Cunduacán, 8660, México*

[2] *Centro de Investigación en Ingeniería y Ciencias Aplicadas, Universidad Autónoma del Estado de Morelos, Av. Universidad 1001 Col. Chamilpa, Cuernavaca, 62209, México*

[3] *Facultad de Ciencias Químicas e Ingeniería, Universidad Autónoma del Estado de Morelos, Av. Universidad 1001 Col. Chamilpa, Cuernavaca, 62209, México*

(Received 24 June 2021; revised manuscript received 6 September 2021; accepted manuscript online 8 September 2021)

The effects of the interlayer distance on the nonlinear optical properties of n-type quadruple δ-doped GaAs quantum well were theoretically investigated. Particularly, the absorption coefficient and the relative refraction index change were determined. In the effective mass approach and within the framework of the Thomas–Fermi theory, the Schrödinger equation was resolved. Thereby, the subband energy levels and their respective wave functions were calculated. The variations in the nonlinear optical properties were determined by using the density matrix solutions. The achieved results demonstrate that the interlayer distance causes optical red-shift on nonlinear optical properties. Therefore, it can be deduced that the suitably chosen interlayer distance can be used to tune optical properties within the infrared spectrum region in optoelectronic devices such as far-infrared photo-detectors, high-speed electronic-optical modulators, and infrared lasers.

Keywords: delta-doping, n-type GaAs layers, electronic structure, non-linear optical properties

PACS: 42.65.–k, 64.70.Tg, 42.70.Nq **DOI:** 10.1088/1674-1056/ac248e

1. Introduction

Recently, different approaches allow calculations of optical and electronic properties in semiconductors. For instance, the density functional theory (DFT) can describe accurately the physical properties in multiple materials.[1–5] However, in this method, the calculation time efficiency in the processes is mainly determined by the diagonalization routines.[6] Besides, another approach, the Thomas–Fermi (TF) theory[7,8] allows the determination of the electronic structure with a very simple way in comparison to the DFT.

In the last few years, nano-scale semiconductor devices based on quantum dots, quantum rings, quantum wires and quantum wells have been made possible thanks to the remarkable advances in theoretical investigation.[9–13] Within the TF approach, the electronic structure of quantum wells can be determined. These low-dimensional systems have been widely studied due to their optical and electronic properties.[14,15] A great diversity of structures based on quantum wells are currently being studied, such as materials with epitaxial growth, heterostructures and doped-delta. A δ-doped quantum well is a two-dimensional layer doping that creates an approximately V-shaped doped potential profile into a structure, where the charge carriers (electrons or holes) form a two-dimensional gas. These systems are very important for the development of optoelectronic devices since its introduction by Wood.[16]

The doping of semiconductor materials in atomic resolution (δ-doping) is possible due to the precision of molecular beam epitaxy (MBE) growth techniques.[17,18] The synthesis of δ-doped structures has primarily been on gallium arsenide (GaAs). When Si atoms substitute the positions of Ga atoms in the direction (100), a n-type semiconductor[19] is formed . The literature concentrates a lot of information on this material related to subband structure, electron or hole mobilities, and optoelectronic properties.[14,15,20–25] On the other hand, lower number works have been conducted on delta-layers for Si, and this is due to the problems to incorporate dopants in a controlled process of MBE growth for Si.[26]

Another important point is that, in δ-doped potential profiles cases, there are recent studies in nonlinear optical properties.[15,23,27,28] For instance, Durmuslar *et al.*[20] determined the effects on the nonlinear optical rectification, second harmonic generation, and third harmonic generation of n-type asymmetric double delta-doped GaAs quantum well. In this work, the obtained results indicate that an electric field leads to optical red-shift on nonlinear coefficients while the magnetic field causes optical blue-shift. On the other hand, in the previous work,[29] we represented a model for the n-type quadruple δ-doped (QDD) system in GaAs. This paper was the first physical model in the literature for the QDD system. Besides, we investigated the electronic structure of QDD in the framework of TF approach. In recent years, some relevant results reported the effects of the external fields such as the magnetic and electric fields, and also the intense laser field. Dakhlaoui *et al.*[30] investigated the effects of the electric and magnetic

†Corresponding author. E-mail: noverola86@gmail.com

© 2022 Chinese Physical Society and IOP Publishing Ltd

field on the linear and nonlinear optical properties of a quantum well heterostructure containing triple parabolic barriers in GaAs. They obtained that an increase in the intensity of the intense laser field produces a shift in the nonlinear optical properties. Our work, shows the effects of internal parameters (interlayer distance and density of impurities) on nonlinear optical properties for quadruple δ-doped quantum wells.

Up to our knowledge, this work is the first study on nonlinear optical properties in a quadruple δ-doped structure. Here, we use the framework of the TF approach and the effective mass approximation to obtain the electronic structure of n-type QDD. The determination of nonlinear optical properties is carried out from the density matrix equations. Section 2 shows our methodology, and results and related discussions are presented in Section 3. Section 4 includes the conclusion.

2. Methodology

It was made a theoretical investigation for quadruple n-type δ-doped GaAs quantum wells (QDDQWs) for different distances between layers (d) and two-dimensional impurities density (N_{2D}). Within the framework of effective mass and TF approaches, the interaction potential between the carriers and the ionized impurity layer in effective units was defined as

$$V(z) = \gamma\left[\frac{-\alpha^2}{(\alpha|z+3d/2|+z_0)^4} - \frac{\alpha^2}{(\alpha|z+d/2|+z_0)^4} - \frac{\alpha^2}{(\alpha|z|+z_1)^4}\right], \tag{1}$$

where z_0 and α are constants,[27] d is the interlayer distance and γ is a dimensionless parameter explained in more detail in reference.[29] In Eq. (1), we assume all QW are located along the z-axis. Imposing that the potential profile and its derivative is continuous on z axis, we obtain

$$z_1 = \left[\frac{(3\alpha d/2+z_0)^5(\alpha d/2+z_0)^5}{(3\alpha d/2+z_0)^5+(\alpha d/2+z_0)^5}\right]^{1/5}. \tag{2}$$

The relative total optical absorption coefficient $\alpha_{\mathrm{Rel}}^{\mathrm{Tot}}$ is obtained by summing the two precedent terms (linear and nonlinear) $\alpha_{\mathrm{Rel}}^{(1)}+\alpha_{\mathrm{Rel}}^{(3)}$,

$$\alpha_{\mathrm{Rel}}^{(1)}(\omega) = \frac{\omega}{\omega_0}\frac{|M_{fi}|^2}{|M_{10}^{\delta}|^2}\frac{\Delta E_{fi}/\lfloor(\Delta E_{fi}-\hbar\omega)^2+(\hbar/\tau_{\mathrm{in}})^2\rfloor}{\Delta E_{10}/\lfloor(\Delta E_{10}-\hbar\omega)^2+(\hbar/\tau_{\mathrm{in}})^2\rfloor}, \tag{3}$$

$$\alpha_{\mathrm{Rel}}^{(3)}(\omega,P,I) = -\alpha_{\mathrm{Rel}}^{(1)}\times\frac{(2I/\varepsilon_0 n_{\mathrm{r}}c)|M_{fi}|^2}{\lfloor(\Delta E_{fi}-\hbar\omega)^2+(\hbar/\tau_{\mathrm{in}})^2\rfloor}, \tag{4}$$

where $\alpha_{\mathrm{Rel}}^{(1)}(\omega)=\alpha^{(1)}(\omega)/\alpha_{\mathrm{Ref}}^{(1)}(\omega_0)$. In Eq. (3), the denominator indicates the absorption for reference system. In these equations, ω_0 is the frequency (energy associated with an incident photon) for the absorption coefficient peak in the reference system, ΔE_{fi} denotes the energy difference between f and i states, and τ_{in} is the intrasubband relaxation time. In this calculations τ_{in} is a constant and used as 0.14 ps following Ref. [31]. The energy difference between the ground and the first excited level is denoted by ΔE_{10}. Furthermore, I represents the photon energy intensity, ε_0 is the vacuum permittivity, n_{r} represents the refractive index, and c is the speed of light in free space. At low temperatures limit, the relative absorption coefficient is

$$\alpha_{\mathrm{Ref}}^{(1)}(\omega) = \omega\sqrt{\frac{\mu}{\varepsilon_{\mathrm{R}}}}\left(\frac{m^*}{L_{\mathrm{eff}}\pi\hbar^2}\right)\times\frac{|M_{10}|^2(\hbar/\tau_{\mathrm{in}})}{(\Delta E_{10}-\hbar\omega)^2+(\hbar/\tau_{\mathrm{in}})^2}. \tag{5}$$

In Eq. (5), μ is the permeability, m^* represents the effective mass, L_{eff} is the well's width, and $|M_{10}|$ is the matrix elements of the dipole moment for the ground (0) and the first excited state (1). The relative total nonlinear refractive index changes[32] ($\Delta n_{\mathrm{Rel}}^{(\mathrm{Tot})}$) for the intersubband transitions 1–0, and $\Delta n_{\mathrm{Rel}}^{(\mathrm{Tot})}=\Delta n_{\mathrm{Rel}}^{(1)}+\Delta n_{\mathrm{Rel}}^{(3)}$ are given by the following expressions:

$$\Delta n_{\mathrm{Rel}}^{(1)}(\omega) = \frac{|M_{fi}|^2}{|M_{10}^{\delta}|^2}\frac{\Delta E_{fi}(\Delta E_{fi}-\hbar\omega)/[(\Delta E_{fi}-\hbar\omega)^2+(-\hbar/\tau_{\mathrm{in}})^2]}{\Delta E_{10}^{\delta}(\Delta E_{10}^{\delta}-\hbar\omega)/[(\Delta E_{10}^{\delta}-\hbar\omega)^2+(-\hbar/\tau_{\mathrm{in}})^2]}, \tag{6}$$

$$\Delta n_{\mathrm{Rel}}^{(3)}(\omega,I) = -\Delta n_{\mathrm{Rel}}^{(1)}\left\{\frac{(\frac{2I}{\varepsilon_0 n_{\mathrm{r}}c})|M_{fi}|^2}{[(\Delta E_{fi}-\hbar\omega)^2+(\hbar/\tau_{\mathrm{in}})^2]}\right\}, \tag{7}$$

where $\Delta n_{\mathrm{Rel}}^{(1)}(\omega)=\Delta n^{(1)}(\omega)/\Delta n_{\mathrm{Ref}}^{(1)}(\omega)$ and $\Delta n_{\mathrm{Rel}}^{(3)}(\omega,I)=\Delta n^{(3)}(\omega,I)/\Delta n_{\mathrm{Ref}}^{(1)}(\omega)$. Furthermore, $\Delta n_{\mathrm{Ref}}^{(1)}(\omega)$ is defined as

$$\Delta n_{\mathrm{Ref}}^{(1)}(\omega)/n_{\mathrm{r}} = \frac{1}{2n_{\mathrm{r}}^2\varepsilon_0}\left(\frac{m^*}{L_{\mathrm{eff}}\pi\hbar^2}\right)\times\frac{\Delta E-\hbar\omega}{(\Delta E-\hbar\omega)^2+(\hbar/\tau_{\mathrm{in}})^2}. \tag{8}$$

Equations (3)–(5) and (6)–(7) represent the nonlinear optical properties calculated in this work.

3. Results and discussion

The starting parameters for n-type QDDQWs in GaAs are as the following: the reference density impurity is $N_{2D}=5\times10^{12}$ cm^{-2}, $\varepsilon_{\mathrm{R}}=12.5$, and $m_{\mathrm{e}}^*=0.067m_0$, where m_0 is

the free electron mass. Important results on the modulation of nonlinear optical properties for the intersubband transitions. The relative absorption coefficient ($\alpha_{\rm Rel}^{\rm Tot}$) and relative change index ($\Delta n_{\rm Rel}^{\rm (Tot)}$) were calculated with respect to the interlayer distance changes in n-type quadruple δ-doped GaAs quantum wells (QDDQWs) structures. We determine ($\alpha_{\rm Rel}^{\rm Tot}$) and ($\Delta n_{\rm Rel}^{\rm (Tot)}$) by considering the density matrix theory. The difference in the doping concentrations generates potential profile bottom changes in the systems. Figure 1 shows the impact of doping concentrations on potential profile bottom modulation.

The effect of the interlayer distance of the QW on the electronic structure is shown in Fig. 2. In this figure, it can be observed the reference potential profile and for three different interlayer distances of $d = 10$ Å, 25 Å and 50 Å, denoted by (b), (c) and (d), respectively. In the case $d = 0$, corresponding to an insolated δ-doped quantum well (reference system), we observe the five characteristic levels with $N = 5 \times 10^{12}$ cm^{-2} concentration.[33] In order to understand the evolution of the energy levels with the interlayer distance in each of these cases, it is enough to observe the changes at the potential bottom as the d increase. In these diagrams, it can be observed the geometry change of the potential profile and the increase in the relative maximum at $z = 0$ with the increase of the interlayer distance.

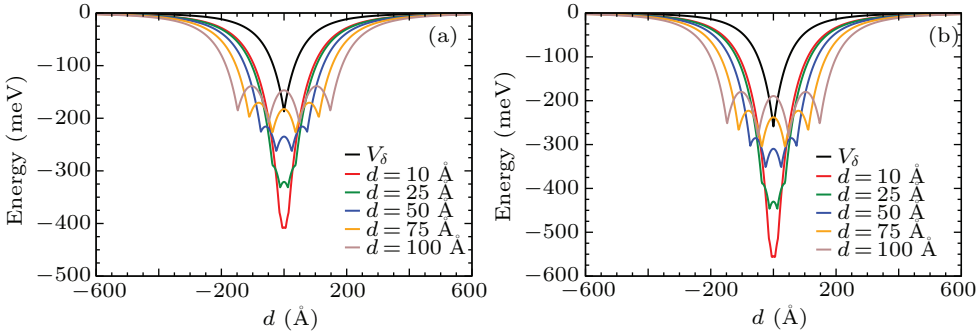


Fig. 1. Potential profile, (a) $N_{\rm 2D} = 5 \times 10^{12}$ cm^{-2} and (b) $N_{\rm 2D} = 7.5 \times 10^{12}$ cm^{-2}.

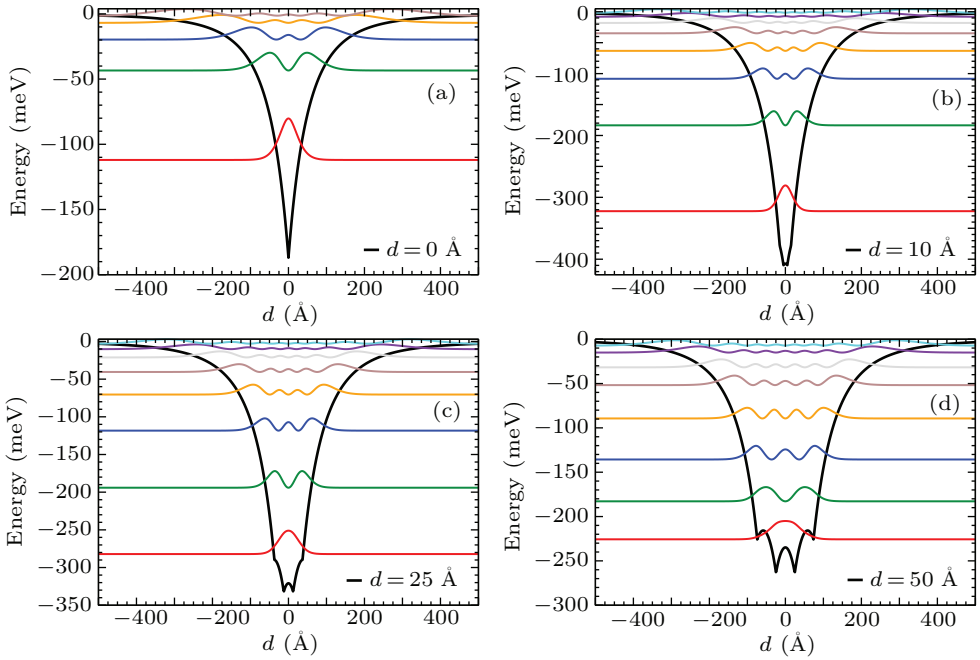


Fig. 2. Evolution of potential profile, energy, and square of waves functions for (a) reference δ-doped, (b) $d_1 = 10$ Å, (c) $d_2 = 25$ Å and (d) $d_3 = 50$ Å. In all cases, the concentration of impurities in the layer is $N_{\rm 2D}^{\rm Ref} = 5 \times 10^{12}$ cm^{-2}.

Figure 3 represents the linear, non-linear, and total relative absorption coefficients as a function of the photon energy for four different interlayer distances $d = 10$ Å, 25 Å, 50 Å and 75 Å. The continuous black line shows the reference absorption coefficient. In this figure, it is possible to observe a red-shift of the total absorption coefficient peak as the interlayer distance is increased. The behavior can be described as follows: by increasing d the ground state and the first energy level tend to get closer to each other as shown in Figs. 2(b)–2(d). In agreement with Eqs. (3) and (4), the absorption peak reduction by increasing d results in requiring lower energy of the incident photon to observe the resonant peak, and this implies the red-shift effect. Besides, the above causes a decrease of the amplitude of the absorption resonant peak, which is di-

rectly proportional to the frequency of the incident photon energy.

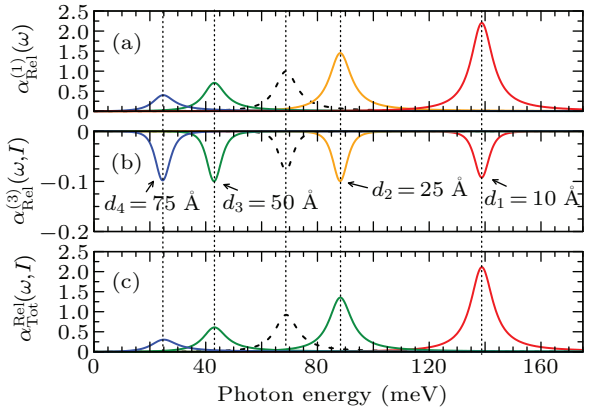


Fig. 3. (a) Linear, (b) non-linear and (c) total relative absorption coefficients as a function of the photon energy for four interlayer distances. The different interlayer distances, are considered $d = 10$ Å, 25 Å, 50 Å and 75 Å. The black dotted line represents the reference system. It was used $I = 0.1$ MW/cm^2 for the incident light intensity.

Finally, we plot in Fig. 4 the (a) linear, (b) nonlinear and (c) total relative refraction index change as a function of the incident photon energy for different interlayer distance values: $d = 10$ Å, 25 Å, 50 Å, 75 Å. We can be seen a red-shift described on the optical absorption coefficient. This shift is controlled by the variation of the transition energy between the two first energy levels.

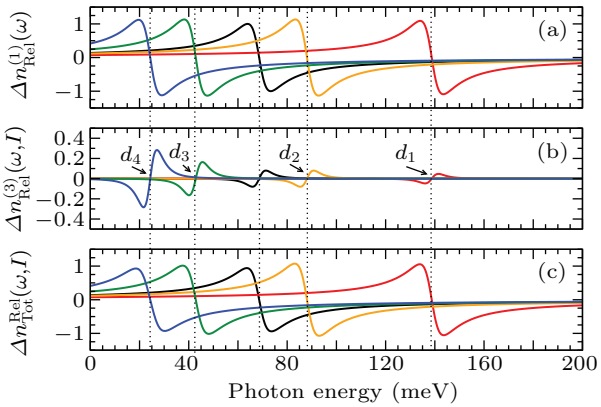


Fig. 4. The relative (a) linear, (b) nonlinear and (c) total refractive index changes as a function of the incident photon energy for four different interlayer distances.

It can be observed in the QDD that the absorption coefficient peak is much higher with respect to other structures (single-delta, double delta, heteroestructures) due to the high ΔE between the ground state and the first excited state. This condition allows that new optoelectronic devices can be designed based on the QDDQWs structure, such as high-speed electronic-optical modulators, far-infrared photodetectors, and infrared lasers.

4. Conclusions

It was performed a theoretical investigation on the behavior of nonlinear optical properties in a symmetric quadruple δ-doped quantum well with respect to the interlayer distance. The ground and the first excited state have been considered in order to analyze the optoelectronic properties. The results show that the positions of the resonant peaks of optical absorption coefficient and relative refractive index change versus incident photon energy exhibit a red-shift with an increment of the interlayer distance. The results show the importance that could be tuned by the interlayer distance, the peak locations, and amplitudes of the nonlinear optical coefficients. Finally, the results could be helpful for the studies based on electronic and optical properties in the δ-doped structures.

References

[1] Ziat Y, Zarhri Z, Hammi M, Laghlimi C and Moutcine A 2020 *Computo. Condens. Matter* **25** 502
[2] Zarhri Z, Houmad M, Ziat Y, Rhazouani O E, Slassi A, Benyoussef A and Kenz A 2016 *J. Magn. Magn. Mater* **406** 212
[3] Zarhri Z, Ziat Y, Rhazouani O E, Benyoussef A and Elkenz A 2016 *J. Phys. Chem. Solids* **94** 12
[4] Zhu C and Yu T 2020 *Chin. Phys. B* **29** 096101
[5] Li Y, Xu P, Zhang X and Liu G 2020 *Chin. Phys. B* **29** 087101
[6] Seifert G, Porezag D and Frauenheim T 1996 *Int. J. Quantum Chem.* **58** 185
[7] Gaggero-Sager L M, Naumis G, Mu noz-Hernandez M A and Montiel-Palma V 2019 *Physica B* **405** 4267
[8] Grimalsky V, Gaggero-Sager L M and Koshevaya S 2011 *Physica B* **406** 2218
[9] Ozturk E 2016 *Opt. Quant. Electron.* **48** 269
[10] Pryor C E and Pistol M E 2005 *Phys. Rev. B* **72** 205311
[11] Rojas-Briseño J G, Del Río-De Santiago A, Mora-Ramos M E and Martínez-Orozco J C 2020 *Optik* **201** 163431
[12] Rodríguez-Magdaleno K, Mora-Ramos M E, Pérez-álvarez R and Martínez-Orozco J C 2020 *Mat. Sci. Semicon. Proc.* **108** 104906
[13] Yang X C and Xing Y 2020 *Chin. Phys. B* **29** 087802
[14] Rodríguez-Vargas I, Gaggero-Sager L M and Velasco V R 2003 *Suf. Sci.* **537** 75
[15] Ungan F, Mora-Ramos M E, Kasapoglu E, Sari H and Sökmen I 2018 *Philos. Mag.* **99** 644
[16] Wood C E, Metze G and Eastman L F 1980 *J. Appl. Phys.* **51** 383
[17] Gossmann H J, Unterwald F C and Luftman H S 1993 *J. Appl. Phys.* **73** 8237
[18] Arpapay B, Duygulu Ö and Serincan U 2020 *Mat. Sci. Semicon. Proc.* **111** 104990
[19] Ploog K 1987 *J. Cryst. Growth* **81** 304
[20] Durmuslar A S, Mora-Ramos M E and Ungan F 2020 *Opt. Quant. Electron.* **52** 495
[21] Sahoo N, Sahu A K and Palo S K 2021 *Physica B* **608** 412798
[22] Salazar-Santa J D, Mora-Ramos M E and Marín J H 2020 *Philos. Mag.* **101** 689
[23] Noverola-Gamas H, Gaggero-Sager L M and Oubram O 2020 *Phys. Scr.* **95** 095813
[24] Ozturk E and Ozdemir Y 2013 *Opt. Commun.* **294** 361
[25] Martínez-Orozcom J C, Rodríguez-Magdaleno K A, Suárez-López J R, Duque C A and Restrepo R L 2016 *Superlattice Microst.* **92** 166
[26] Wang Y, Hamers R J and Kaxiras E 1995 *Phys. Rev. Lett.* **74** 403
[27] Noverola-Gamas H, Gaggero-Sager L M and Oubram O 2019 *Int. J. Mod. Phys. B* **33** 1950215
[28] Noverola-Gamas H, Gaggero-Sager L M and Oubram O 2019 *Chin. Phys. B* **28** 124207
[29] Noverola-Gamas H, Gaggero-Sager L M and Oubram O 2020 *Eur. Phys. J. B* **93** 18
[30] Dakhlaoui H, Ungan F, Martínez-Orozco J C and Mora-Ramos M E 2021 *Physica B* **607** 412782
[31] Ahn D and Chuang S 1987 *IEEE J. Quantum Elect.* **23** 2196
[32] Kuhn K J, Iyengar G U and Yee S 1991 *J. Appl. Phys.* **70** 5010
[33] Ioratti L 1990 *Phys. Rev. B* **41** 8340