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ORIGINAL ARTICLE

Investigations on optical transitions in InAs/InP quantum dash structures

Sanjib Kabi · Abhijit Biswas · Dipankar Biswas · Salil Kumar Biswas

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Abstract In this paper, we report the dependence of the Gaussian nature of absorption spectra of InAs/InP shallow quantum dot or quantum dash systems on the depth of the dash and also on its relative standard deviation. The dash is considered to be an elongated quantum box with a square base having finite potentials at the boundaries. Our observations reveal that the absorption spectra of the quantum dashes are strongly sensitive to the depth and also on the standard deviation of the dash depth. Predicted results help unveil a better physical insight regarding the optical properties of InAs/InP quantum dash structures. The results are in excellent agreement with reported experimental data of photoluminescence and absorption.

Keywords Quantum dot · Quantum dash · Gaussian distribution · Absorption

Introduction

Semiconductor lasers and amplifiers comprising assemblies of nanostructures, such as the quantum dot (QD), quantum wire (QWR), quantum dash (QDH), etc., exhibit considerably improved electronic and optoelectronic characteristics in comparison with conventional quantum well structures. The investigations on self-organized quantum nanostructures of InAs grown on InP have received much attention in recent years due primarily to their potentiality for optoelectronic devices operating in the wavelength range 1.3–1.55 μm (Alen et al. 2001; Gonzalez et al. 2000).

The absorption spectra of the QD or QDH also known as the shallow QD are expected to be a series of delta function like discrete lines due to the nature of the density-of-states. For optimization of the device performance, the shapes of those nanostructures and their distribution should be precisely known. The electronic band structures in which transitions take place depend on the shape and size of the nanostructures. The quantum dash refers to a shallow quantum dot, which is an elongated nanostructure with cross-sectional area of 3–4 nm × 10–20 nm, while its length is hundreds of nanometers (Bimberg et al. 1997; Klopf et al. 2001). One of the noteworthy features of quantum dashes includes significant size fluctuation, which means the width, height and length are not uniform among dashes. The most common and best-developed structures employ self-assembled InAs/GaAs quantum dots which emit light of wavelengths in the range 1–1.3 μm. Most of the earlier work on lasers using GaAs as a substrate material reported light emissions of wavelengths from 1 to 1.3 μm. It was quite challenging to realize the emission having wavelengths in the higher range in particular at 1.55 μm. Different approaches were investigated and are still under development in order to obtain light output at 1.55 μm, as this wavelength has potential application in optical fibre communications. The lattice mismatch between InAs and InP almost reduces to 50 % of the strain produced in the InAs/GaAs system. This feature allows fabrication of high quality InAs-based nano devices using InP. In order to obtain light wavelength at 1.55 μm, QDHs using InAs/InP material systems have yielded promising

S. Kabi · S. K. Biswas
Department of Physics, University of Calcutta,
92 Acharya Prafulla Chandra Road,
Kolkata 700009, India

A. Biswas (✉) · D. Biswas
Department of Radio Physics and Electronics,
University of Calcutta, 92 Acharya Prafulla Chandra Road,
Kolkata 700009, India
e-mail: abiswas5@rediffmail.com

results. High-quality lasers and optical amplifiers at wavelength 1.55 μm have been realized with InAs/InP quantum dash structures (Tan et al. 2010; Khan et al. 2012; Wang et al. 2001; Schwertberger et al. 2002; Bilenca et al. 2002, 2003; Alizon et al. 2003). Several experimental findings of quantum dash lasers and amplifiers show many of the expected nanostructure characteristics (Bilenca et al. 2002, 2003; Alizon et al. 2003). Although there have been some experimental reports on optical behavior of quantum dash structures, a comprehensive theoretical analysis of the properties of quantum dash is still lacking.

This paper addresses the nature of the absorption spectra from a family of InAs/InP QDHs for various depths and the standard deviation of the depth. The theoretical formulation is developed by considering the InAs/InP QDH as a quantum box (QB) characterized by a rectangular base and a finite potential at the barrier (Kabi et al. 2011). We have studied different sets of QDH when the base length remains constant for various values of the relative standard deviation of the dash. The depth is considered to have a Gaussian distribution about the average dash depth. All the necessary formulations are presented and our analytical results for optical data of QDHs have been compared with the reported experimental observations. Computed results obtained from our formulation show excellent agreement with the experimental data.

Model development

A quantum dot is formed when a higher band gap material surrounds a lower band gap material. The resonance energy of a realistic quantum dash having finite potential barriers can be defined as the photon energy needed for the creation of an electron–hole pair, which may be expressed as

$$\hbar\omega_{\mathrm{real}} = E_g + E_e(l^2, m^2, n^2) + E_h(l^2, m^2, n^2), \quad (1)$$

where E_g is the band gap of the low band gap semiconductor material and l, m and n are all positive integers. E_e (l^2, m^2, n^2) and E_h (l^2, m^2, n^2) are the confinement energies of the electron and hole (in units of $\hbar^2/mL^2$) for a finite 3D rectangular well, respectively, as given by the following equations (Kabi et al. 2011):

$$E_e(n^2) = \frac{2P_e^2}{(P_e+1)^2} \times \left[\left(\frac{n\pi}{2}\right)^2 - \frac{1}{3(P_e+1)^3}\left(\frac{n\pi}{2}\right)^4 - \frac{27P_e-8}{180(P_e+1)^6}\left(\frac{n\pi}{2}\right)^6\right] \quad (2)$$

and

$$E_h(n^2) = \frac{2P_h^2}{(P_h+1)^2} \times \left[\left(\frac{n\pi}{2}\right)^2 - \frac{1}{3(P_h+1)^3}\left(\frac{n\pi}{2}\right)^4 - \frac{27P_h-8}{180(P_h+1)^6}\left(\frac{n\pi}{2}\right)^6\right] \quad (3)$$

The lowest state corresponds to $(l^2, m^2, n^2) = (1, 1, 1)$. E_e (l^2, m^2, n^2) and E_h (l^2, m^2, n^2) incorporate the well strength parameters. P_e and P_h are defined as $P_e = \left(\sqrt{2m_0 m_e^* V_0}\right)\frac{L}{2\hbar}$ and $P_h = \left(\sqrt{2m_0 m_h^* V_0}\right)\frac{L}{2\hbar}$, where V_0 is the height of the well (conduction/valance band) and L is the well width. m_0, m_e^* and m_h^* are the rest mass and effective masses of electrons and holes, respectively.

The optical absorption coefficient is defined as the ratio of the energy removed from the incident beam per unit time and unit volume to the incident flux. The energy flux is interpreted as the product of the energy density and the speed of flow. Using this definition, the optical absorption coefficient of a realistic rectangular QDH with depth L and base length L_b is calculated as (Wu et al. 1987):

$$\alpha_{\mathrm{real}} = \frac{A_{\mathrm{real}}}{L_b^2 L}\sum_{(l^2,m^2,n^2)} g(l^2,m^2,n^2)\,\delta[\hbar\omega_{\mathrm{real}} - \{E_g + E_e(l^2,m^2,n^2) + E_h(l^2,m^2,n^2)\}] \quad (4)$$

The aspect ratio (γ) is defined as $\gamma = L/L_b$. $g(l^2,m^2,n^2)$ is the degeneracy of the energy level determined by the values of (l, m, n). A_{real} is a constant in terms of the momentum matrix P_n (Kabi et al. 2011). The interband absorption of a QDH is characterized by a series of discrete lines at photon energies given by Eq. (1). The absorption spectra result from the superimposition of the contribution from each individual QDH. The overall behavior of an array of QDHs is modeled by considering a Gaussian distribution of the depth L of the QDH which can be expressed as following (Wu et al. 1987):

$$P(L) = \left(\frac{1}{D}\right)\left(\frac{1}{\sqrt{2\pi}}\right)\exp\left[-\frac{(L-L_0)^2}{2D^2}\right], \quad (5)$$

where L_0 is the average depth of the QDH system and D is the standard deviation. The relative standard deviation ξ of the dash, is defined as $\xi = D/L_0$.

$$P(L) = \frac{1}{\xi L_0} \times \frac{1}{\sqrt{2\pi}}\exp\left[-\left(\frac{L}{L_0} - 1\right)^2 / 2\xi^2\right] \quad (6)$$

Combining Eqs. (4) and (6), the total absorption spectra of an ideal QDH system due to the non uniform dot size distribution is expressed as

$$\alpha_{\text{real}} = \frac{\gamma^2 A_{\text{real}}}{\xi L_0} \times \frac{1}{\sqrt{2\pi}} \sum_{(l^2,m^2,n^2)} g(l^2,m^2,n^2) \times \int_0^{\infty} \frac{1}{L^3} e^{-(\frac{L}{L_0}-1)^2/2\xi^2} \times \delta[\hbar\omega_{\text{real}} - \{E_g + E_e(l^2,m^2,n^2) + E_h(l^2,m^2,n^2)\}]\mathrm{d}L \quad (7)$$

Using the properties of Dirac delta function, the relative absorption co-efficient is calculated as (Kabi et al. 2011)

$$\alpha_r = \frac{\alpha_{\text{real}}}{\beta_{\text{real}}} = \frac{\gamma^2}{\xi} \times \frac{\pi^2\hbar^2}{\mu L_0} \sum_{(l^2,m^2,n^2)} g(l^2,m^2,n^2) \times \sum_{i=1}^{N} \frac{\frac{1}{L_r^3} e^{-(\frac{L_r}{L_0}-1)^2/2\xi^2}}{\left|[\hbar\omega_{\text{real}} - (E_g + E_e(l^2,m^2,n^2) + E_h(l^2,m^2,n^2))]'\right|_{L=L_r}} \quad (8)$$

where L_r is the root of the function $g(L) = \hbar\omega_{\text{real}} - \{E_g + E_e(l^2,m^2,n^2) + E_h(l^2,m^2,n^2)\} = 0$, and μ is the reduced mass of the system (Kabi et al. 2011). Here "i" ranges from 1 to the total number of roots N.

Results and discussion

The computed results of the absorption spectra for InAs/InP QDH systems are shown in Figs. 1 and 2. In our calculations the, band gap of InAs ($E_{g,\ \text{InAS}}$) and InP ($E_{g,\ \text{InP}}$) were considered to be 0.354 and 1.344 eV, respectively. The effective masses of electrons and heavy holes are assumed to be 0.027 m_0 and 0.4 m_0 for InAs, respectively. The band offset ratio, i.e.,Δ E_C:ΔE_V of InAs/InP system used in our calculation is 60:40.

It is worthwhile to mention that the excitonic effect is ignored in our theoretical model for the computation of transition energies. Several studies on QD structures (Koh et al. 2001; Heitz et al. 2000) reported the excitonic binding energy in the range 10–20 meV. Hence, the energy

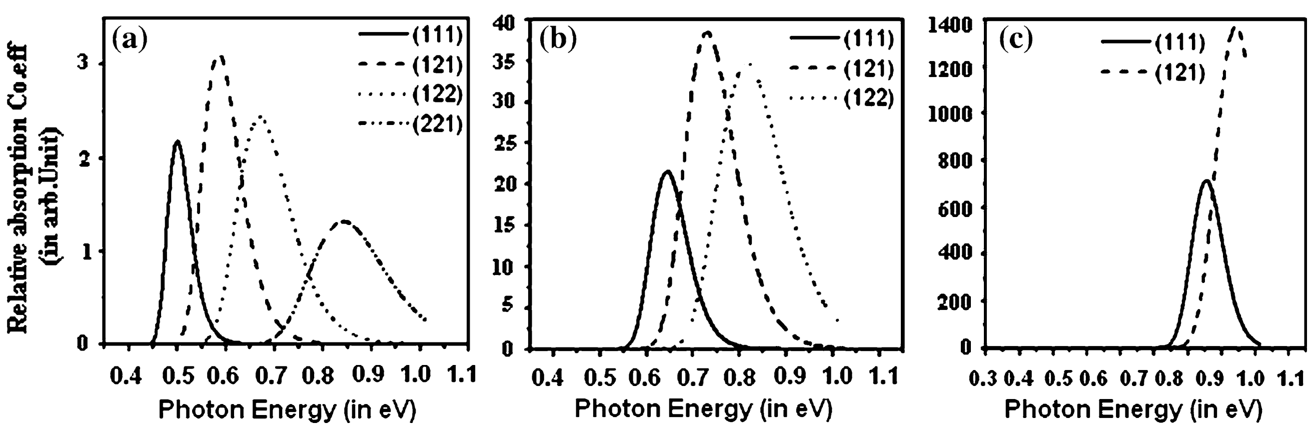

Fig. 1 Absorption spectra of the lowest four possible transitions for InAs/InP QDH systems with base length 20 nm and three different average dash depths **a** 10 nm, **b** 5 nm and **c** 2 nm. The corresponding transition states (*l*, *m*, *n*) are indicated in the *inset*

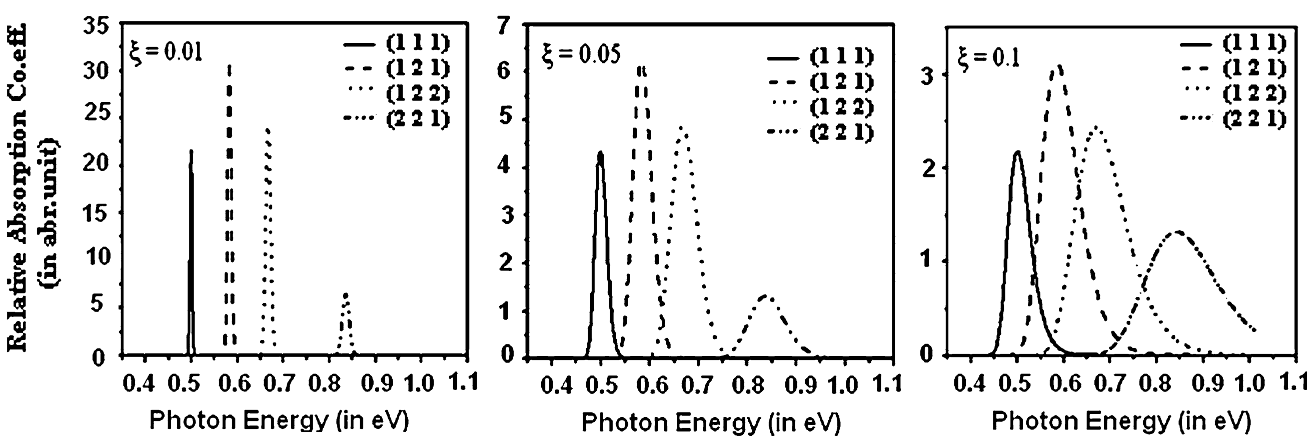

Fig. 2 Absorption spectra of the lowest four possible transitions for InAs/InP QDH systems of base length 20 nm and average dash depth 10 nm for three different relative standard deviations (ξ). The corresponding transition states (*l*, *m*, *n*) are shown in the *inset*

shift due to the excitonic effect would be insignificant for Qdash structures. As a result, our model for QDH systems without considering excitonic effect yields fairly accurate results for the calculation of different energy levels and corresponding transition probabilities. In fact, the entire spectrum will be shifted by a few meV which might introduce a marginal error in our theoretical predictions.

The vertical and horizontal axes in Fig. 1 denote the relative absorption co-efficient of real InAs/InP QDH systems and the photon energy $\hbar\omega_{\mathrm{real}}$, respectively. The absorption spectra for different quantum states of an array of InAs/InP QDH systems are demonstrated in Fig. 1a–c for three different values of the depth of QDH, such as 2, 5 and 10 nm. It is worth mentioning that second (1, 2, 1) and third transitions (1, 2, 2) are doubly degenerate as may be found from the degeneracy factor $g(l^2, m^2, n^2)$, while first and fourth transitions are singly degenerate. In these computations, the base of the QBs and relative standard deviation ξ are kept constant at 20 nm and 0.1, respectively. It is observed from the figure that as the depth of the dash decreases the absorption peak energy shifts to the higher energy, i.e., there is a blue shift in the energy. Further, the number of higher order transitions also decreases with decreasing dash depth. The intensity of the absorption peak attains a quite high value for a lower depth as compared to that for a higher depth due to the presence of degeneracy factor $g(l^2, m^2, n^2)$ as may be observed from Eq. (8). Figure 2 shows four absorption peaks for InAs/InP QDH systems corresponding to four lower quantum transitions states with $\xi = 0.1$, 0.05 and 0.01, the average dash depth of 10 nm, and the aspect ratio $\gamma = 2$. Notably from Fig. 2, one can easily observe that as the value of ξ decreases the linewidth of the absorption spectra decreases. Most interestingly, homogenous growth of QDH yields an extremely small ξ, which results in the spectra as a series of Dirac delta functions. We compared our theoretically calculated results with the reported experimental results in order to evaluate the margin of accuracy of our model. Reithmaier et al. (2007) reported measured absorption spectrum for five different samples of InAs/InP QDH systems. We have computed the optical transition peak energies for two samples, which show very close match with the reported results with an average error of 1.2 and 2 %, respectively.

Conclusion

In conclusion, the paper reports a model for computation of optical transitions and absorption spectra of InAs/InP shallow quantum dashes which have square bases and the Gaussian variation of the depth. Our theoretical investigations reveal that the peak of the absorption spectra of quantum dash systems can be shifted over an energy range by varying the depth of the dash, while the line width and height of the spectrum are influenced by the relative standard deviation of the dash. By the proper choice of the base length and the standard deviation of the depth of quantum dash, it is possible to adjust the position and height of the absorption peak.

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