

EFFECTS OF GEOMETRICAL SIZE ON THE INTERBAND LIGHT ABSORPTION A QUANTUM DOT SUPERLATTICE

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We study in this paper the direct interband transitions in a quantum dot superlattice system. We obtain the analytical expressions for the light interband absorption coefficient and threshold frequency of absorption as the functions of geometrical size of quantum dot superlattice system. According to the results obtained from the present work, we find that the absorption threshold frequency decreases when the size of quantum dot superlattice increases.

Keywords: Absorption coefficient, interband transition, quantum wells, quantum wires, quantum dots, superlattices, quantum dot superlattice.

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Over the last decades, there has been considerable interest in low-dimensional semiconductor systems in which the electron motion is strongly confined such as quantum wires, quantum dots, etc. Low-dimensional semiconductor structures include quantum wells, quantum wires, quantum dots, superlattices, and so on. Since in the systems one, two or three of the dimensions become of the order of the de Broglie wavelength for electrons, new quantum effects are expected [1].

Low-dimensional semiconductor structures, particularly quantum dots are attracting considerable attention recently, in part, because they exhibit novel physical properties and also with potential and real applications in many electronic and optoelectronic devices. In the last decades, a modern technologies, in particular such as Stranski-Krastanov epitaxial method have been developed to grow a wide variety of quantum dots structures having different geometries (spherical, parabolic, cylindrical and rectangular) and potentials (parabolic potential model, the square well model) [2-4].

Recent interest to semiconductor quantum dots is conditioned by new physical properties of these zero dimensional objects, which are conditioned by size-quantization effect of the charge carriers [5-7]. The presence of size quantization in all three directions makes the energy spectrum of charge carriers and strongly dependent on the geometry and linear dimensions of the sample [3]. It is clear that the more geometrical parameters characterize quantum dot, the more exibly one can control its energy spectrum. The subject of quantum dots as low-dimensional quantum systems has been the focus of extensive theoretical investigations. Much effort has recently been done in understanding their electronic, optical and magnetic properties.

In the last few yeas there has been considerable theoretical and experimental study has been carried out on the electronic and optical properties of multiple quantum well heterostructures. The central motivation of such studies has been the possible applications of these systems in optoelectronic devices. Growth

techniques, such as molecular-beam epitaxial and metal-organic chemical vapor deposition, have made possible the fabrication of highly pure structures with abrupt interfaces, allowing for the tailoring of the electronic structure to suit almost any need. An interesting example is the variably spaced semiconductor superlattice [8].

Quantum dot superlattices are hence expected to display radically different non-equilibrium transport properties than quantum well superlattices. Potential applications for high performance thermoelectric converters [9], photovoltaics[10], and quantum cascade lasers [11] further motivates the fundamental understanding of the nonequilibrium transport properties of superlattices with 3D quantum confinement.

Quantum dot superlattice structures, which have a delta-function distribution of density of states and discrete energy levels due to three-dimensional quantum confinement, a potentially more favorable carrier scattering mechanism, and a much lower lattice thermal conductivity, provide the potential for better thermoelectric devices [12].

As we know, the study of the optical properties of low-dimensional semiconductor structures is important, not only to know, but also in the fabrication and subsequent working of electronic and optical devices based on such systems. There are many theoretical and experimental works on the optical properties of nanostructures such as quantum dots, quantum wires, and quantum wells [13-21]. The optical properties of low-dimensional semiconductor systems are especially useful in giving detailed information about their microscopic physics. One of the interesting optical properties is the light interband absorption coefficient. The spectroscopy of optical transitions across the band gap (interband transitions) is a powerful and versatile method to study the electronic structure of semiconductors. The optical properties of quantum dot for the first time were considered by Efros and Efros [4] at theoretical investigation of direct light absorption in spherical quantum dot with indefinitely high walls. Andreev and

Lipovskii [22] discussed the influence of anisotropy of band structure on optical transitions in spherical quantum dots.

Even though considerable attention has been given to the study of the light interband absorption of the semiconductor quantum dots superlattice structures.

The light interband absorption of quantum dot superlattice structures has not been investigated so far. In the present work, we study the interband light absorption in a quantum dot superlattice structures. We obtain the light interband absorption coefficient and show dependencies of the absorption threshold frequency and on geometrical size of quantum dot superlattice structures.

The interband absorption in a quantum dot superlattice with a periodic potential $U(z)$ of period d

$$H = \frac{(p_x^2 + p_y^2)}{2m^*} + \frac{m^*}{2}(\omega_x^2 x^2 + \omega_y^2 y^2) + \frac{\Delta}{2}(1 - \cos \frac{p_z d}{\hbar}), \quad (2)$$

where Δ is the miniband width. The electron effective mass $m^* = m_e$, when the conduction band is considered; and $m^* = m_h$ when the valence band is considered, where m_h is the effective mass of the hole.

along the z-direction of the harmonic oscillator form is considered:

$$V(x, y) = \frac{m^*}{2}(\omega_x^2 x^2 + \omega_y^2 y^2), \quad (1)$$

where m^* is the effective mass, ω_x and ω_y are the confinement frequencies in the x- and y-directions, respectively. Harmonic oscillator belongs to the most important and most commonly used physical models. Due to the formal simplicity, it is considered as one of the exactly solvable quantum mechanical problems. It is used to model a wide variety of phenomena ranging from molecular vibrations to the behaviour of quantized fields [23]. In the strong-coupling approximation, the Hamiltonian for charge carriers in a quantum dot superlattice can be written as [24, 25]:

The normalized eigenwave functions of the electron $\Psi_{n,e,k_z}(r)$ and the eigenvalues of the energy $E_{n,l}(k_z)$ in the conduction band are set, respectively, in the form [26]:

$$\Psi_{n,l,k_z}(r) = \frac{1}{\sqrt{L_z}} \Psi_n(x) \Psi_l(y) \xi_{k_z}(z), \quad (3)$$

$$E_{n,l}(k_z) = (n + \frac{1}{2})\hbar\omega_x + (l + \frac{1}{2})\hbar\omega_y + \frac{\Delta}{2}(1 - \cos k_z d) = \varepsilon_{n,l} + \varepsilon(k_z), \quad (4)$$

where $n(=0,1,2,\dots)$ and $l(=0,1,2,\dots)$ are the level indices of the electronic subbands, k_z is the component of the wave vector in the z-direction, $\Psi_n(x)$, $\Psi_l(y)$ are the eigenwave functions of the harmonic oscillator, $H_n(x)$, $H_l(y)$ is the Hermite polynomial, $l_x = \sqrt{\hbar/(m^*\omega_x)}$, $l_y = \sqrt{\hbar/(m^*\omega_y)}$,

$\xi_{k_z}(z)$ is the Bloch function in the approximation of strong coupling in the z-direction, and L_z is the normalized length in the direction.

The eigenwave functions of the harmonic oscillator for the conduction band are set,

$$\Psi_{n_e} \left(\frac{x}{l_{xe}} \right) = \sqrt{1/\sqrt{\pi} l_{xe} 2^{n_e} n_e!} \exp[-x^2/2l_{xe}^2] H_{n_e} \left(\frac{x}{l_{xe}} \right) \quad (5)$$

$$\psi_{l_e} \left(\frac{y}{l_{ye}} \right) = \sqrt{1/\sqrt{\pi} l_{ye} 2^{l_e} l_e!} \exp[-y^2/2l_{ye}^2] H_{l_e} \left(\frac{y}{l_{ye}} \right) \quad (6)$$

The eigenwave functions of the harmonic oscillator for the valence -band can be expressed as

$$\Psi_{n_h} \left(\frac{x}{l_{xh}} \right) = \sqrt{1/\sqrt{\pi} l_{xh} 2^{n_h} n_h!} \exp[-x^2/2l_{xh}^2] H_{n_h} \left(\frac{x}{l_{xh}} \right) \quad (7)$$

$$\psi_{l_h} \left(\frac{y}{l_{yh}} \right) = \sqrt{1/\sqrt{\pi} l_{yh} 2^{l_h} l_h!} \exp[-y^2/2l_{yh}^2] H_{l_h} \left(\frac{y}{l_{yh}} \right) \quad (8)$$

Expressions Eqs (3) - (8) show the charge carriers energy spectrum and wave functions in quantum dot superlattice system. These relations allow to calculate the direct interband light absorption coefficient in quantum dot superlattice system.

Since in the future we will consider transitions in the quantum dot superlattice, where instead of

quasicontinuous bands of the energy spectrum we have a set of discrete energy values, it follows that after integration, we should proceed to summation over quantum numbers. As a result, the equation for the absorption coefficient of a quantum dot superlattice can be expressed by [4]:

$$K(\Omega) = A_0 \sum_{v,v'} \left| \int_V \psi_v^e \psi_{v'}^h dV \right|^2 \delta[\hbar\Omega - E_g - E_v^e - E_{v'}^h] \quad (9)$$

where A_0 is the quantity proportional to the square of dipole moment matrix element modulus, taken on Bloch functions.

The $\sum_{v,v'} \left| \int_V \psi_v^e \psi_{v'}^h dV \right|^2$ can be obtained using following expressions

$$J_{n_e n_h} = \int_{-\infty}^{\infty} \Psi_{n_e} \left(\frac{x_e}{l_{ye}} \right) \Psi_{n_h} \left(\frac{x_h}{l_{yh}} \right) dx \quad (10)$$

$$J_{l_e l_h} = \int_{-\infty}^{\infty} \Psi_{l_e} \left(\frac{y_e}{l_{ye}} \right) \Psi_{l_h} \left(\frac{y_h}{l_{yh}} \right) dy \quad (11)$$

where $J_{n_e n_h}$ and $J_{l_e l_h}$ are overlap integrals between the valence and conduction bands.

From Eqs.(9)-(10) it follows that quantum numbers n_e, n_h can change arbitrarily. The argument of the Dirac δ -function allows to define the threshold frequency of absorption Ω_{00} .

CONCLUSION

In this work, we have studied the direct interband transitions quantum dot superlattice. We obtained the analytical expressions for the light interband absorption coefficient and threshold frequency of absorption geometrical size of quantum dot superlattice. We studied the dependence of absorption threshold frequency on quantum dot superlattice size. According to the results obtained from the present work, it is deduced that the quantum dot superlattice size play important roles in the absorption threshold frequency.

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- [1] *M.J. Kearny and P.N. Butcher.* Journal of Physics C: Solid State Physics, 1987, Volume 20, Number 147.
- [2] *Z.I. Alferov.* Semiconductors. The history and future of semiconductor heterostructures, Fiz. Tekh. Poluprovodn. 32, 1–18 (January 1998).
- [3] *D.D. Bimberg, M. Grundmann, and N.N. Ledentsov.* Quantum Dot Heterostructures, Wiley, Chichester, 1999.
- [4] *A.L. Efros and A.L. Efros.* "Interband absorption of light in a semiconductor sphere", Semiconductors 16 (7), 772–775, 1982.
- [5] *P. Harrison, Quantum Wells, Wires and Dots.* Theoretical and Computational Physics (John Wiley & Sons Ltd, NY, 2005).
- [6] *G. Bastard.* Wave Mechanics Applied to Semiconductor Heterostructures (Les editions de physique, Les Ulis Cedex, Paris, 1989).
- [7] *M. Bayer, O. Stern, P. Hawrylak, S. Fafard, A. Forchel.* Hidden symmetries in the energy levels of excitonic 'artificial atoms', 2000, Nature 405, 923.
- [8] *J.N. Zuleta, E. Reyes-Gómez.* Effects of crossed electric and magnetic fields on the interband optical absorption spectra of variably spaced semiconductor superlattices. Physica B 2016, <http://dx.doi.org/10.1016/j.physb.2016.02.011>
- [9] *Y.M. Lin and M.S. Dresselhaus.* Thermoelectric properties of superlattice nanowires, Phys. Rev. B 68, 075304, 2003.
- [10] *A. Nozik.* Quantum dot solar cells, Physica E 14, 115, 2002.
- [11] *N. Wingreen and C. Stafford.* Quantum-dot cascade laser: proposal for an ultralow-threshold semiconductor laser, IEEE J. Quantum Electron. 33, 1170, 1997.
- [12] *T.C. Harman, P.J. Taylor, M.P. Walsh, B.E. La Forge.* Quantum Dot Superlattice Thermoelectric Materials and Devices. Science 297, 2002, p. 2229-2232.
- [13] *R. Khordad.* Effects of magnetic field and geometrical size on the interband light absorption in a quantum pseudodot system Solid State Sciences 12, 2010, 1253-1256.
- [14] *G.B. Ibragimov.* Free - Carrier Absorption in Quantum Well Structures for Alloy - Disorder Scattering Physica Status Solidi B v.231, Issue2 June 2002 Pp. 589-594.
- [15] *G.B. Ibragimov.* Interface roughness induced intrasubband scattering in a quantum well under an electric field Semiconductor Physics Quantum Electronics & Optoelectronics, 2002, tom 5, № 1. — C. 39-41.
- [16] *V.V. Karpunin, V.A. Margulis.* Absorption of the electromagnetic radiation in quantum wire with a anisotropic parabolic potential placed in the

- transverse magnetic field. FTP 50, 6, 2016, pp. 785-790.
- [17] A.V. Shorokhov, V.A. Margulis. Intraband resonance scattering of electromagnetic radiation in anisotropic quantum dots. Nanosystems: Physics, Chemistry, Mathematics, 2010, 1, 1, 178–187.
- [18] D.Q. Khoa, N.N. Hieu, T.N. Bich, Le T.T. Phuong, B.D. Hoi, Tran P.T. Linh, Quach K. Quang, C.V. Nguyen, H.V. Phuc. Magneto-optical absorption in quantum dot via two-photon absorption process. Optik, 2018, v. 173, 263-270.
- [19] V. Lozovski and V. Piatnytsia. “The analytical study of electronic and optical properties of pyramid-like and cone-like quantum dots,” J. Comput. Theor. Nanosci. 2011, 8(11), 2335–2343.
- [20] F.M. Hashimzade, T.G. Ismailov, B.H. Mehdiyev and S.T. Pavlov. Interband electron Raman scattering in a quantum wire in a transverse magnetic field Phys.Rev. 2005, B 71, 165331.
- [21] F.M. Peeters. “Magneto-optics in parabolic quantum dots,” Phys. Rev. B 42(2), 1990, 1486–1487.
- [22] A.D. Andreev, A.A. Lipovskii. Effect of anisotropy of band structure on optical gain in spherical quantum dots based on PbS and PbSe, Semiconductors 33(12), 1999, 1304–1308.
- [23] Sameer M. Ikhdair, Majid Hamzavi, Ramazan Sever. Spectra of cylindrical quantum dots: The effect of electrical and magnetic fields together with AB flux field. Physica B 407 (2012) 4523–4529.
- [24] W.M. Shu and X.L. Lei. Miniband transport in semiconductor superlattices in a quantized magnetic field. Phys. Rev. B 50, 1994, 17378.
- [25] S.C. Lee, D.S. Kang, J.D. Ko, Y.H. Yu, J.Y. Ryu and S.W. Kim. Magnetophonon Resonances in the Miniband Transport in Semiconductor Superlattices J. Korean, Phys. Soc. 39, 2001, 643.
- [26] S.C. Lee. Electrophonon Resonance in Quantum-Dot Superlattices J. of Korean Phys. Soc, 52, 2008, 1081.

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