Oscillator Strength of Gaussian Double Quantum Well for Intersubband Transition

Debasmita Sarkar and Arpan Deyasi

Abstract Oscillator strength and absorption cross-section of Double quantum well triple barrier structure with Gaussian geometry is analytically computed for intersubband optical transition between ground state and first excited state. Electric field is applied along quantum confinement, and Kane-type conduction band nonparabolicity of first order is considered for near accurate computation. Result suggests that oscillator strength monotonically increases with wavelength, and is higher when nonparabolicity factor is considered. Cross-section is higher for lower well dimension. Result is also compared with parabolic overestimation. Simulated findings are important for designing optical detector.

1 Introduction

Emerging nanophotonic devices becomes one of the field of research in last decade due to various novel applications in medical [1], defense [2] or communication [3] arena. As far the application is concerned, the fundamental property of the nanostructure that needs to be evaluated is the eigenstate, which is the function of device dimension [4, 5] and material composition [6]. Solution of eigenstates for complex geometrical structures are very difficult by existing analytical method and thus different numerical methods are incorporated by theoretical researchers [7–9] for near accurate composition. In this connection, consideration of band structure of the device plays crucial role in determining energy state [10], and thus band nonparabolicity factor should be considered in mathematical analysis. Photonic properties of quantum heterostructures are heavily dependent on the eigenenergies.

D. Sarkar (✉) · A. Deyasi
Department of Electronics and Communication Engineering,
RCC Institute of Information Technology, Kolkata, West Bengal 700015, India
e-mail: sarkar.debasmita100@gmail.com

A. Deyasi
e-mail: deyasi_arpan@yahoo.co.in

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In low-dimensional semiconductor structure, quantization of energy states makes them characteristically different from existing bulk devices and transition in inter and intra level controls their electronic and optoelectronic properties. Oscillator strength is such a parameter which speaks the probability of transition between any two quantized energy levels, and thus its near accurate determination plays crucial role for application of the device in precise field. Absorption cross-section determines the area of the device required for photodetector application. The first one is determined form the absorption coefficient, and the later is dependent on the former. Thus computation of absorption coefficient and photoluminescence study becomes important for theoretical research in the point of view of device design. Oscillator strength for quantum wire [11–13] is already calculated for field-induced transition, and also for quantum dot [14, 15]. Absorption cross-section is also calculated for wire [13] and dot [16].

Present paper deals with the computation of oscillator strength of Gaussian double quantum well in presence of field with the consideration of Kane-type band nonparabolicity. Corresponding absorption cross-section is also calculated for different structural parameters. Results are important for the structure for optical detector application.

2 Mathematical Modeling

Absorption coefficient for a quantum well structure may be put in the following form

$$\alpha(\omega) = \frac{n_s \pi q^2 \hbar}{2\varepsilon_0 \varepsilon_r c n_r m^* L} f_{21} \delta(\Delta E - \hbar\omega) \tag{1}$$

where L is the length of quantum well, n_s is the sheet charge density, f_{21} is defined as the oscillator strength for the transition between ground state and 1st excited state. f_{21} is given by

$$f_{21} = \frac{2}{m^* \hbar \omega} \left[\frac{8\hbar}{3L}\right]^2 \tag{2}$$

For practical profile, the delta function is replaced by Lorentzian lineshape function, which modifies (1) as

$$\alpha(\omega) = \frac{n_s \pi q^2 \hbar}{2\varepsilon_0 \varepsilon_r c n_r m^* L} f_{21} \frac{\Gamma}{\pi\left[(\hbar\omega - \Delta E)^2 + \Gamma^2\right]} \tag{3}$$

where ΔE is the intersubband transition energy, Γ is the full-width at half-maximum.

Once oscillator strength is calculated, absorption cross-section may be defined as

$$\sigma_{2,1} = \frac{q^2 T}{2\varepsilon_0 m^* nc} f_{21} \left[1 + T^2 \left(\frac{E - \Delta E_{2,1}}{\hbar} \right)^2 \right]^{-1} \tag{4}$$

where T is the relaxation time.

3 Results and Discussions

Using (3) and (4), oscillator strength and absorption cross-section of double quantum well structure are computed and plotted as a function of wavelength and energy respectively. Figure 1 shows the variation of oscillator strength with wavelength for DQW structure. In Fig. 1a (in left), it is seen that oscillator strength monotonically increases with wavelength. Also with increase of well width, oscillator strength decreases. This can be directly predicted from (2). This can be explained as follows: higher well width reduces quantum confinement, which, in turn, lowers eigenenergies. This reduces the separation between energy values, so oscillator strength decreases. In Fig. 1b (in right), comparative study is made with the results obtained for parabolic overestimation, which shows that consideration of band nonparabolicity gives higher magnitude of oscillator strength for a given structural parameters with constant electric field. This speaks in favor of higher transition probability when accurate band structure is considered in modeling.

Figure 2 shows the absorption cross-section of the structure as a function of incident radiation for different well widths. It is seen form the plot that peak position of cross-section remains invariant w.r.t well dimension. But height of the profile increases as well layer width decreases. This is due to the fact that with

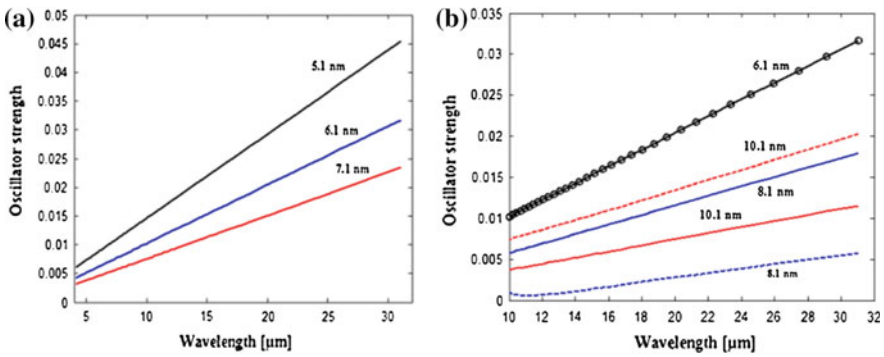

Fig. 1 **a** Oscillator strength with wavelength for different well widths for nonparabolic dispersion relation in presence of electric field; **b** Oscillator strength with wavelength for parabolic and nonparabolic dispersion relations in presence of electric field

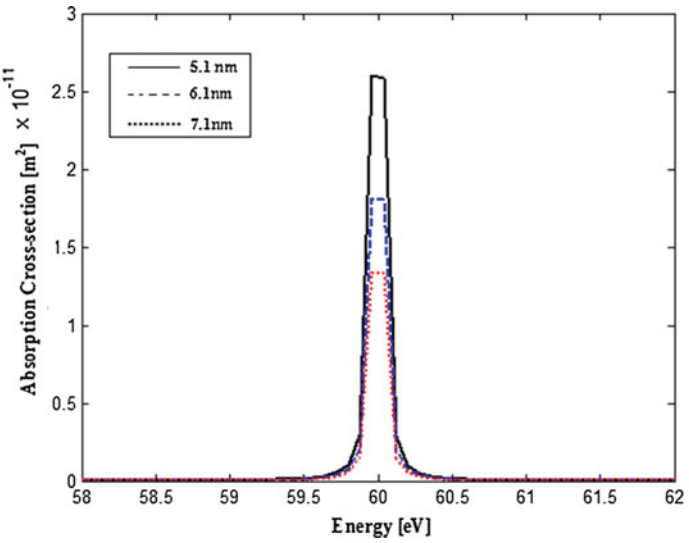

Fig. 2 Absorption cross-section with incident radiation for different well widths

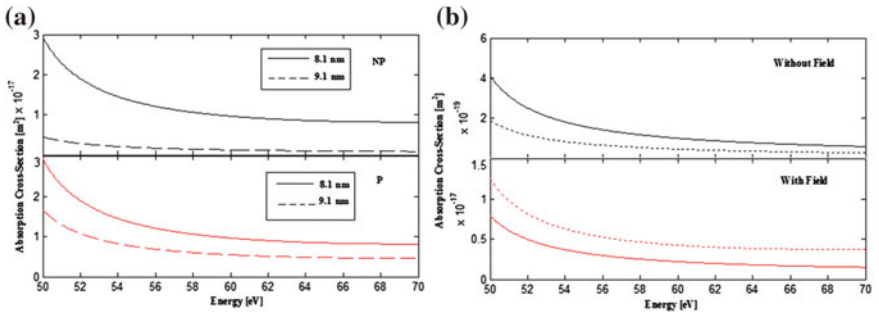

Fig. 3 Absorption cross-section with incident radiation for (a) different dispersion relations; (b) in presence and absence of electric field

increase of well width, quantum confinement decreases, hence oscillator strength decreases. The quantity absorption cross-section, is directly proportional to absorption coefficient, and inversely related with well dimension. Hence it reduces for higher well width.

Figure 3a and 3b exhibits the variation of absorption cross-section with incident energy. Figure 3a shows the variation for different dispersion relations, whereas Fig. 3b studied the same in presence and absence of electric field. It has been observed that effect of field reduces cross-section. This is due to the fact that electric field lowers the eigenstate of the device, and hence subband transition energy reduces. This reduces the absorption cross-section. Similarly, band nonparabolicity

factor reduces eigenstate, more precisely it affects the higher quantum state. If Kane-type nonparabolicity is considered, then computation already revealed that eigenvalue is reduced compared to that calculated for parabolic band structure. The change is more significant for higher energy values. Thus lowermost curve of cross-section gets affected compared to the plots generated for lowermost transition energy.

4 Conclusion

Oscillator strength and absorption cross-section of a double quantum well system is analytically computed using the knowledge on eigenstates. Result suggests that cross-section decreases with increasing well width, and it is more significant when band nonparabolicity is considered for thicker well layer. Application of electric field along the quantized direction reduces the cross-section. The same nature is also exhibited for oscillator strength. Results are important for optoelectronic application of the structure, more precisely for designing of quantum detector.

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