Optical response of quantum dot multilayer structures

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Abstract. We theoretically study optical response of *InAs/GaAs* quantum dot multilayered structures. Based on the multi-scale hybrid discrete-continuum description the optical response of an isolated layer of embedded quantum dots has been determined. Using the propagation-matrix approach we express the amplitudes of incident, reflected and transmitted electromagnetic waves in a multilayered structure by the reflection and transmission coefficients of the isolated layers. We study the overall reflectance and transmittance dependencies on the number of layers and distance between consecutive layers. The increase of the number of the layers considerably enhances the overall reflectance of the structures. Interference effects become significant for certain distances between layers in the structures.

1. Introduction

In the past years progress in modern technology makes it possible to fabricate semiconductor nano objects such as quantum dots within wide ranges of shapes and sizes. Those nano objects become very promising elements in constructing small building blocks for integrated photonics and nano-structured metamaterials [1,2,3]. Generally the metamaterials are designed as artificial multilayered structures. Optics of isolated layers of semiconductor quantum dots, quantum rings and quantum dot molecules was studied in details recently (see [4,5,6] and references therein). Therefore a proper modeling of the optical response from multilayered structures is on demand. In this study we performed simulations of multilayered structures made from *InAs* lens-shaped quantum dots embedded in infinite *GaAs* matrix. In our model each layer is characterized by the reflection and transmission coefficients obtained in [5, 6]. Based on the propagation-matrix approach [7] the overall reflection and transmission coefficients of multilayered structures are derived. We study the overall optical coefficients as functions on the optical transition's energy and distance between consecutive layers.

2. Theoretical approach

The structure to be investigated consists of consecutive layers of quantum dots composed of *InAs/GaAs* with interlayer distance d, (as it is shown in figure 1). In our consideration the electromagnetic plane wave is incident to the first layer, propagates through the structure and emerges at the last layer. We assume that the consecutive incident angles of the wave on each layer are identical. Therefore all layers in the multilayered structure are described by the same reflection and transmission coefficients. Using the propagation-matrix approach [7] for the following amplitudes of the incident (A_i, A_{i+1}) and reflected (B_i, B_{i+1}) waves at ith and (i +1)th layers we can write

$$\begin{pmatrix} A_i \\ B_i \end{pmatrix} = P_i \begin{pmatrix} A_{i+1} \\ B_{i+1} \end{pmatrix} \tag{1}$$

The propagation matrix P_i is commonly written as [7]

$$P_i = \frac{1}{t_i}\begin{pmatrix} e^{-i\phi_i} & r_i e^{i\phi_i} \\ r_i e^{-i\phi_i} & e^{i\phi_i} \end{pmatrix}$$

where r_i and t_i present the reflection and transmission coefficients of the ith layer respectively, $\phi_i = ik_z d$, k_z is the perpendicular to the layer component of the wave vector $k = n\omega/c$ (n is the semiconductor matrix refractive index, ω is the wave frequency, and c is the light speed in the vacuum).

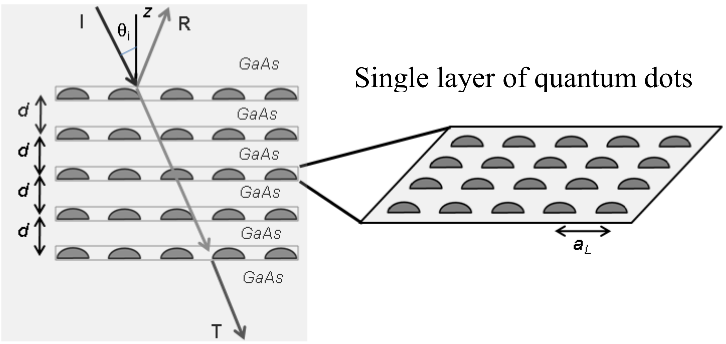

Figure 1. Scheme of the quantum dot multilayer structure.

By iteratively carrying out equation (1) we can obtain the overall propagation matrix P which connects the amplitudes of the incident, reflected and transmitted waves for the structure of finite number of layers N:

$$\begin{pmatrix} E_0 \\ rE_0 \end{pmatrix} = \begin{pmatrix} P_{11} & P_{12} \\ P_{21} & P_{22} \end{pmatrix} \bullet \begin{pmatrix} tE_0 \\ 0 \end{pmatrix} \tag{2}$$

where E_0 is amplitude of incident wave at the first layer, r and t are the total reflection and transmission coefficients, respectively. From (2) we obtain the reflectance and transmittance of the multilayered structure:

$$R = |r|^2 = \left|\frac{P_{21}}{P_{11}}\right|^2, T = |t|^2 = \left|\frac{1}{P_{11}}\right|^2 \tag{3}$$

To simulate the overall optical response (reflectance and transmittance) of multilayered structures the reflection and transmission coefficients of each ith layer are required. We use the Vlieger's expressions from [8] to obtain them:

$$r_i^{(ss)} = f(A_y \cos\theta_i - f)^{-1}, t_i^{(ss)} = 1 + r_i^{(ss)},$$

$$r_i^{(pp)} = \frac{f\cos\theta_i}{A_x - f\cos\theta_i} - \frac{f\sin^2\theta_i}{A_z\cos\theta_i - f\sin^2\theta_i},$$

$$t_i^{(pp)} = \frac{f\cos\theta_i}{A_x - f\cos\theta_i} - \frac{A_z\cos\theta_i}{A_z\cos\theta_i - f\sin^2\theta_i}, \quad (4)$$

where subscripts "*ss*" and "*pp*" refer to the light polarization, θ_i is the incidence angle,

$$A_u = \alpha_0\alpha_{BE,uu}^{-1}(\omega) - \varepsilon_m^{-1}(f + \alpha_0 t_u), f = 2\pi i a_L k,$$

$$t_u = -\frac{N_u}{\varepsilon_0 V} + \frac{ik^3}{6\pi\varepsilon_0},\ \alpha_0 = 4\pi\varepsilon_0 a_L^2, \varepsilon_m = n^2.$$

In the last equations: N_u $\{u = x, y, z\}$ and V denote the depolarization factor and the volume of the quantum dot, respectively. The inter-planar transfer tensor **f** is defined for two dimensional lattice of the quantum dots as: $f_x = f_y = - f_z/2$, fz = 9.03362 [4], $\alpha_{EB,uu}(\omega)$ is the polarizability of an isolated quantum dot defined in [4, 5]. The polarizability includes the static and dynamic parts and the last one depends on the optical transition energies ($E = \hbar\omega$) [4, 5, 6].

3. Simulation results and discussion

For all numerical simulations to determine the polarizability of isolated quantum dots we use the COMSOL MultiPhysics package (www.comsol.com). We accept realistic semiconductor material parameters from [6, 9, 10]. The dimensions of a single *InAs/GaAs* lens-shaped quantum dot are taken as 2 nm in height and 15 nm in radius. The lattice constant in a layer is a_L = 100 nm. The reflection and transmission coefficients of a layer of the dots are calculated by using equation (4). Finally we used computed coefficients to simulate the overall reflectance and transmittance of multilayered structures. The reflectance of the structures including several layers for *s*-polarized light is shown in figure 2. The peaks in the reflectance relate to the allowed optical transitions in the quantum dots. Clearly, for a single layer the reflectance is weak. However the reflectance still reproduces important information on quantum mechanics of individual quantum dots.

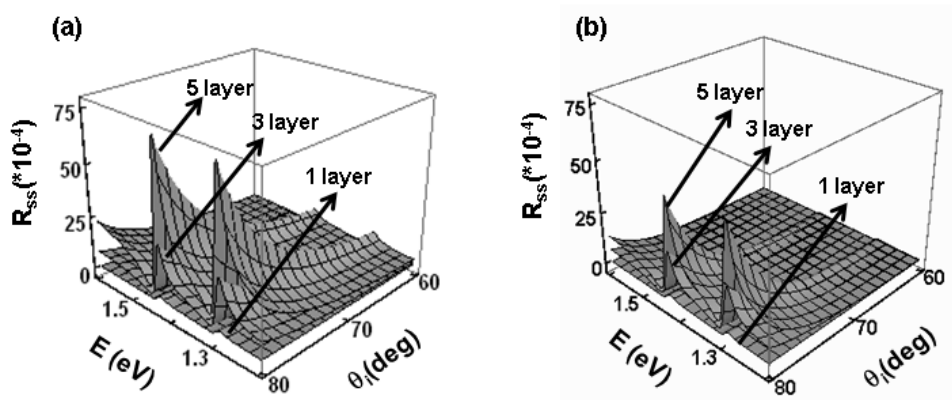

Figure 2. Reflectance of the quantum dot multilayered structures as a function on the transition energy and angle of incidence: (a) d = 10nm and (b) d = 50nm.

For structures with small *kd*, the electromagnetic wave phase change formed between consecutive layers can be neglected and no interference effects can be seen in the total reflectance. When the number of the layers in the structure increases the overall reflectance of the structure considerably enhances (see figure 2). For large enough *d* the interference becomes significant and this leads to the appearance of the periodical peaks in the reflectance. The dependence of the overall reflectance on the transition energy and distance *d* (incident angle θ_i =60^0) for the structure consisting of five layers is presented in figure 3. Clearly at some specific distances the peaks related to the allowed optical transitions in the quantum dots can be intensified or vanished because of the interference.

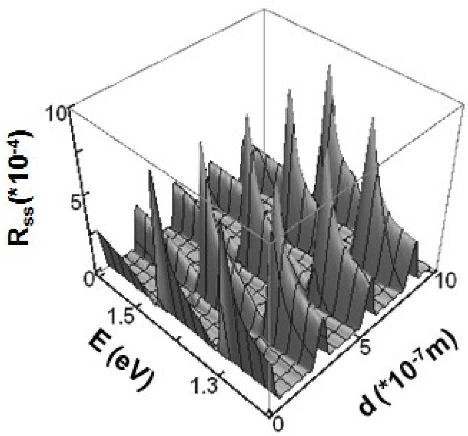

Figure 3. Reflectance of the quantum dot multilayered structure consisting of five layers as a function on the transition energy and distance between the consecutive layers.

In short conclusion, using the propagation matrix approach we theoretically study magneto-optical response of the quantum dot multilayered structures. Our simulation results show that when the distance between layers is comprehensively small the overall reflectance of the structures increases with increasing number of layers. The interference effects appear for the appropriate distances between the layers. Our approach to model semiconductor multilayered nano structures is useful for simulations optical properties of semiconductor metamaterials.

Acknowledgements
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