Photoluminescence from a quantum-dot cascade structure

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We present our theoretical studies of the luminescence spectra of a quantum cascade laser where the quantum wells in the active regions are replaced by parabolic quantum dots. In recent years there has been considerable progress in quantum-dot laser research. This is because of the discrete atom-like structure of energy levels in quantum dots. As a result of this energy structure the quantum-dot lasers are expected to have better performance than the quantum-well lasers. We study the optical properties of quantum dots cascade lasers for a finite size system by finding numerically eigenfunctions and eigenvalues of many-particle Hamiltonian with Coulomb interaction between the electrons. A typical laser structure [1], emitting at a wavelength 10.5 μm, was employed in our numerical simulations. The size (up to 20 nm) and the shape (circular or elliptic) of the quantum dots and the number of electrons (up to 9 electrons) in an active dot are varied. We also study the influence of external magnetic field on the emission spectra of quantum dot cascade structures.

Typical emission spectra of the system under consideration are shown in Fig.1 for circular quantum dot in the active region. The main outcome of our numerical simulations is the following. For smaller quantum dots the emission lines of the non-interacting system have the internal structure which is entirely due to the nonparabolicity of electron dispersion, see Fig. 1. The nonparabolicity also gives the small redshift of emission line for non-interaction electrons. For larger quantum dots there is only single line for all number of electrons of non-interaction system. Such structure of emission line is because non-parabolicity in this case becomes less important due to smaller values of quantum dot confinement energies. The electron-electron interactions result in a huge blueshift of the emission spectra compared to the results for non-interaction electrons. The blueshift becomes smaller for larger quantum dots and also decreases for elliptic dots. This is due to weaker interactions between the electrons when the in-plane spreading of the electron wave function becomes larger. The interactions between the electrons also modify the shape of the emission line. This becomes more pronounce for smaller quantum dots, see Fig. 1. For larger quantum dots the disorder makes the emission line almost single-peaked especially for larger number of electrons when the interaction between the electrons have less affect on the properties of the quantum dot system [2]. For smaller quantum dots the change of the shape of the dots changes the shape of the emission line considerably. But for larger dots the shape of the emission line is less sensitive to the shape of the quantum dots and the line has almost the single peak for both circular and elliptic dots. Although the ground state of the electron system in the initial state obeys the Hund's rule for circular dots (for number of electrons in the dot equals to 4 and 9) we did not find any singularity in emission spectra due to the electron shell filling.

We have also studied the magnetic field effect on intersubband transitions in quantum dots embedded in a quantum cascade structure subjected to a strong magnetic field applied perpendicular to the quantum dot plane [3]. One of the important observation which follows from our simulation is that at a given value of magnetic field the inter-electron interactions tend to suppress the excitation gaps. The strength of this suppression is a non-monotonic function of magnetic field.

We have found also a strong correlation between the energy and emission spectra of quantum dot structures:

(i) If the energy gap are relatively large and, as a result, has a weak dependence on magnetic field, then the emission spectra also weakly depend on the magnetic field.

(ii) A non-monotonic dependence of the maximum of the emission line on magnetic field is observed whenever the energy gap shows strong non-monotonic dependence on magnetic field.

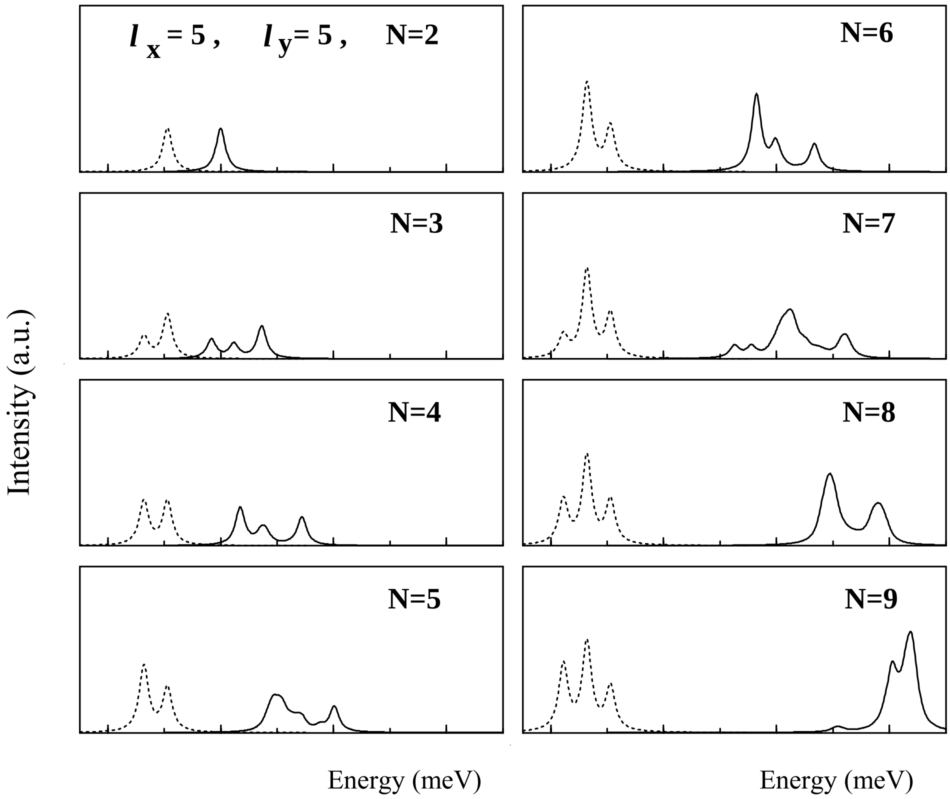

FIG. 1. Luminescence spectra of a quantum cascade laser with circular (size $l_x = l_y = 5$ nm) quantum dots containing $N = 2$ - 9 electrons in the active region. Solid and dotted lines correspond to interacting and non-interacting systems, respectively.

The correlation between the energy and emission spectra is due to the specific feature of the system under consideration. Namely, the main transitions are the transitions between the ground state of the initial system and the excited states of the final system.

Mid-IR luminescence from a cascade of coupled GaAs quantum wells and self-assembled AlInAs quantum dot layers in the active region and injection superlattices has just been reported [4].

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