Intraband optical properties of self-assembled InGaAs quantum rods and their dependence on the rod height

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A new type of self-assembled quantum-dot structures with a large height to diameter ratio, so called quantum rods (QRs) or quantum posts, have been recently experimentally realized [1]. From the application perspective, QRs may have potential advantages over quantum dots, e.g. offering a wider control of frequency and polarization sensitivity in detection of terahertz radiation. However, until recently, the difficulties in fabricating QRs have limited the investigations of their fundamental properties and potential applications in devices. Recent work shows that QRs act as efficient electron traps after optical excitation, and a capture time of a few picoseconds was determined [2], pointing to the possibility of using QRs as active elements in future unipolar optoelectronic terahertz devices.

An inportant advantage of QRs is a good controllability of their height. This is achieved by alternating deposition of very short (of the order of monolayer) layers of InAs and GaAs. Subsequent intermixing of InAs and GaAs leads to the InGaAs quantum rod with large and precise height-to-diameter aspect ratio. In this work, the eight band $\vec{k}\cdot\vec{p}$ model [3] was used in calculation of the electronic and intraband optical properties of InGaAs/GaAs cylindrical quantum rods. The eigenvalue problem of the Hamiltonian was solved using the wave function expansion method, where the basis of eigenfunctions of a particle in a cylinder with infinite walls was used [2]. It was found that the conduction band electronic structure includes states of the elongated dot and states of the surrounding well, as well hybridised states coming from the dot-well coupling. We have examined the influence of rod height on the electronic structure and on the intraband terahertz absorption and its dependence on the lattice temperature.

As an example of the results obtained, the electronic structure diagrams for rod heights of 60 nm and 10 nm are presented in Figure 1. The InAs/GaAs short-period superlattice, away from the quantum rod, becomes an InGaAs quantum well layer with In composition of 16% [1] during the growth of the structure. The In content in the quantum rod is approximately 45% [1]. Wavefunction moduli squared for a number of states are also given in Figure 1, where the cylindrical symmetry is implicit in these 2D plots in radial and growth directions. States are denoted according to the total angular momentum quantum number $m_f = 1$ and an additional good quantum number n, which account for quantization in radial and growth directions.

The transition strengths due to optical absorption in the conduction band were calculated in the dipole approximation, using Fermi golden rule. As expected, absorption of growth-polarized radiation is due to transitions between dot states or between well states with different parity. On the other hand, only transitions from dot states to well states contribute significantly to absorption of radially polarised radiation. Those transitions are restricted from states with quantum number $m_f = 1$ and $m_f = -1$ to higher states due to selection rules (Figure 1). By varying the height of the structure it is possible to tune the energy difference of all bound states (Figure 1). Energy difference between consecutive dot bound states was decreased by increasing the dot height (Figure 1). The same applies to energy spacing between consecutive well-like states with the same m_f, but belonging to different subbands (Figure 1). This affects the ordering of well and dot states (Figure 1) and also causes frequency tunability of absorption and emission, which makes space for engineering and optimization of these novel structures for THz detector applications, or even for cascade lasing structures.

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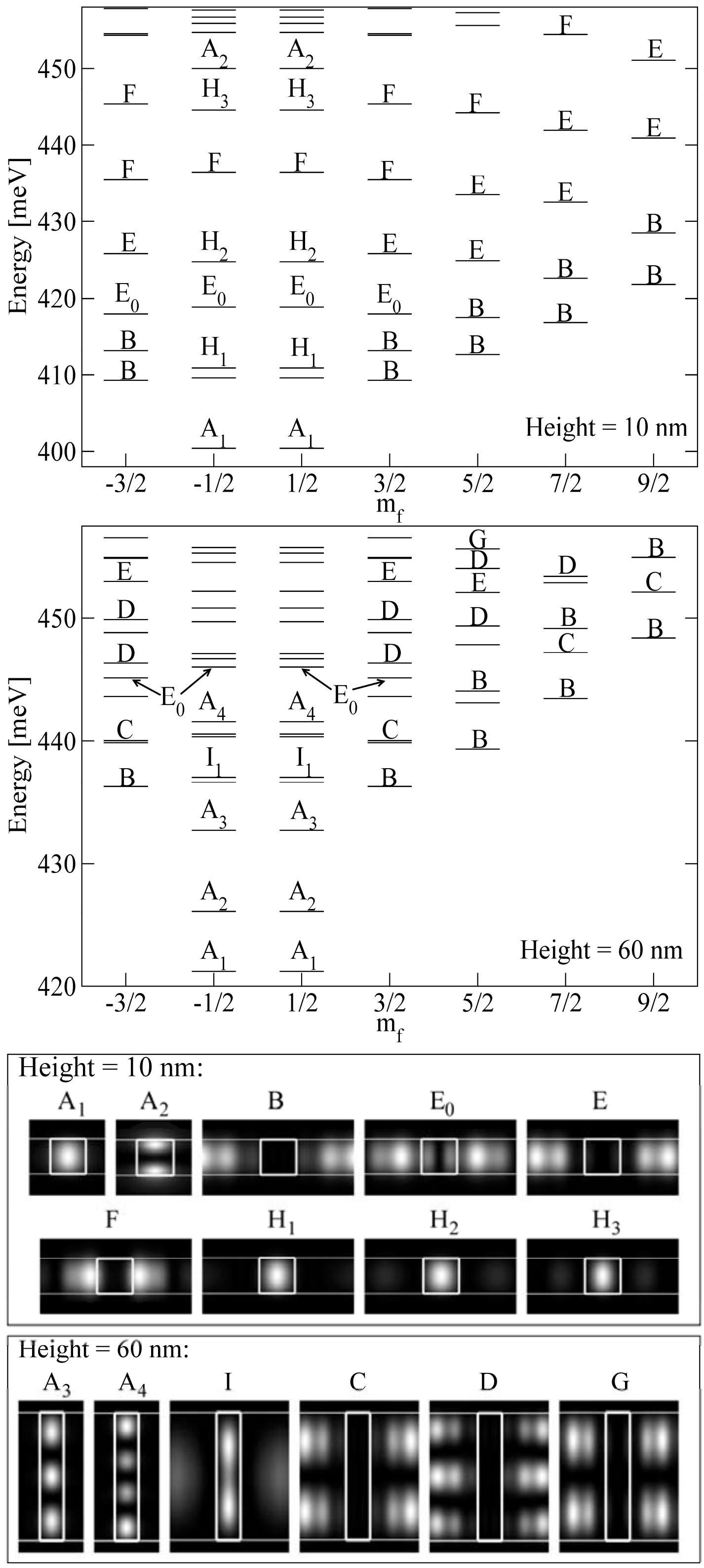

Figure 1: Electron energy diagrams of InGaAs quantum rods with 10 nm (upper diagram) and 60 nm (lower diagram) rod height. Different types of states have different labels. Lower part of the figure shows selected electron wave functions in quantum rods. States with the same label are the same type of state, regardless of the rod height. Dot states are labeled with “A” and well states with “B” for the first subband, “C” for the second subband and “D” for the third subband. Other labels are used for different types of hybridised states due to dot-well coupling.