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Quantum well and superlattice

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Physics**Physics at Nanoscale – IV**

Quantum well and superlattice

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4.4) Quantum Well and superlattice

4.4.1 Quantum well

A quantum well is a potential well in which particle can have only discrete energy values, not continuous energy band. Usually, quantum well in the context of semiconductor heterostructure demonstrate confinement of particle in 1D potential profile, however free to move in 2D, by forcing them to confine in a plane. The effects of quantum confinement take place when the quantum well thickness becomes comparable to the de Broglie wavelength of the carriers, leading to energy levels called "energy subbands", i.e., the carriers can only have discrete energy values. Figure 4.2 shows the alignment of the conduction and valence band edges of three types of hetero junctions. Let us focus on the $Al_xGa_{1-x}As$ to GaAs hetero junction which is a type I heterostructure. The conduction band offset between these materials is about 65% of the total band gap difference, which makes the valence band offset about when $x \leq 0.43$. When $Al_xGa_{1-x}As$ layers are stacked alternately with different x , it possible to fabricate materials with unusual artificial band structures with novel properties. Figure 4.14 shows several such possibilities. In fact, by alternating very thin layers of materials such as GaAs and AlAs, one can construct a super lattice material, which is unlike either of its constituent semiconductors. Both the conduction- and valence-band profile of Figure. 4.14(a) are the semiconductor analogs of the classic quantum-mechanical problem of a particle in a one-dimensional box. In this case, the conduction and valence bands can be analyzed exactly as in elementary quantum mechanics. The particle can be either a heavy or light hole with effective mass m_{hh}^* or m_{lh}^* or an electron with effective mass m_e^* . When the width of the potential well is sufficiently thin, the particle inside behaves quantum mechanically; i.e., the particle exhibits discrete energy levels. The semiconductor system is referred to as a 1D quantum well. In the other two dimensions, the particle behaves semi-classically with a continuum of energy levels as dictated by the usual band structure. For the structure of Figure. 4.14(a), eigenstates of electrons and both types holes (light and heavy) of a single 12-nm-thick square quantum well are plotted in Figure.4.15. The energy eigenvalues of electrons and both types of holes are plotted as a function of well thickness

within the band in Figure 4.16. It is clear that the onset of quantum mechanical effects in the GaAs/ $Al_xGa_{1-x}As$ system occurs when the quantum-well thickness is below 50 nm.

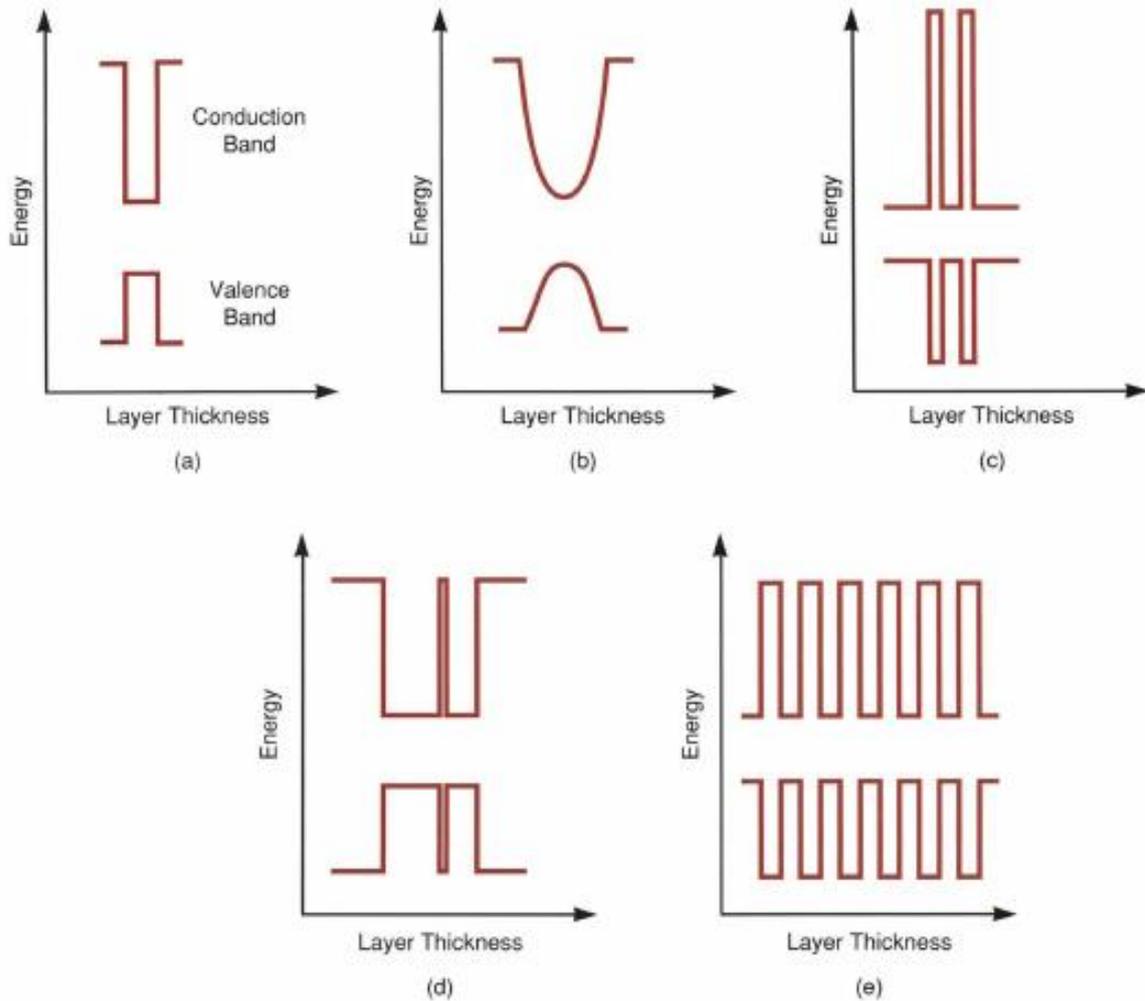


Figure 4.14 Artificial band structures that can be created by growing alternate layers of GaAs and $Al_xGa_{1-x}As$ using different heteroepitaxial growth methods such as molecular beam epitaxy (MBE) or metal organic chemical vapor deposition (MOCVD). The diagrams are of (a) a square quantum well, (b) a parabolic well, (c) a double-barrier structure, (d) an asymmetric coupled quantum well, and (e) a superlattice.

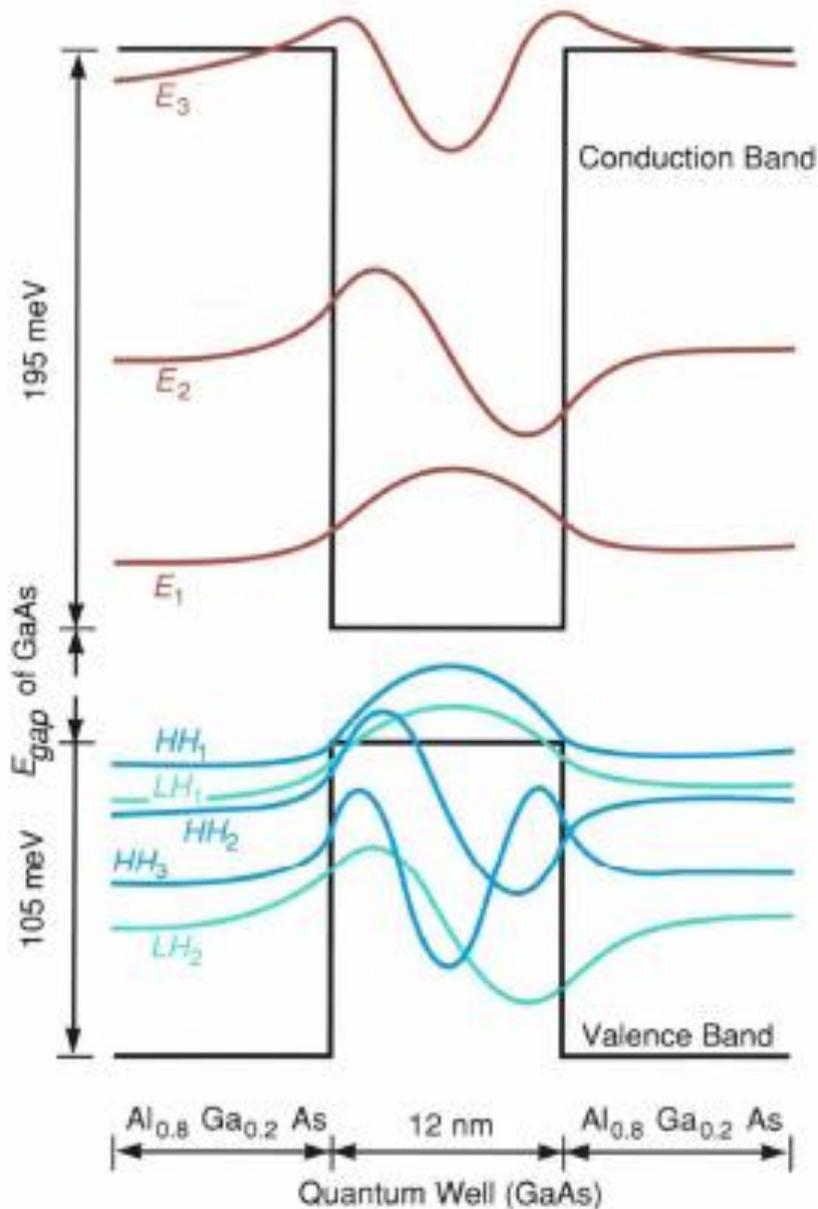


Figure 4.15 Electron and hole wave functions of a 12-nm-thick square quantum well formed with GaAs and $\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}$. E_n denotes the n th electron state; LH_n denotes the n th lighthole state; and HH_n denotes the n th heavy-hole state.

The height of the quantum well is determined by the composition x of alloy counterpart $\text{Al}_x\text{Ga}_{1-x}\text{As}$. The no of bound states in single quantum well depends on the width of the quantum well. It is clear that it is possible to have different transitions either from light hole or heavy hole states in valence band to electron states in conduction band.

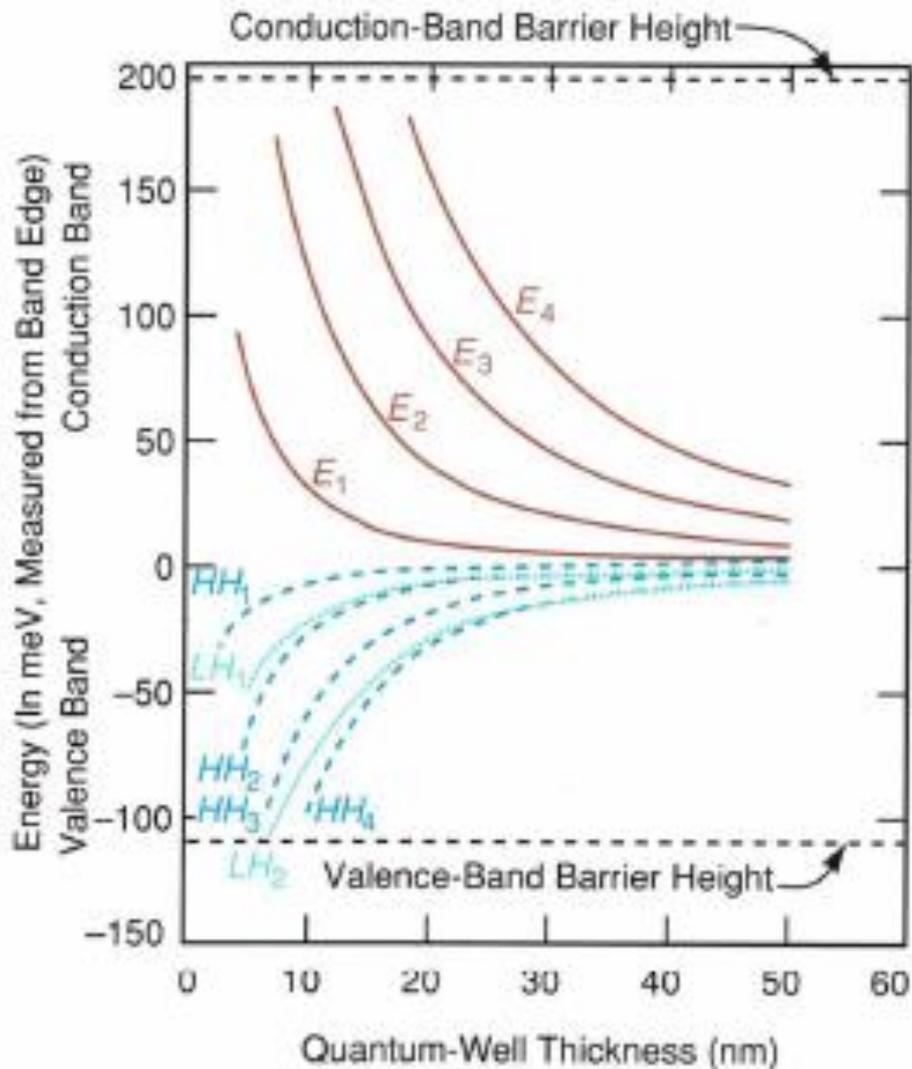


Figure 4.16 How energy eigenvalues for electrons and light- and heavy-hole in conduction and valence bands of square quantum well formed with GaAs and $Al_{0.2}Ga_{0.8}As$ are shown here. E_n denotes the n th electron state, LH_n denotes the n th lighthole state, and HH_n denotes the n th heavy-hole state.

In addition to the relatively simple single square well, Figure. 4.14 contains more complicated band structures in which additional variables allow for the engineering of wave functions with greater complexities. For the asymmetric coupled well of Figure. 4.14(d), Figure. 4.17 shows wave functions of the structure under the influence of electric fields of various strengths. From Figure 4.17, it can be observed that either by an application of electric field or by varying the well width it is possible to engineer the e_1 and h_2 wave

functions. When an moderate electric field is applied to the well, e_1 and h_2 wave functions overlap, which creates a strong absorption at a photon energy equal to $E_{gap} + E_{h_2} + E_{e_1}$. As the absorption coefficient can be controlled by the strength of the applied electric field, so asymmetric coupled wells can be used for electro-absorptive modulation devices. The properties of the single direct-band gap square quantum well can be engineered for light absorption and emission, and electron transport properties perpendicular and parallel to the epitaxial layers.

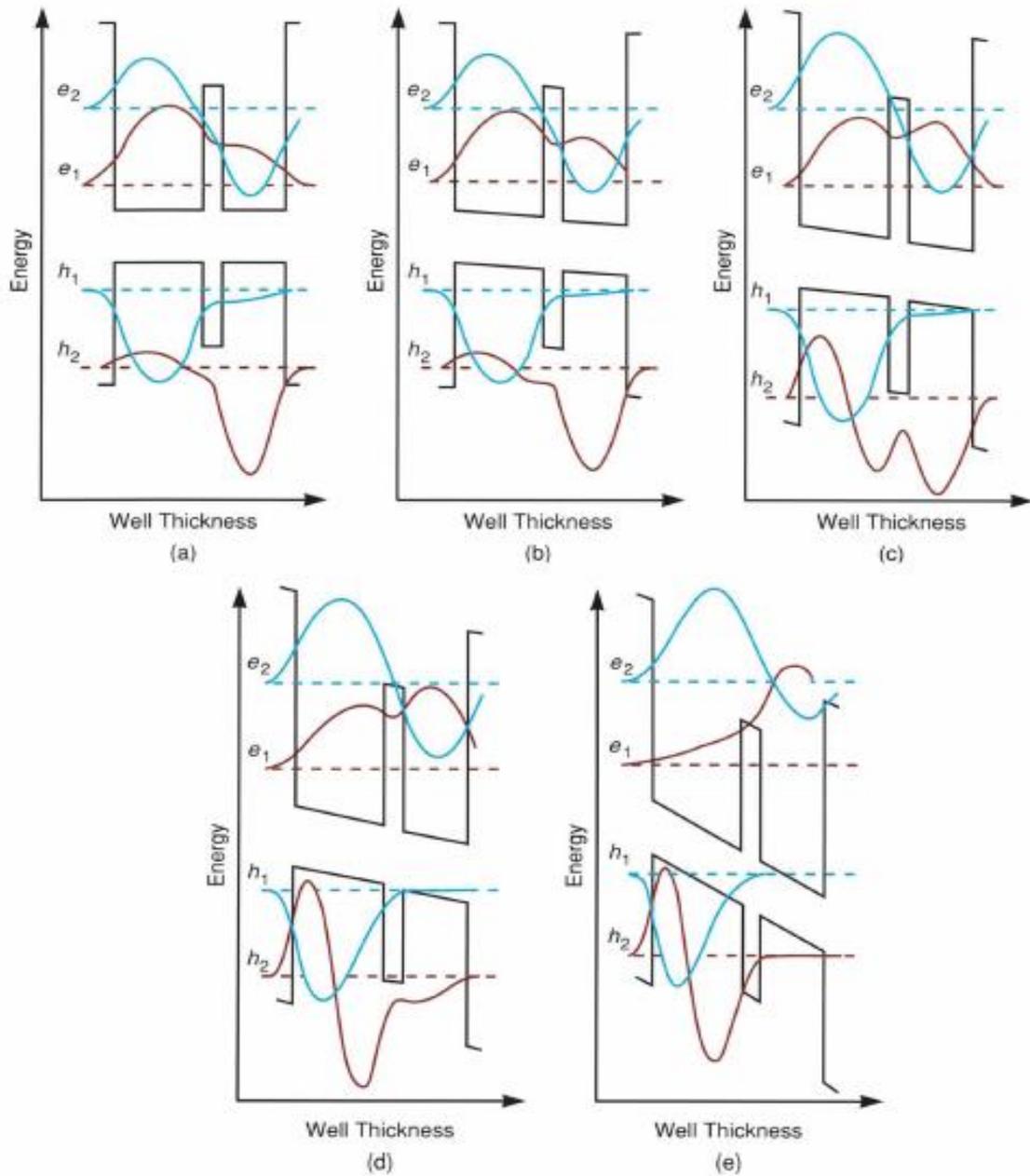


Figure 4.17 Showing how the behavior of the wave functions of an asymmetric coupled quantum well can be modulated with an application of an electric field. Here e_1 and e_2 denote bound electrons while h_1 and h_2 denote bound holes.

4.4.2 Superlattice

A superlattice is a periodic structure of layers, typically of thickness of few nanometers, of two (or more) materials in one particular direction. The two different semiconductor materials are deposited alternately on each other to form a periodic structure

in the growth direction. It is already discussed that quantum confinement leads to the observation of quantum size effects in isolated single heterostructure or double heterostructure, known as quantum well. Now if two quantum wells are grown on one another, there could be two situations depending on the thickness of separation layer between two quantum wells. If the thickness of the separation layer is less than certain thickness, so that the eigenstates of the carriers in individual quantum well overlap substantially so that the tunneling of the carrier from one quantum well to another quantum well. If the thickness of the separation layer is higher than certain thickness (L_B), then the overlap between eigenstates of the carriers in individual quantum well will be negligible resulting absent of tunneling of the carrier from one quantum well to another quantum well. A periodic structure of first type quantum well is called superlattice and second type of quantum well is called multiple quantum well, as shown in Figure 4.18.

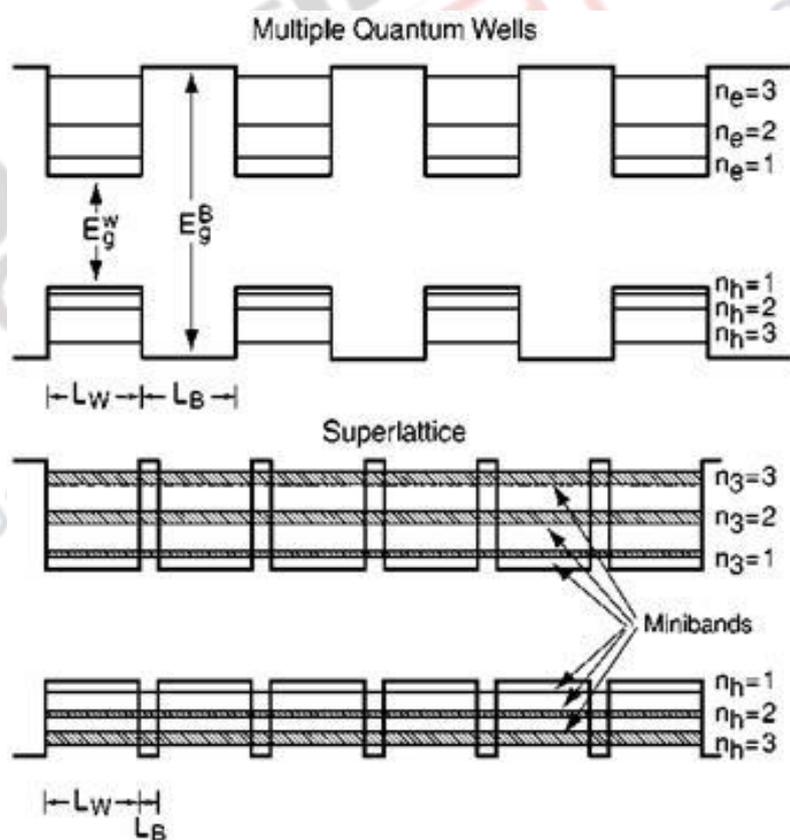


Figure 4.18 Periodic structure of layers, typically of thickness of few nanometers, of two (or more) materials in one particular direction. Depending on thickness of barrier, L_B , periodic structure is called multiple quantum well or superlattice. In case of multiple quantum well, electron energies are discrete as in single quantum well. In case of superlattice, due to overlap of eigenstates, there are minibands.

Superlattice miniband structures depend on the heterostructure type, either *type I*, *type II* or *type III*. For type I the bottom of the conduction band and the top of the valence subband are formed in the same semiconductor layer. In type II the conduction and valence subbands are staggered in both real and reciprocal space, so that electrons and holes are confined in different layers. Type III superlattices involve semimetal material, such as HgTe/CdTe. Although the bottom of the conduction subband and the top of the valence subband are formed in the same semiconductor layer in Type III superlattice, which is similar with Type I superlattice, the band gap of Type III superlattices can be continuously adjusted from semiconductor to zero band gap material and to semimetal with negative band gap. While group III-V semiconductors have been extensively studied, group IV heterostructures such as the $\text{Si}_x\text{Ge}_{1-x}$ is recently becoming very important because in addition to modulation of the band structure, due to large lattice mismatch in this system, the strain modification of the subband structures is interesting in these quantum structures.

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