Semiconductor Physics and Nanoscience

Semiconductor Quantumdots

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Abstract

This paper is a short summery of the talk given in St. Petersburg during the Joint Advanced Student School. In this talk the concept of low dimensionality, especially on zero dimensional systems, is shown. Zero dimensionality is achieved with different semiconducting materials via different fabrication techniques. I present experiments and possible or realized applications with porous silicon, II-VI quantum dots and III-V quantum dots.

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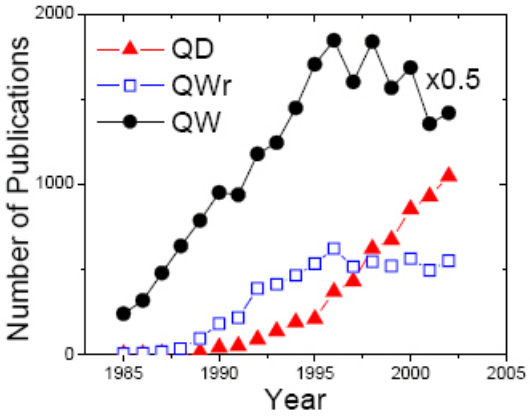
1 Introduction

The field of semiconductor nanotechnology began in the late 1960's and early 1970's. Initially the field developed slowly, pioneered by the experiments of Esaki and Tsu for the "carrier transport properties" and by R. Dingle for the optical processes. The field received a sudden impulse in the mid seventies due to the advent of a new crystal growth technique known as MBE (molecular beam epitaxy) that enabled the growth of mixed semiconductor crystals with atomic layer precision. For this first time, this development enabled the growth of high quality quantum well structures in which electrons and holes show quantization of their energy spectrum predicted by simple quantum mechanics for a particle localized within a rectangular potential. These effects were first unambiguously observed in 1975 by R. Dingle using optical absorption measurements. Since then, the technology for the growth of semiconductor crystals and nanostructure fabrication has improved dramatically resulting in a gradual shift of interest from quantum wells to "lower dimensional" systems in which carrier motion is restricted in two (quantum wires) or all three spatial dimensions (quantum dots). Today, much of the research performed in the field concentrates on such ultra-low dimensional nanostructures.In order to try to visualize these trends, take a look at the following plot that shows the annual number of publications returned by the INSPEC science citation database (http://axiom.iop.org/) for 2D, 1D and 0D systems respectively. Since the early 1990's, interest in quantum dots has



increased dramatically in comparison with nanostructures having higher dimensionality. The origins of this trend can be traced to key technological advances such as the fabrication of selfassembled dots and has, in turn, stimulated interest within other scientific communities. In particular, there has been an upsurge in interest from the quantumoptics and quantum information science fields over recent years due to the potential "quantum dots" may provide for future solid-state implementations of quantum information processing and the possibility to perform "atom-optics" type experiments on man-made atoms quantum dots.

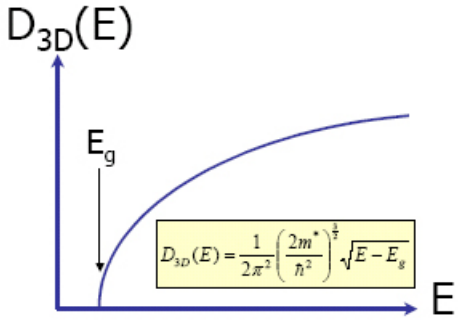
2 Low Dimensional Systems

Different materials with similar crystal structures and lattice constants but strongly differing bandgaps can be combined as heterostructures without introducing strain, and consequently unwanted crystal defects. This is the main reason why semiconductor multilayers provide such strong flexibility for the almost arbitrary realization of different potential profiles. Crucial to the electronic and optical properties of a semiconductor multilayer system is the thickness (L) of the constituent semiconductor layers. If the thickness of a "potential well" is made sufficiently small, quantum effects dominate the motion of the electrons and holes in the

direction perpendicular the layer. Such ultra thin potential wells lie at the heart of low dimensional semiconductor structures

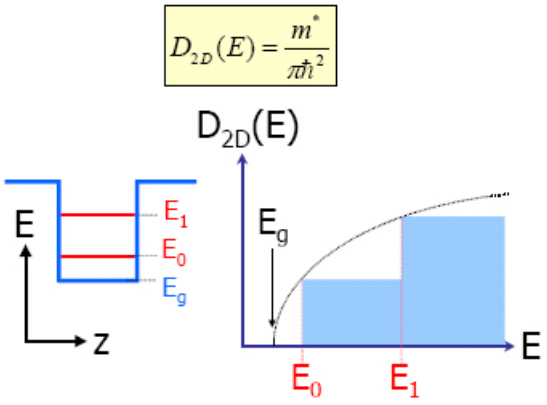
2.1 Density of States

The interesting physics associated with low dimensional nanostructures can all, at some level, be traced to the modification of the density of electronic states that arises from quantization of the kinetic energy discussed above. For simplicity, we consider the example of a 3D band electron sitting at the bottom of a parabolic, isotropic band including the two-fold spin degeneracy. This means that the dispersion relation can be written $E(k) = \frac{\hbar^2 k^2}{2m^*}$, i.e. $k = \sqrt{2m^*E}/\hbar$. In such a system of non-interacting Fermions, the total number of states is $N = 2 * \frac{4}{3}\pi k^3 (\frac{L}{2\pi})^3$, so the number of states per unit volume $V = L^3$ is $N/L^3 = 2 * \frac{4}{3}\pi k^3 (\frac{1}{2\pi})^3$. Defining the density of states (D_{3D}) as the number of states per unit volume, per unit energy yields $D_{3D}(E) = V^{-1}\frac{dN}{dE} = \frac{1}{2\pi^2}(2m^*/\hbar^2)^{3/2}\sqrt{E}$, where E is the energy above the band band edge (E_g). This function is sketched below showing the familiar square root dependence of the density of states in 3D, reducing to zero as one approaches the band edge.



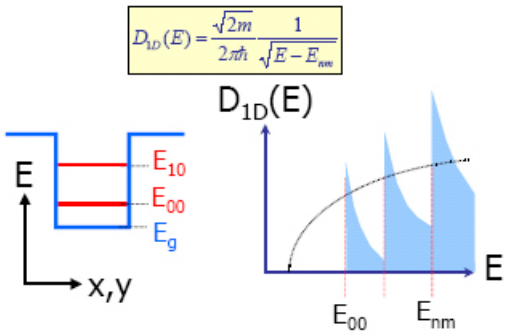
2.2 Quantum Well

In two dimensions, the phase space becomes two-dimensional and the density of states reduces to $D_{2D}(E) = \frac{m^*}{\pi\hbar^2}$, i.e. a step-like function increasing by $\frac{m^*}{\pi\hbar^2}$ for each 2D-subband populated. The situation is sketched schematically below showing a pair of 2D subbands, at energy E_0 and E_1 respectively. The picture shows the confinement energy $E_{0/1} - E_g$ due to motional quantization along the z-direction.



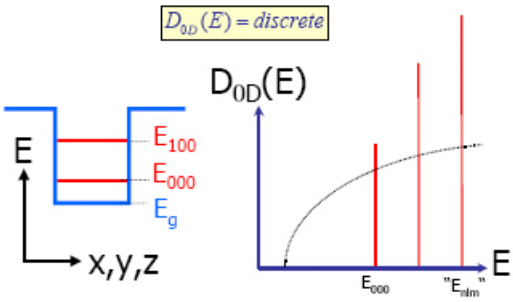
2.3 Quantum Wire

In a one dimensional system, similar arguments give rise to a strongly peaked density of states that is very large at the edge of each one dimensional subband reducing as $D_{1D}(E) = \frac{\sqrt{2m^*}}{2\pi\hbar}\frac{1}{\sqrt{E-E_{nm}}}$ away from the edge as shown below. The indices n, m of each one dimensional subband denote the discrete kinetic energy quantum number for quantized motion along the x or y directions respectively.



2.4 Quantum Dot

For zero dimensional systems, kinetic quantisation occurs along x,y and z directions and the energy spectrum is fully quantised. Thus, $D_{1D}(E) = discrete$ as for the case of an atom. In reality, the energy separation between the different 0D-levels is very important for device applications as the different 0D-levels will be populated with some equilibrium probability at finite temperature. As a rule of thumb, for device applications the 0D states should be separated by energies greater than $> k_BT$ in order for thermal activation of carriers into excited states of the system not to spoil the 0Dcharacter of the device.



3 Fabrication - Experiments - Applications

In the talk, presented in St. Petersburg, the realization of quantum dots was shown for porous silicon, II-VI and III-V semiconductor heterostructures. In order to get an impression of these areas of research, please take a look at the presentation. For more detailed information and references please contact.