An Introduction to Quantum Dots: Confinement, Synthesis, Artificial Atoms and Applications

John Sinclair
Univeristy of Tennessee
Solid State II
Instructer: Dr. Dagotto

April 9, 2009

Abstract

This paper will introduce ideas of quantum dots. It will focus on the ideas of quantum confinement and applications of quantum dots to lasers and biological systems.

1 Introduction

Nanoscience is a very interesting and technologically relevant area of condensed matter physics. Quantum dots are one of the zero dimensional systems in this field and the subject this paper will focus on. The paper will introduce the idea of quantum confinement and the relevant length scales associated with it. Then it will focus on experimental evidence for confinement in these systems. Lastly we will discuss a few applications of quantum dots to lasers and biology.

2 Confinement

Advances in surface and subsurface imagaing techniques have really helped advance nanoscience over the last ten years. Techniques such as scanning

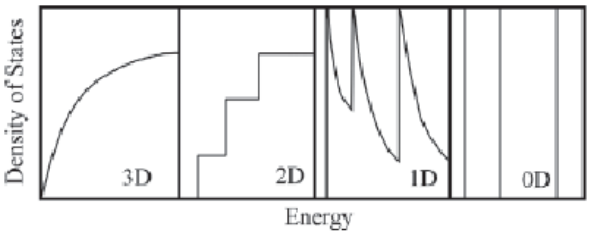

Figure 1: This figure shows a cartoon of how the density of states of a material would change as the dimenstionality is reduced. The usual band-like structure is seen in 3-D, in 2-D we see steps, in 1-D lines begin to develop and by 0-D we see an atom like DOS[**?**]

tunneling microscopes (STM), atomic force microscopes (AFM), near-field scanning optical microscopes (NSOM) and scanning transmission electron microscopes (STEM) allow scientists to have to resolution small enough to now resolve dots that have nm diameters. So you made a small dot, now what? The question is what is the dimensionality of this dot. Here dimensionality of a material means how many dimensions do the carriers of the material act as free carriers. For example in a nanowire the electrons or holes only act a free carriers in one direction. In a dot none of the carriers act as free carriers in any direction. As the dimensionality is reduced the density of states changes drastically[**?**]. In 0-D the density of states of the material looks very much like an atom, a topic which will be discussed later.

The Exciton

What is the relevant length scale for confinement? Optical exitations in a semiconductor should require a minimum energy equal to the band gap, but exitations are seen just below this energy. This exitation is a bound electron-hole pair. This is because the pair bound and therefore it requires less energy to excite it. This pair is called an exciton and has a lot of properties similar to the hydrogen atom and like the hydrogen atom the exiton has a Bohr diameter. This length is material dependent and when the size of the material becomes comperable to the exciton Bohr diameter confinement effects become important.

If the size of the dot is 3-10 times the exciton Bohr diameter the dot is said to be in the week confinement regmine, but if it is smaller the dot is in the strong confinement regime[**?**].

Semiconductor	Exciton Bohr Diameter	Band gap Energy
CuCl	13Å	3.4 eV
ZnSe	84Å	2.58 eV
CdS	56Å	2.53 eV
CdSe	106Å	1.74 eV
CdTe	150Å	1.50 eV
GaAs	280Å	1.43 eV
Si	37Å(longitudinal) 90Å(transverse)	1.11 eV
Ge	50Å(longitudinal) 200Å(transverse)	0.67 eV
PbS	400Å	0.41 eV

Figure 2: Shown is a table of exciton Bohr diameters. This is the relevant length scale for confinement. Clearly it is material dependent.

Observing Confinement

There are a varitey of ways to experimentally observe confinement. Just an image of a small dot is not enough to say that there is quantum confinement present. This paper will discuss optical absorption, raman scattering and photoluminescence spectroscopy experiments. Optical absorption is a way to directly measure the band gap of a material. If a material is experience confinement effects there should be a shift of the band gap edge toward the blue wavelengths. As seen in figure ? Bukowski et al. present the optical absorption of Ge quantum dots in a SiO_2 matrix. There is a clear shift in the band edge toward shorter wavelengths as the size of the dot decreases. The amount of blue shift due to size effects is a material dependent phenomona. Ge is shown here because it has a very large blue shift. The amount of shift is due to the shape of the band gap.

Another important technique for determining if the dots that are synthesized are quantumly confined or not is Raman vibrational spectroscopy. Raman spectroscopy occurs when light is shinned onto a sample and it excites vibrational modes. This casuses the light to lose energy and change wavelength and is then detected. A strong narrow peak is a key indicator of

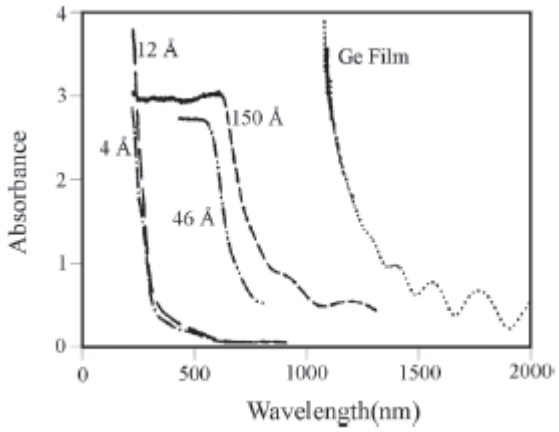

Figure 3: Here Bukowski et al. present optical data of Ge quantum dots. A clear blue shift of the band edge is seen. It is also clearly dependent on the size of the dots[**?**].

a crystalline sample. As a nanocrystal starts to feel the effects of confinement the Raman spectrum broadens. In figure ? we can see the Raman shift of several different sizes of Ge dots. There is also a shift of the peak but often times that feature is missing due to surface strain.

The last experimental technique this paper will discuss is photoluminescence spectroscopy. In photoluminescence spectroscopy a laser is tuned to a specific energy that then excites carriers in the quantum dots and when the excitations recombine photons are emitted and then measured. As the dots get smaller the photoluminescence spectrum broadens and becomes spikey. Some very clean systems even have very narrow photoluminescence peaks and can be used to make quantum dot lasers[**?**].

3 Lasers

The atomic like density of states a quantum dot has is ideal for creating solid state lasers with single narrow excitation modes. Also because the position of the descrete peaks in the density of states is a function of size it should also make the excitation modes tuneable. Also it is hopefully possible to create quantum dot lasers that have very low theashold current densities. These lasers are often used to make infrared lasers that may be important to

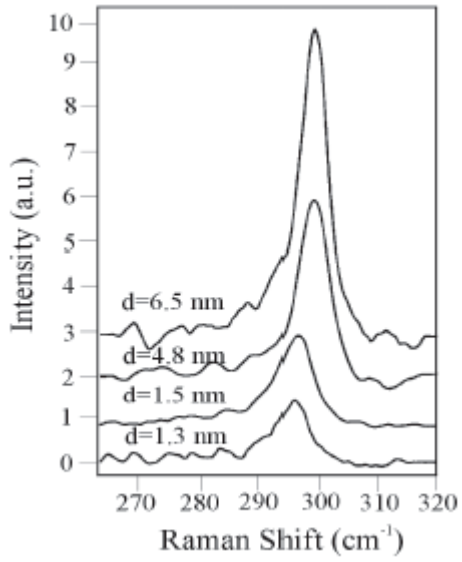

Figure 4: Here we see Raman data for several different sizes of Ge quantum dots. We see a clear broadening of the peak as well as a shift toward the laser wavelength. This feature is counter ballenced often times by surface strain so it is sometimes absent[**?**].

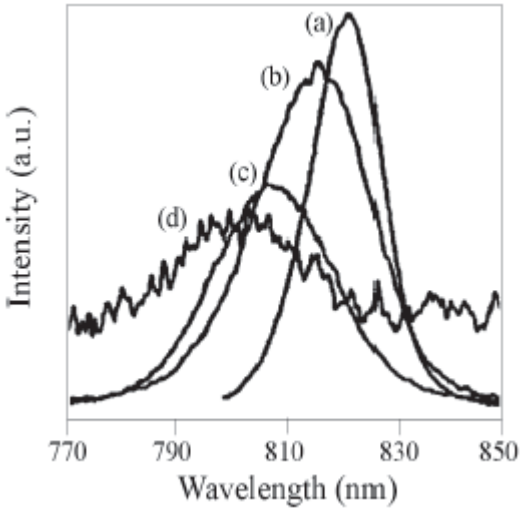

Figure 5: Here we see the photoluminescence peak broaden and become spikey which shows the 0-D behavior of this material[**?**].

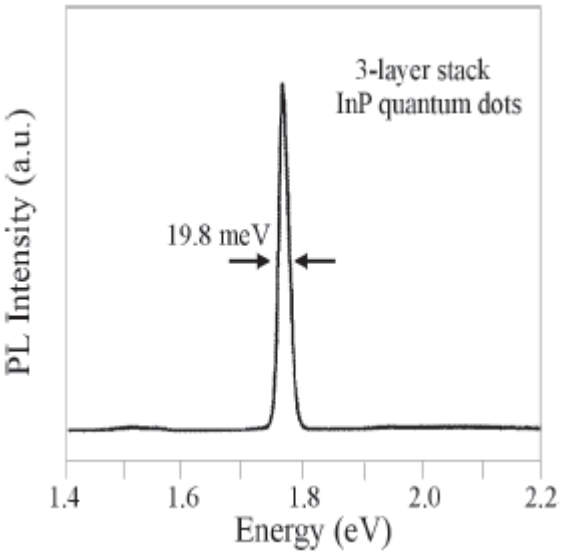

Figure 6: Here we see the photoluminescence peak of InP quantum dots that are used for lasers. We see a very narrow photoluminescence peak that is very spike like a hallmark of 0-D behavior[**?**].

the communications industry. One of the problems seems to be that the QD lasers have large threshold current densities, though smaller than quantum well lasers now[**?**]. This paper will discuss the findings of two papers. First in 1998 an QD laser made from GeAs dots was synthesised. At 79 K the 1.31 μm laser had a threshold current desity of $11.5 A/cm^2$ which was much better than what had been seen in the early das of QD lasers, over $1 kA/cm^2$[**?**] and lasing presisted all the way able 300 K with a threshold current density of $270 A/cm^2$. At room temperature the laser now operated at 1.22 μm[**?**]. In 2006 a group had produced a QD laser a 1.54 μm laser with no temperature dependence on the emmitted wavelengh. It had a threshold current density on the order of a few mA/cm^2 but it could not lase at room temperature[**?**].

4 Biological Applications

Last but not least this paper will discuss some possible biological applications of quantum dots and nanocrystals. Three interesting biological applications will breifly be discussed to show the interdisiplinary nature of nano-scale

physics. The first possible application is creating multifunctional particles. Imagine that one takes two different dots with different properties. One could then imagine placing a ligand molecure on the first dot and a receptor molecule on the other. This would combine to make a material with both properties and would allow controlled assembly at the nanoscale. This process is usually done with nanocrystals Secondly one could put ligand molecules on nanoparticles and decorate a substrait with receptors to pattern a substrait with quantum dots, this is particualrly useful to studying biological circuits such as studying properties of DNA. This is done using semiconducting quantum dots and semiconducting nanocrystlas. Lastly ligand modified quantum dots could be used to lable cellular structures that have receptors to that ligand, this process would replace antibody taging[**?**].

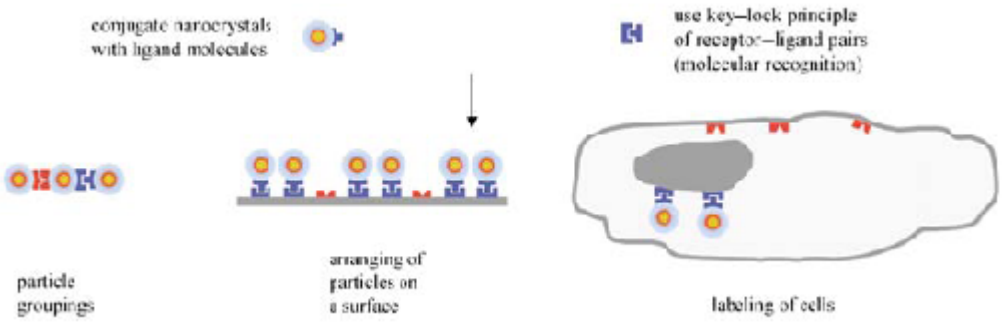

Figure 7: Here is a pictorial view of functionalized qunatum dots for use in biology. Ligands are attacted the the quantum dots and are either used to build structures, pattern substraits or lable cellular structures.

References

[1] J. H. S. Tracie J. Bukowski, Critical Reviews in Solid State and Materials Sciences (2002).

[2] Z. Z. O. B. S. D. L. Huffaker, G. Park and D. G. Deppe, Applied Physics Journal (1998).

[3] I. H. S. C. L. L. E. H. S. S. Hoogland, V. Sukhovatkin, Optics Express (2006).

[4] T. L. A. M. J. L. M. Teresa Pellegrino, Stefan Kudera and W. J. Parak, small (2005).