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Quantum Wells, Wires and Dots

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Abstract

Nano electronics, with a broad range of potential applications, is an evolving, enabling and multidisciplinary field. Although there is no single definition of nanoelectronics, it is widely considered as a capacity to regulate nano-meter-scale material for building new components with unique properties like physical, chemical, and biological and features like quantum effects.

This chapter provides theoretical information about how quantum dots, wires and wells works differently than classical particles. Object in quantum physics behaves like both particles and waves, which can be analyzed in effects like Coulomb blockade, Quantum confinement and Tunneling effect. Quantum particles contains so few electrons that removal or addition of electron to particles shows very different effects. Applications of quantum dots, wires, wells and physical working of those applications are discussed in this chapter. Some of those applications are still under research and can revolutionize human lives in the future.

Introduction

All electronic-and optical properties of semiconductor devices are dependent upon the band structure of the constituting semiconductor materials. Changing the band structure can obviously become a powerful tool to design semiconductor devices with superior performance characteristics. Over the last decade the modification of band structure has provided a new and exciting dimension in device design. Many physical phenomena can modify the electronic band structure like alloying of two or more semiconductors, use of built-in strain via lattice mismatch epitaxy(the growth of crystals on crystalline substance).

If the size or dimension of a substance is reduced to a very small size from a large or macroscopic scale, such as meters or centimeters, the properties at first remain the same, then small changes start to occur until the size falls below 100 nm.

We will take example of Gold. Excited ?? Who doesn't like gold with sparkling yellow colour. Sorry but at nanoscale Gold is not sparkling yellow. Nano gold is small gold particles. It has some surprising properties when gold is nano-sized. Nano gold, for instance, may look red, orange, or even blue. The color depends on the size and shape and distance of the nanoparticles. The various colors of nano gold are derived from a phenomenon called resonance of surface plasmon. Smaller nano gold particles absorb and resonate with luminous wavelengths of purple, black, green, and yellow, so they look red. Larger nano gold particles absorb and resonate with light wavelengths of green, yellow, and red, so they look blue.

Now one will ask what are the benefits to study properties of elements at the nanoscale ??? If you know the properties of elements at the nanoscale, you can take advantage of that knowledge and use that properties for our advantages, we can make useful devices or we can improve the efficiency of our existing devices. We can also design elements device at nanoscale to get desired behaviour. Take example of Quantum Dots. Quantum dots are used in QLED display. Quantum Dots produce richer and accurate colours which enhances our experience of television. They are also cost efficient.

Physical Principle

The particle-wave duality proposed by de Broglie is a key aspect of quantum mechanics. Each particle may thus be correlated with a matter-wave that wavelength is inversely related to the particle's linear momentum ($\lambda = h/mv$). The principles of quantum mechanics best describe the actions of the particles when the size of a given system is comparable to the wavelength of a particle.All the info about the particle is collected by solving the Schrodinger equation. The solutions of this equation represent the potential physical conditions under which the system can be found.

Physical Structure

Electrons are generally free to move across all three directions in a 3D structure. This is a typical example of the structure of bulk. Now we have three options to bring this structure to nano scale either we choose one dimension or two dimensions or three dimensions to reduce. If we choose to reduce only one dimension at nanoscale we can get quantum well like thin film or graphene. If we choose to reduce two dimensions at the nanoscale we can get quantum wire like nano wires, nanorod and nanotube. If we choose to reduce all three dimensions at the nanoscale we can get quantum dot (2-10 nm). like nano dot.

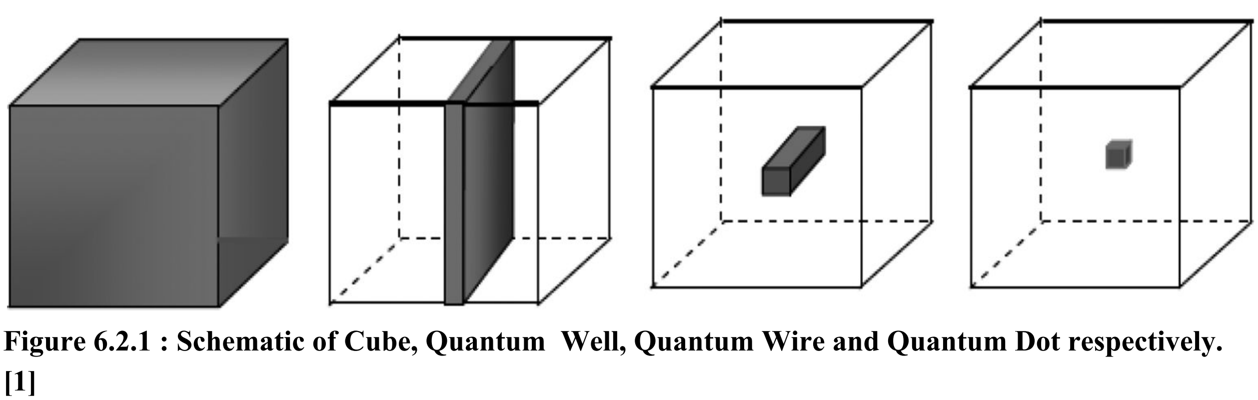

Figure 6.2.1 : Schematic of Cube, Quantum Well, Quantum Wire and Quantum Dot respectively. [1]

Single electron effects

Quantum Confinement

- Quantum confinement is a constraint on the movement of rapidly and randomly moving electrons in a substance to different discrete levels of energy. It is an impact where a typical material's dimensions are comparable to the electrons involved de-Broglie wavelength.
- So as we introduced quantum well in which only one dimension is confined , so electron can not move in that particular dimention.in quantum wire two dimensions are confined so electron can not move in those two dimensions.in quantum dot all three dimensions are confined so electron can not move in any dimension.

Coulomb Blockade

The junction of the tunnel is a thin barrier of insulation around two conducting electrodes. No current(electron) can flow through an insulating barrier according to the classical electrodynamics. Tunnel junction acts as a resistor with a constant resistance.The resistance is proportional to the width of the barrier and normally it is in nanometers.

The tunnel junction is charged by the tunneled electrons which creates voltage of $v=e/C$ where C is the capacitance of junction and e is the charge of an electron ($1.6*10^{-19}$ coulomb).so at lower capacitance the voltage will be very high and at lower bias voltage resistance of barrier will be too high for electrons to cross junction.so in short the Coulomb blockade is the increase in differential resistance around zero bias.

To achieve coulomb blockade 3 conditions must satisfy:

1. The bias voltage that we apply must be smaller the ratio of elementary charge and capacitance of junction $v < e/C$.

2. Thermal energy(KbT) of the system must be less than $e^2/C*2$.other wise electron will get enough energy from environment to cross the junction.

3. The resistance of the tunnel must greater than h/e^2, where h is planck constant.

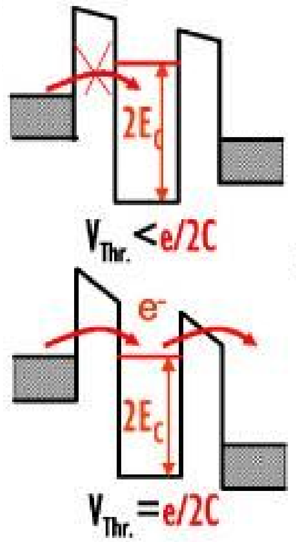

Figure 6.2.2 : Coulomb Blockade [2]

Tunneling Effect

- Electron doesn't revolve around atom, but it simply appears in different probabilistic energy levels.
- When a particle appears at the other side of the energy barrier without having the sufficient energy to cross the energy barrier. This phenomena is quantum tunneling, where it seems like the particle has tunneled through the energy barrier.
- If Classical particles doesn't have sufficient energy to get over the barrier, then it reflects back and can not continue to move forward.
- Whenever the position of something is represented in Quantum Mechanics, it is represented with a degree of uncertainty related to the degree of uncertainty in its momentum. For things on human scales, these uncertainties can be incredibly small and totally ignorable.
- The uncertainty in position of the quantum particle as it reaches a barrier means that there is some probability that the particle is in fact on the other side. This probability is seldom high, but sometimes it is, and even with low probability and a lot of particles reaching a barrier, some will get thrown. We say they tunneled through. There is no real tunnel, this term just present a metaphor for something that doesn't exist in any theory of classical physics.

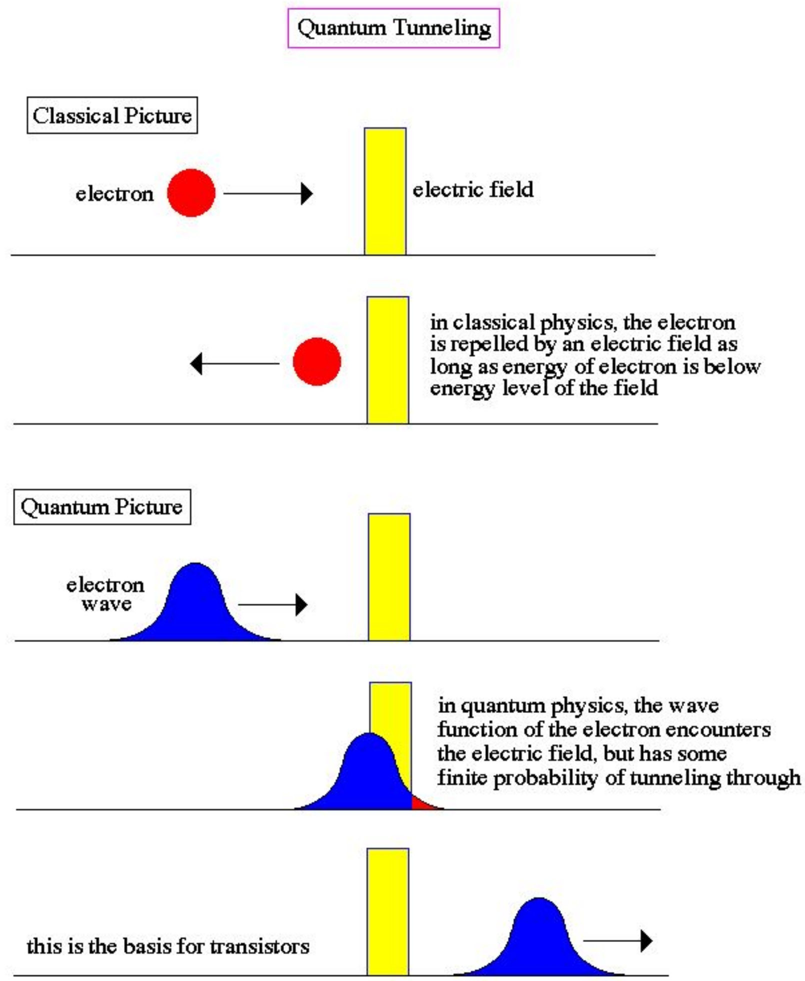

Figure 6.2.3 : Schematic of Tunneling Effect [3]

- The amplitude of the wave decreases exponentially across regions where potential energy is greater than the wave's energy.If the region is sufficiently narrow than the other side of the wave may have a non-zero amplitude.
- The tunneling current is classified as a ratio of current density resulting from a barrier divided by a current incident of density of the barrier. If this ratio of transmission is non-zero value across the barrier, then through the barrier there is a finite probability of particle tunneling.

Applications:

Quantum Dots

- **Light emitting devices**

  QDs are very promising for the devices which are based on light emitting and can improve the quality of light LEDs resulting in a new QLED (Quantum Dot Light Emitting Diode) design. In view of their special optical properties, QDs are really useful for display devices. QLEDs are usually used in displays which are called Quantum Dot Displays or QLED Displays. With the help of QLEDs we can get colours more accurately and clearly and they are more efficient than normal LEDs.

  In normal LCD display we use white LEDs and with the help of colour filters we get red, blue and green colours. Here colour filters are not 100% efficient we lose some of the light(energy) there. In QLEDs we use blue LEDs and QDs with different sizes which may help to generate red,blue and green colours. As we know QD reflects colour according to size so we get pure red, green and blue colours with the help of QDs. So we get two benefits, first we get pure/accurate colours and we don't lose light/energy which we were losing because of colour filters as we don't need them at all.

- **Quantum Computing**

  Quantum dots have been used in powerful supercomputers commonly termed as quantum computers. Quantum computers use ' qubits'(quantum bits) for operating and storing information that can exist in both on and off state at the same time. This amazing development allows the time complexity and memory complexity of information processing to be vastly improved compared to conventional computers.

Quantum Well

- **Solar Cells**

  Quantum wells were designed such that it can improve the efficiency of solar cells.The conventional single-junction cells ' theoretical maximum efficiency is about 34% primarily due to their inability to absorb several different light wavelengths. Solar cells consisting of multiple N-P junctions of various series connected band gaps can improve the efficiency(theoretically) extending the range of absorbed wavelengths, though the complexity of manufacturing and production costs restrict their use to narrow applications.But if we use one or more than one quantum wells in internal region in P-i-N junction of solar cells than that gives increased photocurrent over dark current which can increase efficiency over traditional P-N solar cells.

- **Thermoelectrics**

  Quantum wells showed potential as thermoelectric devices for energy harvesting. It is claimed that they are easier to manufacture and give the ability to work at normal room temperature. A central cavity is attached to two electrical reservoirs by the quantum wells. The central cavity is maintained above the reservoirs at the hotter temperature. The quantum wells perform a roll of filters allowing the passage of electrons from certain energies.

  An observational device produced output power of approximately 0.18 W / cm2 for a temperature with difference of 1K, almost doubling the power of the harvester of quantum dot energy. Larger currents were allowed by the extra level of freedom. It has a slightly lower efficiency than the harvesters of quantum dot energy. Quantum wells can transmit electrons of any energy above a certain threshold, while quantum dots can transmit only electrons of some specified energy.

  One of the possible applications is to convert the unwanted heat back into electricity from electrical circuits, e.g. in the computer chips, reducing the need for powering and cooling the chip.

- **Quantum well laser**

  A QW laser is a type of laser diode where the device's active region is so small that there is occurrence of quantum confinement . Compound semiconductors components that are efficient in emitting light are used to produce Laser diodes. The wavelength of light emitted by a quantum well laser is determined not just by the bandgap of the material from which it is built, but by the width of the active region. We can change laser wavelength by alternating the width of quantum well layers but in standard lasers we have to change layer structure. It implies that with the help of specific semiconductor material, we can obtain longer wavelengths with QW lasers than of traditional laser diodes.

  Because of the stepwise structure of its state density function, QW laser has better efficiency than a traditional laser diode.

QuantumWire

- **Nanowire**

  Using graphene which is coated with zinc oxide nanowires, Scientists of MIT University develop a solar cell. Nanowires have several interesting features Unseen in bulk and 3-D materials (three-dimensional). This feature in nanowires because of the electrons which are in nanowires are laterally confined to the quantum and thus they fill the energy levels other than the conventional spectrum of energy levels or bands which are not present in bulk materials.

- **Electronic devices**

  It is possible to use nanowires for transistors. Transistors are widely used in today's electronic circuits as an important building element. key challenges that are facing during the construction of future transistors is to make sure good channel gate control. Wrapping the dielectric gate on every side of the nanowire channel can lead to better electrostatic control of the channel potential because of the increased aspect ratio. So that turning on and off the transistor effectively.

Quantum tunneling effect

- **Use of tunneling effect in Quantum computers:**

  Today's computers will be considered slow in the future. Therefore, with the development of the technology, the demand for high speed computers can be made possible with quantum computers. Today's computers function by viewing data as a sequence of ' bits ' or binary digits(zeros and ones). This code is obtained by transistors. Transistors are minute switches that can be either on or off, indicating either one or zero. In comparison, quantum computers will benefit from a phenomenon described in the theory of quantum: Objects, such as atoms or electrons, may be simultaneously in two places, or they may exist simultaneously in two states. This theory can be explained by tunneling effect. This means that quantum computers would have "qubits"(quantum bits) that exist in both on and off states at the same time, enabling them to process information much more quickly than conventional computers. Quantum bits represent photons, ions, electrons or atoms reflect molecules, ions, photons and electrons and their respective control devices which function together to serve as a processor or computer memory.

  Since a quantum computer can hold such multiple states at the same time, it has the potential to be millions of times stronger than the most powerful supercomputers of today.

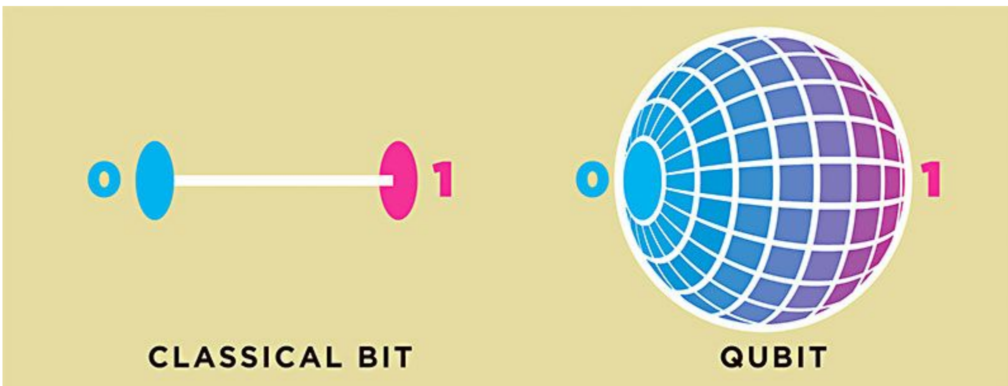

Figure 6.2.4 : Schematic of Classical Bit and QUBIT [4]

- **Tunnel diode :**

  In tunnel diodes, a low voltage which is less than the depletion region's built-in voltage induced electrical current as a result of quantum tunneling between p and n regions. The narrow area of depletion is needed to ensure that the thickness of the barrier is sufficiently low for tunneling.

So tunnel diodes are being used as ultra-high-speed switches, in logic memory storage systems, control oscillator circuits. These are widely used in the nuclear industry due to the high sensitivity to radiation.

- ## Scanning Tunneling Microscopes:

A Scanning Tunneling Microscope (STM) operates by scanning through the surface of a substance a really sensitive conducting probe. The electric current is passed down the probe's tip and tunnels into the material through the gap. As the distance becomes broader and smaller, the tunneling current, respectively, becomes larger or smaller. Using this information, it was possible to construct an incredibly detailed surface image, even to the level of solving humps on the surface possibly because of particular atoms.This technique has provided a better understanding of surface physics and chemistry.

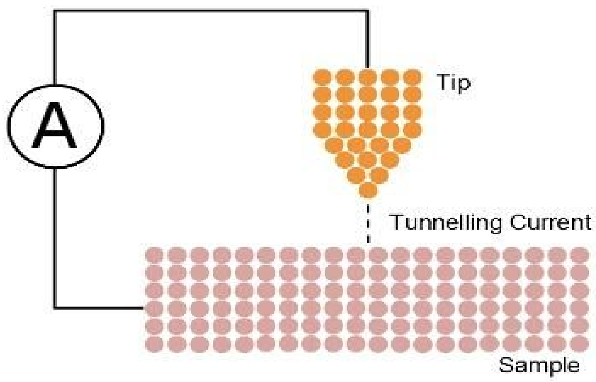

Figure 6.2.5 : Schematic of STM [5]

STM schematics-the tunneling current tends to vary with distance between both a tip and a surface atoms, making it possible to map defects as well as individual atoms.

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