First Demo

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Introduction

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.

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).

When a material's size or dimension is [9] reduced from a large or macroscopic size, such as meters or centimeters, to a very small size, the properties remain the same at first, then small changes begin to occur, until the size drops 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 [15] depends on the nanoparticles ' size and shape and their distance. 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

A most important aspect of quantum mechanics is the particle–wave duality which was introduced by de Broglie, according to which any particle can be associated with a matter wave whose wavelength is inversely proportional to the particle’s linear momentum ($\lambda = h / mv$). Whenever the size of a physical system becomes comparable to the wavelength of the particles, the behavior of the particles is best described by the rules of quantum mechanics. All the information about the particle is obtained by solving its Schrodinger equation. The solutions of this equation represent the possible physical states in which the system can be found.

Physical Structure

In general in 3D structure electrons are free to move in all three directions. This is a classic example of bulk structure. 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.

Single electron effects

Quantum Confinement

Quantum confinement is [12] a restriction on the motion of randomly moving electrons present in a material to specific discrete energy levels rather than to quasi continuum of energy bands. It is an effect where the dimensions of a typical material [13] is comparable to the de-Broglie wavelength of the electrons involved.

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 tunnel junction is a thin insulating barrier between two conducting electrodes.No current can flow through an insulating barrier according to the classical electrodynamics.However, according to quantum mechanics, there is a non -zero (greater than zero) probability for an electron to reach the other side of the barrier that is called an electron tunneling effect.

When a bias voltage is applied, this implies a current will occur and the tunneling current will be proportional to the bias voltage. In other words, tunnel junction behaves as a resistor with constant resistance.The resistance is proportional to the width of the barrier and normally it is in nanometers. So arrangement like this in which two conductors has insulating layer in between them also act as a capacitor.so tunnel junction behaves as a capacitor and insulating barrier behaves as dielectric.now if we replace insulating layer with quantum dot and uses single electron then this arrangement is called single electron transistor.

The tunnel junction is charged by the tunneled electron which creates voltage of $v=e/C$ where C is the capacitance of junction and e is the electron charge (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:

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

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

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

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.

In regions where the potential energy is higher than the wave's energy, the amplitude of the wave decays exponentially. If the region is narrow enough, the wave can have a non-zero amplitude on the other side.

The tunneling current is defined as the ratio of the current density emerging from the barrier divided by the current density incident on the barrier. If this transmission coefficient across the barrier is a non-zero value, then there is a finite likelihood of a particle tunneling through the barrier.

Applications:

Quantum Dots

Light emitting devices

QDs are promising for light emitting devices and may improve the performance of light-emitting diode (LED), leading to the new design of "Quantum Dot light Emitting Diode". QDs are very useful for display devices considering their unique optical properties. They are capable of presenting visibly more accurate and outstanding colors. A proof-of-concept QDs display has been successfully achieved from technical perspective years ago, and shows a good performance and bright emission in the region of visible and near infrared spectrum.

Photovoltaic devices

Because of the tunable of the absorption spectrum and high extinction coefficient, QDs are desirable for light harvesting, is beneficial for photovoltaic devices. QDs have the potential to boost the efficiency of silicon photovoltaic cells and lead to reduced costs.

Bioimaging

Various kinds of organic dyes have been used in bioimaging for decades. However, most of the organic dyes suffer from low quantum yield and photostability. However, with the advancement of nanotechnology, QDs have been considered to be superior to traditional organic dyes in many respects. For example, it has been found that QDs are

20 times brighter and 100 times more stable than traditional fluorescent reporters. With well-established inorganic synthetic techniques are now available for generating QDs with high brightness. For bioimaging applications, fluorescent probes have to remain well-dispersed and stable in the aqueous medium with a wide range of pH and ionic strengths. Fortunately, numerous approaches have been developed to make the QDs water-dispersible. Up until now, great efforts have been devoted to employing QDs for in vitro and in vivo imaging, which are expected to be important to the diagnosis of many diseases, the understanding of embryogenesis, and lymphocyte immunology.

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Quantum Computing

Quantum dots have paved the way for powerful ‘supercomputers’ known as quantum computers. Quantum computers operate and store information using quantum bits or ‘qubits’, which can exist in two states – both on and off simultaneously.This remarkable phenomenon enables information processing speeds and memory capacity to both be greatly improved when compared to conventional computers.

Quantum Well

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Solar Cells

Quantum wells have been proposed to increase the efficiency of solar cells. The theoretical maximum efficiency of traditional single-junction cells is about 34%, due in large part to their inability to capture many different wavelengths of light. Multi-junction solar cells, which consist of multiple p-n junctions of different band gaps connected in series, increase the theoretical efficiency by broadening the range of absorbed wavelengths, but their complexity and manufacturing cost limit their use to niche applications. On the other hand, cells consisting of a p-i-n junction in which the intrinsic region contains one or more quantum wells, lead to an increased photocurrent over dark current, resulting in a net efficiency increase over conventional p-n cells.

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Thermoelectrics

Quantum wells have shown promise for energy harvesting as thermoelectric devices. They are claimed to be easier to fabricate and offer the potential to operate at room temperature. The wells connect a central cavity to two electronic reservoirs. The central cavity is kept at a hotter temperature than the reservoirs. The wells act as filters that allow electrons of certain energies to pass through. In general, greater temperature differences between the cavity and the reservoirs increases electron flow and output power.

An experimental device delivered output power of about 0.18 W/cm2 for a temperature difference of 1 K, nearly double the power of a quantum dot energy harvester. The extra degrees of freedom allowed larger currents. Its efficiency is slightly lower than quantum dot energy harvesters. Quantum wells transmit electrons of any energy above a certain level, while quantum dots pass only electrons of a specific energy. One possible application is to convert waste heat from electric circuits, e.g. in computer chips, back into electricity, reducing the need for cooling and energy to power the chip.

Quantum well laser

A quantum well laser is a laser diode in which the active region of the device is so narrow that quantum confinement occurs. Laser diodes are formed in compound semiconductor materials that (quite unlike silicon) are able to emit light efficiently. The wavelength of the light emitted by a quantum well laser is determined by the width of the active region rather than just the bandgap of the material from which it is constructed. This means that much longer wavelengths can be obtained from quantum well lasers than from conventional laser diodes using a particular semiconductor material. The efficiency of a quantum well laser is also greater than a conventional laser diode due to the stepwise form of its density of states function.

QuantumWire

Nanowire

Researchers at MIT have developed a solar cell using graphene coated with zinc oxide nanowires. The researchers believe that this method will allow the production of low cost flexible solar cells at high enough efficiency to be competitive.

Electronic devices

Nanowires can be used for transistors. Transistors are used widely as fundamental building element in today's electronic circuits. One of the key challenges of building future transistors is ensuring good gate control over the channel. Due to the high aspect ratio, wrapping the gate dielectric around the nanowire channel, can result in good electrostatic control of the channel potential, thereby turning the transistor on and off efficiently.

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 work by representing information as a series of ones and zeros, or binary digits called "bits." This code is received by transistors, which are minute switches that can either be on or off, representing a one or a zero, respectively. In comparison, quantum computers would take advantage of a phenomenon described by quantum theory: Objects, such as atoms or electrons, can be in two places at the same time, or they can exist in two states at the same time. This theory can be explained by tunneling effect. This means that computers based on quantum physics would have quantum bits, or "qubits," that exist in both the on and off states simultaneously, making it possible for them to process information much faster than conventional computers. Qubits represent atoms, ions, photons or electrons and their respective control devices that are working together to act as computer memory and a processor. As a quantum computer can contain these multiple states simultaneously, it has the potential to be millions of times more powerful than today's most powerful supercomputers.

Tunnel diode :

In tunnel diodes, a small voltage that is less than the built-in voltage of the depletion region produces an electric current due to quantum tunneling between the n and p regions. The narrow depletion region is required so that the barrier thickness is low enough for tunneling. Tunnel diodes are used in logic memory storage devices, relaxation oscillator circuits, and as ultra-high-speed switches. Owing to the high resistance to radiation, they are commonly-used in the nuclear industry.

Scanning Tunneling Microscopes:

A Scanning Tunneling Microscope (STM) works by scanning a very sharp conducting probe across the surface of a material. An electrical current is passed down the tip of the probe, and it tunnels across the gap into the material. As the gap gets wider or narrower, the tunneling current gets smaller or larger, respectively. Using this data, an incredibly detailed picture of the surface, even to the point of resolving humps on the surface due to individual atoms, could be built. This technique has allowed a greater understanding of the physics and chemistry of surfaces.

Schematic of an STM - the tunneling current varies with the distance between the tip and the atoms on the surface, allowing defects and even individual atoms to be mapped.

First Demo

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