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Quantum Dots an Upcoming Concept of Semeconductors & Nanotechnology

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ABSTRACT:-

Quantum dot is an uprising concept promising a lot in conservation of energy by efficiently trapping solar energy as well as by some other means, which basically is a combination of semiconductor and nanotechnic.Quantum dots can be used in solar cells instead of normal photovoltaic cell to improve theoretical efficiency up to 66%. This paper consists of background concepts, introduction to quantum dots, methods of production and theirvarious important applications. Also an important question "How Quantum Dots Could Double Solar Cell Efficiency" is discussed at the end.

***Keywords-** **Nanotechnic, Solar cell, Semiconductors, Photovolatic Cell**.*

● Theory:

Quantum dots are basically nano scaled portion of semiconductor materials, which

have electronic properties intermediate between those of bulk semiconductors and discrete molecules.

To know more in details about those quantum dots, we must 1st know all the basics things related to it. Most important background needed for this concept is semiconductors.

● Semiconductors:-

All materials have discrete energy bands in which electrons can exist. When no electrons are excited, they will be in lowest possible energy band, however, due to the Pauli Exclusion Principle, each energy band can only accommodate a finite number of electrons. For this reason, it is the outermost two energy bands, the valence band and the conduction band, which have the greatest effect on the material's electrical properties. The energy difference between these two states is referred to as the band gap energy. For an electron to change energy states, it must receive an amount of energy at least equal to the band gap energy.

When in its lowest energy, or ground, state semiconductors have a full valence band and empty conduction band and behave, electrically, exactly like an insulator. The difference is that semiconductor materials have much smaller band gap energies on the order of 1 eV. The band gap energy is low enough that it is possible for photons to excite electrons from the valence band into the conduction band. For a photon to excite an electron, it must have a minimum energy, ''hv'', equal to the band gap energy of the semiconductor in which case the photon is absorbed. A photon with energy less than the band gap cannot be absorbed by the semiconductor. Photodiode detectors are based upon this principle. When photons strike the semiconductor, electrons are excited into the conduction band where they are free to move. An induced potential is applied causing the electrons to flow in a photocurrent, which is then detected.

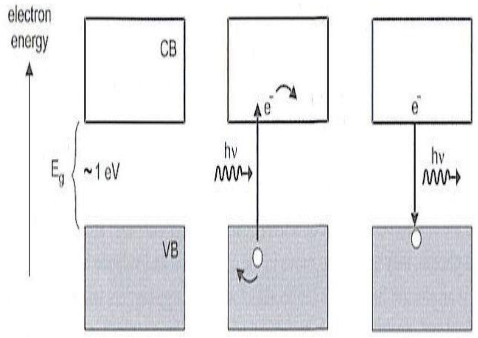


Figure 1: Semiconductor Energies

When an electron is excited into the conduction band, it leaves behind a hole, which can be treated as a positive particle. It is possible for a photon to have more energy than the band gap energy and still be absorbed, in which case the electron is excited from lower in the valence band to higher in the conduction band. This excess energy is lost, however, through inelastic collisions as the electron settles to the bottom of the conduction band and the hole rises to the top of the valence band. Since materials will always return to their ground state if possible, the hole and the electron will then recombine emitting a photon with energy equal to the band gap energy. A schematic of the energy band gap, a semiconductor absorbing a photon, and a semiconductor emitting a photon is shown above.

Due to the minimum energy required to excite an electron, at very long wavelengths, which correspond to low photon energies, the semiconductor will not be absorbent at all. However, as wavelength is decreased, there will come a point at which the material will suddenly begin to absorb.

● Quantum well :-

A quantum well is a potential well with only discrete energy values. Basically they are structures characterized by a region of low potential of width surrounded by essentially infinite potential, confining any and all particles within the well. By convention, the potential inside the well is set to zero.A practical example of quantum well is in the CD player. The laser that reads information of the discs is a quantum well laser and confines electrons by sandwiching materials together: simplistically, like a thin piece of capicolla between thick Italian bread (forming the quantum well). The electrons are confined to the thin piece of capicolla, and produce a really efficient laser! Keeping the middle layer thin is important to confining the electrons here.

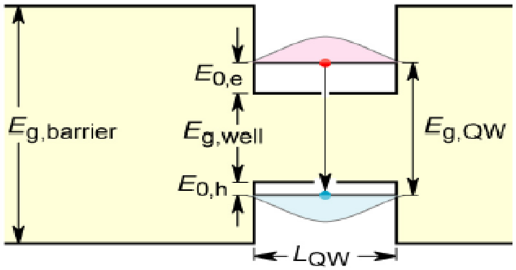


Figure 2: Basic concept of quantum well

● Quantum confinement :-

Quantum confinement is change of electronic and optical properties when the material sampled is of sufficiently small size - typically 10 nanometers or less. The bandgap increases as the size of the nanostructure decreases. Specifically, the phenomenon results from electrons and holes being squeezed into a dimension that approaches a critical quantum measurement, called the exciton Bohr radius.

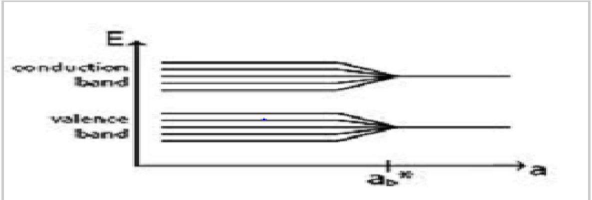
● INTRODUCTION TO QUANTUM DOT

A quantum dot is a portion of matter (e.g., semiconductor) whose excitons are confined in all three spatial dimensions. Consequently, such materials have electronic properties intermediate between those of bulk semiconductors and those of discrete molecules. They were discovered at the beginning of the 1980s by Alexei Ekimov in a glass matrix and by Louis E. Brus in colloidal solutions. The term "quantum dot" was coined by Mark Reed.

Quantum dots are semiconductor nanocrystals that exhibit unique optical properties due to a combination of their material band gap energy and quantum well phenomena, discussed above. Due to their extremely small size, on the order of a few nanometers, the dots behave similarly to three dimensional quantum wells. When an electron is excited by a photon striking the quantum dot, it behaves as a particle confined in an infinite potential well, since the electron cannot escape from the quantum dot.

It is experimentally observed that reducing the size up to nano level changes the basic structure as well as some properties of the material.Since no two nearby electrons can share the exact same energy level according to Pauli Exclusion Principle, leading to quantum confinement.

When the size of the quantum dot is smaller than the critical characteristic length called the Exciton Bohr radius, the electrons crowding lead to the splitting of the original energy levels into smaller ones with smaller gaps between each successive level. This phenomenon is better understood by this figure.



Splitting of energy levels for small quantum dots due to the quantum confinement effect. The horizontal axis is the radius, or the size, of the quantum dots and a_b^* is the Exciton Bohr radius.

The band gap can become smaller in the strong confinement regime where the size of the quantum dot is smaller than the Exciton Bohr radius (ab* in the figure) as the energy levels split up. Hence gap btween 2 band levels increases.

Generally, the smaller the size of the crystal, the larger the band gap, the greater the difference in energy between the highest valence band and the lowest conduction band becomes, therefore more energy is needed to excite the dot, and concurrently, more energy is released when the crystal returns to its resting state. For example, in fluorescent dye applications, this equates to higher frequencies of light emitted after excitation of the dot as the crystal size grows smaller, resulting in a color shift from red to blue in the light emitted. In addition to such tuning, a main advantage with quantum dots is that, because of the high level of control possible over the size of the crystals produced, it is possible to have very precise control over the conductive properties of the material.

Constituents:-

Typical dots are made of binary alloys such as cadmium selenide, cadmium sulfide, indium arsenide, and indium phosphide. Although, dots may also be made from ternary alloys such as cadmium selenide sulfide. These quantum dots can contain as few as 100 to 100,000 atoms within the quantum dot volume, with a diameter of 10 to 50 atoms.

Optical properties:-

An immediate optical feature of colloidal quantum dots is their coloration. While the material which makes up a quantum dot defines its intrinsic energy signature, the nanocrystal's quantum confined size is more significant at energies near the band gap. Thus quantum dots of the same material, but with different sizes, can emit light of different colors. The physical reason is the quantum confinement effect.

• PRODUCTION OF QUANTUM DOTS:-

One of the basic advantage of quantum dot technology is that it is very cheap to use practically. It can be produced easily by using some non-expensive raw materials. Production processes are also quite simple. Some of those processes are as follows.

▪ Colloidal synthesis:-

Colloidal semiconductor nanocrystals are synthesized from precursor compoundsdissolvedin solutions, much like traditional chemical processes. The synthesis of colloidal quantum dots is based on a three-component system composed of: precursors, organic surfactants, and solvents. When heating a reaction medium to a sufficiently high temperature, the precursors chemically transform into monomers. Once the monomers reach a high enough supersaturation level, the nanocrystal growth starts with a nucleation process. The temperature during the growth process is one of the critical factors in determining optimal conditions for the nanocrystal growth. It must be high enough to allow for rearrangement and annealing of atoms during the synthesis process while being low enough to promote crystal growth.

▪ Fabrication:-

Some quantum dots are small regions of one material buried in another with a larger band gap. These can be so-called core-shell structures, e.g., with CdSe in the core and ZnS in the shell or from special forms of silica called ormosil.

The main limitations of this method are the cost of fabrication and the lack of control over positioning of individual dots.

▪ Electrochemical assembly:-

Highly ordered arrays of quantum dots may also be self-assembled by electrochemical techniques. A template is created by causing an ionic reaction at an electrolyte-metal interface which results in the spontaneous assembly of nanostructures, including quantum dots, onto the metal.

▪ Cadmium-free quantum dots:-

Cadmium-free quantum dots are also called “CFQD”. In many regions of the world there is now a restriction or ban on the use of heavy metals in many household goods which means that most cadmium based quantum dots are unusable for consumer-goods applications A new type of CFQD can be made from rare earth (RE) doped oxide colloidal phosphor nanoparticles.

• APLICATIONS OF THE QUANTUM DOTS:-

Quantum dot is a new concept which is not extensively used yet, though it proves Itself a promising next generation resource. Now a days also we use them inmany applications specially in optical sector but quantum dots promises much more than what weare usingnow. There are amazing concepts based on quantum dot which can be used in early future. Some of its advantages are as listed below.

- **Photovoltaic devices:-**

Quantum dots may be able to increase the efficiency and reduce the cost of today's typical silicon photovoltaic cells. According to an experimental proof, quantum dots of lead selenide can produce as many as seven excitons from one high energy photon of sunlight (7.8 times the bandgap energy). This compares favorably to today's photovoltaic cells which can only manage one exciton per high-energy photon, with high kinetic energy carriers losing their energy as heat. Quantum dot photovoltaics would theoretically be cheaper to manufacture, as they can be made "using simple chemical reactions." The generation of more than one exciton by a single photon is called multiple exciton generation (MEG) or carrier multiplication.

- **Light emitting devices:-**

There are several inquiries into using quantum dots as light-emitting diodes to make displays and other light sources, such as "QD-LED" displays, and "QD-WLED" (White LED). In June, 2006, QD Vision announced technical success in making a proof-of-concept quantum dot display and show a bright emission in the visible and near infra-red region of the spectrum. Quantum dots are valued for displays, because they emit light in very specific gaussian distributions. This can result in a display that more accurately renders the colors that the human eye can perceive. Quantum dots also require very little power since they are not color filtered. Additionally, since the discovery of "white-light emitting" QD, general solid-state lighting applications appear closer than ever. A color liquid crystal display (LCD), for example, is usually powered by a single fluorescent lamp (or occasionally, conventional white LEDs) that is color filtered to produce red, green, and blue pixels. Displays that intrinsically produce monochromatic light can be moreefficient, since more of the light produced reaches the eye.

In optoelectronics, QDs are now being considered for a new generation of Light Emitting Diodes (LEDs); these devices, if compared with the standard ones used now, will be more energy-efficient and produce brighter colors.

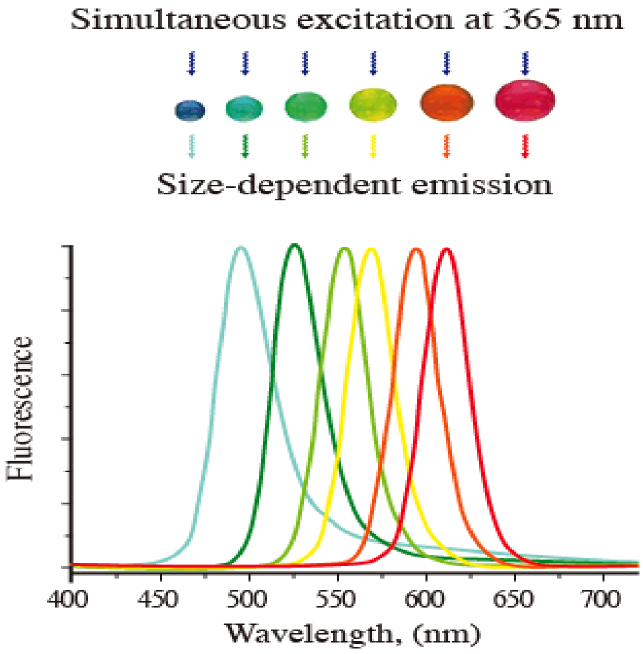


Figure 4: Showing mechanism that actually is used in "QD-LED" display

- **Optical properties of quantum dot used here:-**

Unlike atoms, a quantum dot fabricated from a given material has the unusual property that its energy levels are strongly dependent on its size. For example, CdSe quantum dot light emission can be gradually tuned from the red region of spectrum for a 5 nm diameter dot, to the violet region for a 1.5 nm dot. The physical reason for QD coloration is the quantum confinement effect and is directly related to the energy levels of quantum dot. The bandgap energy that determines the energy (and hence color) of the fluorescent light is inversely proportional to the square of the size of quantum dot. Larger QDs have more energy levels which are also more closely spaced, and this allows the QD to absorb photons of smaller energy (redder color). In other words, the emitted photon energy increases as the dot size decreases because greater energy is required to confine the semiconductor excitation to a smaller volume.

- **What happens in QD-LED**

A layer of cadmium-selenium quantum dots is sandwiched between layers of electron-transporting and hole-transporting organic materials. An applied electric field causes electrons and holes to move into the quantum dot layer, where they are captured in the quantum dot andrecombine, emitting photons. The spectrum of photon emission is narrow, characterized by its full width at half the maximum value.

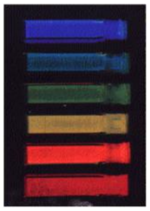


Figure 5. Solutions of quantum dots of varying size. Note the variation in color of each solution illustrating the particle size dependence of the optical absorption for each sample. Note that the smaller particles are in the blue solution (absorbs blue), and that the larger ones are in the red (absorbs red).

In a power generating paint:-

A team of researchers in the Notre dame university have made a major advance in this field by inventing this paint, which contains semiconducting Nano particles evolving to the development of solar paint. The material that is used in this paint is quantum dots. By making this Nano particle into a spreadable component they can be coated on to any surface without any special equipment. Nano sized particles of titanium dioxide, which were coated with either cadmium sulfide or cadmium selenide when these particles were suspended in a water-alcohol mixture to create a paste. When the paste was brushed onto a transparent conducting material and exposed to light, it created electricity.

This paint can be made cheaply and in large quantities. If we can improve the efficiency somewhat, we may be able to make a real difference in meeting energy needs in the future.

Biology

It has been estimated that quantum dots are 20 times brighter and 100 times more stable than traditional fluorescent reporters. Hence they can give much better results when used in technology instead of conventional dyes. It is possible to get clear and magnified picture of all the processes going on at the cellular level. As an example, the structure of cell seen with the quantum dots technology is given below.

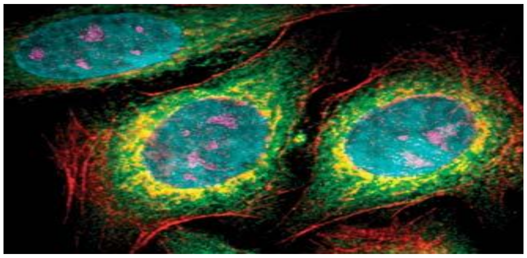


Figure 5: Cell structure seen with the help of quantum dots technology.

Computing:-

Quantum dot technology is one of the most promising candidates for use in solid-state quantum computation. By applying small voltages to the leads, the flow of electrons through the quantum dot can be controlled and thereby precise measurements of the spin and other properties therein can be made.

How Quantum Dots Could Double Solar Cell Efficiency:-

When it comes to turning sunlight into electricity, today's technology leaves lots of room for improvement. The most efficient solar cells on the market, which are made of silicon, convert less than 20 percent of the light that hits them into electricity, and the theoretical maximum efficiency of these cells is around 31 percent. One reason for this low efficiency is that much of the incoming light contains energy that is too high for solar cells to capture, so it's lost as heat. Now researchers have shown that it's possible to harvest that energy before it escapes, meaning that engineers could one day develop next-generation solar cells with efficiencies of up to 66 percent. The research, funded by the Department of Energy, is described in the June 18 edition of the journal Science.

When light hits a solar cell, a fraction of its energy is absorbed, exciting electrons in the cell's material and knocking them free. An electric field then forces the free electrons to flow in a specific direction, producing electric current. The energy that is absorbed is determined by the bandgap—a limited range of energies the cell's material can capture.

But sunlight is composed of particles, called photons, representing a very broad range of energies. The energy from photons too high to be absorbed takes the form of high-energy electrons—or, as scientists call them, "hot electrons"–and is lost as heat. However, if one could remove the hot electrons before they cool then you essentially shut down this heat-loss pathway, and you increase efficiency by more than a factor of two.

To accomplish this, the group of scientists used nanoscale materials known as quantum dots, who exhibit very different properties than their larger counterparts. For one thing, they can hold on to a hot electron for a longer period of time, stretching out the amount of time it takes for the electron to cool. In fact, previous research has shown that quantum dots can increase the lifetime of hot electrons by as much as 1000 times.

Once a hot electron is confined within a quantum dot, then comes the hard part: removing it so its energy can be harvested. The electron likes to stay inside thequantum dot, so we needed tofind something that would attract it out. For this role, the researchers chose titanium oxide, a well-studied compound known for its ability to accept new electrons.

LIMITATIONS OF QUANTUM DOTS:-

As we have now come across various concepts about quantum dots and there applications, lets now quickly see what are the limitations and drawbacks of quantum dots.

- Not enough technology available for complete utilization of the concept.
- Lack of knowledge.
- No effective method which can withdraw energy of excited electrons very efficiently.
- Cadmium used is poisonous and is harmful for health.
- Need of research.

production processes, they are really effective when it comes to conversion of solar energyinto electricity. We also have seen that use of quantum dots in displays makes the equipment more efficient.

By considering all those things, and many more what quantum dots offers we can conclude that they are really important in near future for electrical energy conservation as well as production. What we need to do is more and more research, improvement in technology, and effective utilization.

CONCLUSION:-

By knowing all the concepts above we can easily understand the importance of quantum dots. As we have seen that quantum dots are relatively cheap because of inexpensive raw material and production processes, they are really effective when it comes to conversion of solar energy into electricity. We also have seen that use of quantum dots in displays makes the equipment more efficient.

By considering all those things, and many more what quantum dots offers, we can conclude that they are really important in near future for electrical energy conservation as well as production. What we need to do is more and more research, improvement in technology, and effective utilization

REFERENCES

I . Quantum Dots: A Survey of the Properties of Artificial Atoms by T. Chakraborty
II. Quantum Dots by Lucjan Jacak, Pawel Hawrylak, Arkadiusz Wojs
III. Single Semiconductor Quantum Dots by Peter Michler
IV. Quantum Dots: Fundamentals, Applications, and Frontiers by Bruce A. Joyce
V. Handbook of Nanophysics: Nanoparticles and Quantum Dots by Klaus D. Sattler
VI. Non-Equilibrium Nano-Physics: A Many-Body Approach by Jonas Fransson