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## Review Article

# TUNNELLING IN SEMICONDUCTOR NANOSTRUCTURES: A REVIEW

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In this paper we describe the science of electron transport through nanostructured schemas. We describe here the fabrication and characterization of quantum dot semiconductors; and their improved electronic properties. The tunnelling of electrons through the semiconductor nanostructures helps us to control the transfer modes of electrons which provides us with the numerous advantages and new applications in the field of electronics.

**Keywords:** Quantum dots, Coulomb Blockade, Kondo effect, TEM, Non- Linear Transport, Single electron transistor

## INTRODUCTION

The electronic world is flooding with a substantial number of new devices coupled with an always growing test of making these as small and minimal as could be (Boutin Chad, 2002; Requist, 2013). Nanoscale science and building has reformed the logical and innovative advancements in nanoparticles, crystalline materials, nanodevices and frameworks (Mapa, 2005).

A quantum dot is a semiconductor nanostructure that limits the movement of conduction band electrons, valence band holes, or excitons in each of the three spatial directions, the electronic properties vary between that of bulk semiconductors and discrete particles (Reed, 1993; Brus, 2007; Norris, 1995; Kluson, 2007; Ghanem *et al.*, 2004). Demonstrating our

electronic material as a box permits us to disregard atoms and accept that the material is consummately homogeneous. We will consider confines distinctive measurements: 3-d (Bulk Materials), 2-d (quantum wells), 1-d (quantum wires), 0-d (quantum dot).

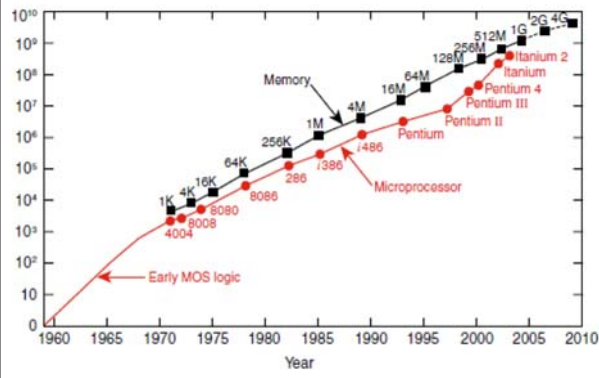
The electrons are confined to all three directions in Quantum dot (0-d) and there is no such k space to be filled with electrons, so we describe density of states for quantum dots with the delta function  $\delta$  (Liboff, 2003; Mark Lundstrom).

$$\rho_{energy} = 2 \sum_{nx,ny,nz} \delta(E - E_{nx,ny,nz}) \quad \dots(1)$$

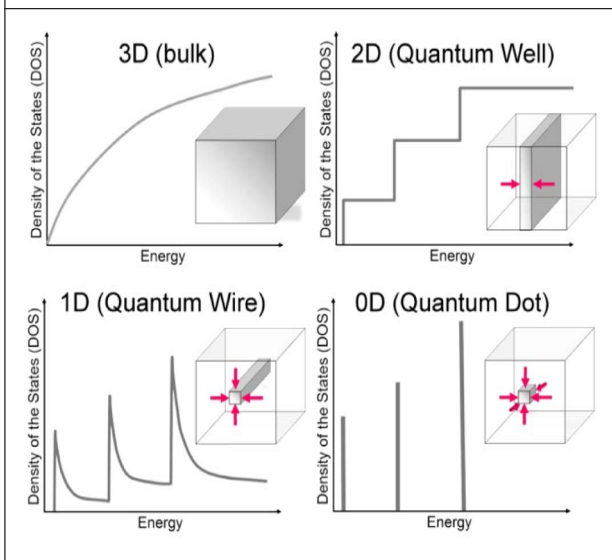
$E_{nx,ny,nz}$  are the confined energies of the carrier, characterized by the indices  $nx$ ,  $ny$ ,  $nz$ . The factor of 2 accounts for spin degeneracy.

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**Figure 1: Moore's law indicating to the exponential development in transistor thickness on a solitary chip (Harry, 2005)**



**Figure 2: Density of states with Energy for varying dimensions (Mino et al., 2013)**



By appending current and voltage tests to a quantum dot, it is conceivable to measure its electronic properties. In Figure 2 two quantum dot geometries are shown. The parallel dot is coupled to three terminals. Particle exchange can just happen with two of the terminals, as demonstrated by the arrows. These source and channel contacts interface the dot to the perceptible world. The third terminal serves as a gate electrode and is utilized to change the dot's electrostatic energy.

## FABRICATION OF QUANTUM DOTS

Different techniques like MBE (Molecular beam Epitaxy), RF (Radio Frequency) sputtering, LPE (Liquid Phase Epitaxy), etc., can be used to synthesize semiconductor quantum dots but the chemical route has been found to be the most attractive method due to its numerous advantages (Mohanta, 2003; Lee Jun Woo, 2005).

### Sol Gel Technique

Sol-gel techniques have been used for many years to synthesize nanoparticles including Qdots (Bang et al., 2006; Bera et al., 2008; Spanhel, 1991; Bera, 2008). In a typical technique, a sol is prepared using a metal precursor (generally alkoxides, acetates or nitrates in an acidic or basic medium). The three main steps in this process are hydrolysis, condensation and growth. The metal precursor hydrolyzes in the medium and condenses to form a sol, followed by polymerization to form a network (gel) of dots by changing the voltage on the terminal. This method has been used to synthesize II-VI and IV-VI Qdots, such as CdS (Sashchiuk et al., 2002), ZnO (Bang et al., 2006; Bera et al., 2008; Spanhel, 1991; Bera, 2008), PbS (Sashchiuk et al., 2002). As an example, ZnO Qdots have been prepared by mixing solutions of Zn-acetate in alcohol and sodium hydroxide, followed by control aging in air (Bang et al., 2006). The process is simple, cost-effective and suitable for scale-up.

### Evaporating Metal Gate Electrode (Figures 4 a-d)

First and foremost, a layer of organic resist (Poly-Methyl-Methacrylate, PMMA) is spun on top of the heterostructure. The gate pattern is defined by electron beam writing in the electron-sensitive

resist (Figure 4a) At the spots where the resist is uncovered, the polymers are broken. The uncovered parts are uprooted by a developer (result of methyl isobutyl ketone, MIBK, and isopropyl liquor, IPA), as indicated in (Figure 4b). In the following step, metal is vanished, which just reaches to the heterostructure at the spots where the resist has been uncovered and evacuated (Figure 4c). Thereafter is the removal of the remaining resist by acetone. Thus the metal on top of the resist is removed as well, the so-called 'lift-off' (Figure 4d).

**Dry Etching (Figure 4 e-h) (Harold, 1990)**

The Ion Beam Etching (IBE) is a physical dry etch process. Thereby argon ions are radiated onto the surface as an ion beam with about 1 to 3 KeV. Because of the energy of the ions, they strike out material of the surface. The wafer is held perpendicular or tilted into the ion beam, the etch progress is absolute anisotropic. The selectivity is low because there is no differentiation of the individual layers. The gas and the strike out material are exhausted by vacuum pumps, however, particles can deposit on the wafer or on chamber walls since the reaction products are not in gaseous state.

Quantum dots could be produced using a scope of materials, right now the most ordinarily utilized materials incorporate Zinc Sulfide (Wang, 2008), Lead Sulfide (Wang, 2008) , Cadmium Selenide (Hines, 2003) and Indium Phosphide

**CHARACTERIZATION OF QUANTUM DOTS**

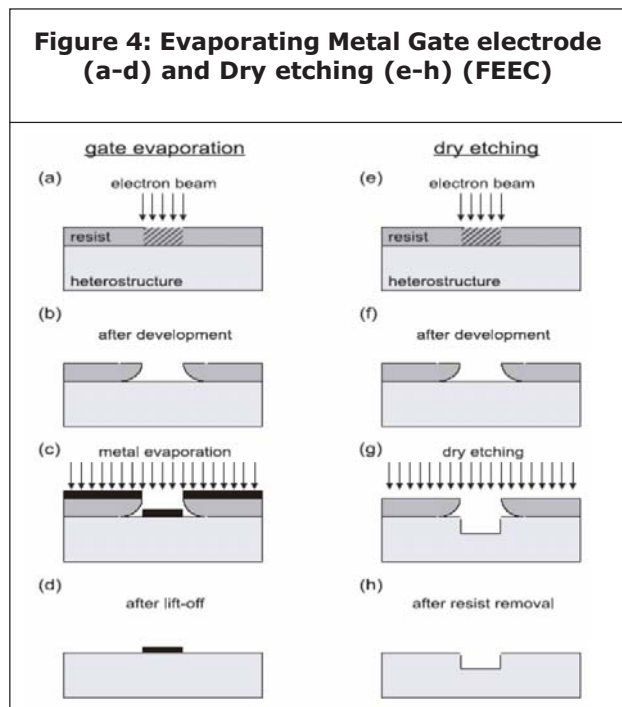
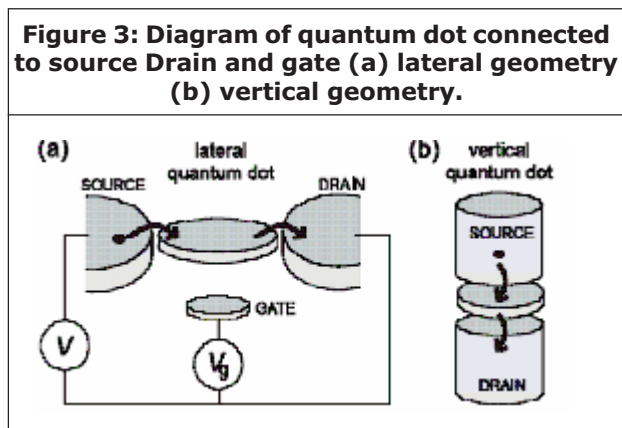
For the determination of the structural and chemical properties of nanosized objects like the QDs methods providing a lateral resolution of smaller than 1 nm have to be applied. A very well

suited method is Transmission Electron Microscopy (TEM) including all the modes of imaging, diffraction and spectroscopy. An extensive overview of the various methods is given (Williams, 1996) .

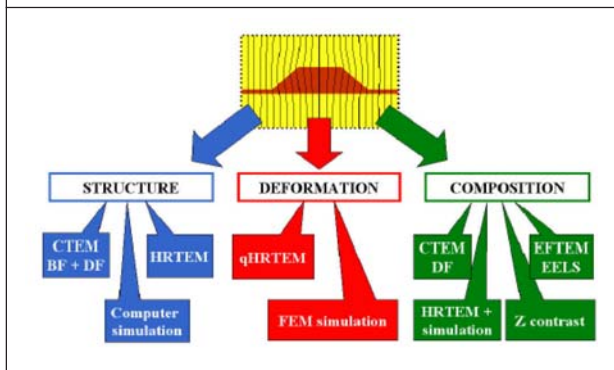
**ELECTRON TRANSPORT MECHANISMS**

**Coulomb Blockade and Single Electron Transistor**

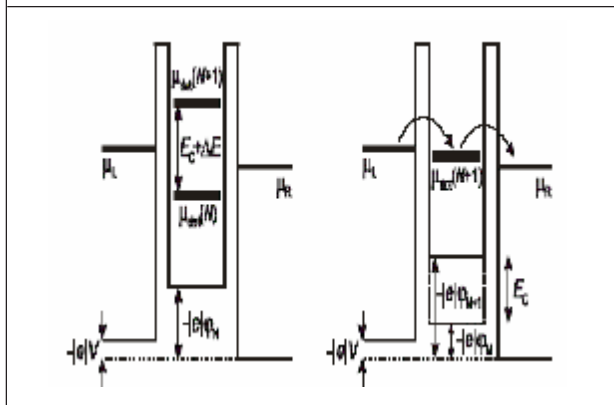
With reference to Figure 3 The Coulombic interactions among electrons in the dot, and



**Figure 5: TEM methods for investigation of QD properties (Williams, 1996)**



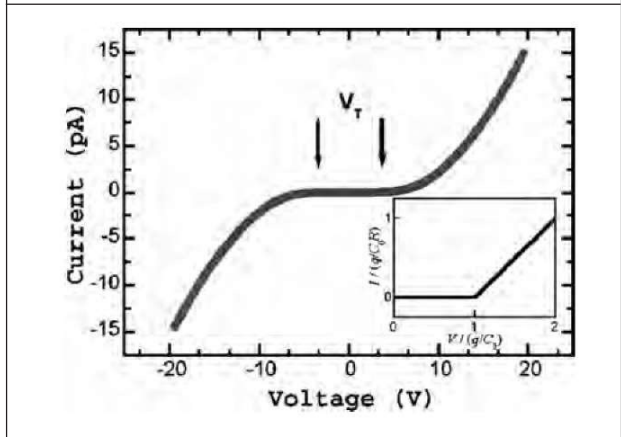
**Figure 6: Potential landscape of quantum dot**



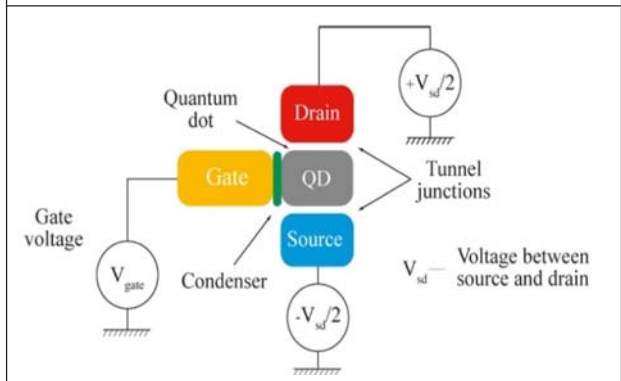
between electrons in the dot and those in the surrounding domain, are parameterized by a solitary, steady capacitance,  $C$ . This Capacitance is the combination of the three capacitors: capacitances between the dot and the left lead (source),  $CL$ , the right lead (drain),  $CR$ , and the gate,  $Cg$ :  $C = CL + CR + Cg$ . For small systems the capacitance may be so small that the charging energy  $e^2/2C$  is larger than temperature. The energy cost for tunnelling into the quantum system is then increased by  $e^2/2C$ , and lead to a Coulomb Blockade. The potential scene of a quantum dot along the transport direction is as shown in the Figure 6.

The minimum energy required to add an electron from source to Quantum dot or from

**Figure 7: Graph depicting the Coulomb Blockade Current-voltage (I-V) characteristic for a weakly coupled gold nanocrystal superlattice array at low temperature (12 K)**



**Figure 8: Single electron transistor (Arun et al., 2012)**



quantum dot to drain is  $\mu_L$  and  $\mu_R$  respectively. The electro chemical potentials of the leads are related to the bias voltage,  $V$ , by

$$-|e|V = \mu_L - \mu_R \quad \dots(2)$$

The net chemical potential for the quantum dot is

$$\mu_{dot}(N) = mch(N) + ejN \quad \dots(3)$$

The electrochemical potential is the sum of the chemical potential  $\mu_{ch}(N)$  and the electrostatic potential  $ejN$ . The electrochemical potential for adding the  $N^{th}$  electron to the dot,  $\delta\mu_{dot}(N)$ , lies below the lowest electrochemical potential of the leads (i.e.  $\mu_R$ ). The electrochemical potential for

adding the next electron,  $\mu_{\text{dot}}(N+1)$ , is separated from  $\mu_{\text{dot}}(N)$  by the addition energy,  $E_C + DE$ , which is higher than  $\mu_L$  so that the  $(N+1)^{\text{th}}$  electron cannot enter the dot. In this configuration the number of electrons on the dot,  $N$ , is fixed and transport through the dot is blocked (Coulomb blockade). Coulomb Blockade is an effect of the charge quantization. It is a consequence of sequential (non-coherent) tunnelling through a small system (Kouwenhoven *et al.*, 1991; Korotkov *et al.*, 1990, 1991; Meir *et al.*, 1991, Nagamune *et al.*, 1994; Glazman and Shekhter, 1989).

### Single Electron Transistor

Single electron tunnelling is the most clear impact of sequential tunnelling. At the point when one electron overcomes the charging energy and tunnels into the quantum system, it hinders the tunnelling of a second one since it would charge moreover the quantum system by a sum  $e^2/2C$ . The impact is that one electron tunnels at once. SET is a three-electrode tunnelling device that

consists of a conductive island with low self-capacitance connected to source and drain electrodes by low-capacitance and low conductance tunnel junctions and having a capacitive coupling with the gate electrode (Arun *et al.*, 2012; Om *et al.*, 2012; Amiza *et al.*, 2005).

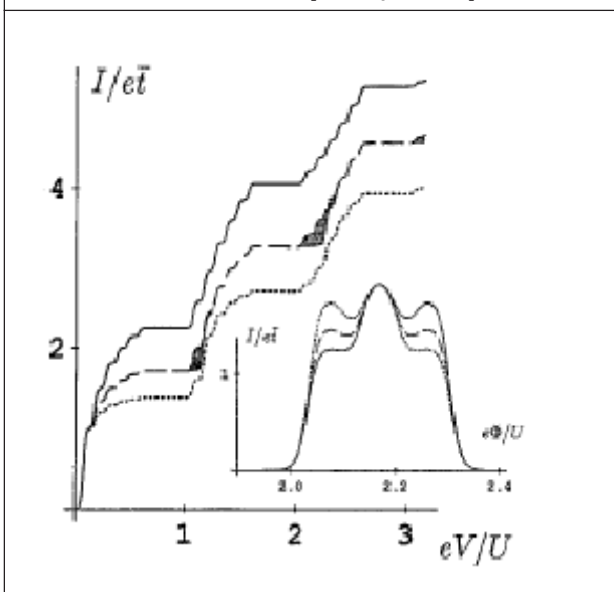
### Non Linear Transport

Periodic oscillations of the conductance through quantum dots that are feebly coupled to leads (Meiray, 1992) are well built results of the charging vitality of single electrons entering or leaving the dot at sufficiently low temperatures. They are observed in linear transport as a function of the carrier density. At bias voltages bigger than the contrasts between discrete excitation energies inside the dot, a characteristic splitting of the conductance peaks is observed (Johnson, 1992; Weis, 1992).

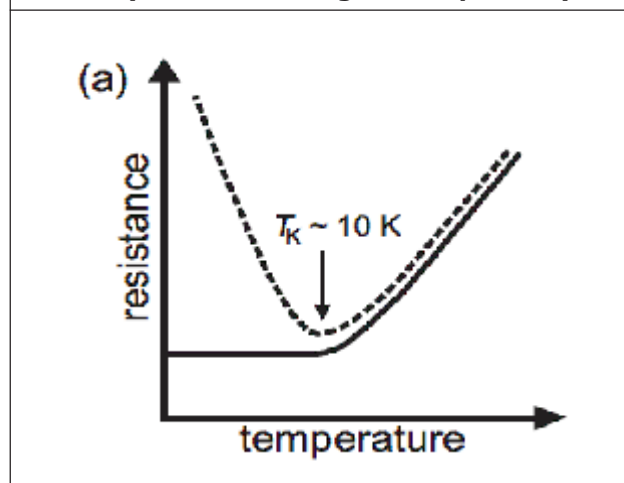
### Kondo Effect

The Kondo effect is an unusual scattering mechanism of conduction electrons in a metal due to magnetic impurities, which contributes a term to the electrical resistivity that increases logarithmically with temperature as the

**Figure 9: Non Linear Variation of Current and voltage relationship. The graph is a stepped Function. Splitting of conductance peaks is also shown (Pfaff, 1994)**



**Figure 10: Dependence of resistance on temperature. Solid Line (Metals) and Dotted Line (Metals with magnetic impurities)**



temperature  $T$  is lowered (as  $\log(T)$ ) (Gesa von Bornstaedt, 2005; Glazman and Raikh, 1988; Kouwenhoven and Marcus, 1998; Ng and Lee, 1988).

In a quantum dot, on the contrary, all the electrons have to travel through the device, as there is no electrical path around it. The Kondo resonance makes it easier for states belonging to the two opposite leads to mix. This mixing process increases the conductance, that is the Kondo effect produces the opposite behavior in a quantum dot to that of a bulk metal (Gesa von Bornstaedt, 2005; Glazman and Raikh, 1988; Kouwenhoven and Marcus, 1998; Ng and Lee, 1988).

Figure 11 represents the main characteristics of electron transport through a quantum dot, showing the Kondo effect. (a) Linear conductance,  $G$ , versus gate voltage,  $V_g$ . The solid curve is for  $T \ll T_K$ , the dotted curve for  $T < T_K$  and the dashed curve for  $T \gg T_K$ . The Kondo effect only occurs for odd electron number, resulting in the odd-even asymmetry between the different Coulomb valleys. (b) In the Kondo valleys the conductance increases logarithmically with

lowering temperature, saturating at  $2e^2/h$ . (c) The Kondo resonance leads to a zero-bias resonance in the differential conductance,  $dI/dV$ , versus bias voltage,  $V$  (*Handbook of Nanophysics*)

## APPLICATIONS OF QUANTUM DOTS IN ELECTRONICS

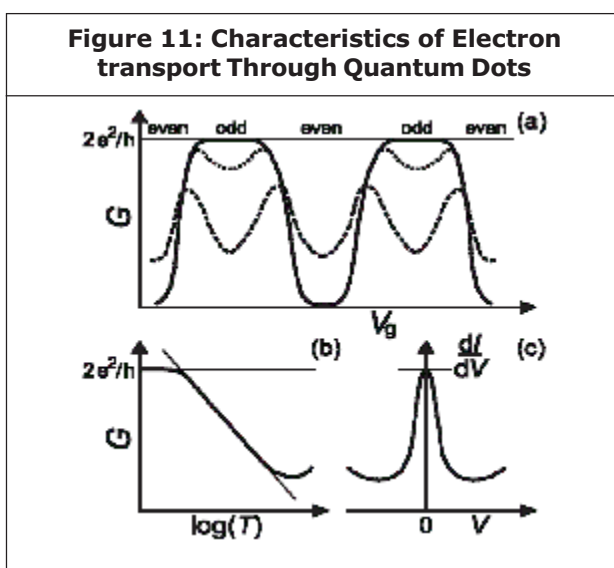
The unique size and structure tuneable electronic property of these small, semiconducting quantum dots make them extremely engaging for an assortment of uses and new innovations (Vahala, 2003).

### Logic Gates and Quantum Computers Using Quantum Dots

At the point when two unit cells, each one contained four or five quantum dots, are orchestrated neighboring one another, electrons move among the dabs in every unit cell and the state of each dot in the two cells is self-rulingly decided. Utilizing these, logic gates might be fabricated and Quantum Computing begins with designing of logic gates using Quantum Dots. Shor's algorithm allows extremely quick factoring of large numbers, a classical computer can be estimated at taking 10 million billion years to factor a 1000 digit number, where as a quantum computer would take around 20 min (Magazine articles).

### Quantum Dot Light Emitting Diodes

Quantum LED's are used to produce inexpensive quality white light. Quantum LED's are particularly engaging for their narrow bandwidth and basic color-tunability, since changing the span of a quantum dot transforms its discharge wavelength. Qleds, which frequently contain both natural and inorganic materials, might additionally have longer lifetime (Benzamin). The efficiency is also close to the theoretical maximum for any planar thin-film LED, which is 20%.



## Quantum Dot Dispersed Solar Cell

Greenham *et al.* made an inorganic-organic hybrid solar cell using a mixture of 5 nm CdSe Qdot in MEH-PPV polymer that was spin-coated onto an ITO/glass substrate and an Al cathode was deposited to complete the device. The energy conversion efficiency under monochromatic illumination at 514 nm (5 W/m<sup>2</sup>) was 0.2% (Greenham, 1997).

Where, ITO: indium tin oxide; MEHPPV: poly[2-methoxy-5-(2-ethylhexyloxy)-1,4 phenylenevin—ylene]; PEDOT:PSS: poly (3,4-ethylenedioxy-thiophene) poly(styrene-sulfonate); P3HT: poly-3(hexylthiophene)

## Quantum Dots in Optoelectronic Devices

III-V group semiconductors, such as InGaAlN, GaP, GaAs, InP and InAs, are very important for the development of optoelectronic devices as it is possible to engineer III-V Quantum dots simply by tuning the Quantum dot size and composition to emit anywhere from the IR to the UV (Williams, 2006; Pan, 2006). Nitride based Quantum dots have attracted enormous research interest because of their large built-in electric fields (Williams, 2006). Quantum dots can be controlled by size as well as the Arsenic and Phosphorus concentrations, and are important for fibre optic telecommunication systems (Barik, 2006).

**Table 1: Solar cells using Quantum Dots**

Q-dot size	Conversion Efficiency %	Device Structure	Reference
PbS: 4nm	0.7	ITO//PEDOT: PSS//PbS: MEHPPV//Al	62
CdSe/ CdS(7nm)	1.7	ITO//CdSe: P3HT//Al	63

## CONCLUSION

Selected characteristics of the structure, properties, application and performance of Quantum dots have been examined. Among the different extensions in nanotechnology, these zero measurement nanostructures have prepared for various advances in both fundamental and connected sciences. This is because of the way that the Quantum dot display altogether diverse optical, electronic and physical properties as contrasted with bulk materials. As for amalgamation of Quantum dots, noteworthy advancement has been made in investigations of the growth kinetics through both theoretical models and experimental data.

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