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Semiconductor Nanoparticles Theory and Applications

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Abstract

When the size of semiconductor materials is reduced, their physical and chemical properties change drastically, resulting in properties due to their large surface area or quantum size effect. Currently, semiconductor nanomaterials are still in the research stage, but they are promising for applications in many fields, light-emitting nano devices, laser technology, waveguide,. Further development of nanotechnology will certainly lead to significant breakthroughs in the semiconductor industry. This paper deals with the some of the current initiatives and critical issues in the improvement of semiconductors based on nanoparticles the efficiency of low dimensional system increases with decreasing size R of the semiconductor nanoparticles. It has been found that the size-dependence of the luminescence efficiency η

$$\eta = \frac{1}{(1+\beta R^2)}$$

Keywords: Semiconductors, Nanoparticles, Light Emitting nano Devices and Luminescence efficiency.

INTRODUCTION

Recently there has been substantial interest in the preparation, characterization and application of semiconductor nanoparticles that play a major role in several new technologies. When the size of semiconductor materials is reduced to nanoscale, their physical and chemical properties change drastically, resulting in unique properties due to their large surface area or quantum size effect. The conductivity of the semiconductor and its optical properties (absorption coefficient and refractive index) can be altered. Semiconductor nanomaterials and devices are still in the research stage, but they are promising for applications in many fields, such as solar cells, nanoscale electronic devices, light-emitting diodes, laser technology, waveguide, chemical and biosensors, packaging films, superabsorbents, components of armor, parts of automobiles, and catalysts. Further development of nanotechnology will certainly lead to significant breakthroughs in the semiconductor industry many kinds of diodes including the light-emitting diode, the silicon controlled rectifier, and digital and analog integrated circuits. Some of the semiconductor nanomaterials such as Si, Si-Ge, GaAs, AlGaAs, InP, InGaAs, GaN, AlGaN, SiC, ZnS, ZnSe, AlInGaP, CdSe, CdS, and HgCdTe etc., exhibit excellent application in computers, palm pilots, laptops, cell phones, pagers, CD players, TV remotes, mobile terminals, satellite dishes, fiber networks, traffic signals, car taillights, and air bags. The aim of this review is to overview and highlights the applications of semiconductor nanoparticles and synthetic methods. Most semiconducting materials, such as the II-VI or III-VI compound semiconductors show quantum confinement behavior in the 1-20 nm size range. Herein we describe and discuss the current use of semiconductor nanoparticles and their applications.

Size reduction affects most of the physical properties (structural, magnetic, optical, dielectric, thermal, etc.) due to surface effects and quantum size effects. Owing to the extremely small dimensions, these materials exhibit properties, which are fundamentally different from, and often superior to those of their conventional counterpart. In recent past, there has been considerable interest in the study of size effect in semiconductors of reduced dimension (in nanometer scale) due to their applications in optoelectronic devices, single electron devices, resonant tunneling devices, memory devices, magnetic sensors, catalysis, etc. [1-5] Optical spectroscopy being the non-contact method, has proved to be the most suitable technique to monitor the size-evolution of the electronic structure.

SEMICONDUCTOR NANOPARTICLES AND CLASSIFICATIONS OF SEMICONDUCTOR NANOSTRUCTURES

Semiconductor nanocrystals (NCs) are made from a variety of different compounds. They are referred to as II-VI, III-V or IV-VI semiconductor nanocrystals, based on the periodic table groups into which these elements are formed. For example, silicon and germanium are group IV, GaN, GaP, GaAs, InP and InAs are III-V, while those of ZnO, ZnS, CdS, CdSe and CdTe are II-VI semiconductors.

In nanocrystalline materials, the electrons are confined to regions having one, two or three dimensions (Fig. 1) when the relative dimension is comparable with the de Broglie wavelength. For a semiconductor like CdSe, the de Broglie wavelength of free electron is around 10 nm. The nanostructures of semiconductor crystals having the z direction below this critical value (thin film, layer structure, quantum well) are defined as 2D nanostructures. When the dimension both in the x and z direction is below this critical value (linear chain structure, quantum wire) the nanostructures are defined as 1D and when the y direction is also below this threshold (cluster, colloid, nanocrystal, quantum dot) it is referred to as 0D. Classifications of Semiconductor Nanostructures.

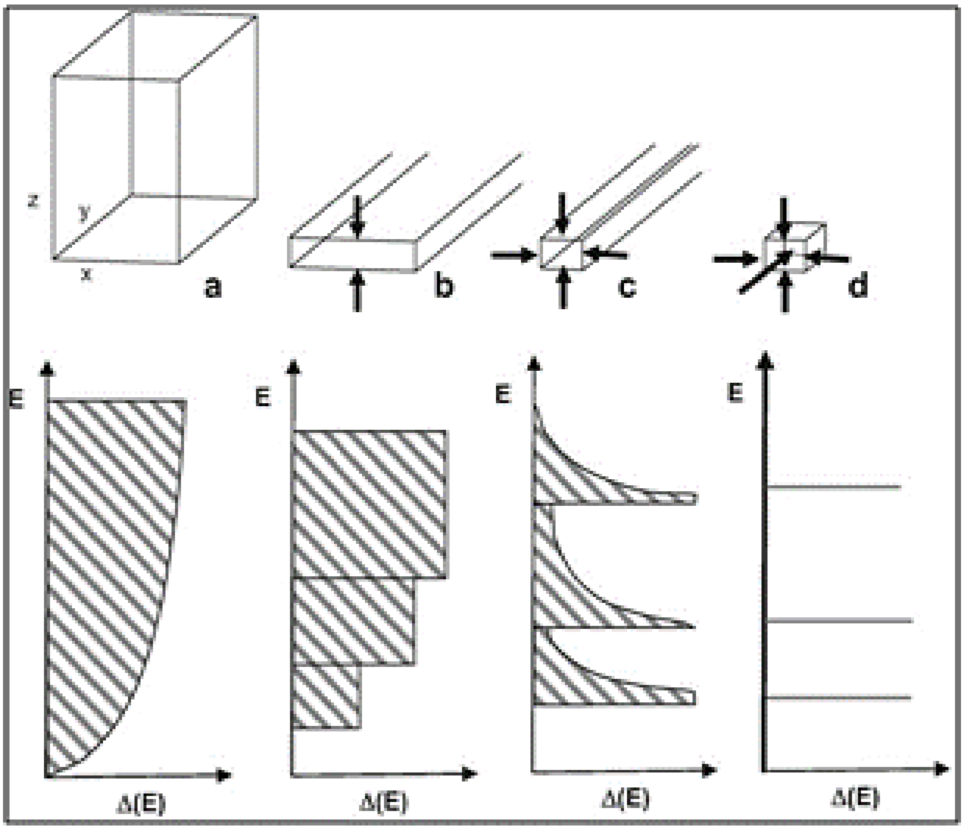

Figure 1. Schematic drawing to show the concept of system dimensionality: (a) bulk semiconductors (3D); (b) thin film, layer structure, quantum well (2D); (c) linear chain structure, quantum wire (1D); (d) cluster, colloid, nanocrystal, quantum dot (0D). In the bottom, the corresponding density of states[Δ(E)] versus energy (E) diagram (for ideal cases)

Quantum Confinement Effects

The quantum confinement effects in low dimensional semiconductor systems were studied two decades ago. In the last decade, comprehensive, well written reviews appeared which concentrated on the quantum confinement effects of various semiconductors with the emphasis on the optical properties, including absorption and luminescence[6-7]. Obviously, the confinement of an electron and hole in nanocrystals significantly depends on the material properties, namely, on the Bohr radius a_B. These effects take place in bigger nanocrystals and depend on the material properties, namely, on the Bohr radius a_B = 2.34 nm and a_B of about 10 nm, which would have Cd related compounds such as CdTe, CdZnTe and CdTeSe. One of the most important consequences of the spatial confinement effect is an increase in the energy of the band -to-band excitation peaks (blue shift), as the radius R of a microcrystalline semiconductor is reduced in relation with the Bohr radius. Theoretically, the regimes of quantum confinement differ in their main electron-hole interaction energy, i.e., the Coulomb term and the confinement energy of the electron and hole and kinetic energy.

Organic Optoelectronic Materials and Devices

Much research has been focused on a series of highly functional organic molecules, such as organic optoelectronic materials with strong photoluminescence, nonlinear optical materials, and some important low molecular weight pharmaceutical materials, etc. First, is the design and synthesis of organic compounds with intended functions. Second, is to controllably prepare the corresponding nanomaterials through various pathways, followed by structure characterization and theoretical calculation/simulation, to analyze the relationship between the lattice structure and nanostructure. Third, by investigating the differences between organic nanomaterials and bulk or molecular state materials in their optical, electronic, catalytic, chemical and sensor-related properties, try to discover the advantages of organic nanomaterials, construct the nanodevices and explore their practical applications. Organic optoelectronics has developed into a new interdisciplinary research field, involving organic chemistry, physics, electronic engineering and materials science. Organic optoelectronic devices, such as organic electroluminescent devices (OLED), organic photovoltaic (OPV) and organic thin film transistors (OTFT), have attracted significant attention in academics and industries, due to their great application potential in flat-panel and flexible display, solid-state lighting, information transport and storage, new generation energy, photocatalyst and so on. Owing to the advantages of solid-state, self-emission, full color capability and flexibility, OLED has been recognized as one of the most promising flat-panel display technology and has just become into commercial.

THEORY OF SEMICONDUCTOR NANOPARTICLES

In bulk crystalline ZnS:Mn, the partially spin-forbidden Mn^{2+} $^4T_1 \rightarrow ^6A_1$ transition has a lifetime of 1.8 ms at room temperature. In ZnS:Mn of 3nm size there are two lifetimes τ_1=3.7ns,τ_2=20.5nsIn ZnS : Cuλ_{em}=480nm, τ_1=2.9ns, τ_2=20.5ns, , two different recombination centers may be involved in nanoparticles firstly the recombination centers lying on surface and secondly the recombination centers lying inside the bulk.

To interpret these observation it is suggested that the hybridization of s-p electron state of host with the d-electron state of Mn^{2+}, is caused to a significant extent by the spatial overlap of these states owing to the confinement.

The luminescence efficiency η may be expressed as:

$$\eta = \frac{\alpha_r}{\alpha_r + \alpha_{nr}} \qquad ...(1)$$

α_r and α_{nr} are radiative and non-radiative rates, respectively.

The radiative recombination takes place at the surface. Thus, α_{nr} should depend on the number of surface atoms per units volume and it may be expressed as:

$$\alpha_{nr} \propto \frac{4\pi R^2}{\frac{4}{3}\pi R^3} \qquad \propto \therefore \frac{1}{R} \qquad .....(2)$$

α_r should depend on the number of Mn^{2+} at Zn^{2+} sites. In case of a single Mn^{2+} ion within a nanocrystal may expressed as:

$$\alpha_r \propto R^{-3} \qquad ....(3)$$

Thus from Eqs (1), (2) & (3) we get:

$$\eta = \frac{\frac{C_1}{R^3}}{\frac{C_1}{R^3} + \frac{C_2}{R}} \qquad = \frac{1}{(1 + \frac{C_2}{C_1} R^2)}$$

$$\eta = \frac{1}{(1 + \beta R^2)} \qquad ....(4)$$

where $\beta = \frac{C_2}{C_1}$

Fig. (2) shows the size dependence of the luminescence efficiency of ZnS:Mn nanoparticles. It is seen that the dependence of η or R of Eq (4). To performs this experimental [4] precipitated, nanocrystalline Zns powder by reacting diethylzinc with hydrogen sulfide in toluene to form ZnS.Bulk ZnS is usually doped by thermal diffusion at high temperatures [>1100°C] but since nanocrystallits sinter at extremely low temperatures, they must be doped during precipiation. To dope the ZnS: Manganese chloride is reacted with ethyl magnesium chloride to form diethylmanganese in a tetrahydrofuran solvent and added to the reaction. The separation of the particles is maintained by coating with the surfactant methacrylic acid. In the coated ZnS:Mn particle system a gradual but significant increase is observed in the luminescent intensity of Mn^{2+} emission when exposed to exciting 300nm UV light (UV curing) and the photoluminescent efficiency of 27-33Å ZnS:Mn nanocrystalline powder is about 18% at room temperature.

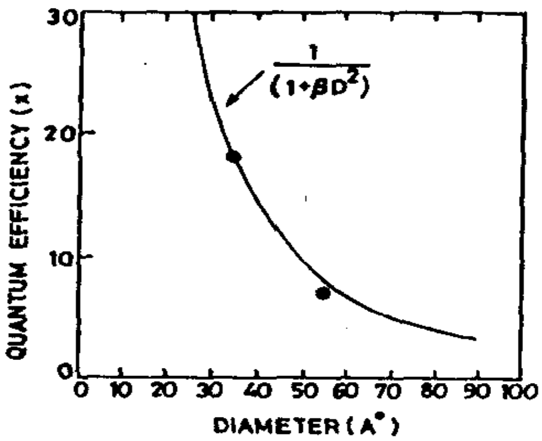

Fig. 2 Variation of luminescence quantum efficiency of ZnS: Mn^{2+} nanocrystals as a function of the radius. The solid line represents the equation 1/(1+βR^2).

Application of Semiconductor Nanomaterials

Semiconductor nanomaterials have interesting physical and chemical properties and useful functionalities, when compared with their conventional bulk counterparts and molecular materials. Narrow and intensive emission spectra, continuous absorption bands, high chemical and photobleaching stability, processability, and surface functionality are among the most attractive properties of these materials. The development of "nanochemistry" is reflected in an immense number of publications on the synthesis of semiconductor nanoparticles[8]. For instance, the spatial quantum confinement effect results in significant change in optical properties of semiconductor nanomaterials. The very high dispersity (high surface-to-volume ratio), with both physical and chemical properties of the semiconductor has a major influence on their optical and surface properties. As a result, semiconductor nanomaterials have been the focus of research for about 20 years and have attracted significant interest in research and applications in diverse disciplines such as solid-state physics, inorganic chemistry, physical chemistry, colloid chemistry, materials science, and recently biological sciences, medical sciences, engineering, and interdisciplinary fields. Among the unique properties of nanomaterials, the movement of electrons and holes in semiconductor nanomaterials is primarily governed by the well-known quantum confinement, and the transport properties related to phonons and photons are largely affected by the size and geometry of the materials[9-12]. The specific surface area and surface-to-volume ratio increase drastically as the size of the material decreases[9, 13]. Parameters such as size, shape, and surface characteristics can be varied to control their properties for different applications of interest[14]. These novel properties of semiconductor nanomaterials have attracted significant attention in research and applications in emerging technologies such as nanoelectronics, nanophotonics, energy conversion, non-linear optics, miniaturized sensors and imaging devices, solar cells, catalysis, detectors, photography biomedicine etc., In this section we discuss the application of semiconductor nanomaterials in catalysis and medical sciences.

CONCLUSIONS

Semiconductor nanomaterials are advanced materials for various applications, which have been discussed at length. The unique physical and chemical properties of semiconductor nanomaterial make it suitable for application in emerging technologies, such as nanoelectronics, nanophotonics, energy conversion, non-linear optics, miniaturized sensors and imaging devices, , detectors, photography. The purification and size selected techniques developed can produce nanocrystals with well-defined structure . the luminescence efficiency of ZnS:Mn nanocrystals increases with decreasing size R and follows the relation :

$$\eta = \frac{1}{(1+\beta R^2)}$$

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