Optoelectronic devices-application of Nanotechnology-a review

S. S. Manaktala, K. M. Singh

Abstract— This paper is a review of fundamental principle of optoelectronics and its applications , nanotechnology and its growth are highlighted. Various properties of Nanomaterial for development of optoelectronics have been studied. Nanomaterial fabrication techniques are studied also the effect of nanonmaterial alloys on improvement of quantum efficiency is studied. Limitations of nanotechnology for optoelectronics devices as well future optoelectronic is also discussed in the paper.

Index Terms—Nanomaterial, Quantization, Semiconductor, Optoelectronics, Quantum Efficiency

---

1 INTRODUCTION

In recent year with the invent of molecular beam epitaxy, metal organic chemical vapor deposition and other experimental techniques, low dimensional structures having quantum confinement in one two and three dimensions have revealed new phenomenon in the nanoscience and technology. The classical laws of physics and chemistry do not readily apply at this very small scale for two reasons. Firstly, the electronic properties of very small particles can be very different from their larger cousins. Secondly, the ratio of surface area to volume becomes much higher, and since the surface atoms are generally most reactive, the properties of a material change in unexpected ways. For example, when silver is turned into very small particles, it takes on anti-microbial properties while gold particles become any color you choose. Photonic semiconductor devices like LED, Laser Diode, Photodiode, Solar Cell are used for various applications in electronics and communication industry.

Nanostructure science and technology is a wide area of research which involves various disciplines of science and technology. It has greatly contributed to the worldwide growth over the years.

• *S. S. Manaktala is currently working as associate profrssor in electronic engineering in JECRC, Jaipur, 302022. E-mail: ssmanaktala.ece@jecrc.ac.in*

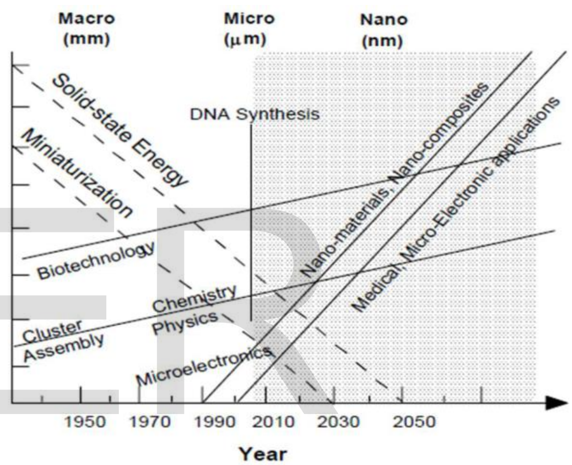

Fig 1:Evolution of science and techology and future[1]

Nano scale materials are those objects where the dimensions if measured then at least one dimension is less than nearly 100 nanometers. A nanometer is measured as one millionth of a millimeter -Which is almost 100,000 times thicker than the diameter of a human hair. Nanomaterial generate huge interest for researchers as at Nano size of substances distinguished optical, magnetic, electrical, and other properties are surfaced. These newly highlighted properties have the ability for great impacts in electrical, electronics, medicine, and other fields.

Fig 2:Nanomaterial for Example (Carbonnanotube) [1]

In the previous decade, nanostructured materials and nanoparticles have been emerging as the necessary ingredients for electro-optical applications and enhancement of device performance by using of the light management aspects of the nanomaterials. Some application areas which are transformed profoundly by use of nanomaterials includes smart coating devices (e.g., photochromic, electrochromic, and thermochromic devices), solar energy, and sensing[2].

The two main reasons for distinct behavior of materials at the Nano scale are increased relative surface area and new development in quantum effects. Nanomaterial has greater chemical reactivity due to much greater surface area to volume ratio as compared to their conventional sized material, hence adversely affects their strength. Quantum effects play an important role at the nano scale in determining the materials properties and characteristics, which results in novel magnetic, electrical and optical behaviors. Nanotechnology provides the greater surface area to volume ratio than their conventional- design, the production and application, the Manipulation, the building, the properties-responses and functionality of structures, by controlling the shape and size, and devices and systems of the order or less than 100 nm [18]

Nanotechnology is an emerging technology as researchers have seen great prospect into advancement of already established products by applying nanotechnology principles and developing wide range of new applications. Application areas of Nano sciences and Nano engineering lie in the fields of pharmaceutics, advanced materials, electronics, cosmetics, packed food, chemical engineering, precision mechanics, optics, energy production and storage , and environmental sciences.

Nanotechnology is a dynamic and emerging field where more than 50,000 nanotechnology articles have been published annually worldwide in recent years. European Patent Office have got more than 2,500 patents filed [18].

Nanotechnology can be instrumental in solving serious humanity problems such as energy Sufficiency, climate change or dreaded diseases:

The world's desire for energy is rapidly growing while at the same time problem of critical environmental issues as well as dwindling resources is emergent. To manage this situation new means to produce, transport, store and consume energy in more efficient ways are required to be developed.

The amount of the current installed solar PV capacity, the continuous reduction in cost of installed PV systems, and the continuous reduction in cost of PV generated electricity are the three factors that have established fact that PV technology is no longer a pure research area, PV technology is a very important method to generate green electricity for meeting the requirements of rich and poor all over the world [3].

Nanotechnology promises to be the handy tool which will solve our problem and provide necessary assistance. Designing and developing new innovative material properties on the Nano scale have enables new applications and solutions. Energy-efficient LED lights, low friction nano lubricants, new nanomaterial for thermal insulation, and lightweight Nano composites on the market. This is just the beginning [15].

Nanotechnologies will be able to revolutionize the entire field of energy from usage to supply, conversion and storage. Improvement in energy efficiency is the need of hour.

2 Methods And Principles Of Nanotechnology

Unique Nanostructures

Nanostructured material which is the main building block of unique nanostructures was first used by Romans in fourth century AD to decorate royal cups and glasses. They have made glass using bulk gold metal film and gold colloidal film. Most of the visible part of the electromagnetic spectrum and very strongly in the IR and at all longer wavelengths are absorbed by the thin, bulk gold metal film. It dips slightly near 400–500nm, it appears blue due to the weak transmission of light in this wavelength when held up to the light[18].

Noble metals resonate in the visible or infrared area of the electromagnetic spectrum. Decoration of the glass is guided by visible properties of the spectrum. Glass matrix has metallic particles whose electrons are excited due to light effect, blue and green light are absorbed and scattered by the cup which is relatively shorter wavelength of electromagnetic spectrum. In reflected light effect greenish appearance is given by cup where as if white light source is placed ,long wavelength phenomena scatters red color as it absorbs the shorter wavelength only.

Size Dependence

Nobel metals and other such as Gold can behave uniquely at nanostructured stage only because their optical and electronic properties are governed by quantum confinement in nanoparticles. Electrons can move freely in bulk size semiconductor within the range of few hundred nanometres.as defined by Bohar radius. There is separation between the conduction and valance band by energy gap for bulk semiconductors. But when size is reduced to quantum dot stage(Nano scale), excitations cannot move freely discrete atomic states that are determined by quantum dot radius appear. Semiconducting Quantum Dots have many similar characteristics to bulk semiconductors and because of their small size their Exciting Bohar radius is confined [4]. When size of bulk material is reduced to nanometer size quantum mechanical characteristics of the electron contribute to its behavior such that it dominates physical properties. Electrons are confined in all the three dimensions.

Surface effect also dominates at Nano crystal size. When size of a crystal is reduced from 30 to 3 nm, the number of atoms on its surface increases from 5% to 50%, it will begin to perturb the periodicity of the "infinite" lattice hence fewer direct neighbors than atoms in the bulk atoms at the surface will result in less stabilized than bulk atoms [18].

Metal NPs

Thermal and electrical conductivity of metal is determined by electron mean free path(MFP) which also determines color of the metal. General value of MFP is between 5-50 nm. Any

International Journal of Scientific & Engineering Research Volume 10, Issue 5, May-2019
ISSN 2229-5518

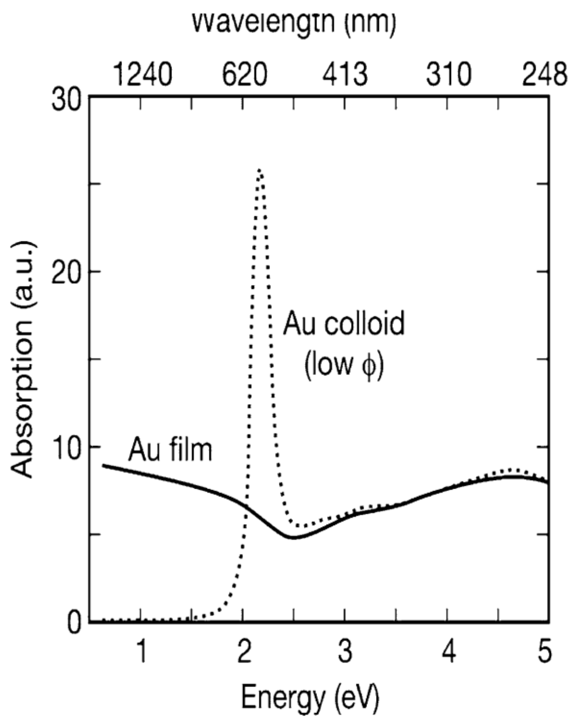

Fig 3: Absorption spectra of a gold Nano crystal film which absorbs only above 1.8 eV like a Semiconducting material due to the quantum confinement effect and a thin, bulk gold metal film of equivalent thickness which absorbs like a typical metal in the infrared energy region. _ is the volume fraction of gold in the sample [18]

reduction in the MFP value allows electrons to scatter of the crystal surface which results in increase of resistivity of metal particles. Change in state of conduction and valance band will occur for small particles at discrete level. For example gold particles such change results in change of gold color from red to orange at size around 1.5nm.

3 From Microelectronics To Nanoelectronics

Gordon Moore has predicted in 1965 that no of transistors to be fabricated over an IC is expected to be doubled in every two years, this prediction is well known as Moore's law in microelectronics. Development in microelectronics has reached to state that in 2010 Intel's processor exceeded 2,000,000,000 transistors [18].

The development is now approaching a dead end where the smaller and compact is no longer any faster. The main reason for this restriction in growth is amount of power dissipated is beyond limit and the heat generated in the process could not be handled at such microelectronic scale of semiconductor fabrication.

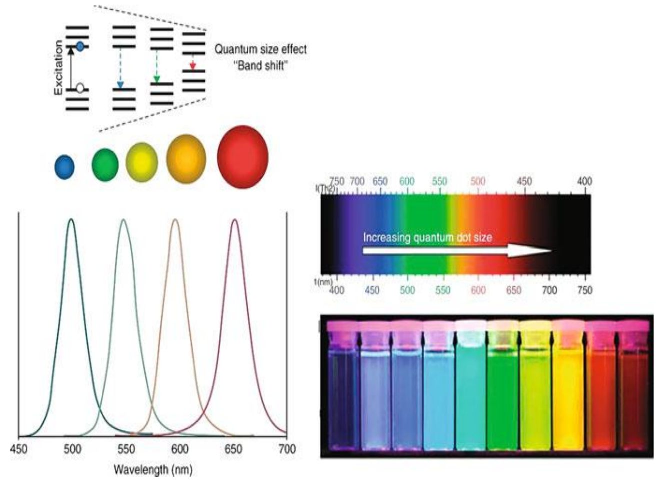

Fig 4: Schematic drawing representing the changes on optical behavior of nanoparticles Associated with their size. Top: Electronic structure of QDs with "blue shift" due to quantum confinement [18]

MOSFET which is preferred as transistor where we think of compact active device element is desired. Miniaturization is achieved by reducing channel length between source and drain for example the channel length which was made of silicon which was doped with n or p type of material was of 50nm in 2003 and has been reduced to 10nm today. Critical size limit usually called the lithographic limit does not allow feature size to be reduced below a physical limit in top down development model of MOS fabrication followed in microelectronics. Reduction of channel length is very critical as it results in more no of transistors over and IC or more no of logic gates ie increased processing power hence decrease in the response time for logic operations.

Nanoelctronic research has opened new dimensions where quantum –mechanical laws are more dominant such that Nano electronics will operate on quantum-principles [18].Thus nanoelectonics and microelectronics both provide different device and system level solutions. Three dimensional topology of nanostructured objects which are synthesized using bottom-up fabrication which demonstrate quantum concept and electomechnical principles.

Nano electronics thus provide path for absolute miniaturization also the bottom up solution approach of fabrication is more efficient than the conventional top down approach with given technical advancements.

4 Nanomaterial Alloys

Inorganic LEDs are light-emitting diodes (LEDs) made from a crystalline semiconductor. The optical emission wavelength can be selected by varying material composition. Example active regions include germanium, gallium arsenide, and gallium nitride and indium phosphide. Inorganic LEDS are prized for their low power consumption and are rapidly replacing conventional incandescent light bulbs.

Technololgical advancements for red and yellow color LEDs have been phenomenal in the decade that has completed . Researchers have been trying to develop LEDs in visible spectrum with shorter wavelength ie moving from green to violet but they are not very much successful yet.LEDs have been manufactured with SiC in II-VI compounds of materials like ZnSe .LEDs made with such composition have not been efficient also the lifetime of such devices is less as defect formation is easy.LEDs formed with III-V periodic table nitride materials , which has wurtzite crystal structure, which is strong and longer lifetime(eg.GaN , AlN, InN and their alloys) and also shown improved efficiency in shorter wavelength.Direct bandgap transition for 3.4 eV for GaN, to 6.2 eV for AlN at room temperature and has shown higher thermal conductivity . Alloys such formed of GaN have been useful for high-power and high-temperature electronic devices with short-wavelength (visible and ultraviolet) optoelectronic devices.

5 GAN LIGHT EMITTING DIODE

Blue LED made of p-n junction diode of III-nitride material with homojunction GaN LED was initially produced in year 1991.LED demonstrated an output power of 42µW at 20 mA at 430 nm wavelength.The color of blue light was due to dopant impurity of magnesium in p-GaN layer.Blue LED such formed was comparatively much higher efficient then SiC blue LEDs readily available in year 1991. Technological advancements in year 1993 shown the development of GaN double heterostructure LEDs at 440 nm operating wavelength and more then 100µW output power at bandgap of InGaN active region formation.

Commercial development of blue LED came into existence in year 1993 by Nichia Chemical Company. Impurity content of Zn-Si was introduced in InGaN active region to produce blue LED at 450nm wavelength The output power was as high as 1.5 mW, corresponding to an external quantum efficiency of 2.7% and a luminous efficiency of 2.1 lumens/watt.EQE referred to the no of photons produced per electron crossing the pn junction where as luminous efficiency is to measure response of human eyes towards LED input power.Greeen spectral is most sensitive for luminous efficiency where as sensitivity is least in ultraviolet or infrared region of spectrum Production of blue-green LED was possible around 490nm as it required slight changes in epitaxial growth process.Blue LED with Zn-Si dopent ,making blue-green was challenging as it led to noticeable wavelength shift in color also whitish appearance caused due to wide emission spectrum

Improved bright blue and green color LED were available first time in 1995. Second generation of LED was the result of modified SQW structure, which resulted in improved efficiency for blue-green LED.

LED/BEHAIOUR	Blue LED	Green LED
Output power	4.8 mw	3.0 mw
Wavelength	450 nm	525 nm
Luminous-efficiency	3.0 lumens/watt	22.0 lumens /watt

Thus such produced LED shown wavelength at 470nm – blue, 495nm-blue/green and at 525nm –green color at much higher values of efficiencies. Color of light is much pure compared to first generation of LED as spectral width is narrower to its earlier version. Shift in color is proportional to the operating current which is a challenge..

1- GaN optoelectronic properties make it suitable for high power applications such as making a violet laser without optical frequency doubling.

2- GaN applications include

Applications	Feature of GaN
• Solar Cell array for satellites	• Less sensitive towards ionizing radiation
• Miltry and Space applications	• Stable in radiation environment
• Good power amplifier at microwave frequency	• Can operate at high temperature and voltages

3. GaN is tough and strong and stable.mismatch in lattice consants is also no hurdle for its deposition in becoming crack resistant

4 GaN with a high crystalline quality can be obtained by depositing a buffer layer at low temperatures. Such high-quality GaN led to the discovery of p-type GaN, p-n junction blue/UV-LEDs and room-temperature stimulated emission (essential for laser action). This has led to the commercialization of high-performance blue LEDs and long-lifetime violet-laser diodes, and to the development of nitride-based devices such as UV detectors and high-speed field-effect transistors.

5. High-brightness GaN light-emitting diodes (LEDs) completed the range of primary colors, and made applications such as daylight visible full-color LED displays, white LEDs and blue laser devices possible. The first GaN-based high-brightness LEDs were using a thin film of GaN deposited via MOCVD on sapphire. Other substrates used are zinc oxide, with lattice constant mismatch of only 2% and silicon carbide (SiC). Group III nitride semiconductors are in general recognized as one of the most promising semiconductor family for fabricating optical devices in the visible short-wavelength and UV region.

6 LED PERFORMANCE PARAMETERS

LED performance can be majored using following parameters-

1- External Quantum Efficiency
2- Injection Efficiency
3- Internal Quantum Efficiency
4- Extraction Efficiency
5- Wall-Plug Efficiency
6- Feeding Efficiency

1- **External Quantum Efficiency (EQE)**
The ratio of the number of photons emitted from the LED to the number of electrons passing through the device - in other words, how efficiently the device coverts electrons to photons and allows them to escape.

EQE = [Injection efficiency] x [Internal quantum efficiency] x [Extraction efficiency]

2- **Injection Efficiency**
In order that they can undergo electron-hole recombination to produce photons, the electrons passing through the device have to be injected into the active region. Injection efficiency is the proportion of electrons passing through the device that are injected into the active region

3- **Internal Quantum Efficiency (IQE - also termed Radiative Efficiency)**
Not all electron-hole recombination are radiative. IQE is the proportion of all electron-hole recombination in the active region that are radiative, producing photons.

4- **Extraction Efficiency (also termed Optical Efficiency)**
Once the photons are produced within the semiconductor device, they have to escape from the crystal in order to produce a light-emitting effect. Extraction efficiency is the proportion of photons generated in the active region that escape from the device.

5- **Wall-Plug Efficiency (also termed Radiant Efficiency)**
Wall-plug efficiency is the ratio of the radiant flux (i.e. the total radiometric optical output power of the device, measured in watts) and the electrical input power i.e the efficiency of converting electrical to optical power.

Wall-Plug Efficiency = [EQE] x [Feeding efficiency]

6- **Feeding Efficiency**
Each electron-hole pair acquires a certain amount of energy from the power source when the LED is operating. Feeding efficiency is the ratio of the mean energy of the photons emitted and the total energy that an electron-hole pair acquires from the power source.

7 APPLICATIONS OF GAN LED

GaN-based violet laser diodes are very much used to read Blu-ray Discs. We can dope with a suitable transition metal such as manganese to get GaN as a promising spintronics material (magnetic semiconductors). We can make colorful LED with dopents considering the badgap in a range allowed. GaN HEMTs have been available commercially since 2006. They are having high efficiency and high voltage operation which makes them suitable for using in various wireless infrastructure applications. Higher frequency telecom and aerospace applications can be developed using second generation technology with shorter gate lengths.

GaN based MOSFET and MESFET transistors are used in automotive and electric car applications due to lower loss in high power electronics.

GaN-based electronics (not pure GaN) has the potential to drastically cut energy consumption in consumer applications and power transmission utilities.

8 FUTURE OF OPTOELECTRONICS

Nanotechnology gives new array of properties which are not possible with bulk material. Eric Drexler has written a book in 1981 with title “molecular manufacturing” and another book in 1986 with title “Engine of creations”. These books have given the direction to nanoscale manufacturing. Atomic manipulation of Xe atoms is done in 1989 at IBM.
In electronics size is very important. Nanoscale miniaturization will lead to reduction of effective electron path and reduction in

electron scattering which will lead to faster operation of electron devices but it will require more complicated manufacturing process and it will lead to increase in the fabrication cost.

Unusual properties are seen at nanometer size. For example- electrons which are delocalized becomes confined so the properties depending on localization of electron will change. Metal becomes non-metal due to this. Similarly reactivity will change due to change of surface to volume ratio. Disorder of dipoles increases with decrease of size which will result in transition from magnetic to nonmagnetic material. Different size of gold particles appears in different colors which can be explained with the help of nanoscience.

Electronic and optical properties of materials can be controlled by controlling their size and shape. III-V materials are being increasingly used in integrated optoelectronics, passive filter devices, distributed feedback lasers and Bragg reflectors.

In recent years, with the advent of MBE, MOCVD and other experimental techniques, the influence of quantization of band states on the different physical properties of nanostructured materials such as quantum wells, quantum well wires, quantum dots, inversion layers, magnetic quantization, and different field added dimensionally reduced systems. The influence of band structures on the physical properties of quantized structures is becoming increasingly important.

In recent years, development of the field of III-nitride (III-N) semiconductor technology has been spectacular.

Advantages of III-nitride	Direct band gap energies of 6.2 and 3.4	Cover spectra from UV to entire visible
	Stronger chemical bond	Makes nitride stable and resistant to degradation under strong and high current

Numerous GaN-based devices, including light emitting diodes (LEDs), laser diodes (LDs), photodetectors and high power microwave power switches have been developed and brought to market during the last several years. LEDs are used in various lighting applications, including flash lights, automotive lighting, traffic signals, TVs and very large displays, and they are now widely commercially available5. Other applications for blue LEDs include medical diagnostic equipment and photolithography. The future, especially for general lighting applications, is promising since white light can be produced by exciting wide band phosphors by blue or UV-LEDs. MOCVD is a non-equilibrium growth technique, which relies on vapor transport of the precursors and subsequent reactions of group-III alkyls and group-V hydrides in a heated zone

At DuPont used computational fluid dynamics (CFD) software to optimize coating processes for a new solution-coated AMOLED display technology that is competitive in cost and performance with existing chemical vapor deposition (CVD) technology. Using custom modeling and analytic approaches, Samsung has developed short and long-range film-thickness control and uniformity that is commercially viable at large glass sizes.

References

[1] A. Alagarasi, *Introduction to Nanometre* ,Chand S.Kumar(2015)
[2] Vo-Van Truong, Jai Singh, Sakae Tanemura, and Michael Hu4, Nanomaterials for Light Management in Electro-Optical Devices, open access article distributed under the Creative Commons Attribution (2012)
[3] Rajendra Singh, Githin F. Alapatt, and Akhlesh Lakhtakia, Making Solar Cells a Reality in Every Home: Opportunities and Challenges for Photovoltaic Device Design (2013)
[4] Lenore Kubie, Applying Nanotechnology to Solar Energy, University of Rochester ,June 1st, 2012
[5] Thomas Juehne, Sigma-Aldrich Corp., St. Louis, MO, Nanomaterials Yesterday, Today and Tomorrow (2015)
[6] Song Liu1 and Xuefeng Guo1,2, Carbon nanomaterials field-effect-transistor-based Biosensors, NPG Asia Materials (2012)
[7] Nishu Gupta, a and K.M.Gupta, Emerging Scope of Hybrid Solar Cells in Organic Photovoltaic Applications by Incorporating Nanomaterials, *Advanced Materials Research* Vol. 548 (2012) pp 143-146(2012).
[8] Henne van Heeren, Nano Materials (2005)
[9] Zaki Ahmad, Future Trends For Nanotechnology and the Application of Nanotechnology in Solar Cells, *Nanofibres, Sensors, Ultra Light Materials and Corrosion Prevention* (2013)
[10] The stationary officer, Using nanomaterial at work, Health and Safety Executive(2013)
[11] Vo-Van Truong, Jai Singh, Sakae Tanemura, and Michael Hu, Nanomaterial for Light Management in Electro-Optical Devices, *Journal of Nanomaterial* Volume 2012 (2012),
[12] Chun-Wei Chen, Nanomaterial in optics, electronics and energy applications, Department of Materials Science and Engineering ,National Taiwan University(2012)
[13] Jonathan Loeffler, Overview on Promising Nanomaterial for Industrial Applications, nanoRoad(2015)
[14] Prem Felix Siril, Nanotechnology and its application in renewable energy, School of Basic Sciences IIT Mandi (2010)
[15] David Arthur , Nano Connect Scan diva , Nanotechnology for Energy Applications(2014)
[16] Juh Tzeng Lue, Physical Properties of Nanomaterial, Encyclopedia of Nano science and Nanotechnology Volume X: Pages (1–46) (2007)
[17] Thomas Abraham, Nanotechnology and Nanomaterial-Application and global market research, Innovative Research and Products (iRAP)(2015)
[18] S. Logothetidis, Nanotechnology: Principles and Applications, *Nano Science and Technology*, DOI 10.1007/978-3-642-22227-6 1,
[19] © Springer-Verlag Berlin Heidelberg (2012)