

Recent Advances in Luminescent Nanomaterials for Solid State Lighting Applications

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Abstract: Nanotechnology has led to a profound paradigm shift after the developments in recent years and after being recognised as one of the most important areas of impending technology. Nanomaterials are the basis of newly emerging nanotechnologies for various applications in sensors, photonics, drug delivery, proteomics, biomolecular electronics, and homeland security. Luminescent nanomaterials have attracted great interest worldwide because of their unusual structural, optical and electronic properties as well as efforts to prepare miniaturised devices. By understanding and manipulating these properties, the performance of the resulting optical structure can be tailored for desired end-use applications. Luminescence nanoparticles have tremendous potential in revolutionizing many interesting applications in today's emerging cutting-edge optical technology such as solid state lighting. Solid-state lighting (SSL) relies on the conversion of electricity to visible white light using solid materials. SSL using any of the materials (inorganic, organic, or hybrid) has the potential for unprecedented efficiencies. The development of novel mercury-free inexpensive nanomaterials, that convert longer wavelength UV to blue light eventually into white-light and are eco-friendly with improved luminous efficacy, energy-saving, long-lifetime, and low-power consumption characteristics, is discussed. In this review, we present a general description of EL related to nanomaterials as the emitter and outlines basic research requirements that could enable solid-state lighting to achieve its potential. Continuing progress in the synthesis and purification of SSL materials are beginning to enable separation of extrinsic and intrinsic phenomena and improve device performance. This review mainly focuses on the basic mechanism, classification, synthesis and characterization of luminescent nanomaterials. The review also covers recent advances in lanthanide-based nanomaterials and photoluminescent nanofibers formed by combining electrospun polymeric nanofibers and quantum dots (QDs) for lighting applications. In spite of the remarkable scientific progress in preparation processes and applications of nanomaterials, they are still not widely used by the industry. Finally, we conclude with a look at the future challenges and prospects of the development of electroluminescence (EL) devices for lighting.

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1. Introduction

The increasing demand for energy-saving and environment-friendly lighting technology is driving the growth of the global solid state and other energy efficient lighting systems market. At present, 19% of global electric energy is consumed for illumination. It accounts for 1.9 GT of CO₂ emissions [1]. Therefore, high-efficiency lighting to significantly reduce global power demands becomes inevitably pressing. In the past decade, solid-state lighting based on III-nitride semiconductors has been considered to be a next-generation light source because they can directly convert electricity to light much more efficiently [2]. Lighting applications that use light-emitting diodes (LEDs), organic light-emitting diodes (OLEDs), or light-emitting polymers, are commonly referred to as solid-state lighting [3-7]. Solid-state lighting (SSL) is the direct conversion of electricity to visible white light using semiconductor materials and has the potential to be just such an energy-efficient lighting technology. By avoiding the indirect processes (producing heat or plasmas) characteristic of traditional incandescent and fluorescent lighting, it can work at a far higher efficiency.

Solid state lighting (SSL) based on semiconductor light-emitting diodes (LEDs) has the potential to have a dramatic global impact. There are approximately two billion people without access to electricity. These people use traditional fuels (e.g., kerosene or bio-mass) that degrade their environment and cost over 1500 times more per lumen-hour than the conventional lighting using electricity in developed countries. Solid-state lighting can be highly beneficial to developing countries by providing efficient lighting technology that can be implemented in small increments and that works well with small, micro-power systems (e.g., solar photovoltaic, small hydroelectric generators, etc.). If LED electrical-to-optical energy conversion efficiency goals of 50% or greater can be achieved, worldwide electricity consumption due to lighting could be decreased by more than 50%, and total consumption of electricity could be decreased by more than 10% [8].

Electronics technology is transforming the lighting market. The technological developments in the last decade made it possible for LEDs to be used in signal devices, like traffic lights and exit signs, and in some limited illumination applications, such as flashlights [9-10]. However, cutting-edge research now shows a bright future for solid-state lighting as the next generation of light sources for general illumination (from homes to commercial applications). Since lighting represents 20-30% of our electrical energy consumption, and since these new white light sources require ten times less energy than ordinary light bulbs, the use of efficient blue LEDs leads to significant energy savings, and hence of great benefit to mankind. Recently, *Akasaki, Amano and Nakamura* were rewarded 2014 Nobel Prize for Physics [11] for inventing a new energy-efficient and environment-friendly light source – the blue light-emitting diode (LED) which has enabled bright and energy-saving white light sources.

The market for world solid state as well as other energy efficient lighting systems is expected to grow to \$53,469.5 million in 2015[12]. Solid-state lighting is already successful in niche markets, such as those for architectural, security, industrial and entertainment lighting. Specialty markets justify the premiums paid for SSL by reaping the benefits of zero warm up; integrated data signalling; and the ability to generate pure colours by mixing red, green and blue, instead of using energy-wasting white-hot arcs with colour filters.

Why Solid-State Lighting?

Solid-state lighting is increasingly used in a variety of lighting applications because it offers many benefits, including:

- **Long life** — LEDs can provide 50,000 hours or more of life, which can reduce maintenance costs. In comparison, an incandescent light bulb lasts approximately 1,000 hours.
- **Energy savings** — 21% of electric energy used is in lighting and half of this energy can be saved by switching to efficient and cold solid-state lighting sources. The best commercial white LED lighting systems provide three times the luminous efficacy (lumens per watt) of incandescent lighting. Coloured LEDs are especially advantageous for coloured lighting applications because filters are not needed. Annual electrical energy savings would be 1.20 PWh (Peta = 10¹⁵). It is projected that financial savings from solid-state lighting might reach \$115 billion by year 2020.
- **Better quality light output** — LEDs have minimum ultraviolet and infrared radiation and are the most efficient sources of coloured light in almost entire visible spectral range.
- **Intrinsically safe** — LED systems are low voltage and generally cool to the touch.
- **Smaller, flexible light fixtures** — The small size of LEDs makes them useful for lighting tight spaces and for creating unique applications.
- **Durable** — LEDs have no filament to break and can withstand vibrations.
- **Environmental benefits**
 - Reduction of CO₂ emissions, 952 M tons, global warming gas
 - Reduction of SO₂ emissions, acid rain
 - Reduction of Hg emissions by coal-burning power plants
 - Reduction of hazardous Hg in homes.

Table 1: Comparison of various Light sources

<i>Light Source</i>	<i>Luminous Efficacy</i>	<i>Lifetime</i>
Incandescent bulb	16 lumens/watt	1000 hours
Fluorescent lamp	85 lumens/watt	10,000 hours
Today's white LEDs	30 lumens/watt	20,000 hours
Future white LEDs	150-200 lumens/watt	100,000 hours

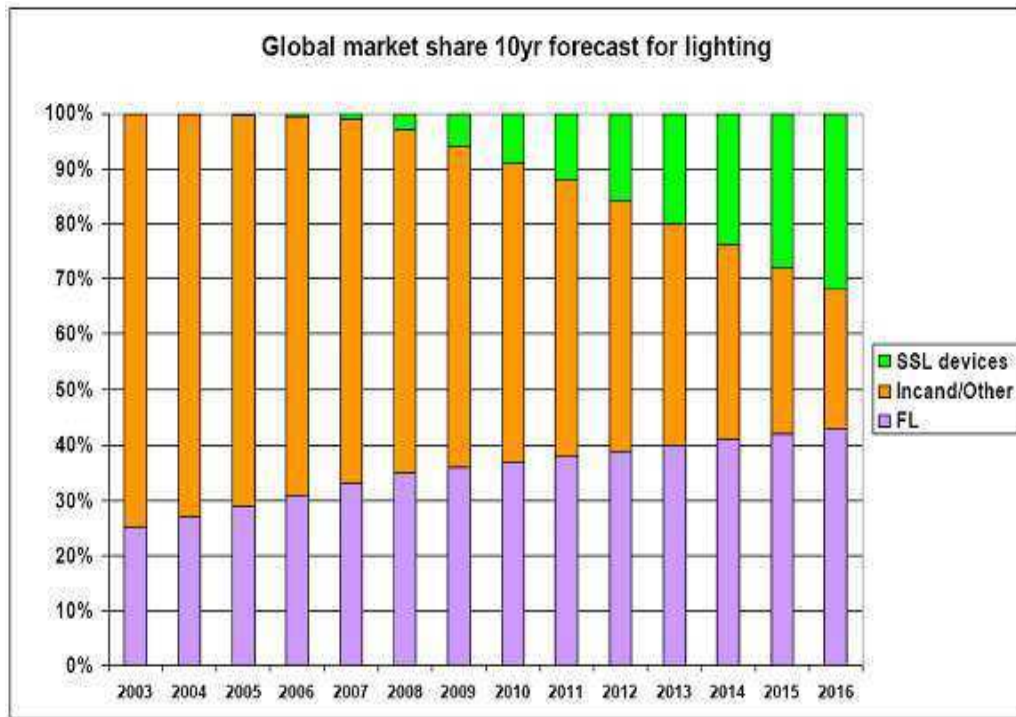
Solid-state lighting solutions such as LEDs and organic LEDs (OLEDs) seem perfectly placed to take over where the incandescent bulb leaves off. Today, LEDs already are being used in both functional and decorative light fixtures, where they offer a marked advantage in energy saving. Compared with incandescent lighting, LED-based lighting delivers visible light with reduced heat, and its solid-state nature provides greater resistance to wear, shock and vibration, dramatically increasing its life span.

Currently these most energy-efficient lights on the market – the light-emitting diode, or LED variety – are up to three times more expensive than their traditional counterparts. LED street lights can save money in the long run by consuming 50 to 80 percent less energy than conventional lighting products and virtually eliminate maintenance costs for up to 20 years. These benefits provide a 5-year payback in most cases [13]. Inorganic and organic white LEDs are shown in fig. 1.

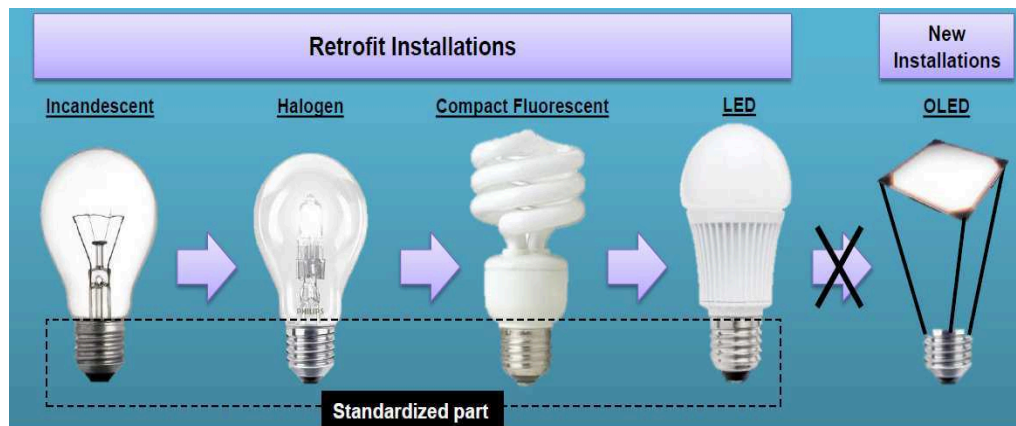


Fig. 1: Inorganic (left) & Organic (right) semiconductor white LEDs for solid state lighting.

The rapid growth in SSL technology is illustrated in fig. 2(a). Efficient semiconductor LEDs have the potential to replace both fluorescent and incandescent lights as the primary lighting source. They are potentially more efficient and more environmentally benign (no Hg) than these current lighting sources. In addition, semiconductor LEDs have unique properties that make them attractive for lighting applications—it is possible to electrically control the spectral properties of the light emitted and they can be arranged over large areas in various shapes for aesthetic purposes.



(a)



(b)

Fig. 2: (a) Progress in SSL devices [14], and (b) Lighting installations for traditional, inorganic LEDs and OLEDs. OLED panels unlike other lighting products require new installation.

The performance of solid-state lighting will need to be substantially improved. For example, improvements in materials and devices, and the physics that underlies them, are needed to improve the luminous efficacy and colour rendering quality of the white light. The cost of solid-state lighting will also need to be substantially reduced. This will require improvements in the manufacturing processes and materials. For example, improvements are needed in the processes used to deposit the active semiconductor layers of the LED in order to improve yields, increase throughput, and reduce overall capital and operating costs.

There are two basic kinds of semiconductor LEDs being explored for solid state lighting: inorganic semiconductor LEDs, and organic semiconductor LEDs. With the advent of high performance LEDs and the emergence of OLEDs for lighting, there is rapid evolution of new lighting systems that are designed to deliver improved illumination as well as new lighting features and services based on the electronically controllable properties of Solid State Lighting (SSL). Inorganic semiconductor LEDs use crystalline materials like GaN and organic semiconductor LEDs use disordered materials based on conjugated hydrocarbons (i.e., materials with double carbon-carbon

bonds), like the polymer poly-phenylene vinylene (PPV). Inorganic semiconductor LEDs make bright point light sources. At present inorganic LEDs are somewhat further developed than organic LEDs for solid state lighting applications. Organic light-emitting diodes (OLEDs), based on organic and/or polymer semiconductor materials, are promising candidates for general lighting applications, as they can cover large-area displays or panels using low-cost processing techniques. As an OLED is an area light device, the upgrade of OLEDs in existing luminaires would be difficult and many OLED advantages would be lost by such approach. Therefore, OLED general lighting market development will be driven almost exclusively by new lighting installations as illustrated in fig.2 (b).

Fig. 3(a) depicts the brief history of solid-state lighting (SSL): key materials and device breakthroughs and progress in efficiency was largely an outcome of the exploration and development of new semiconductor materials: first GaP and GaAsP, then AlGaAs, then, finally, AlInGaP. Luminous efficacies improved by more than three orders of magnitude: from about 0.02 lm/W in the 1970s from GaP and GaAsP LEDs; to 10 lm/W in 1990 from AlGaAs LEDs (for the first time exceeding that of equivalent red filtered incandescent lamps); to the current state-of-the-art of >150 lm/W from AlInGaP LEDs. In fig. 3(b) progress in efficiency (as well as progress in high-power packaging) then enabled tremendous progress in lumens per package and cost per lumen is illustrated [13].

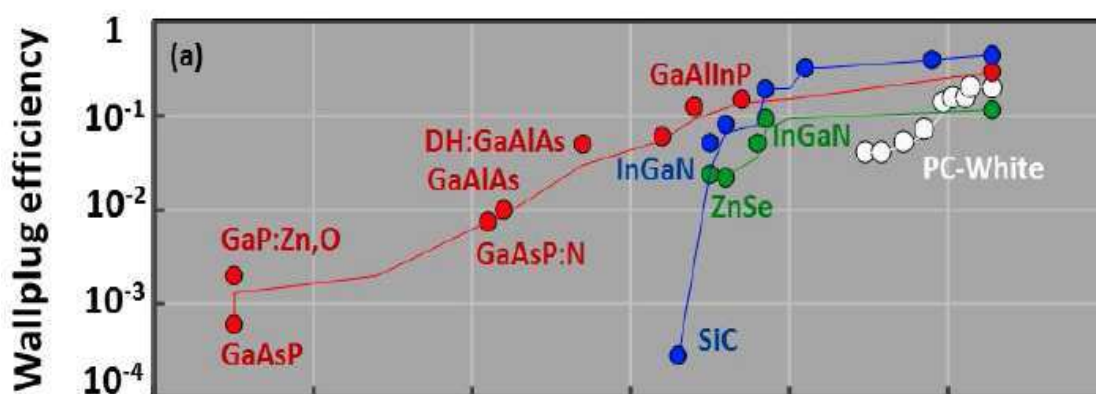


Fig. 3a: Historical evolution of the performance (lm/W) for commercial red, green, blue and Phosphor-converted white LEDs [13].

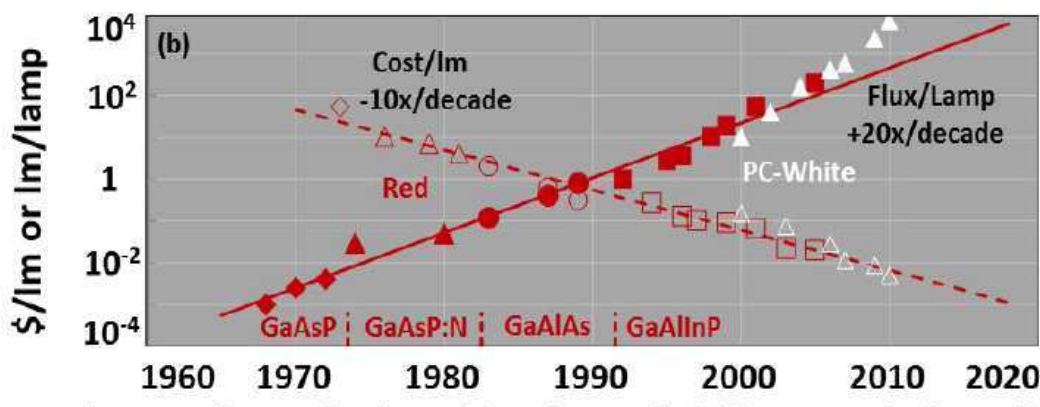


Fig. 3b: Historical evolution of the performance (lm/package) and cost (\$/lm) for commercially available red and phosphor-converted (PC) white LEDs [13].

In the context of materials, the word “nano” means that a tiny sample/cluster of atoms is crystalline and its dimensions lie in the range of a few nm. We can of course have clusters of different morphologies - a few nm in each dimension called quantum dots (zero dimensional- or 0D), a few nm long called quantum rods/nanowires (1D-) and a few nm thick single film/epitaxy or multilayers (MLs) (i.e., 2D-structure). Understandably surface to volume ratio of atoms in any of these nanostructures is higher than poly- and single-crystalline bulk materials, which renders them different properties which are useful for several applications, and thus make these materials so important. Nanomaterials in different forms have drawn much attention in a multitude of fields owing to their outstanding electrical, optical, magnetic, and catalytic properties and exciting application prospects. It is well known that the phases, sizes, and morphologies of nanomaterials have great influence on their properties and potential applications; thereby, the controlled synthesis of nanostructured materials with novel morphologies has recently received much attention. Particularly, the recently emerged luminescent nanomaterials have been expected as promising alternative in terms of the chemical inertness, eco-friendliness, no blinking and low cost. Significant advances have been made in the synthesis of nanomaterials with controlled geometry, physicochemical properties, surface charge, and surface tailoring. Materials properties become a function of their size and shape at 1-100 nm scale due to strong quantum mechanical effects, including surface effects. The promise of nanotechnology is to utilize this strong structure-property relationship of diverse materials at nanoscale for useful applications. By controlling the size and shape of nanomaterials, one can create new materials with functional properties which have not been able to be obtained by existing material technology. Most of the current nanomaterials development is driven by empirical search process of discovering new materials through a repetition of fabrication-characterization cycle guided by empirical gained understanding and insight of nanomaterials behaviour. Due to two dimensional quantum confinement effect in one dimensional nanomaterials, they are responsible for controlling the flow of electrons and photons [15-17]. For practical applications of nanocrystals, it is essential to design them before fabricating them according to specific functional applications. Most striking and intuitive aspect of nanocrystals is the ability to tune the absorption and emission spectra across the visible range by simply changing the particle size. As a result of quantum confinement semiconductor nanocrystals show different optical and electronic properties. Their band gap energy can also be controlled by controlling particle size. As a result of this quantum confinement, blue shift is observed in absorption spectrum by reducing particle size.

Because the vast majority of LEDs use inorganic semiconductors, the acronym LED normally refers to inorganic-semiconductor-based LEDs. Some LEDs use organic semiconductors (carbon-based small molecules or polymers), and the acronym OLEDs refers to these organic-semiconductor-based LEDs. They are similar to inorganic-semiconductor-based LEDs in that passing an electrical current through an OLED creates an excited state that can then produce light. OLEDs are inexpensive than LEDs, in part because they do not need to be crystalline (or "defect free"). Hence, their fabrication processes are more forgiving, and they can even be applied as large-area coatings on curved, flexible surfaces.

Quantum dot LED (QLED) are becoming the next breakthrough in electroluminescent technology for displays and solid-state lighting applications due to their unique combination of extraordinary colour, high efficiency, demonstrated stability and low-cost patterning[18-19]. The most fundamental challenges involve understanding the nanoscale science that governs light generation and extraction from visible LED semiconductor materials and developing nanoscale engineering concepts to achieve the significant increases in LED optical efficiency that are required to make SSL a reality.

The synthesis and characterization of new and novel electroluminescent nanomaterials with well-controlled sizes, shapes, porosities, crystalline phases, and structures are of the utmost importance for breakthroughs in several sustainable, efficient & inexpensive lighting as well as energy technologies.

The review covers brief account of various electroluminescent nanomaterials for SSL, mechanism of EL emission, and their synthesis and characterisation techniques.

2. Nanomaterials for Solid-state Lighting

Illumination technology is currently undergoing a major revolution, with light bulbs and fluorescent tubes being replaced by LEDs. White LEDs currently have an energy efficiency of around 50% when converting electricity into light. Red and green light-emitting diodes have been with us for almost half a century, but blue light was needed to really revolutionize lighting technology and *it took another three decades to finally produce efficient blue LEDs*. Only the triad of red, green and blue can produce the white light that illuminates the world for us.

A key step in the development of blue LEDs was the development of heterojunctions in the early 1990s by research groups led by Akasaki and Nakamura [20-22]. In 1994, Nakamura used a double heterojunction InGaN/AlGaIn to produce a device with a quantum efficiency of 2.7%, which opened the door for efficient blue LEDs to be easily produced [22].

Solid-state lighting (SSL) is among the most recent of these areas, emerging as a concept only in the past decade, with the sudden development in the mid-1990s of blue and green light-emitting diodes (LEDs), and with the increase in brightness of red LEDs to the point where outdoor applications, such as traffic lights, became possible. When Akasaki, Amano and Nakamura obtained bright blue light beams from their semiconductors, the gates opened up for a fundamental transformation of illumination technology. Incandescent light bulbs had lit the 20th century; the 21st century will be lit by LED lamps.

The Laureates' invention revolutionized the field of illumination technology. New, more efficient, cheaper and smarter lamps are being developed all the time. White LED lamps can be created in two different ways. One way is to use blue light to excite a phosphor so that it shines in red and green. When all colours come together, white light is produced. The other way is to construct the lamp out of three LEDs, red, green and blue, and let the eye do the work of combining the three colours into white.

Solid-state lighting (SSL) is among the most recent of these areas, emerging as a concept only in the past decade, with the sudden (almost shocking) development in the mid-1990s of blue and green light-emitting diodes (LEDs) [20], and with the increase in brightness of red LEDs to the point where outdoor applications, such as traffic lights, became possible. As a consequence of being so crucial for SSL, significant research efforts have been expended on the development of new electroluminescent nanophosphor materials. As nanostructured (NsM) materials are materials with a microstructure the characteristic length scale of which is on the order of a few (typically 1-100) nanometers where microstructure refers to the chemical composition, the arrangement of the atoms (the atomic structure), and the size of a solid in one, two, or three dimensions. Nanostructured materials may be grouped under nanoparticles (the building blocks), nano-intermediates, and nanocomposites [23, 24]. They may be in or far away from thermodynamical equilibrium. Nanostructured materials synthesized by supramolecular chemistry yielding nano assemblies are examples of those in thermodynamic equilibrium. Following fig. 4 shows different kinds of nanomaterials.



Fig. 4: Various types of Luminescent nanomaterials [24].

2.1. Requirements for LED Nanomaterials: The general requirements for the electroluminescent nanomaterials are :

1. Desired luminescence features
2. High quantum efficiency
3. Strong absorption in blue and near UV spectral range
4. High thermal stability of luminescence
5. Short emission decay time
6. Long term stability
7. Low cost and low materials usage
8. Environmentally benign composition

The desired luminescence features requirement includes the spectral features of luminescence excitation and emission. The condition at point 2 to 4 are the intrinsic properties that determine the efficiency performance of the nanomaterial. A threshold value is usually set for each of them at the early stage of development, e.g., quantum efficiency $> 60\%$. Requirement 5, short emission decay time, is related to the emission saturation of the nanomaterial when it is excited with high photon flux. The condition 6, long term stability, directly impacts on the life time of the LED which is related to the chemical stability and degradation of the materials under operating conditions. Requirement 7, the cost and low materials usage, is increasingly important as further cost reduction of LEDs enables further implementation of solid state lighting. Requirement 8, environmentally benign composition, limits the selection of constituent elements and hence the chemical formulations of the phosphors to be devised.

Luminescence oxide nanoparticles have tremendous potential in revolutionizing many interesting applications in today's emerging cutting-edge optical technology such as solid state lighting, biomedical labelling, imaging, photodynamic activation and radiation detection. Luminescence properties of impurity added nano phosphors are widely different from those of bulk as impurities can easily influence the electronic structure and transition probabilities between various states. As the particle size becomes smaller, the spacing between energy levels increases. The realistic electronic structure of nanocrystals is quite rich, which is due to interpolation between the quantized limit of atoms and molecules, and the continuum limit of bulk solids which supports many-body interactions. Nanocrystallites doped with optically active colour centres provide new opportunities for luminescence applications. By using various synthesis mechanisms such as chemical precipitation method, solvothermal method, hydrothermal method, reverse micelle method, sol-gel method, lanthenides, metals ions and rare earth ions can be doped in host material. Which results in improved remarkable high sensitivity and extremely wide dynamic range of

electroluminescent devices. These materials show promising features for imaging such as: high absorption cross sections, narrow emission spectra, continuous absorption spectra, and photostability. These characteristics shows their importance in light-emitting diodes (LEDs) and lasers. Despite the recent developments, low luminescence characteristics, poor water solubility, and poor cell selectivity lies in the large oscillator strengths and wide level spacing which should be helpful for developing novel optical gain media.

Nanomaterials which can be excited or emitted in NIR I (650–900 nm) and NIR II (1000–1450 nm) regions, including lanthanide based nanoparticles, carbon based nanoparticles, quantum dots and noble metal nanomaterials are gaining interest worldwide.

One of the main advantages of a nanomaterial is the tuneability of its light emission energy as a function of size. By the choice of nanoparticle size a semiconductor can be tuned to emit light at a desirable energy. An additional way to engineer the luminescence is via alloying. ZnO and MgZnO are promising emerging materials with ability to produce luminescence in the ultraviolet (UV) spectral range.

Phosphors form the basis of many applications in our daily life. Luminescent materials are key technology of the next generation. Phosphors will be used in traffic lights, computer screens, smartphones and tablets, medical devices, as well as in films for X-rays and light sources. It is reported that, worldwide, lighting alone consumes about 20 percent of electric energy and it is predicted that around fifty nuclear power plants could be removed if all the bulbs were replaced with efficient energy saving bulbs or LEDs. Some countries have also initiated it. Table 2, shows various optical applications of nanomaterials.

Nanoscale luminescent materials are highly promising for energy efficient lighting (e.g., white light LED, flat displays) as well as for all kinds of thin-film applications (e.g., labelling, advertising) by incorporating in or depositing on transparent substrates (e.g., polymers, glass).

Table 2 : Field of applications for different type of nanomaterials.

Nanomaterials	Fields of Application
Nanometallics	Sensors or energetic materials, antimicrobial and sector of catalyst, conductive layers of screens
Nanoceramics	Components anti-UV-Polishing substrates (wafers) in micro-electronics, Structure composite materials, Chemical-photocatalytic applications
Massive nanomaterials	Structural components for aerospace industry, automotives, pipes for oil, Hard coatings and gas, sport and anticorrosion industries
Nanoporous	Aerogels for thermal insulation in the areas of electronics, optics and catalysis- bio-medical field for tracing
Nanotubes	Electrical conductive nanocomposites, structural materials-singlewalled nanotubes for application in the field of electronic screen
Dendrimers	Medical field, domain cosmetic
Quantum dots	Optoelectronics screen, inks and paints, photovoltaic cells
Fullerenes	Sport (nanocomposites) and cosmetic sectors
Nanowires	Applications in the conductive layers of screens or even solar cells and electrical devices

White solid-state light can be generated using three different approaches: By employing three diodes that emit red, green and blue light respectively, by using a near-UV LED that excites several phosphors that emit over the complete spectral range, or the third, most widely used alternative entailing down-conversion of a portion of blue LED light to longer wavelengths in such a manner that white light emerges [25, 26]. The other strategies are less used due to certain intrinsic difficulties. For example, LEDs that efficiently emit in the green region of the visible spectrum cannot currently be produced and this holds back the three-LED strategy, and the near-UV with full down-conversion strategy is intrinsically inefficient due to the large Stokes shifts involved. Inorganic phosphors play a key role in carrying out the widely employed partial down-conversion strategy.

A schematic representation of solid-state white lighting device is shown in fig. 5(a) and 5(b). It consists of a blue-emitting LED chip with the phosphor directly above the chip, dispersed in transparent silicon, or in form of a cap. The blue light passes through this phosphor layer that converts part of the blue light to yellow, which yields (cool) white light. There are many issues of efficiency (many phosphors do not possess near 100% quantum efficiency), appropriate colour rendition, and colour temperature that drive phosphor research. Loss of efficiency at elevated temperatures is also considerable and is becoming increasingly relevant to higher-power LED white light sources, such as those used in the front-lighting of automobiles.

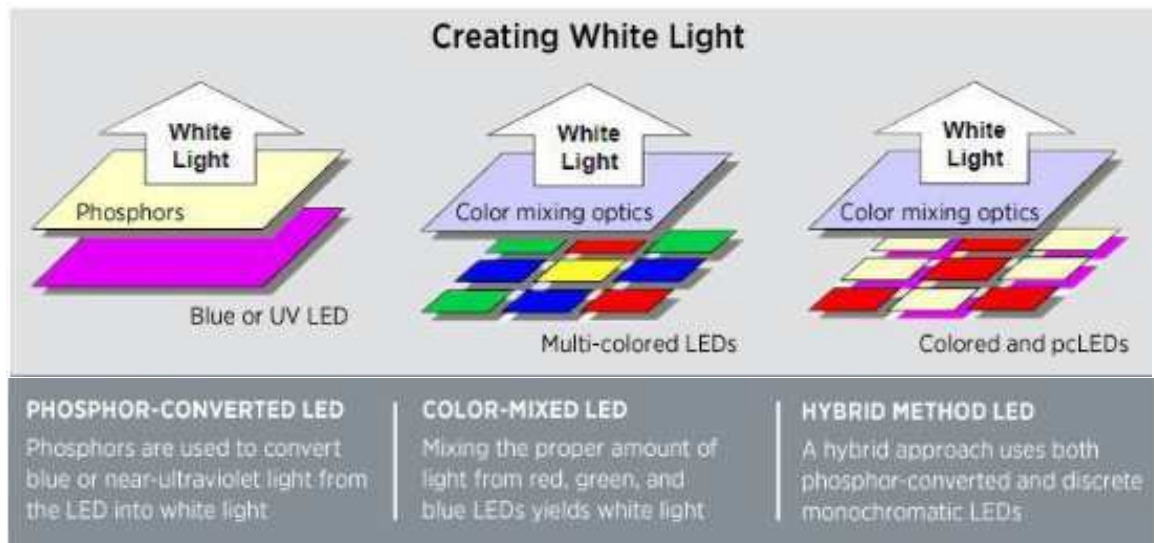


Fig. 5a: Creation of White Light [27].

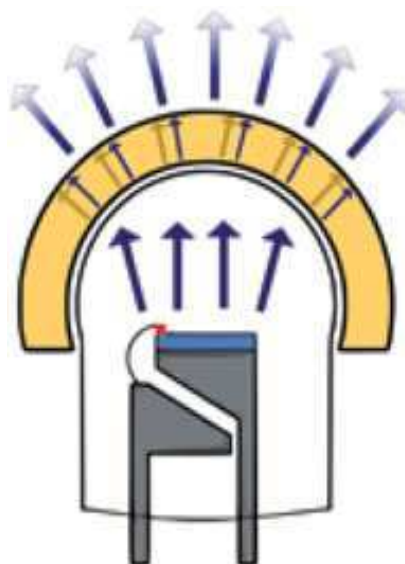


Fig. 5b: Generation of white light by emission of blue light from a LED, which is then down-converted by a yellow nanophosphor encapsulated in silicone resin cap [27, 28]

Materials for solid-state lighting are classified into three broad categories as illustrated in fig. 6; ranging from crystalline inorganic semiconductors (left) to waxy organic materials (right) to hybrid structures (middle) such as core-shell nanoparticles combining both material sets into engineered structures [29]. The white OLED (bottom right) is 25 cm² in area and optically coupled to an acrylic luminaire. Phosphorescent materials are employed to achieve 30 lm/W at 1,000 cd/m² normal emission. An incandescent lamp is shown in the background. (OLED photograph courtesy Universal Display Corporation). Inorganic LED chips made from AlInGaN compound semiconductors (bottom left) are typically 1 mm² or smaller in area and may be coated with phosphors to generate white light. A schematic cross-section of a packaged Luxeon TM LED chip made by Philips Lumileds Lighting Company is shown (encapsulation removed to reveal LED chip). Nanocrystalline electroluminescent materials such as ceramic, metal and metal oxide nanoparticles; nanotubes and related structures; nanofibers and wires, and precise organic as well as hybrid organic-inorganic nano-architectures such as dendrimers and polyhedral silsesquioxanes are shown in fig. 6.

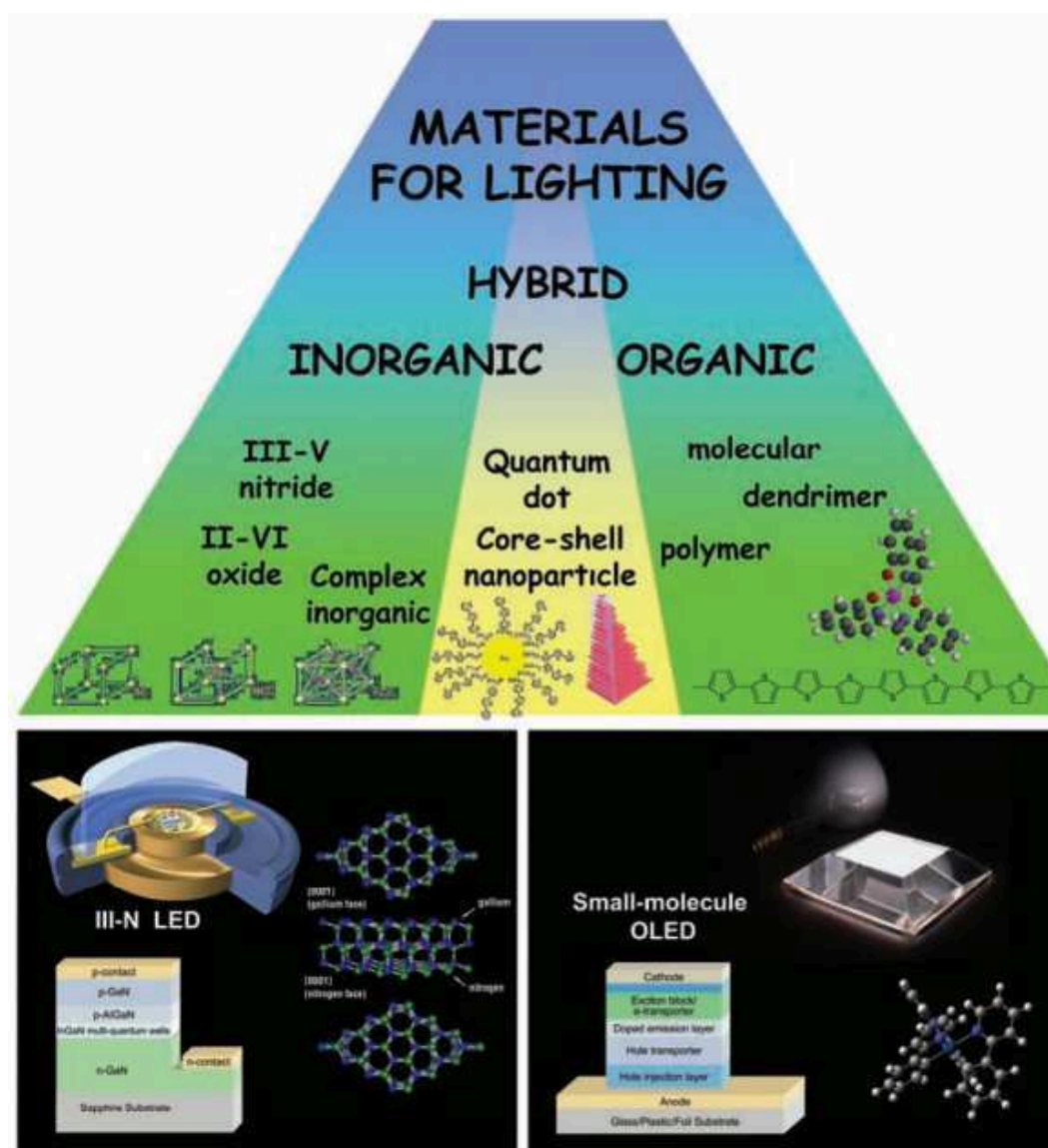


Fig. 6: Broad categories of electroluminescent nanomaterials for SSL [29].

These electroluminescent nanomaterials are discussed below:

2.2. Inorganic Electroluminescent Nanocrystalline Materials: Single-colour, inorganic, light-emitting diodes (LEDs) are already widely used and are bright, robust, and long-lived. The challenge is to achieve white-light emission with high-efficiency and high-colour rendering quality at acceptable cost while maintaining these advantages. The bulk of current research focuses on the group III-nitride materials. Our understanding of how these materials behave and can be controlled has advanced significantly in the past decade, but significant scientific mysteries remain. These include (1) determining whether there are as-yet undiscovered or undeveloped materials that may offer significant advantages over current materials; (2) understanding and optimizing ways of generating white light from other wavelengths; (3) determining the role of piezoelectric and polar effects throughout the device but particularly at interfaces; and (4) understanding the basis for some of the peculiarities of the nitrides, the dominant inorganic SSL materials today, such as their apparent tolerance of high defect densities, and the difficulty of realizing efficient light emission at all visible wavelengths.

Nanocrystalline materials include ceramics, metals, and metal oxide nanoparticles. These materials are assembled from nanometer-sized building blocks, mostly crystallites. The building blocks may differ in their atomic structure, crystallographic orientation, or chemical composition. In cases where the building blocks are crystallites, incoherent or coherent interfaces may be formed between them, depending on the atomic structure, the crystallographic orientation, and the chemical composition of adjacent crystallites. Materials assembled of nanometer-sized building blocks are micro structurally heterogeneous, consisting of the building blocks (e.g. crystallites) and the regions between grain boundaries. This inherently heterogeneous structure on a nanometer scale that is crucial for many of their properties and distinguishes them from glasses, gels, etc. that are micro-structurally homogeneous [30].

Grain boundaries play a major role in nanomaterials, and strongly affect properties and processing. The properties of NsM deviate from those of single crystals and glasses with the same chemical composition. This deviation results from the reduced size and dimensionality of the nanometer-sized crystallites and from the numerous interfaces between adjacent crystallites. Nanocrystallites of bulk inorganic solids exhibit size dependent properties, such as lower melting points, higher energy gaps and non-thermodynamic structures [31-32]. Nanopowders of metal alloys exhibit increased ductility as compared to macro-scale powders [33-34].

Metals are used as heterogeneous catalysts in a variety of reactions in chemistry. Heterogeneous catalyst activity is surface dependent. Due to increased surface area of macro-scale materials, nanometals and oxides are ultra-high active catalysts. They are also used as desirable starting materials for a variety of reactions, especially solid-state routes. Nanometals and oxides are also widely used in the formation of nanocomposites and in addition to their synthetic utility, they have many useful and unique magnetic, electric, and optical properties [35-36].

Since the mid-1990s, electroluminescent nanomaterials have played a key role in emerging solid-state white-lighting technologies that are based on combining a III-nitride-based near-UV or blue solid-state light source with down conversion to longer wavelengths. Inorganic phosphors usually consist of a host crystal that could be an oxide, oxynitride, nitride, halide or oxyhalide selected for their wide band gaps and other key features, doped with a small amount of rare earth and/or transition metal ions that act as the emissive center [28, 37-41]. As shown in the CIE (Commission Internationale de l'Eclairage) diagram in fig. 7, virtually every colour can be rendered with the use of inorganic luminescent materials in combination with a near-UV or blue light source.

Electroluminescent nanomaterials can be prepared using the rare earth ions such as Eu^{3+} , Tb^{3+} or Sm^{3+} . However, in these systems, the emission relies on f to f transitions which are parity forbidden and therefore rather inefficient. In addition, the lower lying f -orbitals are rather well-shielded from the coordination environment of the ion and, consequently, the emission arising from those f - f transitions are sharp and not very suitable for covering a large region of the visible spectrum. To circumvent these issues of narrow, inefficient emission, the most frequently used phosphors are doped with broad-emitting ions, such as Mn^{2+} , Ce^{3+} , or Eu^{2+} [Fig.7]. In the case of Ce^{3+} and Eu^{2+} , light is emitted due to $4f$ to $5d$ transitions within the ion.

Almost all widely used nanophosphors comprise a crystalline oxide, nitride, or oxynitride host that is appropriately doped with either Ce^{3+} or Eu^{2+} . These ions, with $[\text{Xe}] 4f^n 5d^0$ configurations ($n = 1$ for Ce^{3+} and 7 for Eu^{2+}) have proximal excited states that are $[\text{Xe}] 4f^{n-1} 5d^1$. Optical excitation into these states and concomitant re-emission can be tuned into the appropriate regions of the visible spectrum by the crystal these ions are hosted in [42].

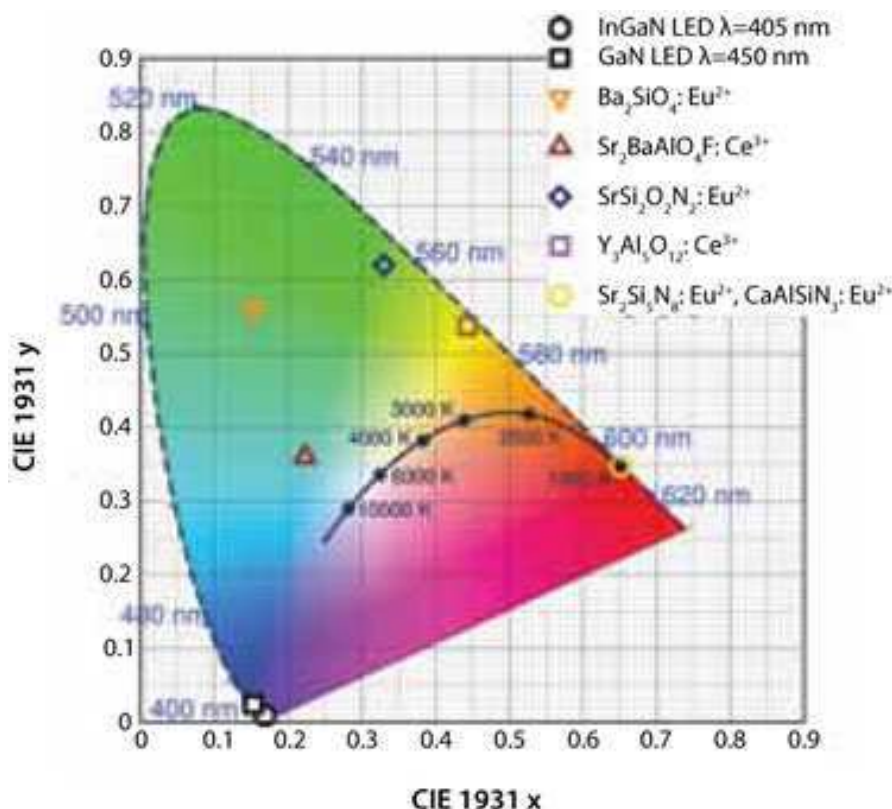


Fig. 7: Colour coordinates of Electroluminescent materials in combination with a near- U.V. or blue light source [41].

Gadolinium oxide nanoparticle is one unique rare-earth oxide material that has many advanced technological applications [43-46]. There are various methods to fabricate Gd_2O_3 materials such as solid-state reaction, sol-gel and flame spray pyrolysis [47-49]. This material has two common lattice structures which are monoclinic and cubic crystal structure. It is white odourless powder and is insoluble in water. Gadolinium oxide has a wide band gap of 5.4 eV and high thermal stability than silicon. It possesses a high permittivity ($k=10-16$). It has important usages as high index optical film material, infra-red absorbing automotive glass, microwave applications and catalyst in oil industry. Optical properties of this material reveals that when doped with Tb^{3+} or Ce^{3+} , this material becomes an efficient green-emitting phosphors that can be used as colour TV tube phosphors. Due to its paramagnetic properties and symmetric electronic ground state, Gd^{3+} is also widely used as contrast agent for magnetic resonance imaging.

II-VI semiconductors find numerous applications due to their wide and direct band gap structure. Unlike the III-V semiconductor, the II-VI semiconductor nanoparticles can be prepared with the precipitation techniques in aqueous solutions or solid matrix. Much attention has been paid to modify the surface of nanoparticles to improve their optical responses. However, there also exist the stability and difficulty in extracting these nanoparticles from the solution. Pyrolysis, alternatively, is also a successful technique to obtain free-standing nanoparticles. A modified organometallic chemical vapour deposition technique is used to incorporate luminescent II-VI nanocrystals (NCs) into ZnS thin films by Heine et al. [50]. The NCs are synthesized in organic solution and consist of a CdSe core and ZnS shell. The ZnS matrix is deposited by OMCVD from diethyl zinc and hydrogen sulphide while the NCs are delivered to the film surface via electrospray. Varying the size of the CdSe NC core enables tunable emission from the blue to the red. The ZnS shell provides electronic and chemical passivation of the CdSe core improving its luminescence and thermal stability. The thin films exhibit room temperature photoluminescence (PL) and cathodoluminescence dominated by emission from the NCs. PL quantum efficiencies greater than

10% have been achieved. Okuyama et al. [51] prepared ZnS and CdS fine particles with different particle sizes by an ultrasonic spray-pyrolysis method. The particle size was changed from sub-micrometer to micrometer size by changing the concentration of the metal nitrates in the starting aqueous solution containing $\text{Zn}(\text{NO}_3)_2$ or $\text{Cd}(\text{NO}_3)_2$ and $\text{SC}(\text{NH}_2)_2$. Crystalline phase and fluorescence properties of ZnS and CdS particles did not depend on the particle size, which is quite different from other.

When transition metal ion is doped in wide-band semiconductor, it creates different luminescent nanomaterial. Electroluminescent polycrystalline ZnS:Mn films with luminance output of 103 cd m^{-2} and luminous efficiency of $0.61 \text{ mW}^{-1}/(\lambda = 585 \text{ nm})$ have been obtained by the DTC-CVD method [52]. Simultaneous pyrolysis of zinc and manganese dithiocarbamates at a temperature of 200°C - 300°C at atmospheric pressure in a non-sealed system is convenient for large scale production. It is also reported that annealing of the ZnS:Mn films in vacuum or nitrogen atmosphere leads to a significant increase of luminance and luminous efficiency [53]. ZnS films as obtained and activated by annealing in the deposition mixture show EL efficiency as high as 104 cd m^{-2} and luminous efficiency of 61 mW^{-1} .

Yong Chen et al. (2014) [54] have reported an intense red phosphor, $\text{CaYAlO}_4:\text{Mn}^{4+}$, developed by solid state reaction which exhibits a broadband excitation extending from 250 to 550 nm and emits an intense red light at 710 nm with high colour purity and stable chromaticity coordinates. These results demonstrate that Mn^{4+} ion can play a role of activator in narrow red emitting phosphor potentially useful in UV ($\sim 370\text{nm}$) GaN-base or Blue ($\sim 460\text{nm}$) InGaN-base LED.

Luminescent nanomaterials doped with lanthanide ions have gained attractive research interest due to their remarkable down-conversion (DC) and up-conversion (UC) luminescent properties and potential applications in many fields such as lasers, display devices, solar cells, and biomedical imaging. Lanthanide elements are spectroscopically rich species. The lanthanide 4f orbitals are buried beneath the 6s, 5p, and 5d orbitals; hence, spectra arising from f-f transitions are narrow and insensitive to their environment, unlike transition metal (3d) spectra. Most importantly, this gives rise to a rich energy level structure in the NIR, visible (VIS) and ultraviolet (UV) spectral range. Triply ionized lanthanide ions in solid hosts typically have emission line widths of 10 to 20 nm (FWHM, full width at half maximum), which is about half that observed for quantum dots (25 to 40 nm) and much narrower than that observed for organic dyes (30 to 50 nm) or transition metal ions (100 nm). This feature allows more resolvable bands to be packed into the same spectral bandwidth, which enables a larger number of distinct combinations. Because lanthanide emissions involve only atomic transitions, they are extremely resistant to photo-bleaching. The energy level structure of lanthanide ions also creates the possibility for large shifts between the excitation and emission bands. This shift can be several hundred nanometers containing discrete gaps with zero absorption. By comparison, the HOMO-LUMO (highest occupied molecular orbital-lowest unoccupied molecular orbital) transition in organic dyes typically results in overlapping excitation and emission bands and a Stokes shift of only 10–30 nm between the absorption and emission maxima. The large variety of absorption and emission wavelengths, the independence on host materials and low vibration energy losses make lanthanide ions ideal for spectral conversion. Lanthanide ions can be doped in a variety of solids such as crystals, fibres or glass ceramics to give them the desired down conversion and up conversion optical properties [55-60].

Recently, lanthanide doped up-converter nanomaterials are considered as a new generation of probes for multimodal bio-imaging owing to their unique up-conversion properties of converting near-infrared (NIR) light to visible and NIR light. Ln^{3+} ions have special $4f^n 5d 0^{-1}$ inner shell configurations that are well-shielded by outer shells and have abundant and unique energy level structures and can exhibit sharp luminescence emissions via intra-4f or 4f-5d transitions. Their remarkable luminescence properties, such as narrow bandwidth, long-time emission, and anti-

Stokes emission, have been widely applied in lasers, solar cells, analytical sensors, optical imaging, photodynamic therapy, and so on [61-63]. Combined with excellent DC/UC and X-ray absorption properties, the lanthanide doped luminescent nanomaterials containing magnetic elements also possess large magnetic dipole moment, making them ideal contrast agents for UC/MRI/CT multimodal bio-imaging. To pursue these applications, an improved understanding of fundamental structural, optical, and luminescent properties is needed.

In recent years, great advancement has been made in developing high-efficiency, high-power GaN-based ultraviolet [64] and blue [65] light-emitting diodes (LEDs) because of wide market needs and the academic importance of the blue laser. Amorphous GaN nanoparticles were synthesized by in-situ thermal decomposition of cyclotrigallazane incorporated into a polystyrene-poly (N, N-dimethyl-4-vinylaniline) copolymer by Yang et al. [66]. TEM, energy dispersive X-ray spectrometry, and XPS (X-ray photoelectron spectroscopy) show that the composite material consists of amorphous GaN nanoparticles having average diameter ~ 40 nm well dispersed in the copolymer. The PL spectra show blue light emission from the amorphous GaN nanoparticles, peaked at ~ 426 nm. Wells et al. [67] proposed new precursor methods of nanocrystalline cubic/hexagonal gallium nitride. New polymeric gallium imide can be converted to nanocrystalline, cubic/hexagonal GaN ranging in colour from yellow to light grey. These nanophase GaN materials have also been characterized by room temperature photoluminescence measurements. In general, the observed emission spectra are strongly dependent on pyrolysis temperature and typically exhibit weak defect yellow-green emission. While the as-prepared GaN does not exhibit band-edge PL, a brief hydrofluoric acid etch yields nanophase GaN exhibiting an intense blue emitting PL spectrum with an emission maximum near 420 nm. GaN can also be prepared by the pyrolytic conversion of both from $[\text{Ga}(\text{NEt}_2)_3]_2$ and its ammonolysis product at 600°C for 4 h under Ar [68].

By carefully controlling chemical reactions in solution, scientists are able to make nanometre-scale crystals of semiconductor material that absorb and emit light efficiently. Moreover, by building large, hybrid structures to incorporate more than one kind of material, size and shape of these structures can be controlled. All this control over nanometre-scale structure makes it possible to engineer the colours of light absorbed and emitted by the materials, particularly in the previously inaccessible infrared frequency range. Scientists are working on the challenges associated with producing high-quality, low-cost nanometre-scale materials that are stable and emit light efficiently.

The most efficient visible light-emitting materials today are drawn from three-and-four component systems such as aluminium indium gallium phosphide or nitride (AlInGaP or AlInGaN) Light-emitting devices (most commonly diodes) made from these and other inorganic materials are known as light-emitting diodes, or LEDs.

An example of the current state of the art in the synthesis of high-quality nanostructured materials is shown in fig. 8. These inorganic semiconductor nanowires [69] are important nanostructures for solid-state lighting (SSL) that could potentially outperform their thin film counterparts. These nanowires have several unique characteristics important for SSL: (1) InGaAs, and InGaN; (2) their diameters can be controlled precisely from 2 to 200 nm in width (potentially enabling quantum confinement effects to be utilized for optimization of the output wavelength and emission quantum efficiency); (3) their size and surface properties permit solution processing for easy integration into device architectures, (4) their electronic and conductive properties — including crystal structure, doping density, mobility, and band gap — can be exactly defined; and (5) their lattice structure is a near ideal crystalline structure. The luminescence wavelength of the nanowires is tunable over the visible and near-infrared spectrum because of different available compositions and quantum size effects similar to that seen with semiconductor nanocrystals (quantum dots). The dislocation-free nature of these semiconductor nanowires is expected to have significant impact on the emission characteristics, and, most importantly, the quantum efficiency.

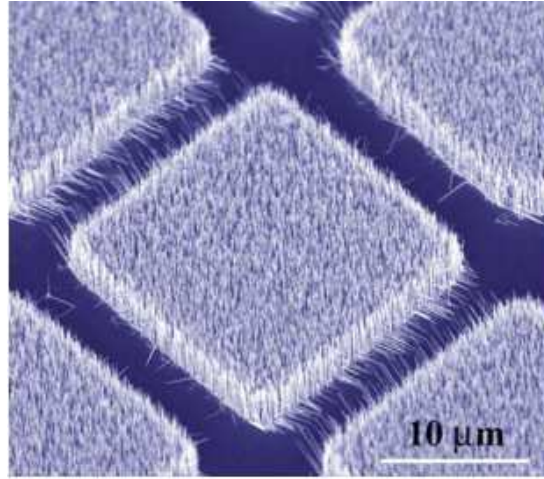


Fig. 8: Patterned GaN nanowire arrays grown via a metal organic chemical vapour deposition (MOCVD) process [70]

This problem can be circumvented by intensive study of polar materials and heterostructures. Most known inorganic semiconductors with band gaps wide enough to emit light in the ultraviolet (UV) and visible are polar because band gaps tend to increase with bond polarity (the sequence Ge, GaAs, ZnSe is a relevant example). Indeed, GaN, the semiconductor that is central to current SSL technology, is among the most polar of the III-V semiconductors [29, 70], and any inorganic semiconductor that might displace GaN in SSL is also likely to be polar. Because polar materials and heterostructures are characterized by internal electric fields, which can cause spatial separation of electrons and holes, they can suffer from lower radiative recombination rates. Hence, to fully exploit materials and heterostructures for SSL, it will be important to gain a fundamental understanding of the electronic and optoelectronic properties of polar materials and heterostructures, and to develop methods for their manipulation.

2.3. InGaN QW Heterostructure: Compound semiconductors that emit light are generally single-crystal materials grown as thin films at very high purity using layer-by-layer growth processes such as molecular beam epitaxy or metal-organic chemical vapour deposition. It is reported that particular InGaN QW heterostructure designs enabled significantly reduced voltages and ideality factors in InGaN LEDs. In particular, n-type doping of GaN barrier layers in the InGaN MQW active region had a strong impact on these device parameters. A major bottleneck to the realization of energy efficient SSL is the limited internal quantum efficiency (IQE) of InGaN-based visible LEDs. While violet and blue LEDs have been shown to have IQE of ~70 % at low current densities [71], LED efficiency is greatly reduced at longer (green) wavelengths and under high current density operation (so-called “efficiency droop”). Previous studies have revealed that InGaN alloys are dominated by a range of nanoscale materials properties and phenomena that play a crucial role in the light emission process. The efficiency droop, prominent in GaInN-based light-emitting pn-junction devices, is the gradual decrease of the power efficiency as the injection current increases. This phenomenon is a severe problem affecting predominantly high-power light-emitting diodes (LEDs) and semiconductor injection lasers, both of which operate at inherently high current densities. Understanding and mitigating efficiency droop is especially critical to attaining viable LEDs for solid-state lighting applications. Although LED technology for use in white lighting applications has advanced considerably in the last five years, improvements to light extraction are still required to reach the final goal of 90% extraction efficiency. By placing InGaN quantum wells in close proximity to a metal surface which can support surface plasmon modes, a significant enhancement to the luminescence efficiency can be observed for a properly designed structure. A typical electrically injected InGaN surface plasmon LED is shown schematically in fig. 9.

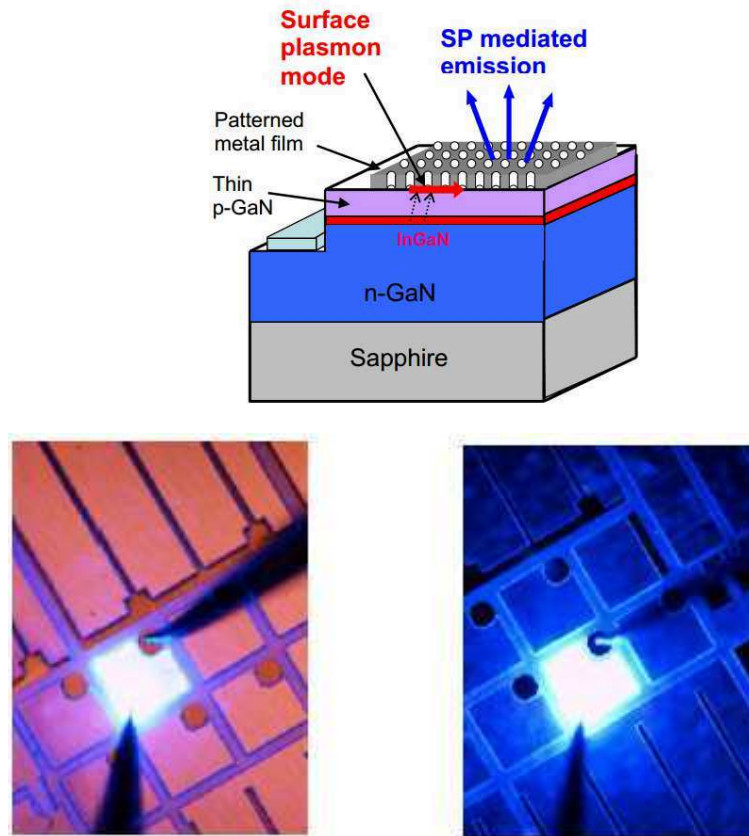


Fig. 9: A typical electrically injected InGaN surface plasmon LED MQW active region [27].

Efficiency improvements using surface-plasmon-mediated emission depend on a rapid transfer of energy between QW excitations and surface plasmons. This rapid energy transfer is in turn dependent on QW in very close proximity to the metal surface supporting the surface plasmon modes.

A practical implementation of high-efficiency colour conversion in an electrically pumped LED using nonradiative ET is illustrated in fig. 10 [72, 73]. Based on a new LED design that offers both strong ET coupling and efficient carrier injection, it was shown that a hybrid structure comprising of a single monolayer of CdSe NCs assembled on top of an InGaN/GaN QW provides nearly 10% colour conversion efficiency. This value is significantly higher than that for a traditional absorption-re-emission colour-conversion scheme in a similar device structure. Furthermore, these hybrid devices can also provide improved efficiencies, not only compared to phosphor-based structures, but also to standalone LEDs.

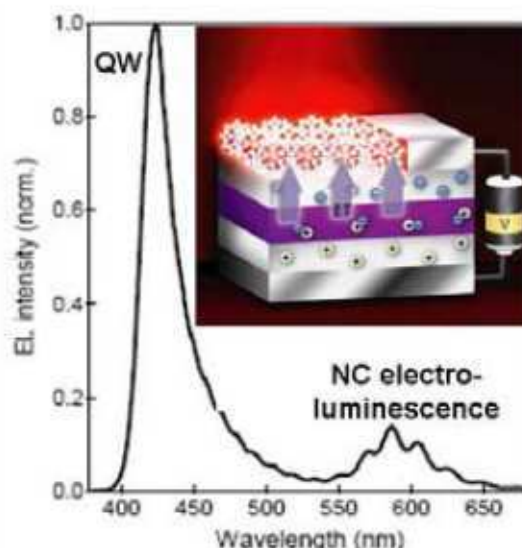


Fig. 10: Practical implementation of high-efficiency colour conversion in an electrically pumped LED using nonradiative ET [72].

Two key characteristics of LEDs based on inorganic materials are small size and high brightness. Typically, they are a square millimetre or less in area. And, because of the robustness and high thermal conductivity of inorganic semiconductors (GaN, for example, can be considered a refractory ceramic material), they may be “driven” very hard. The brightness (or luminance) of the emitting surface of current commercial LEDs is already as high as 2×10^8 cd/m² (more than 400,000 times brighter than the 200–500 cd/m² of a typical video screen), and there does not appear to be a fundamental physical reason why it could not be ten times brighter still. At this brightness, a single mm² chip should produce the same amount of light now produced by a 60 W to 75 W incandescent light bulb. At these power levels, however, light-emission efficiencies can decrease significantly and, worse, defects can form, thus shortening the lifetime of the device below levels acceptable for SSL.

2.4. Organic Solid State Lighting Technology

Organic semiconductors are carbon-based solids that may be discrete molecules, often called “small molecules” although the molecular weight typically exceeds 400 [74], long chain polymers [75] or dendrimers [76]. The first OLED was demonstrated in single crystals of anthracene, although the operating voltage was extremely high. Organic light-emitting devices (OLEDs) have been widely developed for flat-panel displays, but only recently the efficiency of white OLEDs has risen to the point where they can be considered for solid-state lighting (SSL) applications. Low-voltage devices have subsequently been demonstrated using amorphous materials engineered into extremely thin films, typically only a few tens of nanometers thick. The molecular structure of one efficient organic light emitter, consisting of three phenylpyridine moieties chelated to an iridium ion is shown in fig.6. [77]. A modern approach of conjugated polymers as peculiar light emitting materials is their suitability for achieving efficient solid state lighting (SSL) [78-88]. In contrast to conventional point source LEDs, conjugated polymer based LEDs distribute light throughout the surface area and are not restricted by their size. This brings about the possibility of having high luminance flux without glare.

Organic light emitting devices (OLEDs) based on polymeric or molecular thin films have been under development for about two decades, mostly for applications in flat-panel displays, which are just beginning to achieve commercial success. They have a number of attractive properties for SSL, including ease (and potential affordability) of processing and the ability to tune device properties

via chemical modification of the molecular structure of the thin film components. There are, in principal, two competing technologies: organic light emitting diodes - OLEDs - and polymer light emitting diodes - PLEDs. OLEDs are, in principle, based on complex multiple layer device structures of thermally evaporated low molecular weight molecules. Whereas PLEDs are solution-processable structures based on a single white-light emitting polymer, deposited by printing on to charge transport layers; typically PLEDs are three or four layers thick. Both devices represent extended emissive surfaces with areas up to one-fifth m² already being demonstrated from the laboratory. However, in general, lab-made devices are much smaller, generally tenths of square centimetres in area. The main research effort continues within the materials, striving for improved quality of white light, lifetimes and efficacy. Presently, OLEDs outperform PLED technology on laboratory test samples, but due to the complexity of manufacturing multiple layer structures, it is widely believed that solution-processable PLED technology will be first to demonstrate high direct yield manufacturing levels, due to their less complicated device structures and atmospheric pressure deposition printing processes, which also will yield very high material utilization (>90%).

Organic stack materials include emissive layers (EML), hole and electron injection layers (HIL, EIL), transport layers (HTL, ETL), and blocking layers (HBL, EBL). Organic stack materials can be polymeric or small molecule materials. At present, most high-performance lighting panels employ small molecule organics deposited using vapour deposition techniques. Polymer materials have not yet demonstrated the high efficiency and lifetime that is achieved in small molecules, but are being explored because they work well with flexible substrates, can be aligned to aid in light extraction, and may potentially lead to lower deposition costs as they are more amenable to solution processing. Sumitomo Chemical has developed P-OLED inkjet-printing technology and their materials have been used by Panasonic to create a 56" printed OLED TV. They have also demonstrated these materials in flexible P-OLED lighting panels produced in an ink-jet printed process. Though small molecules are typically formulated for evaporation, ligands can be attached to the molecules to create soluble small molecules. This approach is in development as it offers compatibility with solution processing as well as materials performance that is approaching that of evaporated small molecules. Companies such as Konica Minolta, DuPont, Pioneer, Universal Display Corporation (UDC) and Merck are working on soluble small molecule solutions.

Two classes of organic materials are commonly used for organic light-emitting devices: polymeric substances and so-called "small molecule materials" which do not exhibit any orientating property and therefore form amorphous films. One interesting aspect of organics-based optoelectronics is the possibility to use simple screen printing or wet deposition techniques for cost-effective fabrication of large-area devices. Nowadays, this applies only to polymeric organics, whereas evaporating techniques still have to be applied for small molecules

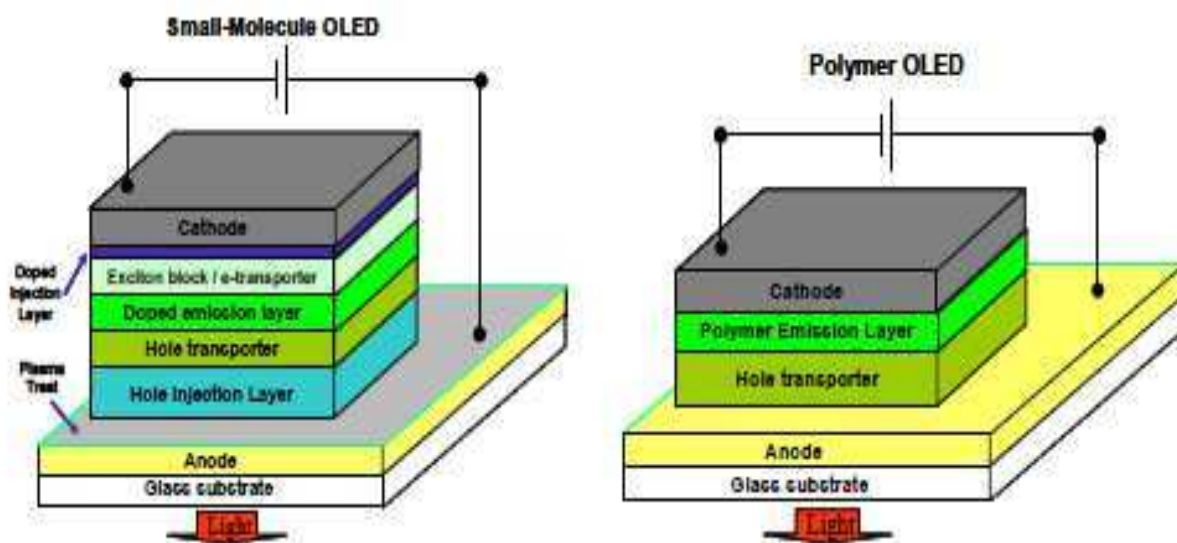


Fig. 11: Schematic diagram of a small-molecule OLED (SM-OLED) and a polymer OLED (PLED).

The most efficient OLEDs are currently SM-OLEDs - a schematic of a SM-OLED is shown in fig. 11. An organic light-emitting diode (OLED) consists of several semiconducting organic layers sandwiched between two electrodes, at least one of them being transparent. The device is fabricated by sequentially depositing organic layers on a conducting substrate followed by another conducting electrode. A common device structure comprises a glass substrate coated with indium tin oxide (ITO) as transparent anode and a thin, opaque metal film as cathode. The organic stack including the electrodes is usually thinner than 1 μm [89-92].

PLEDs are attracting great interest in the display technology industry due to their promising low cost large area manufacturing and relative ease of fabrication using low processing temperatures. Polymers can be deposited over broad areas with relatively simple solution-based approaches such as spin casting or doctor-blading, which are less capital-intensive than vacuum deposition. The need to pattern more than one colour of device on a single substrate has led to the further development of ink-jet printing techniques [93-95].

The potential of OLED is coupled with challenges that have so far prevented the simultaneous achievement of high brightness at high efficiency and long device lifetime. Organic thin films are often structurally complex, and thin films that were long considered “amorphous” can exhibit order on the molecular (nano) scale. Research areas of particularly high priority include: (1) quantifying local order and understanding its role in the charge transport and light-emitting properties of organic thin films, (2) developing the knowledge and expertise to synthesize and characterize organic compounds at a level of purity approaching that of inorganic semiconductors, and understanding the role of various low-level impurities on device properties in order to control materials degradation under SSL-relevant conditions, and (3) understanding the complex interplay of effects among the many individual materials and layers in an OLED to enable an integrated approach to OLED design. A highly efficient small molecule based multifunctional materials for OLED is depicted in fig. 12.

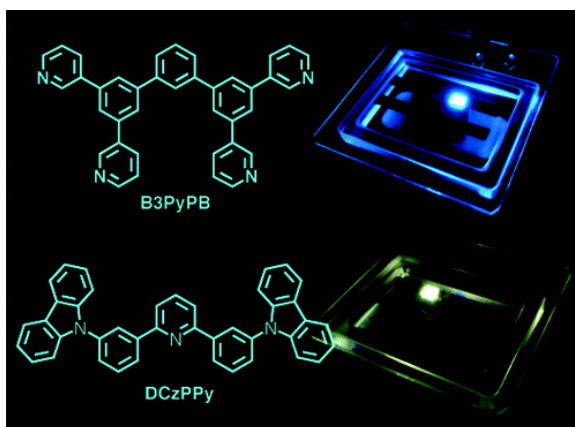


Fig. 12: Small molecule-based multifunctional materials in high-performance OLEDs [89].

Organic light emitting diodes are capturing the creative fantasies of progressive light designers. Lightweight panels or "light tiles" composed of extremely thin functional layers on plastic or glass substrates make exclusive, futuristic looking OLED luminaires for home or office use as shown in fig. 13.

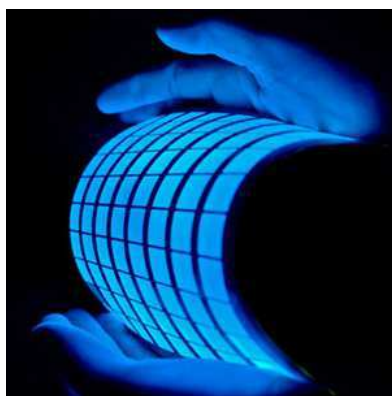


Fig. 13: Lightweight panels or "light tiles" composed of extremely thin functional layers on plastic or glass substrate.

They are offered as commercial products by large vendors like Osram and Philips. OLEDs give off a pleasant warm-white light; they can be tuned to individual colour temperatures and dimmed. And they are "instant-on" at their full brightness right after flicking the switch. OLEDs are widely believed to be a key to the next generation of solid-state white lighting, promising substantial advantages over incandescent, fluorescent, and inorganic LED devices. They can be incorporated into entire walls, causing them to radiate an even glow of light, or even into tiles, which can be fitted to ceilings as an alternative to hanging light fixtures. The homogeneous output, unusual appearance, low heat emission, extremely flat nature and high degree of controllability of OLEDs offer designers, artists and architects great freedom in creating ground breaking new lighting concepts and experiences. The applications of White LEDs are shown in fig. 14.



Fig. 14: Versatility of white OLED.

An organic light emitting device consists of one or more semiconducting organic thin films sandwiched between two electrodes – one of which must be transparent. In a typical “down-emitting” device, indium tin oxide (ITO) is utilized as a transparent anode electrode and an evaporated metal is utilized as the cathode. The device is made by starting with a glass or plastic substrate that has been pre-coated with ITO and then sequentially depositing device layers onto the substrate. The organic device layers consist of materials that transport charge and emit light. These are applied via either a solution-based or a vapour-based coating process. The number and type of layers depends upon the chosen materials and fabrication methodology but the overall thickness of all the layers is typically of the order of 100 nm. An electron injecting cathode is applied on top of the organic layers via thermal evaporation. Typically this electrode consists of a low work function metal such as calcium or a magnesium silver alloy. Finally, the entire package is sealed to prevent ingress of water or oxygen. When voltage is applied between the two electrodes, diode-like rectification is observed with appreciable current flow occurring when the ITO anode is biased positively. Under this forward bias, light is generated and emitted into the surroundings through the transparent substrate.

2.4.1. OLEDs’ Lighting benefits: Energy policies encourage technologies that can offer maximum energy savings and OLED technology falls into this category. OLEDs offer many advantages over both LCDs and LEDs. Adoption of OLED lighting has the following advantages:

- OLEDs have a significantly lower price than LCDs or plasma displays due to the fact that they can be printed onto any suitable substrate using an inkjet printer or even screen printing technologies.
- The ability of OLEDs to be printed onto flexible substrates has opened the gate to several new applications, like roll-up displays and displays embedded in fabrics.
- OLED pixels directly emit light, thus provides a greater range of colours, brightness, and viewing angle than LCDs.
- One remarkable advantage of OLEDs is the ability of colour tuning.
- Energy saving potential.
- Mercury-free.
- New freedom in design.
- OLED substrates can be plastic rather than the glass used for LEDs and LCDs.
- High luminous efficacy.
- The OLED needs to operate at very high brightness (over 7,000 cd/m²) and colour temperature (over 10,000K), while still maintaining long lifetime (> 60,000 h).

Indeed, single-colour OLED displays are already available commercially. A mix of red, green and blue-emitting materials can be used to generate white light, but these bands of colour often interact with one another, degrading device performance and reducing colour quality.

Using polymer nanoparticles to house light-emitting 'inks', a thin film OLED using iridium-based guest molecules to emit various colours of visible light has been designed. The polymer nanoparticle surrounding a guest light-emitter serves as a 'do not disturb' sign, isolating guest molecules from one another. Each guest can then emit light without pesky interactions with neighbouring nanoparticles, resulting in white luminescence.

A new organic material that shines with phosphorescence could lead to cheaper, more efficient and flexible display screens. Researchers are able to make metal free organic crystals that were white in visible light and radiated blue, green, yellow and orange when triggered by ultraviolet light. The new luminous materials, or phosphors, could dramatically improve upon current organic light emitting diodes (OLEDs) and solid state lighting.

Although light-emitting organic materials are often characterized as amorphous, thin-film structure on the molecular scale is not well understood, and local order may influence the properties of the solid. In the case of polymers, disparity in molecular weight and conjugation length adds further complexity. Structural and optical isomers of an organic molecule may be chemically identical but electronically distinct, and the further presence of molecular fragments makes the assay of purity and quantification of the role of impurities a complex task. Thus, an understanding of the roles of purity and degrees of order in light-emitting organic materials as they relate to SSL is necessary. It is also highly probable that an understanding will need to be gained of how to produce organic materials at a level of purity that is unimaginable today. Progress in these areas can be anticipated to lead to OLED lifetimes that are sufficient for large-scale deployment in the consumer market.

2.5. Dendrimers (Organic Nanoparticles): In recent years, a new structural class of macromolecules, the dendritic polymers, has attracted the attention. The term "dendrimer" was derived from its tree-like branching structure. They are highly branched, mono-disperse macromolecules. The structure of these materials has a great impact on their physical and chemical properties. Their properties open up avenues for electronic and optoelectronic materials and are suitable for a wide range of biomedical and industrial applications. They can be used to make a wide range of LEDs, transistors, solar cells and lasers with novel properties and simple manufacturing process than for conventional inorganic semiconductors. In the field of organic light emitting diodes (OLEDs), 'dendronization' of small molecules confers on them the ability to be applied in liquid form. The light emission feature of these materials offers exciting applications. They may be water-soluble but, because of their compact dimensions, they do not have the usual rheological thickening properties that many polymers have in solution. Dendrimers, the most regular members of the class, are synthesized by step-wise convergent or divergent methods to give distinct stages or generations. Dendrimers possess three components: a central core, an interior dendritic structure (the branches), and an exterior surface (the end groups). More than 50 compositionally different families of these nanoscale macromolecules, with over 200 end-group modifications, have been reported [89]. They are characterized by nearly spherical structures, nanometer sizes, large numbers of reactive end group functionalities, shielded interior voids, and low systemic toxicity. This unique combination of properties makes them ideal candidates for nanotechnology applications in both biological and materials sciences. Nanomolecules have their applications in various fields including materials engineering, pharmaceuticals, industrial, and biomedical. Some of the potential applications are nanoscale catalysts, novel lithographic materials, rheology modifiers, targeted drug delivery systems, MRI contrast agents, and bio-adhesives [90-95].

2.6. Carbon Nanotubes /Fullerenes: In the last three decades, zero-dimensional, one-dimensional, and two-dimensional carbon nanomaterials (i.e., fullerenes, carbon nanotubes, and graphene, respectively) have attracted significant attention from the scientific community due to their unique electronic, optical, thermal, mechanical, and chemical properties. While early work showed that these properties could enable high performance in selected applications, issues surrounding structural inhomogeneity and imprecise assembly have impeded robust and reliable implementation of carbon nanomaterials in widespread technologies. However, with recent advances in synthesis, sorting, and assembly techniques, carbon nanomaterials are experiencing renewed interest as the basis of numerous scalable technologies. Synthesis of carbon based nanomaterials including carbon nanotubes, graphene and graphene quantum dots have received much attention in the last decade because of their intriguing properties and potential applications in nanoelectronics, supercapacitors, LEDs, solar cells, and hydrogen storage. Graphene is a one-atom-thick planar sheet of sp²-bonded carbon atoms, densely packed in a honeycomb lattice, that has attracted tremendous recent interest for both fundamental research related to the exotic behaviour of electrons in two-dimensional systems and exhibits many exciting properties, such as room-temperature quantum hall effect, long-range ballistic transport with ~10 times higher electron mobility than in Si, availability of charge carriers that behave as mass-less relativistic quasi particles (Dirac fermions), and quantum confinement resulting in finite band gap and Coulomb blockade effects, which could be useful for making many novel electronic devices. However, graphene is a zero band gap semiconductor, which renders its electronic and optoelectronic properties almost impossible to use for device applications. Interestingly, this zero band gap material has been more recently engineered to form graphene nanoribbons (GNRs) and graphene quantum dots (GQDs) which reveal several significant properties like finite band gap and ballistic transport due to quantum confinement and edge effects. The strong and tunable luminescence of GQDs is especially attractive because of its promising applications in light emitting diodes, electroluminescence, organic photovoltaic devices, biological labelling and medicine. Fullerene chemistry is an emerging field in which scientific community is engaged providing promising new applications every year. Magnetic nanoparticles show great potential for high-density magnetic storage media. It has been seen that C₆₀ dispersed into ferromagnetic materials such as iron, cobalt, or cobalt-iron alloy forms thin films with excellent magnetic properties [96-97]. Efforts are being made to synthesize a number of organometallic-fullerene compounds, especially ferrocene-like C₆₀ derivative and pair of fullerenes bridged by a rhodium cluster [98-99].

Carbon nanotubes are hollow cylinders of carbon atoms. Their appearance resembles rolled tubes of graphite such that their walls are hexagonal carbon rings and are often formed in large bundles. The ends of CNTs are domed structures of six-membered rings capped by a five-membered ring. There are two types of CNTs: single-walled carbon nanotubes (SWNTs) and multi-walled carbon nanotubes (MWNTs). As their names imply, SWNTs consist of a single, cylindrical graphene layer, whereas MWNTs consist of multiple graphene layers telescoped about one another.

Carbon nanotubes (CNTs) were first isolated and characterized by Iijima in 1991[100]. After that various research articles have been published, and new applications for CNTs have been proposed every year. CNTs are extremely strong, about 100 times stronger (stress resistant) than steel and one-sixth weight. CNTs can also act as conductors or semiconductors depending on their chirality, intrinsic superconductors, ideal thermal conductors and can also behave as field emitters [101-107].

Experiments probing the density of states show that nanotubes can have metallic or variable semiconducting properties with energy gaps ranging from a few meV to a few tenths of an eV. Conductivity measurements of single nanotubes have shown rectification effects for some nanotubes and ohmic conductance for others, suggesting that nanotubes could lead to a new generation of electronic devices. Interaction of water molecules with a nanotube helps in

understanding atomistic interaction, which is critical in designing commercial-quality flat panel displays around carbon nanotube.

2.7. Organic-Inorganic Hybrid Electroluminescent Nanomaterials: Organic–inorganic hybrid materials do not represent only a creative alternative to design new materials and compounds for academic research, but their improved or unusual features allow the development of innovative industrial applications. Hybrid combinations of inorganic and organic materials may also play a role in SSL. The inorganic semiconductors have excellent carrier transport properties (e.g., high electron and hole mobilities), whereas organic semiconductors have excellent light-emission properties (e.g., high luminescence quantum yield and colour tunability). Hence, one might imagine a structure within which charge injection and transport occur first in an inorganic material, followed by charge transfer to an organic material, followed finally by luminescence and light extraction [108].

Generally, the hybrid materials are synthesised and processed by using conventional soft chemistry based routes. These processes are based on: a) the copolymerisation of functional organosilanes, macromonomers, and metal alkoxides; b) the encapsulation of organic components within sol–gel derived silica or metallic oxides; c) the organic functionalisation of nanofillers, nanoclays or other compounds with lamellar structures, etc. The organic-inorganic hybrid nanomaterials combine features of inorganic cations and organic anions combining one or more specific functions of both constituents. The inorganic cation provides a low solubility of the hybrid which is necessary to control particle nucleation and growth - and thus, to prepare nanoparticles. Inorganic cations are also relevant for detection based on its eventual magnetism or on X-ray absorption. Whereas the organic anion provides a certain function as fluorescence or gas absorption. Therefore hybrid nanomaterials allow wide adaptability of composition and function. As they can be synthesised in water, access of nanoscale hybrids is quite simple and cost effective.

2.8. Nano-Intermediates: Nano-intermediates are intermediate products –neither the first nor the last step in the value chain—that either incorporate nanomaterials or have been constructed from other materials to have nanoscale features. Nano-intermediates such as nanostructured films, dispersions, high surface area materials, and supramolecular structures are used in LEDs, solar cells and batteries, sensors, catalysts, coatings, and drug delivery systems to improve their properties. Their fabrication is being done using various special techniques such as self-assembly for proper alignment of nanoparticles.

2.9. Nanocomposites: A nanocomposite is a matrix to which nanoparticles have been added to improve a particular property of the material. The properties of nanocomposites have caused researchers and companies to consider using this material in several fields. Typically, nanocomposites are clay, polymer or carbon, or a combination of these materials with nanoparticle building blocks. Nanocomposites are the materials with nanoscale separation of phases. They are of two types: multilayer structures and inorganic/organic composites. Multilayer structures are formed by gas phase deposition or from self-assembly of monolayers. Inorganic/organic composites are formed by sol-gel techniques, bridging between clusters, or by coating nanoparticles. Nanocomposites greatly enhance properties of materials. Clay-polymer nanocomposites are among the most successful nanotechnological materials today because they can simultaneously improve material properties without significant trade-offs. Increased mechanical stability in polymer-clay nanocomposites also contributes to an increased heat deflection temperature. Traditional polymer composites often have a marked reduction in optical clarity; however, nanoparticles cause little scattering in the optical spectrum and very little UV scattering.

3. Quantum Dots and QLEDs for SSL

The technologies based on semiconductor materials made from wafers are not without their limitations, which nano based quantum dot technologies not only take care but move to a new level of sophistication. A quantum dot (QD), also called a semiconductor nanocrystal or an artificial atom, is a semiconductor crystal whose size is of the order of just a few nanometres. Quantum dot technology solves the problem of narrow set of emission frequencies that limit the use of inorganic LEDs. Colloidal semiconductor nanocrystals, also known as “quantum dots” (QDs), represent an example of a disruptive technology for display and lighting applications. Quantum dots are small particles about few nanometres (a billionth of a meter) in size. By adjusting the particles' physical dimensions, their optical and electronic properties can be fine-tuned. Through such a process, the resulting characteristics of the materials are different than the characteristics of the same material in bulk size. The bright and uniquely size-tunable colours of solution-processable semiconducting QDs highlight the potential of electroluminescent QD light-emitting devices (QLEDs) for use in energy-efficient, high-colour-quality thin-film display and solid-state lighting applications. They are available in both organic and aqueous formulations and have unique properties for applications that include LEDs, solid state lighting, displays, photovoltaics, transistors, quantum computing, medical imaging, biosensors, among many others [109-113].

QDs are generally used as optical down-converters. Blue light from an efficient high energy light source (e.g., GaN blue LED) is absorbed and re-emitted at any desired lower energy wavelength. Alternatively, electric current can be used for direct excitation of QDs. QLEDs are an exciting technical challenge and commercial opportunity for display and solid-state lighting applications. Quantum Dots (QDs) can be used to make a white-light LED in several ways. Initially, the greatest benefit can be obtained by replacing just the red phosphor with red-emitting QDs. For a 3000K CCT and 80 CRI source, the benefit is over 20% improvement in spectral efficiency as measured by Luminous Efficacy of Radiation (LER). Higher CRI sources requiring more red in the spectrum will benefit even more. An all-QD solution will be possible in the near future to provide full spectral engineering capability. In this case, three QD colours are used to replace all the phosphor in the package, providing maximum benefit of >40% for a CRI of 95, representing a very high quality of light almost indistinguishable from an incandescent source.

Nowadays efficient down conversion for white light emission is mainly based on rare-earth doped phosphors or cadmium-containing quantum dots. Although they exhibit high luminescence efficiency, the rare-earth mining and cadmium pollution have so far led to extremely high environmental cost, which conflicts the original purpose of pursuing efficient lighting. Fig. 15(a) illustrates that the narrow emission spectra of pure and tunable colloidal quantum dot (QD) can be easily tuned throughout the visible and near-infrared (NIR) spectrum via both quantum size effects and changes in chemical composition. The CIE chromaticity diagram, created by the International Commission on Illumination (CIE) in 1931, allows colour quality to be quantified by mapping colours visible to the human eye in terms of hue and saturation [Fig. 15(b)]. CdSe-based QDs are currently the material of choice for visible applications, as their saturated emission spans the visible spectrum, delineating a large potential colour gamut that approaches that of the human eye and therefore QDs have already begun to find commercial applications as optically excited colour enhancers [114].

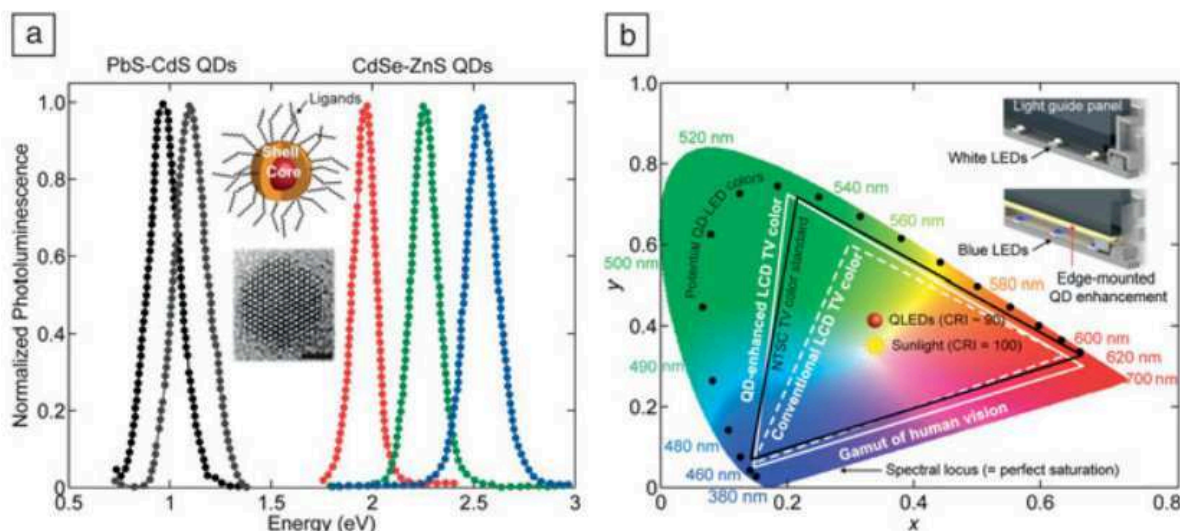


Fig. 15: Pure and tunable colloidal quantum dot (QD) light emission: **(a)** Normalized PL spectra of visible-emitting CdSe- ZnS core shell QDs and near IR-emitting PbS-CdS core shell QDs exhibiting size- and composition-tunable emission colours. QLED electroluminescence typically closely matches the corresponding PL spectra. Upper inset: Core-shell colloidal QD passivated by organic ligands. Lower inset: HR TEM image of a CdSe QD (scale 1.5 nm). **(b)** The CIE chromaticity diagram exhibits an ideal combination of red-green-blue QLED sources which generates the colours defined by the black dots or to serve as a high colour quality (CRI ~ 90) white light source. The colour gamut of conventional LCD televisions (upper inset and dashed white line) is enhanced by ~ 50% by edge-mounted QDs (lower inset and solid white line) so as to match 100% of the NTSC television colour gamut standard (black line) [18, 114].

QLEDs offer all of the functional benefits of emissive display technologies, with the added advantage of simplified manufacturing processes and the potential to consume half of the power of the most efficient OLEDs. QDs red, green and blue QLEDs now meet or exceed the 1953 NSTC colour standard without using colour filters or secondary effects. Quantum dot light-emitting diodes (QLEDs) can provide saturated emission colours and allow inexpensive solution-based device fabrication on almost any substrate. The exceptional colour performance of QLEDs translates into a fundamental 30-40% luminous efficiency advantage over the best known OLED technology. The deep red QLEDs now offer greater efficacy at equivalent colour than the best reported phosphorescent OLEDs, and its green and blue QLEDs match the performance of fluorescent OLEDs, but with far superior colour performance. The red QLEDs consistently achieve peak external quantum efficiencies (EQEs) of more than 18% and efficacies of more than 22 lm/W and 18 Cd/A, at 1931 CIE colour coordinates of (0.68, 0.32).

Table 3: Selected reports on the use of Q dots to down convert blue or UV light from inorganic LEDs [111]. R: red, G: green, B; blue, O: orange; Y: yellow; W; white; CRI: colour rendering index.

Year	Source Light	Quantum Dot	Matrix	Emitted Light	Ref.
2000	UV (Hg lamp), Blue GaN Comm. LED	CdSe/ZnS (2.0, 2.6, 4.6, 5.6nm)	Polyaurylmethacrylate	UV: Blue, orange, red; Blue: red (590 nm)	115.
2005	InGaN (near UV)	ZnSe (TOPO & Stearic acid coated)	Organics coated ZnSe (10 wt%) dispersed in epoxy resin	White; CIE (0.38, 0.41) Conversion efficiency: 30% relative to RGB commercial phosphors	116.
2006	InGaN (455 nm)	CdSe/ZnSe G); CdSe/ZnSe (R) CdSe/ZnSe (Y)	TOPO-coated CdSe/ZnSe dispersed in silicone	White, CIE: (0.33, 0.33), CRI: 91 with R & G; White, CIE: (0.32, 0.33), CRI: 50 with Y; Efficiency: 15-30lm/W	117.
2007	390 nm UV LED	CdSe/CdS/ZnS	2wt% Qdot in chloroform & epoxy resin at 1:1 (by volume); Thermally cured	Red (620 nm)	118.
2007	InGaN/GaN (440 nm, 452 nm)	CdSe/ZnS (440-452)	Qdots blended with resin; 400 -1700 μ m (Qdot density: 3.04-140 nano moles/1mlresin)	White; with 453 nm & CdSe/ZnS (540, 500, 580 & 520 nm): CIE (0.24, 0.33), CRI: 71	119.
2008	InGaN/GaN (blue/green)	CdSe/ZnS (620nm, R) & Au particles (For Surface Plasmon enhanced. emission)	5 wt% Qdots and 0.05 wt% Au in toluene spin-coated on LED (thickness ~200 nm)	White: (0.27, 0.24); Conversion efficiency ~53%	120.

Inorganic quantum dots of semiconductors such as cadmium selenide are well known for their efficient luminescence that can be tuned by changing the size of the particle, but phenomena such as surface quenching can swallow almost all their potential light emission. By “capping” these inorganic nanoparticles with organic molecules, it is possible to improve both fluorescence efficiency and ease of fabrication. The resulting structures can be used as down conversion media (i.e., to convert UV or blue light into longer wavelength colour via fluorescence), and recent work has demonstrated that they can, in principle, be incorporated into the light-emitting structure of an OLED. Thin-film QLEDs emitting white light can be used for large-area lighting systems and backlighting for liquid crystal displays. A number of laboratories reported white QLEDs with the emitting layer assembled of a balanced mixture of red, green, and blue emitting QDs. Selected reports on the use of Q dots to down convert blue or UV light from inorganic LEDs is depicted in Table 3 [115- 120].

Self-assembled quantum dots (SAQDs) grown by epitaxial techniques such as molecular beam epitaxy (MBE) have become a topic of extensive research for their application in electronic and optoelectronic devices [121]. Fig. 16 depicts self-assembled indium gallium arsenide QDs.

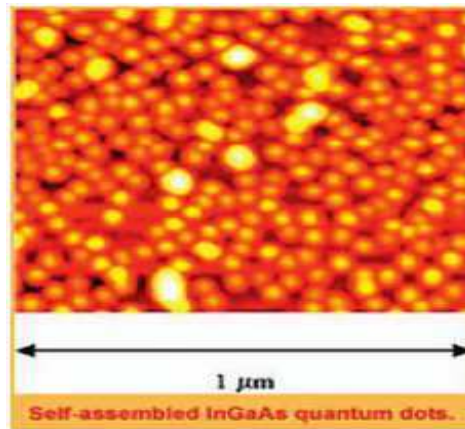


Fig. 16: Self-assembled indium gallium arsenide QDs.

Recently, inorganic QDs have been embedded in organic LED structures, thereby creating hybrid organic-inorganic QD-LEDs [122]. LED colour emission across the visible part of the spectrum and from 1.3 μm to 1.6 μm in the infrared was demonstrated with attractive power-consumption properties. Moreover, white colour emission can be achieved by composing the QD monolayer of a mixture of QD materials with different colour-emission properties. The solutions of QD-LEDs can be precisely mixed to achieve any desired spectrum. This is a unique capability of QD-LED sources that surpasses the tunability of the best OLEDs, and it originates from the simplicity of the QD-LED design and the colour purity of QD materials. A recently demonstrated QD-LED with a mixed QD-emitter layer is shown in the fig.17. The combined emission spectrum generates the appearance of white light with CIE coordinates of (0.41, 0.43) [123-124].

The progression in QLED performance is mapped in terms of external quantum efficiency (EQE), which is defined as the ratio of the number of photons emitted by the LED in the viewing direction to the number of electrons injected. EQE is directly proportional to power conversion efficiency and therefore a key metric for SSL and displays.

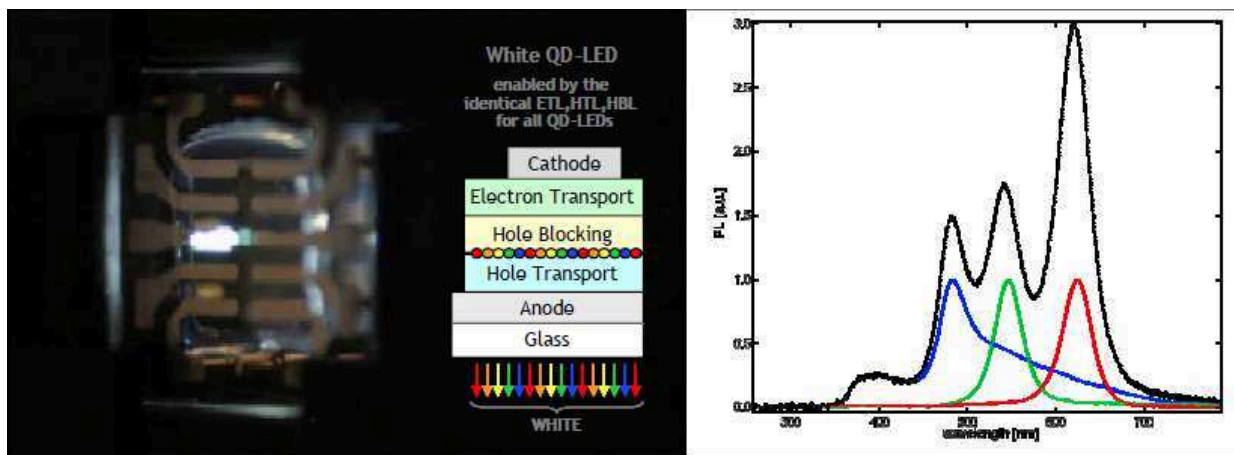


Fig. 17: White QD-LED in operation and a schematic cross section of a white QD-LED indicating that the QD monolayer consists of a mixture of different (multicolour) QD materials. The spectral emission is optimized by adjusting the QD composition ratios. (Right) Spectral emission of the white QD-LED on the left, which incorporates three types of QDs [18, 123-124].

Inverted hybrid organic- inorganic charge transport layers QDs have structure that has risen to prominence owing to its record efficiencies and brightness [18, 125]. The device structure shown in fig. 18 typically comprises a few monolayers of QDs sandwiched between an inorganic metal oxide electron transport layer and an organic hole transport layer.

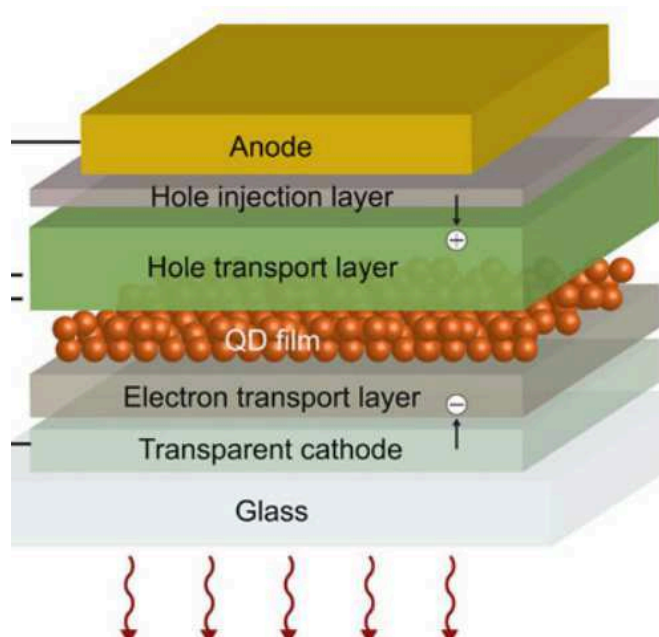


Fig. 18: Inverted hybrid organic-QD-inorganic Type IV quantum dot light-emitting device (QLED) design [18].

3.1. Photoluminescent Nanofibers: Photoluminescent nanofibers (PLNs) are a new class of materials for SSL applications that can be created by combining polymeric nanofibers and luminescent nanoparticles such as QDs [126]. When dispersed across a flexible panel, PLNs are able to diffuse light and provide panel lighting from inorganic LEDs. The polymeric nature of the PLNs imparts the ability to conform to the luminaire design and also provides a mass-producible substrate for housing QDs. Application of QDs to PLNs can be accomplished using common liquid-phase coating methods such as spray coating. The composition of the coating formulations will vary depending upon each QD, and each formulation must be optimized to maintain high quantum efficiencies and acceptable adhesion. PLNs have been demonstrated to produce high luminous efficacy (>50 lumen/watt) lighting prototypes with excellent colour rendering properties.

4. Methods of Synthesis

The synthesis, characterization and processing of nanostructured materials are part of an emerging and rapidly growing field. Research and development in this field emphasizes scientific discoveries in the generation of materials with controlled microstructural characteristics, research on their processing into bulk materials with engineered properties and technological functions, and introduction of new device concepts and manufacturing methods. The research is based on preparation of uniform nanoparticles and nanoparticle arrays with appropriate chemical composition and structure. Sophisticated growth techniques and the development of three (ternary) and four (quaternary) component systems allow for the fabrication of complex multilayer structures. Electrical charge carriers, both negative (electrons) and positive (holes), are confined in conduction and valence bands, respectively, and their allowed energy states can be adjusted by fine tuning both the composition and thickness of the various multilayers. Simultaneously, light can be manipulated in the multilayer structure by arranging the refractive indices of the layers to form, for example, a waveguide. In total, the available toolkit of materials and growth techniques enables the creation of layer structures a few microns thick that allow for the efficient injection of charge, conversion to

light, and, finally, extraction of light back into the outside world. A semiconductor heterostructure consists of two or more layers with different energy bandgaps, formed by changing the composition of the material. Examples include GaAs/AlGaAs and GaN/AlGaN in the III-V compound semiconductors, and Si/SiGe, alloys of elemental semiconductors in column IV of the periodic table. In general, the use of heterostructures allows the energy and flow of electrons in a device to be controlled in a sophisticated manner unobtainable in a single material. By incorporating materials with differing refractive indices, the confinement of photons can also be controlled.

Synthesis and assembly strategies of nanoparticles mostly accommodate precursors from liquid, solid

or gas phase; employ chemical or physical deposition approaches; and similarly rely on either chemical reactivity or physical compaction to integrate the nanostructure building blocks within the final material structure. The variety of techniques that can be classified in top-down or bottom-up approaches are schematically illustrated in Fig. 19. The bottom up approach of nanomaterials synthesis first forms the nanostructured building blocks (nanoparticles) and then assembles these into the final material. The top-down approach begins with a suitable starting material and then sculpts the functionality from the material.

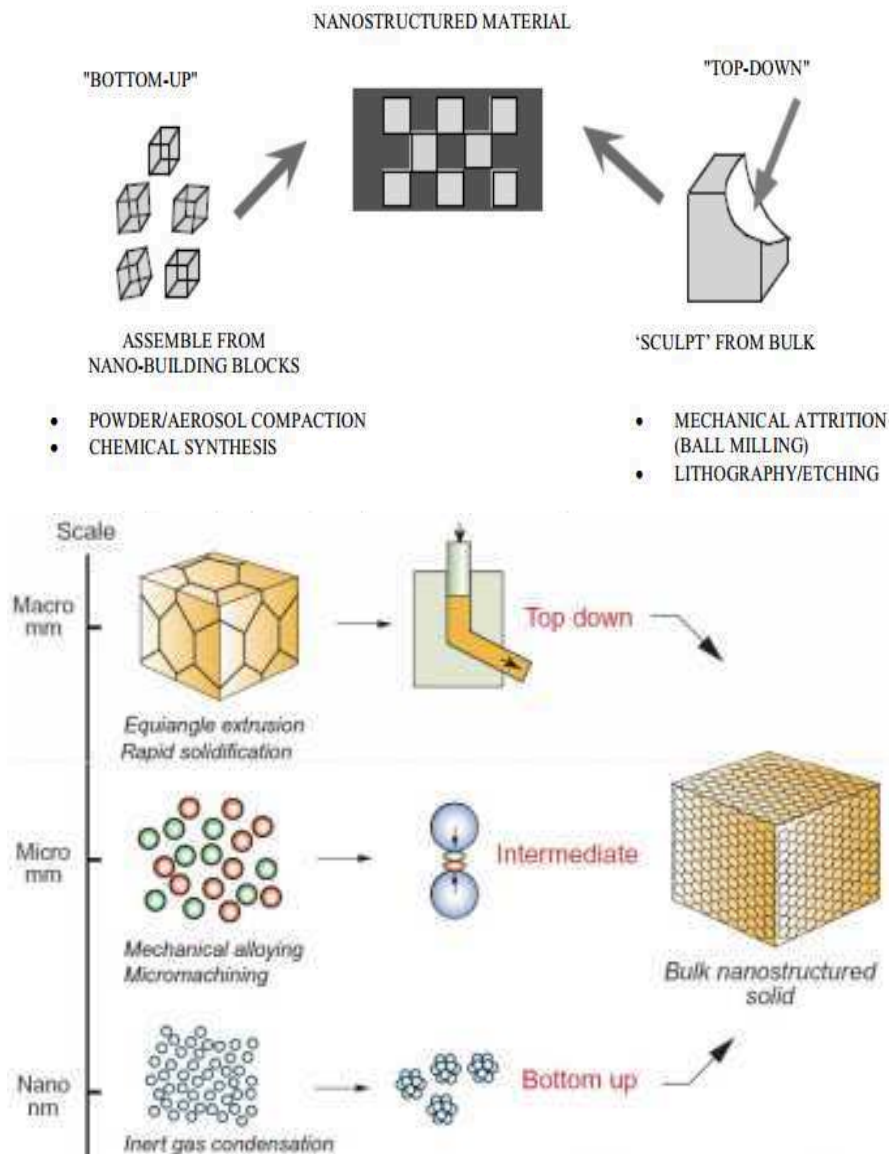


Fig. 19: Schematic of a variety of nanostructure synthesis and assembly approaches.

Various methods of preparation are: solvent evaporation method, spontaneous emulsification or solvent diffusion method, polymerization method, coacervation or ionic gelation method, synthesis

of nanoparticles using supercritical fluid technology, semiconductor nanoclusters, sol-gel deposition, thermal decomposition method and hydrothermal synthesis methods. They are as follows:

4.1. Solvent Evaporation Method: In this process, the polymer is dissolved in an organic solvent which is also used to dissolve the water repellent drug. The mixture containing the drug solution and polymer is then emulsified in a solution containing an emulsification agent to form an emulsion of oil in water. After the formation of emulsion, the organic solvent is then evaporated by continuously stirring the solution or by reducing the pressure. Particle size is influenced by homogenizer speed, the type and concentrations of stabilizer and polymer concentration.

4.2. Spontaneous Emulsification or Solvent Diffusion Method: This is a modified version of the earlier method. Usually the water miscible solvent, together with a small quantity of the organic solvent is used as oil phase. Due to diffusion of solvents, an interfacial turbulence is generated between two phases which in turn leads to the formation of small sized particles. As the quantity of solvent increases, a further decrease in the particle size can be achieved [127].

4.3. Polymerization Method: In this method, monomers are polymerized to form nanomaterials in an aqueous solution. Drug is incorporated by adsorption onto the nanoparticles or by dissolving in the polymerization medium after polymerization has been completed. The suspension is then purified to remove stabilizers and surfactants which were used for polymerization by ultra centrifugation and then re-suspending the particles in a medium free of isotonic surfactants. This technique is suitable for making poly (alkylcyanoacrylate) or polybutylcyanoacrylate nanoparticles. The particle size depends on the concentration of the stabilizers and surfactants used [127-129].

4.4. Coacervation or Ionic Gelation Method: Preparation of nanoparticles from biodegradable hydrophilic polymers such as gelatin, chitosan and sodium alginate is currently gaining much attention. Nanoparticles from hydrophilic polymer can be prepared by the complex coacervation which is the spontaneous phase separation process that occurs when oppositely charged macromolecules are mixed and it is a result of electrostatic and coacervates form under mild conditions where as ionic gelation involves the material undergoing transition from liquid to gel due to ionic interaction. The method involves a mixture of two aqueous phases, of which one is the polymer chitosan and the other is the polyanion sodium tripolyphosphate. In this technique, amino group of chitosan combines with tripolyphosphate to form coacervates with a size in the range of nanometers. These are formed due to electrostatic interaction between the two phases, while ionic gelation involves transition from liquid phase to the gel phase due to ionic interaction which takes place at room temperature [127-129].

4.5. Synthesis of Nanoparticles using Supercritical Fluid Technology: Conventional methods such as solvent diffusion, solvent extraction-evaporation and organic phase separation methods require organic solvents which are harmful to the environment. Therefore, the supercritical fluid technology is generally used as an alternative for preparing biodegradable micro and nanoparticles because supercritical fluids are considered to be environmentally safe. A supercritical fluid can be defined as a solvent at a value higher than its critical temperature at which it remains in a single phase irrespective of pressure. Supercritical CO₂ is the most widely used super critical fluid because of its relatively mild critical conditions ($T_c = 31.1^\circ\text{C}$, $P_c = 73.8$ bars), non-ammability, nontoxicity and lesser cost.

4.6. Semiconductor Nanoclusters: During the past decade there has been a phenomenal growth in the basic research of semiconductor nanoclusters. As the field has evolved the emphasis has shifted from basic theoretical description to field utilization of nanocluster-based devices. Semiconductor nanocluster research is a rapidly growing field driven by the attractive idea to tailor material

properties by acting on the morphology of the structures. The modifications of the electronic and optical properties by changing the size of the nanoclusters are rather well understood theoretically and well controlled experimentally. Silicon clusters and nanocrystals containing up to several thousand atoms per cluster have been generated by Ehbrecht and Huisken [130] using pulsed CO₂-laser-induced decomposition of SiH₄ in a flow reactor. By introducing a conical nozzle in to the reaction zone, the nascent clusters are extracted into a molecular beam apparatus where they are analyzed with a time-of-flight mass spectrometer. Compared to laser vaporization method, this technique is capable of producing considerably larger silicon clusters with diameters in the nanometer size regime. A time-of-flight study of the neutral silicon clusters has shown that the velocity of the particles strongly depends on their size. This feature enables by introducing a chopper into the cluster beam, to considerably reduce the size distribution and to perform experiments with quasi-size-selected neutral clusters. An investigation of the fragmentation behaviour of the ionized silicon clusters as a function of the fluence of the ionizing ArF excimer laser reveals that intermediate size Si_n clusters (n = 22–100) fragment by fission, yielding Si⁺⁶/ - Si⁺¹¹, while nanometric silicon clusters evaporate single Si⁺ and Si⁺² ions if the influence of the ionizing laser is large enough. At the same time, multiply charged nanoclusters are observed. Quantum dots are three-dimensional semiconductor materials matrix. Nanocomposites from semiconductor materials belong to this group. Sometimes, it is difficult to differentiate between quantum dots and nano defects. SiO₂ implanted with Ge, is used for photoluminescence (PL) experiments. Precipitation on glass is being used in the manufacturing of CdS, CdSe, CdTe, GaAs, and Si nanocrystallites. The additives are added to the melt, and after annealing from 600 to 1400 °C, they form precipitates of controlled size, for instance, 2 nm for CdTe dots in boron silicate glass. Quantum dots can also be manufactured by means of lithography. For high resolution, electron beam lithography is used. The procedure takes place mostly in such a way that the material which is to be converted into quantum dots is deposited on a substrate like GaAs via MBE. CdSe nanowire arrays are being prepared on glass slides by electrodeposition on 30 nm thick nickel film. Electrodeposition can be carried out in a one-compartment, three-electrode electrochemical cell.

4.7. Sol-Gel Deposition: Sol-gel technology is a well-established colloidal chemistry technology, which offers possibility to produce various materials with novel, predefined properties in a simple process and at relatively low process cost. Sol-gel techniques have been used for many years to synthesize nanoparticles including Qdots [129, 131, 132]. In a typical technique, a sol (nanoparticles dispersed in a solvent by *Brownian* motion) 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 (sol formation) and growth (gel formation). In brief, the metal precursor hydrolyzes in the medium and condenses to form a sol, followed by polymerization to form a network (gel). The sol-gel method offers a unique opportunity for ceramic fabrication at relatively low temperatures, often at room temperature. Later the sol-gel method was successfully adopted for the processing of a wide variety of materials, from monolithic ceramic and glasses to fine powders, thin films, ceramic fibers, microporous inorganic membranes, and extremely porous aerogel materials [133]. The main idea of the sol-gel process is the spontaneous formation of a dual phase material (gel), containing a solid frame filled with solvent, from the solution (sol), containing either solid clusters or required chemical reagents (e.g., inorganic precursors and stabilizing agents). Further transformation of the gel phase is driven by the evaporation of the solvent, and the subsequent formation of the xerogel phase. The sol-xerogel transformation may take place in the bulk of the solution, but it works much more effectively when the solution is spread over the surface of solid substrate. Thin xerogel films (in the range of 100 nm) can be formed on the solid substrates by dip coating, spin coating, or spraying of the solution. Heating of the xerogel completely removes solvent molecules, and stabilizes, therefore leading to further aggregation of inorganic clusters and the formation of solid materials, either in bulk or in the form of thin films. Repetition allows the formation of thicker multi-layered films. A quick, supercritical drying carried out at high temperature leads to the formation of the aerogel which is extremely porous material having

porosity greater than 75% . On the other hand, a very slow evaporation of the solvent at ambient conditions causes the precipitation of solid phase yielding fine and uniform particles. As shown in fig.20, the sol-gel is implemented in the industrial processing of ceramic materials in the form of sheets, tubes, and fibers [134-139] .

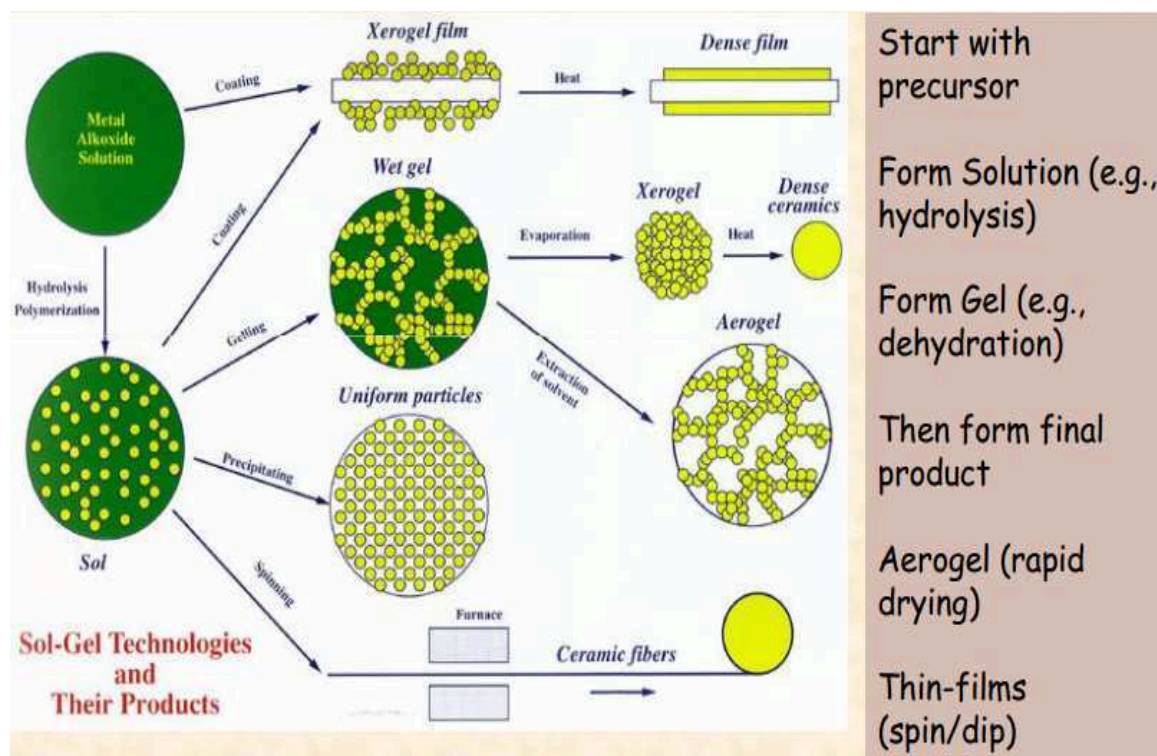


Fig. 20: Sol-gel technology and their products [134].

An alternative route of sol-gel reaction lies in the usage of colloidal sols as precursors. The sol-gel reaction is very often performed in the dip-coating regime, in which the solid substrate is slowly pulled out from the solution containing the required chemicals. The reaction known as gelation (i.e., sol-gel transition of the solution in contact with the atmosphere) takes place in a thin liquid layer wetting the substrate, as shown schematically in fig. 21. The xerogel coating obtained requires additional annealing to remove the residual solvent. The thickness of the resulting inorganic layer depends on the viscosity of the solution, the withdrawal speed, and the wetting conditions of the substrate (i.e., the contact wetting angle between the solution and the substrate). The final stage of the formation of thin solid films prepared by the sol-gel route is annealing and two processes occur during annealing: 1) Final evaporation of solvent from the film matrix, and, 2) Further aggregation and sintering of nanoclusters. The resulting films are typically polycrystalline, with the grain size ranging from 10 to 20 nm.

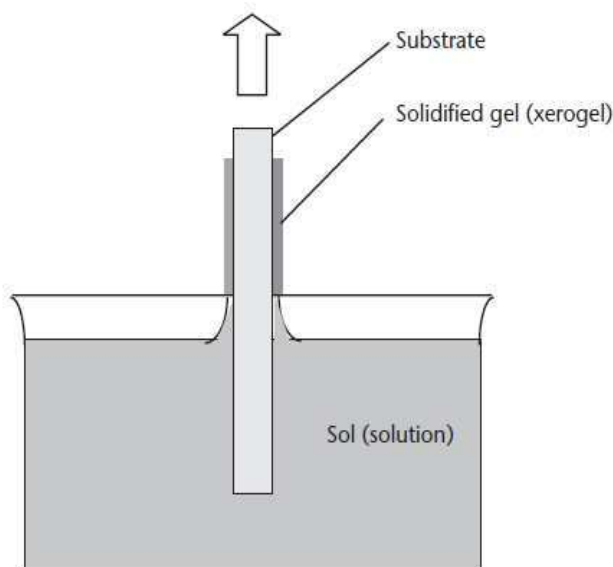


Fig. 21: The schematic diagram of the sol-gel dip-coating technique [139].

4.8. Thermal Decomposition Method: Thermal decomposition, which is one of the most popular synthesis method, gives well shaped particles with good size control in a relatively short reaction time. It usually involves dissolving organic precursors in high-boiling organic solvents with the assistance of surfactants. The commonly used organic precursors are trifluoroacetate compounds, and the surfactants typically have polar capping groups and long hydrocarbon chains, such as oleic acid (OA), omeylamine (OM), and 1-octadecene (ODE). Growth mechanism of nanocrystals has been investigated systematically by Mai et al. [135]. Trifluoroacetate precursors in hot surfactant solutions show delay in nucleation pathway. The synthesis reaction is combination of four stages including nucleation in a delayed time, particle growth by monomer supply, size shrinkage by dissolution, and aggregation. Fig. 22 describes the synthesis steps of $\alpha\text{-NaYF}_4\text{:Yb}^{3+}, \text{Er}^{3+}$ UCNs and by varying the reaction time, concentration of reagents, and reaction temperature, various sizes and shapes of $\text{NaYF}_4\text{:Yb}^{3+}, \text{Er}^{3+}$ upconversion nanoparticles can be obtained.

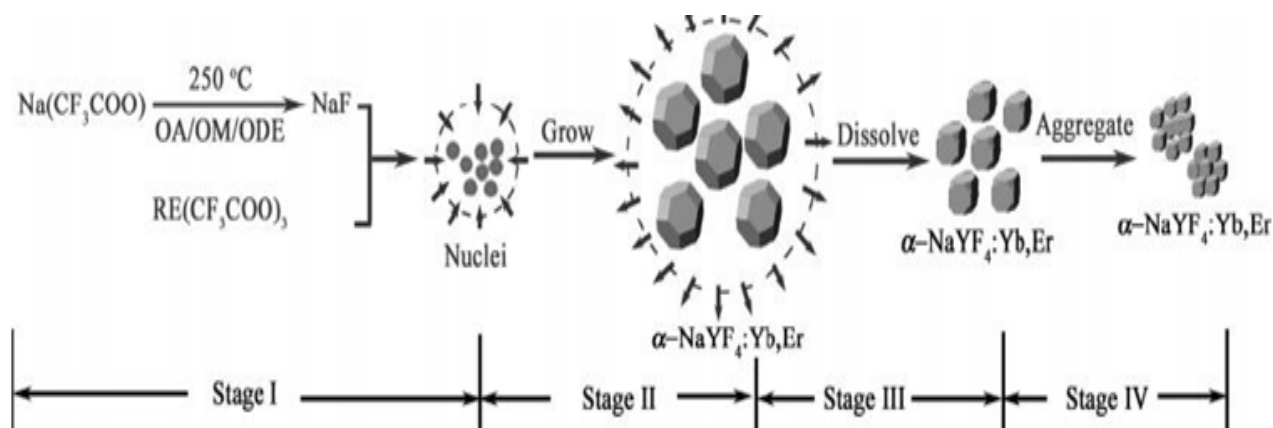


Fig. 22: Schematic illustration of the growth stages of $\alpha\text{-NaYF}_4\text{:Yb}^{3+}, \text{Er}^{3+}$ nanocrystals via a delayed nucleation pathway [135, 140].

4.9. Hydrothermal Synthesis Method: Hydrothermal processing is a non-conventional method to obtain nanocrystalline inorganic materials. It is a solution-based approach, which is usually employed under high temperatures and pressures. The synthesis method uses the solubility of almost all inorganic substances in water at elevated temperatures and pressures, and subsequent crystallization of the dissolved material from the fluid [129, 141-143]. Hydrothermal synthesis can occur in a

water-based system at relatively environmental friendly temperature range (160–220 °C). Both physical and chemical parameters can be varied systematically during the hydrothermal processing in such a way that a direct precursor-product correlation can be established. It is an effective and convenient process of preparing inorganic materials with diverse controllable morphologies and architectures. For example, various shapes of hexagonal NaYF_4 crystals, such as prism, disk, tube, rod, and octadecahedral shapes were synthesized by applying this method [144–145]. The advantage of this method is increased solubility and high temperature is replaced by high pressures and its disadvantage is requirement of specialised equipment like sealed vessel. Recently, the mechanism of synthesizing different shapes of RE fluoride nano-microcrystals is systematically investigated [146–147]. The organic additive trisodium citrate, the fluoride source, and pH values greatly effect the shapes. Hydrothermal processing is rather complex because a great number of interacting parameters play essential roles. Temperature plays an important role in kinetics of product formation, as well as on the thermodynamic stability of the product phase. Pressure is essential for the solubility, the supersaturation range stipulating the crystallization process and for the thermodynamic stability of the product phase (e.g. a too high synthesis pressure leads to crystallization of denser phases). To avoid the influence of the pressure generating temperature, the external pressure mode is actually preferred since low temperature-high pressure syntheses are only available by this high pressure hydrothermal synthesis (HPHS) mode.

High pressure hydrothermal synthesis (HPHS) of nanocrystalline materials has to be controlled by the process parameters temperature, pressure and time, as well as the physical and the chemical parameters of the materials system under investigation (Fig.23). Among the various techniques, thermal decomposition and hydrothermal synthesis have been proven to be the two most popular methods for fabricating the upconversion nanoparticles.

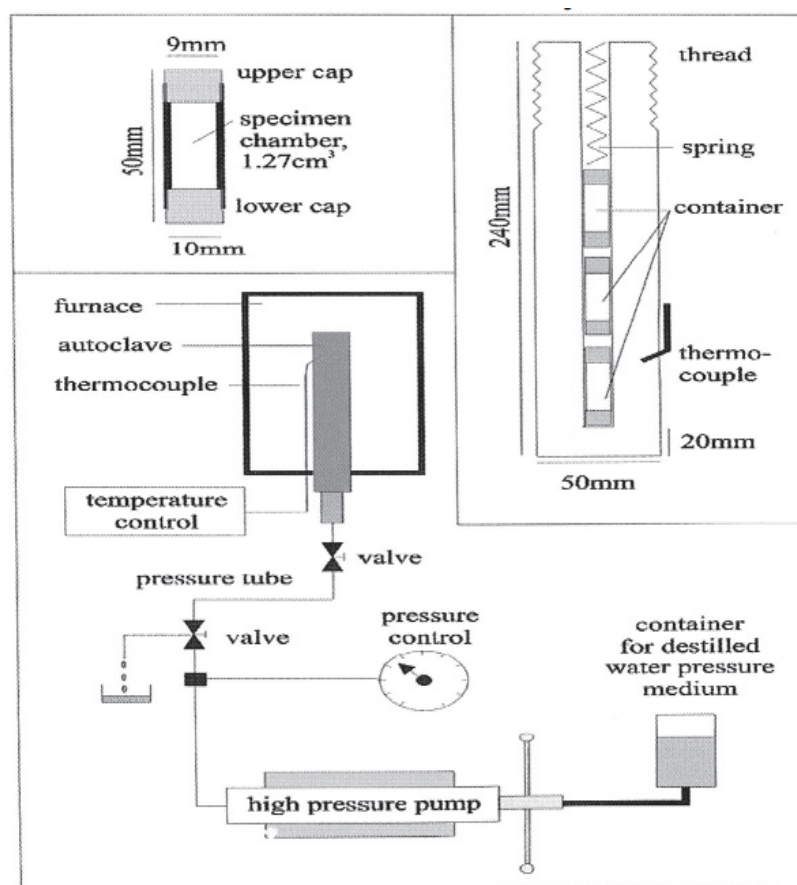


Fig. 23: Standard high pressure hydrothermal synthesis (HPHS)

5. Characterisation of Luminescent Nanomaterials

Nanomaterials with the enhanced mechanical, electrical, and optical properties distinctively different from the bulk material properties allow us to surmount many areas that the conventional technology could not address. Nowadays, such properties of the nanomaterials may be characterized electrically and mechanically by direct contact with the nanomaterials. Nanomaterial characterization is of utmost significance to establish understanding and control of nanoparticle synthesis and applications. Characterization is done by using a variety of different techniques. The features which make nanoparticles attractive for unique sensing applications also cause complications in their characterization processes. Therefore, there is need to search for appropriate characterization techniques having optimum capabilities for studying the characteristics of nanomaterials.

The characterization of nanoparticles can be done by numerous techniques. These characterization methods can be grouped under two categories, first - that estimates values averaged over a large ensemble of particles; second - those that provide information about a limited number of particles. The most important among the latter group of methods are those that are microscopic in nature. The behaviour of nanomaterials is controlled by their global properties, which provide information about ensemble behaviour is achievable. Optical and infrared spectroscopies, photoluminescence, scanning probe microscopies, electrical characterization, and structurally sensitive techniques employing energetic beams of ions, photons, and neutrons continue to improve and provide new insights into the relevant materials and devices.

5.1. Structural Characterization

5.1.1. SEM: Scanning electron microscopy (SEM) is commonly being used to analyse morphology of nanostructures, including various geometrical and structural features, such as uniformity, orientation, length and diameter distribution, and spatial density. As one dimensional nanostructure is primarily defined by its geometrical size, the structure and morphological characterization of nanoscale parameters play an important role in deciding its physical properties. In an ordinary optical microscope, the spatial resolution is limited by the wave length of light. The Abbe limit regulates the smallest feature size that can be resolved to be $\sim 0.5\lambda$, which is several orders of magnitude larger than an atomic scale. But in an electron microscope, the microstructure sample to be analysed is irradiated with a finely focused electron beam; these energetic electrons give rise to a much shorter De Broglie wavelength than that of visible light. Thus specific emission volume determines the achievable image resolution in the nanometre range. Various secondary signals are also produced from the electron beam/specimen interaction, including secondary electrons, backscattered electrons, Auger electrons, characteristic X-rays, and photons [148]. Among these signals, SEM mainly detects secondary electrons and backscattered electrons.

5.1.2. TEM: Transmission electron microscopy (TEM) with its multi-facet capabilities such as nano-beam diffraction, composition analysis and imaging abilities with atomic scale resolution at nanoscale level has become a powerful tool for complete characterization of nanoscale microstructure of nanomaterials. As transmission electron microscopes (TEM) became more accessible to the scientific community at large, the growth of nano-scale materials study drastically developed. High resolution imaging (HREM) in the TEM has evolved as a very powerful tool for probing the structure phases and the defects due to its ability to resolve the interface structures in nanomaterials. By combining TEM with SAED patterns, a wealth of information, such as growth direction, defect or dislocation, crystallinity, and lattice constants, can be studied.

5.1.3. XRD: X-ray and neutron scattering are an important class of experimental tools for materials characterization. The scattering of X-ray and neutron beams by crystalline materials can

be divided into two categories: elastic and inelastic. Elastic scattering, or diffraction, is referred to as a scattering process in which the incident X-ray or neutrons change direction without losing energy when they interact with the material. During inelastic scattering, the incident X-ray or neutrons change both direction and energy. The loss (or gain) of energy by the X-ray or neutron beams excites (or annihilates) fundamental excitations that describe the collective motion of atoms within the material. Similar to the characterization of bulk, XRD and X-ray EDS are commonly used in the characterization of nanowires for structural and compositional analysis. The XRD patterns provide information on crystallinity and preferred growth direction of nanowires. XRD, when combined with SEM technique, also shows the alignment of the nanowire array.

EDS has been used to check the impurity content such as doping level and residue of metal catalyst, component incorporation, and stoichiometry of nanowire [149-152]. However, due to a much shorter X-ray wavelength compared with the size of the nanowire, the scattering effect and thus spectrum broadening should not be ignored.

5.1.4. Scanning Probe Microscopy: In STM, the sample is probed by a very sharp tip. Unlike a conventional diffraction limited far-field technique, STM operates in the near field and is sensitive to the variation of the tip-sample separation. The electron tunnelling mechanism is used to control the distance between sample and tip, where the tunnelling current depends exponentially on the tip-sample separation. Therefore, it is capable of an atomic scale resolution (~ 0.1 nm). Because of its high resolution, scanning probe microscopy (SPM) technique has been employed to study the surface reconstruction of nanowires.

5.2. Optical Characterization: The optical characterization methods are essential in analysing the various fundamental and functional properties of the luminescent nanomaterials. The optical characterization methods take advantage of observing the essential characteristics of the nanomaterials without significantly modifying or permanently damaging them due to their noncontact and non-invasive nature. Common optical characterization methods include absorbance/transmittance, photoluminescence, and Raman scattering measurement. Some of such methods are discussed in brief.

5.2.1. PL Spectroscopy: PL spectroscopy provides a simple, non-destructive, and sensitive way to characterize the optical properties of one dimensional nanostructure. It does not require the fabrication of nanoscale metal contacts. The spatial resolution of the PL spectrum is defined by the diffraction limit of the excitation source. In combination with near field optical techniques, such as fibre probes and NSOM, a sub-wavelength resolution can be achieved [153]. On using an optical cryostat and an ultrafast laser source, temperature-dependent emission and its temporal relaxation behaviour can be studied. PL is also a powerful tool for characterizing the quantum confinement effect in nanowires because of the large electron-hole oscillator strength near the singularity in the joint density of states.

5.2.2. Raman Spectrum: Raman spectroscopy is a useful tool to characterize many properties, such as crystallinity, strain, etc. in bulk and epitaxial materials [154-156]. It is based on the Raman scattering process that corresponds to the interaction between incident photons and the optical modes of lattice vibration.

State-of-the-art advances in several techniques are particularly relevant for meeting the characterization challenges of SSL materials and devices as described below:

- Near-field scanning optical methods,
- Single-molecule spectroscopy,
- Electron-beam methods with enhanced energy and spatial resolution for improved sensitivities and methods that mitigate artefacts due to sample damage,

- Neutron and x-ray scattering, fluorescence, and spectroscopy, including in situ microscopy, ultrafast time resolved scattering and spectroscopy and inelastic scattering; and
- Tools for the assay of organic materials.

Taken together, these advanced experimental and theoretical capabilities promise to enable unprecedented, and in some cases, simultaneous high resolution in energy, time, space, chemical composition, and other parameters.

A recent example of precise nanoscale characterization of both structure and optical properties (spectroscopy) in the carbon nanotube family of materials is illustrated in fig. 24 [157]. The structure of an individual carbon nanotube was determined by advanced electron microscopy. The nanotube was suspended in air between two slits and an electron beam in a transmission electron microscope was incident on the nanotube, creating the diffraction pattern illustrated in part “A” of fig. 24. A theoretical model of the diffraction pattern shown in “B” uniquely determines the structure. The chiral vector indices (n , m) were determined to be (16, 11) for this particular nanotube. The optical spectrum was determined on the same individual nanotube via Rayleigh scattering as shown in panel “D.” The sensitivity of important physical properties on subtle structural changes in this nanomaterial illustrates the need to develop precise characterization techniques.

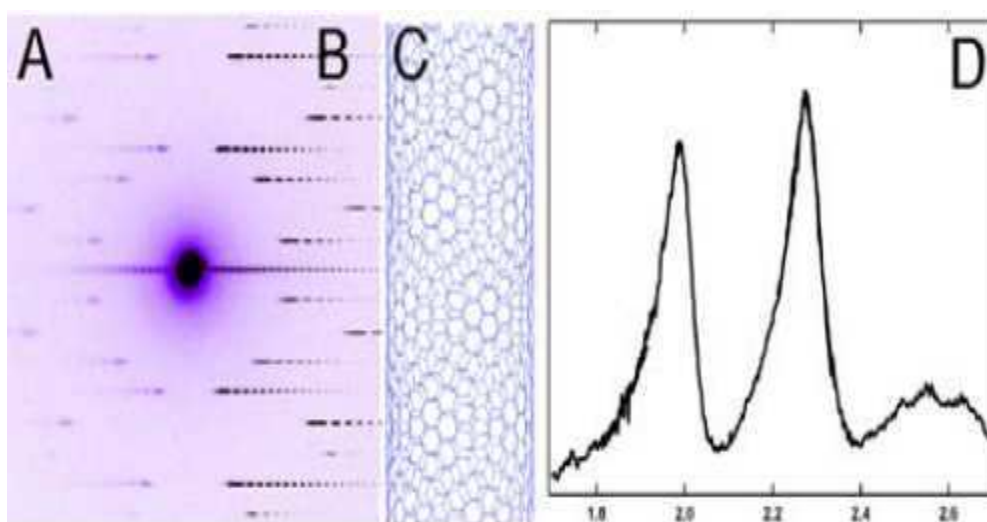


Fig. 24: (A) Experimental electron diffraction pattern from a single carbon nanotube. (B) Theoretical model of diffraction pattern for a (16, 11) nanotube. (C) A model of the (16, 11) carbon nanotube. (D) Rayleigh scattering optical spectrum from the same individual carbon nanotube [157].

6. Applications of SSL

The adoption of SSL is also accelerating. Due to its efficiency, low cost of ownership, controllability, and lifetime, LED lighting has the potential to become the dominant lighting technology, accounting for the majority of the lighting market within the next 20 years. This would represent a fundamental shift in the lighting market and require very rapid growth in SSL production capabilities. The manufacturing processes for LEDs and LED-based lighting products have quickly evolved into large-scale production processes.

LEDs are widely used for display applications in addition to SSL. Backlights are required to illuminate the liquid crystal displays (LCD) from the side or back of the display panel to produce a visible image as LCDs do not produce light themselves. LED backlighting in color screens comes in two varieties: white LED backlights and RGB LED backlights. White or red-green-blue (RGB)

LEDs for backlighting LCDs displays (mobile, notebooks and desktop screens) or RGB LEDs for ultra-large video displays (e.g., LED video billboards).

As explained earlier, OLED lighting offers intriguing potential benefits in terms of lighting quality, functionality, performance, and cost. OLEDs are fundamentally large-area, low-brightness, thin-form factor light sources which could complement high-brightness, small-area LED light sources. OLEDs also have the potential for low cost roll-to-roll (R2R) type production. The potential future system applications for smart, ultra-efficient solid-state lighting are illustrated in fig. 25 [158].

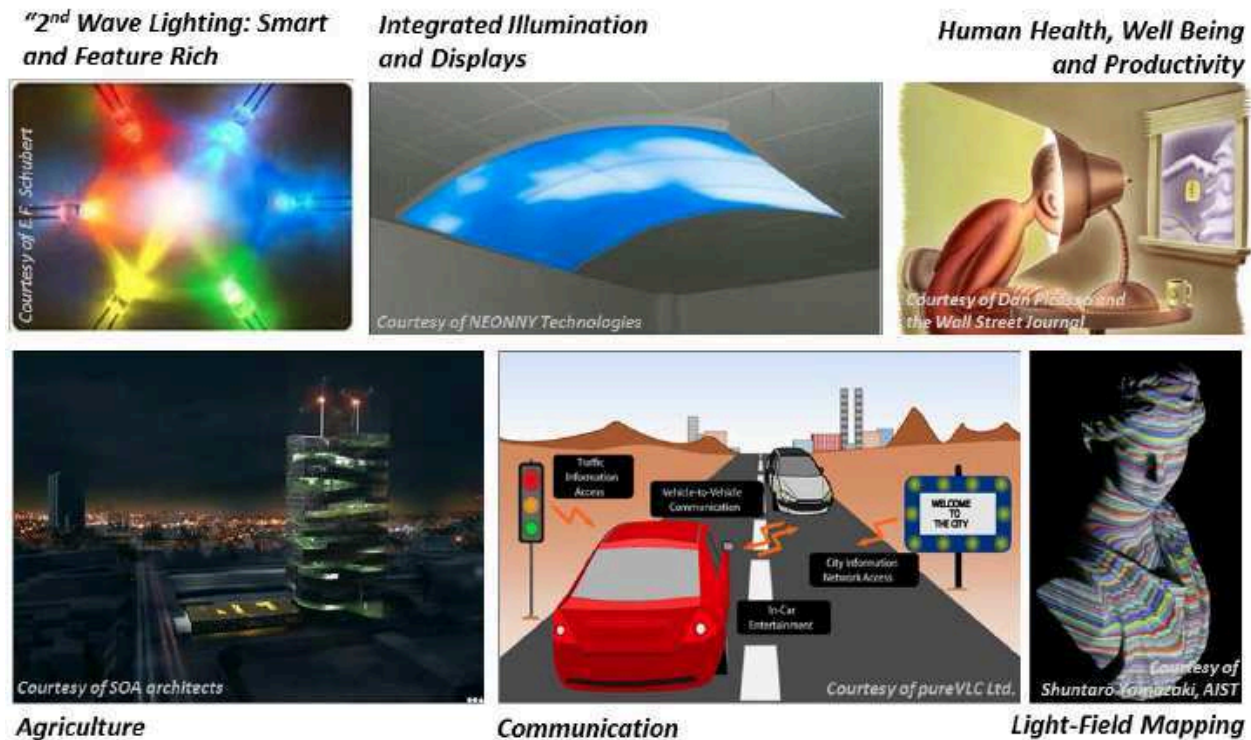


Fig. 25: Potential future system applications for smart, ultra-efficient solid-state lighting [158].

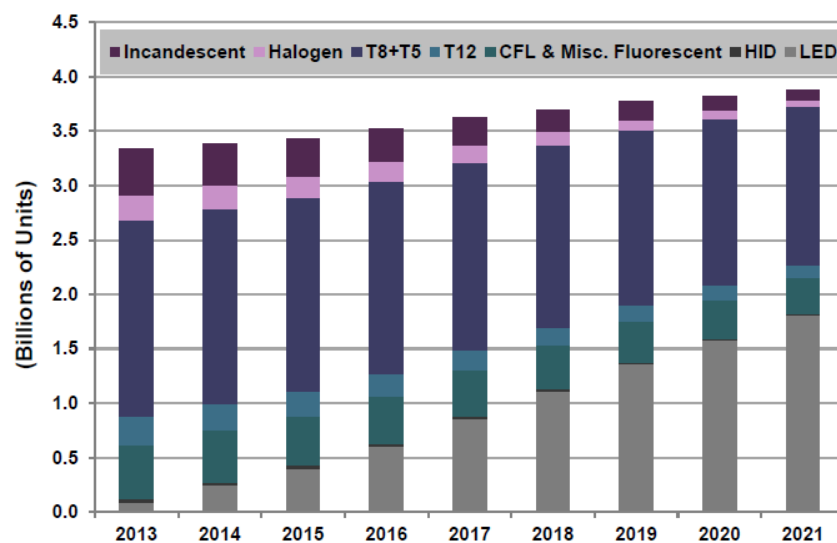


Fig. 26: Forecast of Shipments of Commercial Lamps and Luminaires, 2013-2020 [159].

Fig. 26 shows that SSL technology is projected to dominate the lighting market within 10 years and by 2020, LED light sources are projected to account for almost 50% of all lamp unit sales [159].

This represents an enormous transition in the lighting market and demonstrates the opportunity for LED products in any type of lighting form factor.

7. Conclusions

Solid-state lighting promises to change the way we light the world, yet much work and research are still needed. There are a lot of challenges and opportunities offered by solid-state lighting. At this early stage in the maturation of LED-based SSL there is an opportunity to develop new manufacturing tools, materials, and techniques that can dramatically impact the cost and quality of LED-based lighting and define the manufacturing supply chain. Increasing R&D in the lighting industry is expected to make next-generation lighting sources more efficient and reliable, along with enabling them to provide increased design flexibility over conventional light sources. The research needs fundamental understanding of light-emitting materials and nanostructures leading to solid-state lighting structures rationally designed from the ground up. Successfully addressing these two challenges promises to enable energy-efficient, cost-effective, high-quality white light that will save energy and benefit the environment. Rapidly advancing capabilities to see the atomic structure, chemical composition, and properties (e.g., the ability to convert electricity to light) of materials at the nanoscale are enabling new insights into the structure of matter and its interactions with light. For OLEDs, solution and vapour deposition approaches are both being explored and hybrid approaches are common. Though commercial OLED panels are mostly based on vapour deposition techniques, major efforts are underway to promote solution processed panel production.

While research on inorganic and organic materials has far proceeded independently, the optimal material system and device architecture for SSL may be as yet undiscovered and, furthermore, may require the integration of both classes of materials in a single system. Despite the success to date, further work is required to continue to reduce manufacturing costs to accelerate adoption, and to ensure products meet the levels of quality and reliability demanded by the markets. Research directions that could enable new materials and architectures include: the design, synthesis, and integration of novel, nanoscale, heterogeneous building blocks, such as functionalized carbon nanotubes or quantum dots, with properties optimized for SSL.

8. Future Outlook

Despite the rapid pace of its development, solid-state lighting has not yet come close to achieving its full potential. Significant work remains to be done to further improve performance and reduce costs. The primary challenge for LED lighting is to ramp up production and continue to drive down costs, while maintaining product quality and consistency. The emerging challenge is to demonstrate to the user the added value offered by LED technology, whether it is reduced energy consumption, extended lifetime, or added functionality, and to avoid customer disappointments. More attention needs to be paid to the manufacturing of phosphors/down-converters and the efficient application of these materials within the LED package. There are opportunities to reduce cost, improve efficacy, improve colour quality, increase light output, and simplify the manufacturing process. Optimizing efficiency in LED lighting will hinge on ongoing improvements in materials and light extraction techniques. One direction has been to fit more die area into a given package size to achieve higher lumen output; another has been to use a smaller die area in conjunction with cheaper packaging materials. There are many challenges that still need to be met in order to achieve efficacy goals. For example, we need better greens and reds, as well as multichip monochromatic sources.

OLED technology is less mature than LED technology and still some years away from becoming a practical general illumination source. Innovations are needed on multiple fronts to increase the efficiency, lifetime, and output of OLED devices, and manufacturing infrastructure investments will

be essential to transitioning OLED products from the prototype stage to commercial viability. One of the biggest hurdles is price. Developing stable novel materials and device architectures that have even higher efficiency and are suited to low-cost manufacturing are the other main challenges. In addition to increasing the efficacy of devices, OLED materials costs need to be simultaneously reduced.

The ultimate goal is to develop advanced solid-state lighting technologies that — compared to conventional lighting technologies — are much more energy efficient, longer lasting, and cost-competitive by targeting a product system efficiency of 50 percent with lighting that accurately reproduces sunlight spectrum.

The major bottleneck in this area of SSL is not in solving technological problems or in perfecting theoretical understanding, but in developing suitable electroluminescent materials. That is where contributions from Materials Scientists are called for.

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