Organic Light Emitting Diodes (OLEDs): A Bright Future to the Energy-Efficiency

B Mondal[1] and N Hazra[2]

Abstract:
Cutting down the global energy consumption through efficient use of energy is one of the major research challenges among scientists. Replacing the tungsten filament bulb with novel semiconductor-based light emitting diodes (LEDs) has been a major step forward towards energy-efficiency. Organic light emitting diodes (OLEDs), the third-generation lighting systems, are even better in this move.OLEDs are organic molecules or semiconducting organic polymers that can emit light when exposed to an applied electrical current. Owing to their low-cost, low operating voltage, high energy-efficiency and longer lifetime, OLEDs are expected to soon dominate the lighting world. OLEDs can transform more than 80% of the energy into light, where the long-existing tungsten bulb can produce light out of only 10% of the energy and the rest 90% get drained as heat. Apart from the lighting applications, OLEDs are also proven to dominate over their predecessor liquid crystal display (LCD) in the flat panel display technology. Some of the elegant features of OLED displays include flexibility, wider viewing angle, better contrast ratio, high resolution and ultra-thin thickness. This article has been aimed to provide a concise overview of the evolution of OLED technology and their role in energy-efficiency to the modern world.

Introduction:
The global energy demand has exponentially increased to its peak in the past few decades, which poses serious challenges to the current natural energy resources of the world.This triggers two major areas of research in the present days, namely developing sustainable energy sources and finding efficient solutions to a major energy consuming process.

[1] Department of Molecular Theory and Spectroscopy, Max Planck Institute for Chemical Energy Conversion, 34-36 Stiftstrasse, 45468 Mülheim an der Ruhr, Germany.
[2] University of Cologne, Institute for Chemistry and its Didactics, Herbert Lewin Strasse 2, 50931 Köln, Germany e-mail: pcbhaskar022@gmail.com, ocnabanita@gmail.com

Lighting world is one of the major energy consumers.The long-existing incandescent bulbs are great light producers and serving human need by more than century. However, the energy consumption is very inefficient, as they convert only about 10% of the energy into light. Therefore, new lighting solutions with higher luminous efficacies are of supreme need. Great achievements have been made with fluorescent light bulbs, solid-state lighting (SSL) systems and more importantly, the inorganic semi-conductor based light emitting diodes (LEDs). The use of toxic materials and poor color quality of fluorescent light bulbs limits their applicability. With remarkable energy-efficiency, LEDs have made their way ahead of any existing lighting systems. However, they are relatively costly and possess short lifetime.

In the late 80's there had been ground breaking research, reporting electroluminescence from thin organic film composed of organic molecules (OLEDs)[1] or conducting polymers (PLEDs)[2]. After a decade of research, multicolor OLEDs and PLEDs were developed, which could be used in general lighting.[3] OLEDs then started spreading both in the field of lighting and display technologies.[4] The predecessors of OLED displays,such as cathode ray tube, liquid crystal displays (LCD), plasma displays were leading in the display market. All of these displays have their limitations like low viewing angle, lack of color tunability, requirement of backlighting etc. OLED displays on the other hand features new-generation display qualities, such as super brightness, light-weight, ultra-thin, improved color variation, high-resolution, energy efficient.

This article has been organized in such a way that it can perpetuate some fundamental knowledge about OLEDs and their future prospect among the science community.The content includes physical structure of OLEDs, materials used in OLEDs, the working principle, different OLEDs, application in lighting and display technology, outlook and conclusion.

Structure of OLEDs:

OLEDs consist of thin-film organic semiconductors sandwiched between two electrodes. Small molecule based OLEDs are usually prepared by high vacuum or vapor phase deposition of the organic molecules, whereas the polymer-based ones are prepared by spin-coating techniques.[5]Small organic molecule OLEDs typically feature different thin-film layers with each layer having distinct functionality (Figure 1).A single-layer OLED (Figure 1a) is constructed of a single organic layer sandwiched between anode and cathode. The organic layer, denoted as emitting layer, possesses high quantum efficiency for photoluminescence and can efficiently transport hole and electrons. More efficient OLEDs are usually prepared by placing more than one layer between the electrodes. This makes the electron and hole transport process very efficient. For example, in a two-layer OLED (Figure 1b), one organic layer is chosen to transport holes (hole transport layer) and another is chosen to transport electrons (electron transport layer). The hole-electron recombination at the interface generates electroluminescence. In a three-layer OLED (Figure 1c), the interface between hole and electron transport layer is filled-up with another organic layer that efficiently can take care of the hole and electron transport process and emits light.Multi-layer OLEDs (Figure 1d) are further modified with a hole injection layer, which prevents charge carrier leakage and exciton quenching. All of these different types of OLEDs are physically supported by a glass substrate. Polymer-based OLEDs usually doesn't require multi-layered functionality, as conjugated polymers feature great charge transfer properties.

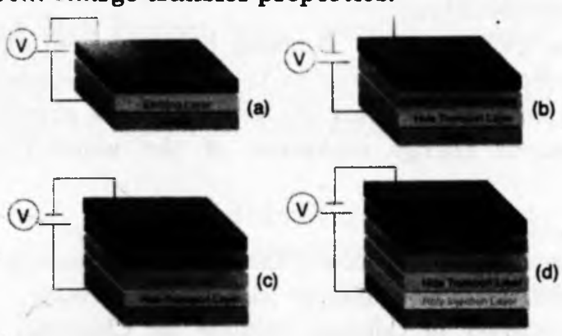


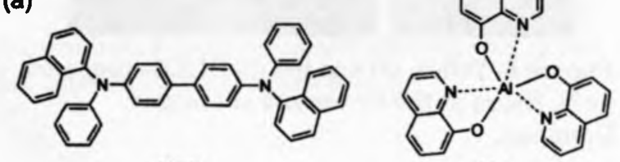
Figure 1. Structure of different OLEDs (a) single-

layer OLED (b) two-layer OLED (c) three-layer OLED (d) Multi-layer OLED.

Anode:
transparent electrode usually made with ITO glass; Cathode: reflective layer made with metal alloy; hole injection layer: material with high mobility and electron blocking capacity; hole transport layer: materials with high hole transport properties and electron blocking properties; emitting layer: the organic layer made with smaH organic molecules or organic polymers, capable of emitting photons; electron transport layer: material that possesses high hole blocking properties and good electron carrier.

Materials used in OLEDs:
Different types of small organic molecules and semiconducting polymers are used in the emissive as well as different hole/electron transport layers OLEDs.The OLED color is dependent on the band-gap, energy gap between the electron-occupied molecular orbitals (HOMO) and electron-unoccupied molecule orbitals (LUMO), of the organic materials. In OLED devices, small molecular materials are used as crystal, whereas the polymeric materials are used in the amorphous state. For examples, aryl amines (NPD, Figure 2a) are used as hole transport layers. Whereas, metal chelates (Alq_3, Figure 2a) are used in emissive layers.In polymer-based OLEDs (PLEDs), nano-composite of polyanilines and polystyrene sulfonate(PANI:PSS) and polyethylenedioxythiophene and styrene sulfonate (PDOT:PSS) are commonly used as conductive layers. Whereas, polymers like polyphenylenevinylene (R-PPV) and polyfluorene (PF) are commonly used in emissive layers on PLEDs.

(a)



(b)

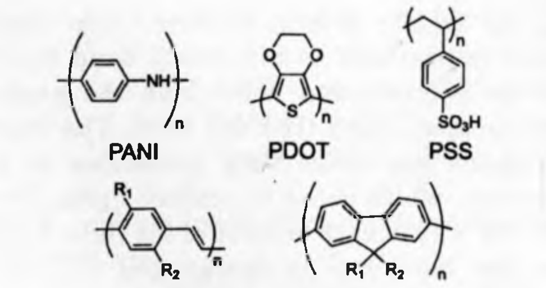


Figure 2. Materials used in OLEDs (a) electrolum-inescent organic molecules (b) electrolum-inescent polymers

OLED working principle:
The basic working principle of an OLED can be best realized using a single-layer polymer-based OLED. According to molecular orbital (MO) theory, molecules are formed from their constituent atoms through an overlap of the atomic orbitals, which in turn generates both bonding and anti-boning MOs.Organic molecules with sp^2 hybridized carbon centers possesses π bonding MOs and the corresponding anti-bonding counterparts (π^*), which formed from the lateral overlap between the carbon p_z orbitals (Figure 3).As the number of π bonds increase in a planar organic molecule the energy gap between the π (HOMO) and π^* (LUMO) decreases. Following this notion long conjugated polymers show semiconductor-like behavior with very small band-gap (E_g, Figure 3). Now, if one electronically excites such organic systems, the π electrons jumps to the π^* and emits energy as light when return back to the ground state. This intrinsic phenomenon makes conjugated organic systems a great charge conductor as well as light emitter.

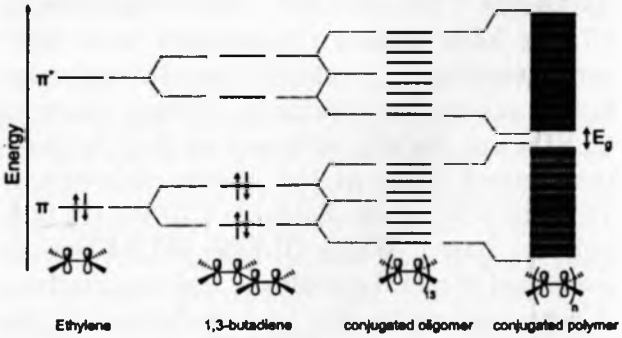


Figure 3. Energy gap (E_g) in conjugated polymers.

In an OLED device, electrons are injected from the cathode to the empty band (LUMO) of the polymer and holes from the anode to the occupied band (HOMO) level. The injected electrons and holes then recombine to from excitons, which decay to produce lights (Figure 4). The wavelength or color of the light depends on the band-gap or energy gap (E_g) of the polymer, whereas the light intensity depends on the applied current.

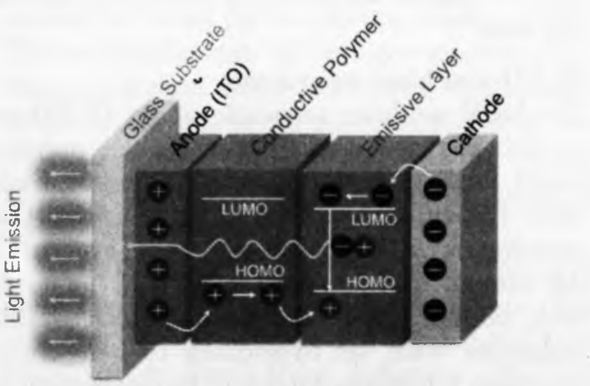


Figure 4. Mechanism of electro-luminescence from an OLED device.

Different OLEDs:

OLEDs are usually categorized based on their formulation, which give rise to different OLEDs. Those are passive-matrix OLED (PMOLED), active-matrix OLED (AMOLED), transparent OLED, top-emitting OLED, bottom-emitting OLED, foldable OLED and white OLED. PMOLED is constructed with organic layer sandwiched between anode and cathode. The same constriction with an additional TFT matrix with cathode gives AMOLED. Transparent and top-emitting OLEDs have similar construction with layer arrangements substrate/anode/conductive layer/emissive layer/cathode. Bottom emitting OLEDs are slightly different as they features transparent glass at the bottom followed by TFT and ITO anode. Foldable OLEDs are fully polymer based. White OLEDs (WOLEDs) are composed of metal complexes and organic dyes. A separate section has been dedicated in this article to discuss about WOLEDs.

Primary colors of OLEDs and materials: Different materials and doping agents can be used to generate different colors. Example molecules/complexes are shown in Figure 5 with the corresponding emission color.A combination of primary color emitting complexes/molecules can allow building up a white light emitting OLED. The primary colors, i.e. red, green and blue have also been successfully generated using polymers (e.g. poly (*p*-phenylene) (PPP), poly (*p*-phenylene vinylene) (PPV), poly thiophene (PT)) as shown in the Figure 5.

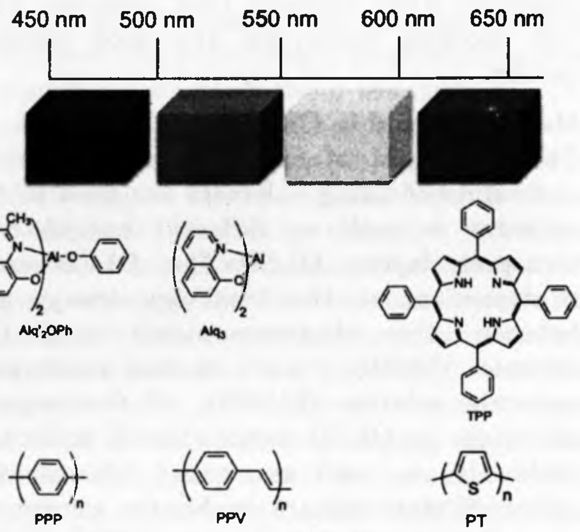


Figure 5. Light emitting molecules and polymers

Yellow emitter OLEDs (Figure 6a) are commonly and cost-effectively prepared using Superyellow® polymer, which features a PPV backbone.[4]

Figure 6 shows laboratory-prepared yellow (a) and red (b) light emitting OLEDs.

Figure 6. Yellow (a) and red (b) OLEDs prepared by N. Hazra at the University of Cologne, Germany.

White OLEDs :

White organic light emitting diodes (WOLEDs) are of growing interest as third generation OLEDs.[6]High efficiency, flexible properties, extremely long lifetime make WOLEDs an excellent candidate for solid-state lighting and backlighting applications. An ideal WOLED should generate white light with spectral distribution similar to the sunlight covering full visible range as much as possible. White LED light sources are commonly constructed from two (blue and orange/yellow) or three (blue, green and red) different luminophores with distinct colors.[7]Figure 7 shows general construction schemes to develop white light emitters.

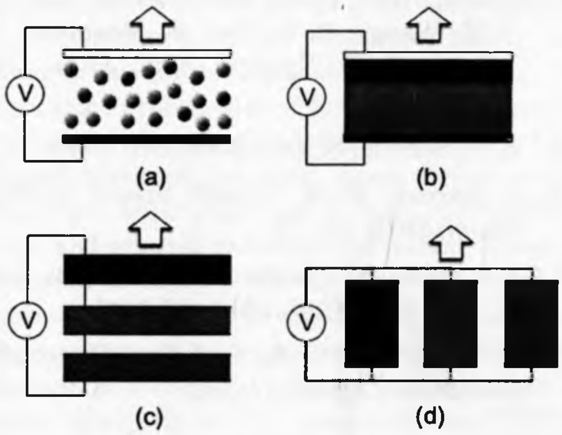


Figure 7. General strategies to construct white OLEDs. (Adopted from ref. 6) (a) single EML structure (b) multilayer EML structure (c) stacking and tandem structure (d) stripped structure

Three primary colors, i.e. red, green and blue phosphors can be doped into either one (Figure 7a) or multiple layers (Figure 7b, c, d) to form single emitting-layers (EML) and multilayer EML white OLEDs respectively. Complementary colors, such as blue and orange can also be used together to generate white emitters. Materials used in WOLEDs are usually organometallic complexes; such as iridium based complexes are used as red, green and blue emitters (Figure 8).

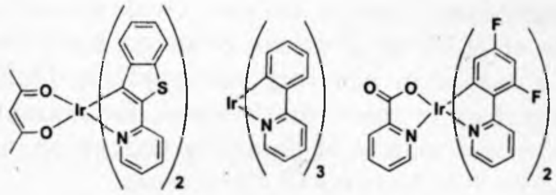


Figure 8. Iridium based phosphorescentdopants for RGB emitters

Modern applications of OLEDs:

Since the first invention in 1980s at Eastman Kodak, the applications of OLEDs in lighting and display technologies have constantly emerged into daily life applications to high-end displays. The first significant commercial OLED applications were in mobile phones, portable digital media players, car radios, and digital camera displays.The OLED application area in lighting is relatively new and growing fast in order to cope up with the energy demand of the modern society. In recent days, globally renowned companies like Philips, LG offer several sophisticated lighting products (Figure 9) for daily life applications. One of the major areas of OLED lighting is the indicator lights used in luxury cars.

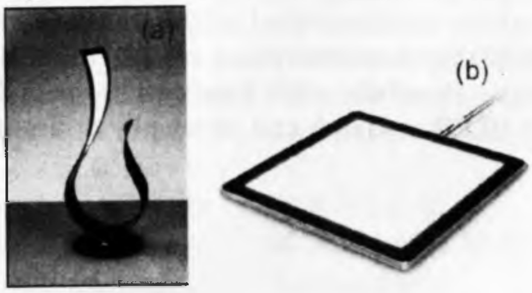


Figure 9. OLED white light panels. (a) LGChem flexible light panel (b) Philips lumiblade light panel. panel.

With the modern developments of OLED display technologies, the thin, bright flat panel displays are now in the market. Since the first OLED TV in 2013, marketed by LG, OLED TVs have become very common in modern display market. Now OLED curved TVs (Figure 10a) are of new generation and companies like Samsung and LG competitively offer them.

Smartphone displays are also a wide spreading area of OLED applications. Samsung has grown as a leader in adopting and applying OLED technology in their smartphones, for example, the recent models of Samsung Galaxy phones (Figure 10b) features OLED screens.

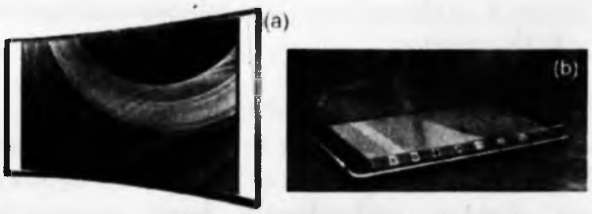


Figure 10. OLED is modern display technology (a) OLED curved TV (b) OLED screen in Samsung galaxy phone

Outlook and Conclusion:

With its energy efficiency, high brightness, longer lifetime, color tunability and flexibility, OLEDs have clearly made a mark in the lighting and display technology. With their fast development, they appear to largely replace the existing high-energy consuming lighting world. However, there are some disadvantages of OLED technology, which are mainly associated with the materials used in OLEDs. Additionally, OLED lights and displays are still expensive to make. Hopefully, such hurdles will remove soon as OLED research and development are one of the fast growing areas in modern science.This article is expected to provide a very concise introduction and overview of a new emerging technology that could play a major role in saving the world from energy crisis.

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