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# Solid-State lighting technologies

Georges Zissis, *Fellow, IEEE*, David Buso, *Member, IEEE*, and Marc Ternisien

**Abstract**—Electrical lighting uses approximately 13.7% of the world’s electricity and impacts heavily human’s visual performance and also well-being, health and security. Electrical power light sources and lighting systems impact also our planet’s resources and our biotope. After decades of stagnation of the performances of legacy lighting technologies, products based on Solid State Lighting (SSL) technology have become the most efficient light sources by far that we can find on the market today. Indeed, the advent of SSLs is considered to be the 3<sup>rd</sup> revolution in the domain. Today, SSL products and more especially Light Emitting Diodes (LEDs) are mature and are on the way to dominate a market worth of more than \$120 billion. Even if someone can argue that innovation in the domain of LED products is decelerating since a couple of years, large-surface, flexible organic light-emitting components opens up new fundamental and technological challenges and offer unsuspected horizons for the light designers of the following decade. Further, the 4<sup>th</sup> revolution in lighting is looming: the advent of intelligent and sustainable lighting systems that could transform the way we conceive of the generation of artificial light, by associating it with information and communication technologies, the Internet of Things, technologies that are transforming our society and are taking a prominent place in everyday life. This review paper, is focusing on the light-emitting (LED) and organic light-emitting diode (OLED) technologies. It explains the basic operating principles, highlights the state-of-art and indicates the main challenges for the next decade. Other papers, in this IAS magazine special issue are devoted to extinguishing legacy technologies and rising sustainable smart lighting systems.

**Index Terms**— Solid state lighting, Light sources, LED Light emitting diodes, OLED Organic light-emitting diodes

## I. INTRODUCTION

**E**LECTRICAL lighting absorbs 13.7% of the world’s electricity net annual production and it is responsible for 4.2% of world’s greenhouse-gas annual emissions [1].

During the last decade, solid-state lighting (SSL) technologies, based on components like Light Emitting Diodes (LEDs) as well as organic light emitting devices (like Organic Light Emitting Diodes-OLEDs and Organic Light Emitting Transistors (OLETs), are replacing rapidly conventional lighting technologies. Solid-State Laser Diodes (SSLD) with phosphor conversion for white light generation are very a promising technology for mid-term, more information on this technology can be found in a paper published by Zissis and

Bertoldi. [2] Further, SSL technology includes some other technologies like electroluminescent thin films, field emitting devices based on nanotubes and even, more futuristic devices exploring bioluminescence, but these technologies are still far from wide use and will not be treated in this paper.

It is anticipated that in short term, all of electric lighting will be based on SSLs and more particular, LEDs proceed to the projected conclusion: replacing legacy technologies, this is a major change in the lighting market that is considered as a revolution.

The arrival of SSL, with efficiencies that now far surpass those of all legacy technologies, has had a direct impact to the energy consumption of the humanity by harnessing the projected increase of electricity demand for lighting. However, this revolution has a "side effect" as it has also paved the way for the era of "digital light", which allows for adjusting the quantity and quality of light based on its use and the needs of the user without compromising their well-being and health. Today, on one hand, "integrative lighting" can be considered part of this digitization of lighting. On the other hand, "connected lighting" is rapidly developing, involving the networking of light sources with sensors to better meet human needs without wasting energy or harming the environment. In the near future “sustainable smart lighting” systems will involve integrating human-centric lighting into a broader network known as the Internet of Things (IoT), enabling interactions not only between technological components but also with the end user, who can express his/her needs. In this concept, light may become a product, and the connected lighting system, offering services powered by light, will be a key component of a larger smart system where the end user is become a "consumer-actor". This represents a radical transformation in the domain of legacy lighting industry and it will require a fundamental shift in the its business models.

This paper is limited to present the state-of-art of the technological and marked advances of the main solid-state technologies, namely light emitting diodes (LED) and organic light emitting diodes (OLED). The reader will find within this special IAS Magazine issue some more insights about lighting technologies and their impacts.

## II. LIGHT EMITTING DIODES (LEDs) FOR LIGHTING

In 1907, the radio pioneer Joseph H. Round was the first to observe light emission from a "Carborundum" crystal, now identified as silicon carbide (SiC), though he was unable to

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explain the phenomenon, named in 1936 “electroluminescence” by a French scientist, Georges Destruau. Unknowingly, O.V. Losev, a Russian researcher, replicated Round’s experiment in 1921 and hypothesized that it was related to the inverse photoelectric effect, as described by Einstein. Losev subsequently filed the very first patent suggesting that this light emission from solids could be harnessed for illumination. However, it was not until 1962, over forty years later, that Nick Holonyak successfully developed the red light-emitting diode (LED). In 1972, George Craford invented the yellow LED, followed by the green LED. The invention of the blue LED by Shuji Nakamura in 1993 marked a significant milestone, paving the way for semiconductor-based lighting. For this groundbreaking achievement, Nakamura, along with I. Akasaki and H. Amano, was awarded the Nobel Prize in Physics in 2014. The technology began to penetrate the illumination market in the early 2000s. By the 2010s, light-emitting diodes (LEDs) had become a mature transformative force, surpassing conventional lighting technologies in all aspects. Nowadays, white LEDs can be categorized in three main families as shown in Table I.

TABLE I  
MODERN WHITE LED FAMILIES, CHARACTERISTICS AND  
MAIN APPLICATION DOMAINS

FAMILY & USE	CHARACTERISTICS
<b>Low-power Conventional “5 mm white LEDs”</b>  <u>Use:</u> <ul style="list-style-type: none"> <li>• Signaling</li> <li>• Gadgets</li> </ul>	Homojunction Crystal surface: $350 \times 350 \mu\text{m}^2$ Nominal Current: 30 mA Nominal Power < 200 mW External Quantum Efficiency: ~ 20 % Luminous flux: 1-3 lm Luminous efficacy: ~ 50 $\text{lm.W}^{-1}$ Format: Dome with Epoxy encapsulation
<b>High-Brightness White LEDs (HB-LED)</b>  <u>Use:</u> <ul style="list-style-type: none"> <li>• General Lighting</li> <li>• Backlighting</li> <li>• Mobile Devices</li> <li>• Automotive</li> </ul>	Heterojunction Crystal surface: $1 \times 1 \text{mm}^2$ Nominal Current: 350 mA Nominal Power: 1W External Quantum Efficiency > 50 % Luminous flux: 20 - 100 lm Luminous efficacy > 110 $\text{lm.W}^{-1}$ Format: manufacturer dependent
<b>Ultra-High-Brightness White LEDs (UHB-LED)</b>  <u>Use:</u> <ul style="list-style-type: none"> <li>• General Lighting</li> <li>• Automotive</li> </ul>	Heterojunction Crystal surface: $2 \times 2 \text{mm}^2$ Current density > 50 $\text{A.cm}^{-2}$ Maximal Power (single junction): 5 W External Quantum Efficiency > 60 % Luminous flux > 100 lm Luminous efficacy > 130 $\text{lm.W}^{-1}$ Format: manufacturer dependent

#### A. LED technology advantages

LEDs, like any other technology have many advantages (and of course drawbacks). The next lines will present some of these

advantages that coined the glory of the LED technology.

Modern LEDs have an incredibly high luminous efficacy. In theory, for an ideal pn-junction the internal quantum radiant efficiency can reach 100%. Today’s commercial products we can achieve radiant efficiencies up to 80% for some wavelengths. Luxeon HL2X’s record-breaking luminous flux, which is more than 318 lm at 700 mA and 85°C junction temperature corresponding to a LE more than 310  $\text{lm.W}^{-1}$  and Philips shown during the Dubai Lighting Fair in 2017 an A-shape LED filament lamp with up to 210  $\text{lm.W}^{-1}$  plugin efficacy. [3] These values are far ahead from any legacy light source technology. Just remind that a single watt of yellow-green radiation at 555nm corresponds to 683 lumens (a candle produce 10 to 15 lm). This the absolute thermodynamic limit. On the opposite side the efficacy of a kerosene flame lamp is 0,03  $\text{lm.W}^{-1}$  and that of a 100W incandescent lamp is around 12-15  $\text{lm.W}^{-1}$ . For more details readers can refer to recent literature. [1], [2]

LED produces high luminance output. This is due to the fact that the emitting element (the die) surface is really tiny (few  $\text{mm}^2$ ). The achieved luminance can challenge sun’s brightness. However, the luminous flux remains low (around 130-150 lm per die) which is not sufficient to light up anything. Further, high luminance induce glare, and LED can be very glary (even dangerous for our eyes...).

LEDs have extremely long lifespan; 50 to 100 thousand hours of continuous operation can be achieved provide that junction temperature stays low (this implies keeping the LED operating in a fridge or in an igloo...). Integrated to a lamp or fixture, for high quality products the life span can reach 35,000-50,000 h, but in low quality products, the value can be lower than 10,000h. Moreover, the radiative flux is also depreciating with ageing of the component. Further, LEDs are robust components and early catastrophic failures are rather unprobeable, however a system integrating LEDs may be fragile and less reliable...

LEDs, as electronic components, are light weight and have small dimensions. However, when integrated in a real system including heat dissipators, the result may be incredibly bulky...

LEDs are rather easy to power. To switch-on and remain lighted, a single LED needs a dc voltage in the order of a few volts and a current in the order of few hundred milliamps (for high power LEDs). The main difficulty here is to obtain very low distortion dc current to avoid light flicker [14] and other undesirable effects especially under dimming conditions. High quality stabilized dc current drivers with amplitude modulation for dimming can be very expensive.

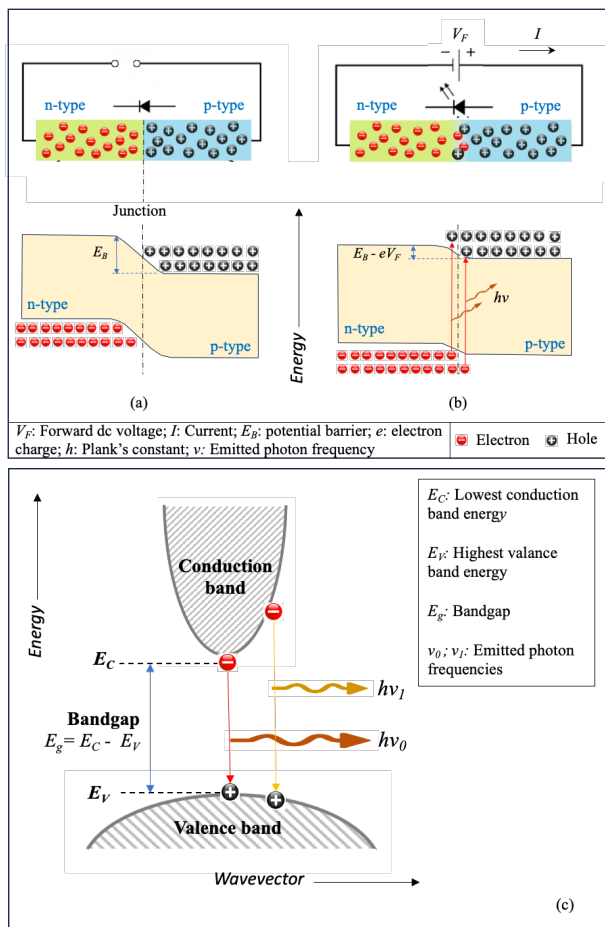
White light LEDs don’t produce ultraviolet or infrared radiation. This makes the technology safe for both human skin and avoids the degradation of painted artwork. However, LED’s do produce blue light that in high doses and at high brightness can be damaging to the human retina

Last but not least, LED prices are expected to decrease in the medium to long term and high-quality products which are able to provide tunable correlate color temperatures lamps/fixtures and new services have been placed on the market. Indeed, while a US Department of Energy (DoE) report shows some substantial reductions in the projected costs of LED fittings

from 2024 until 2035 it is expected that the cost for LED lamps will remain fairly flat. [4]

### B. Operating principles

A Light Emitting Diode is first of all, as its name indicates it, a “diode”. It is constituted by two crystal semiconductors, one having in excess negative charge carriers (electrons), this is called “n-type” and a second, so called “p-type” having positive charge carriers (called “holes” in solid state physics) also in excess. The two crystals are in contact and that way they form a pn-junction, often called “die”. It is known that when a dc voltage (higher than a threshold value, in the order of a few volts) is applied in the junction with the right polarity, a dc current flow across the junction, while when the junction is polarized in inverse way the current is blocked and that for any voltage value below the LED breakdown voltage. This the simplest structure for a Schottky diode called “homojunction”.



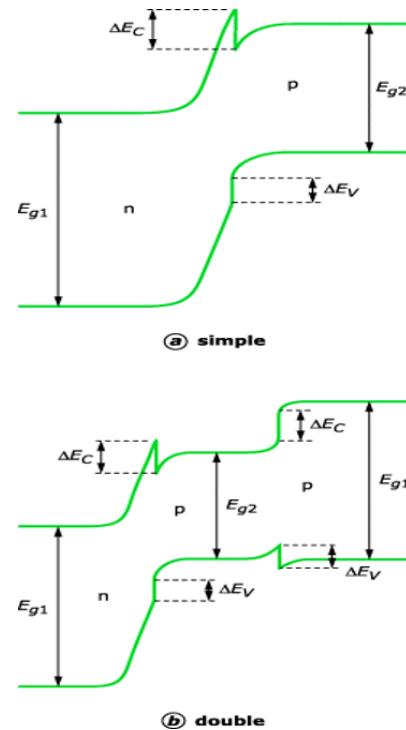
**Fig. 1.** Operating principle of the simplest homojunction (a) junction is not powered; (b) junction is polarized; (c) energy diagram in wavevector space of a direct gap semiconductor and generation of light.

As can be seen in Figure 1a, when the PN junction is not connected to an external voltage generator, the excess electric charges of each side of the junction tend naturally to diffuse towards the other side: electrons from zone n tend to flow towards zone p and holes follow the opposite path. However,

the charges cannot pass physically from one crystal to the other because they need to overcome a potential barrier corresponding to the extraction work of the bulk material. That way, charges will accumulate near the junction and to maintain local electrical neutrality a charge space field will rise across the junction. This internal field opposes to diffusive charge movements till the system equilibrium is reached, and in steady-state not any current flow is observed. When the pn-junction is connected (with the right polarity) to an external voltage generator the field barrier lowers (Fig. 1b).

This allows a current flow across the junction. Electrons and holes can now meet and recombine in the immediate junction neighbourhood area producing photons carrying the full energy without any heat losses. The dominant wavelength of the emitted photon is depending on the bandgap between the top of the valence band and the bottom of the conduction band of the pn-junction system (Fig. 1c). If the semiconductor materials have been dully selected the produced radiation falls in the visible part of the spectrum and the diode produces light.

Conventional LEDs still use this junction architecture today. However, homojunction technology quickly reaches its limits, because by increasing the level of doping to improve injection efficiency, we simultaneously increase the impurities, which in turn constitute additional centers of non-radiative recombination. In addition, the radiation trapping in the crystal increases rapidly with the level of doping. Obtaining diodes producing several hundred lumens requires the implementation of another technology, that of heterojunction.



**Fig. 2.** Example of two different heterostructures architectures used in HB-LEDs and UHB-LEDs (a) simple; (b) double.

The main idea of heterojunction technology is based on the

spatial variation of the semiconductor composition. These structures, called heterostructures, are assemblies of semiconductors of different chemical compositions that also have different energy gaps. Today, as shown in Fig. 2, we use simple (SH) or double (DH) heterostructures.

In the case of a simple heterostructure, the zone p, corresponding to the conduction region, consists of a semiconductor with an energy gap  $E_{g2}$  of a value lower than that of the gap of the zone n,  $E_{g1}$ . The discontinuity between the two energetic structures amplifies the potential barrier visible to the p-carriers wishing to diffuse to the n region. This offset is equal to  $\Delta E_V$ . For their part, electrons (n-carriers) see a decrease in the potential barrier equal to  $\Delta E_C$ . If the value of  $\Delta E_V$  is fixed by the characteristics of the system,  $\Delta E_C$  can vary from zero to a maximum value depending on the suddenness of the junction. In this configuration, the ratio between the electron current ( $I_n$ ) and hole current ( $I_p$ ) currents increases by a factor proportional to  $\exp[\Delta E(k_B T)]$ , where  $\Delta E_V < \Delta E < \Delta E_V + \Delta E_C$ ;  $k_B$  the Boltzmann's constant and  $T$  the temperature. It is therefore possible to act on the efficiency of the injection without having to increase the level of doping indefinitely. The use of heterostructures (DH in the majority of cases today) combined with very thin emissive regions (of the order of the De Broglie-wavelength for the electrons in the crystal) induces quantum phenomena that modify the energy spectrum of the carriers (quantum confinement) and promote the increase of the diode's efficiency. We are therefore talking about single (QW) or multiple (MQW) quantum well LEDs.

### C. White light emission from LEDs

A LED die emits almost monochromatic radiation. The dominant frequency  $\nu_0$  and wavelength  $\lambda_0$  are defined by the bandgap and are depending on the junction temperature  $T_j$  as given by eq. (1):

$$\nu_0 = \frac{E_g}{h} + \frac{k_B T_j}{2h} = \frac{c}{\lambda_0} \quad (1)$$

where  $h$  is the Planck's constant and  $c$ , the speed of light inside the crystal.

Unfortunately, there is a very limited choice of semiconductor materials with direct gap that can emit efficiently in the visible domain of the spectrum. However, today, we are able manufacturing very efficient red LEDs using phosphides as doping material. To the other side of the spectrum, using nitride doped materials lead to very efficient blue emission. Green is more difficult to obtain because there is not any semiconductor combination with direct gap emitting at these wavelengths. This annoying problem is known as the "green gap".

Further, as can be seen in Fig. 1c, the frequency of the emitted photons can deviate slightly from the dominant value  $\nu_0$ . Taking into account the charge carrier distributions in the different bands we can find that the Full Width at Half-Maximum (FWHM) for a LED emission is given by eq. (2).

$$\Delta\nu_{FWHM} = 1.8 \frac{k_B}{h} T_j \quad (2)$$

The typical value is in the order of some 10 nm and it is thus dependent on the junction temperature. However, lighting needs white light generated to an efficient and reliable way. There are several ways to obtain white light from LEDs:

The first solution consists on mixing the 3 primary colors (red, green and blue), which will generate an impression of white for the human eye. This method is known as "RGB for white". This mix can be done by using 3 distinct colored LEDs components, or today it is possible to find in the market single-LED components incorporating RGB dies under the same optics. This solution raises some concerns:

- Overall luminous efficacy for white light is jammed by the green gap that impeach the use of high efficiency green LEDs.
- As only 3 "real" colors are available (3 LEDs at given wavelengths with very limited spectral width) the gamut in the CIE-1931 chromaticity diagram is rather limited. Of course, it includes white but the color rendering will be extremely poor because objects have no light to reflect in wavelengths other than the initial RGB spectral lines. Further, to avoid spatial color uniformity problems in the illuminated area it is necessary to have dedicated color-mixing optics and that increase optical losses reducing the system energy performances. Shrinking the dimensions of the component can solve partially the mixing optics problems but the solution is expensive.
- The apparent correlated color temperature (CCT) for white light can change drastically by just shifting slightly the green LED dominant wavelength and this value is strongly dependent on the doping rates which is difficult to control with high precision during the manufacturing process.
- Finally, having three independent light sources, the white light quality stability control, at any precise moment or along the system lifespan, is not-intuitive and the associated drivers are complex and expensive.

Some of the above cited issues can be solved. For instance, for enlarging gamut and obtaining better color rendering it is possible to mix more than three elementary colors, but this adds in the system complexity and impacts its overall reliability. For these reasons, even if potentially color-mix is forecasted being the dominant technology for the next decade, today is exclusively used for decorative, architectural or/and scenic lighting.

The second way to produce white light impression is based on the 2<sup>nd</sup> Grassmann's law of the colorimetry stipulating that mixing two pure colors it is possible to obtain all intermediate-colored shades lying on the straight line linking the two pure color *loci* in the CIE-chromaticity diagram. In fact, mixing blue emitted but the junction with the its opposite color (as defined by the CIE-chromaticity diagram barycenter), yellow, obtained by down-conversion by a luminescent material (called "phosphors"), we can obtain white. LEDs using that technique are also called pcw-LEDs (phosphor converted white LEDs). More precisely: High power LEDs using nitrides can produce blue light with extremely high radiant efficiency (~70%). Blue photons can be absorbed by down-converting phosphors to produce yellow light thanks to Stokes shift. Mixing the remain blue emission with the down-converted yellow, it is possible to get white light. At the very beginning, the technology faced some issues:

- The process can lead to bad color rendering and unpleasant

correlated color temperature, due to the fact that green and red radiations were missing from the spectrum. Indeed, the first white LED using blue-yellow (B-Y) conversion principle had a very high Correlated Color Temperature (CCT > 6,000 K) corresponding to real unpleasant cold bluish shades. Today, this problem is fixed by using custom phosphor layers that can add green and red radiation by down-converting some additional blue photons. Further, to enhance the red spectral content, manufacturers proposed LED components containing a blue and a red die. Moreover, today all CCTs from less than 2,000 K up to 6,500 K (and even higher...) are possible. However, lower the CCT, the luminous efficiency drops (because additional conversions are required) and the lifespan of the component decreases.

- b) A yellow halo effect has been observed in first white LED using B-Y conversion principle because the blue die emits naturally a very directional parallel to the junction plan, when the yellow emission from the phosphor is almost Lambertian (omnidirectional). This was an unpleasant effect. Today, it is possible to override this effect by depositing thin phosphor layers to conform manner on each surface LED die.

Today, these issues are solved and the B-Y conversion technique is dominating the market of white LED components for lighting applications.

The 3<sup>rd</sup> technique to produce white light consists on the use LED dyes emitting violet/near-UV radiation then down-converted by custom phosphors. This very similar to the 2<sup>nd</sup> technique presented in the previous paragraph, the main difference is the use of "GaN on GaN" technology for the dye that can support higher powers per chip. Indeed, GaN on GaN technology (GaN junction grown on GaN substrate) dyes emit violet light at 435 nm to very efficient manner. The technology is very promising because by using custom phosphors we can achieve a "full spectrum" white light mimicking daylight, with excellent color rendering which is complex to obtain with BY technology. Further, blue peak which is toxic at high doses for human retina is now missing. Shuji Nakamura, the inventor of blue diode is forecasting that this technology will supersede all others. [17] The future will show if his prophesy is true... In meantime, this technology has some very first applications in automotive and horticultural lighting. A high-tech spin-off company founded by Nakamura is now commercializing also lamps using that principle for indoor lighting.

#### *D. Challenges for LED technology*

Since the technology is mature, drawbacks related to quality and technical issue have been solved to a satisfactory way. However, innovation in the domain is decelerating. Some evolutions are still out-there.

The first consists to overwhelm the limits imposed by phosphor down-conversion and green-gap. That way, in the near future, DOE forecasted that hybrid LED (Hy-LED) architecture, which is a non-standard but emerging white light architecture hybridizing B-Y conversion and colour emitting diodes, can reach a luminous efficacy as high as 280 lm.W<sup>-1</sup>. [5] Further, by engineering new phosphor materials that reduce down-conversion losses the RGB technology could attain a

maximum luminous efficacy of around 330 lm.W<sup>-1</sup>. [5] This last technology is now-on known as "color mixing white LEDs" (cmw-LED) and, provide that color rendering issues will be solved in a due time, it is speculated to become the dominant method for white light generation in the incoming decade. The arrival of micro-LED ( $\mu$ -LED) technology, the dream to use efficient colour mixing technique may be transformed into reality

At die level, further work on material engineering is also on the way. Nanowires using GaN with variable spatial distribution of doping material shown a potential to produce emissions with wavelengths ranging from the ultraviolet to near-infrared regions from the same nanowire. This may lead to the creation of "native" white-LEDs without phosphor. [6] [7] Further, nanowire LEDs on copper substrate are possible. They exhibit several advantages, including more efficient thermal management and enhanced light extraction efficiency due to the usage of metal-reflector and highly thermally conductive metal substrates.

Recent pioneering works open the door to the introduction of perovskites as quantum dot materials in order to obtain nice saturated colors or even native white light generation. [8] [9] However, severe stability and toxicity problems have to be solved before the technology enters the market.

At die package level also, some evolutions are on the way. Chip Scale Package (CSP) technology eliminates the traditional sub-assembly to connect the LED chip directly to the PCB (Printed Circuit Board), resulting in an overall reduction in system costs. CSPs are increasingly being used by lighting designers. CSP LEDs have a wider emission angle, greater design flexibility, and can be supercharged. However, they are not as efficient as high-power LEDs and are priced much higher currently. As CSP LEDs can be integrated in fully functional thin fixtures that are equal to or slightly larger than the size of a chip, seduce more and more lighting designers. [10] Further, ceramic substrate and surface mounted LEDs are progressing and contribute to better thermal management.

### III ORGANIC LIGHT EMITTING DIODES (OLEDs) FOR LIGHTING

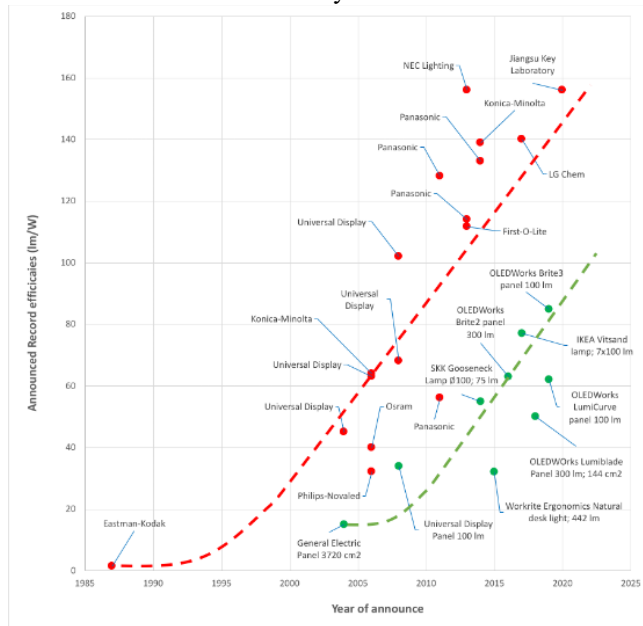
It is commonly accepted that organic materials like plastics are electrical insulators, but this is not a general rule. In 1977 Hideki Shirakawa, Alan MacDiarmid and Alan Heeger published a paper relating the discovery of the simplest conducting polymer, polyacetylene (doped with halogens). The importance of the discovery has been acknowledged by the 2000's Nobel Prize in Chemistry. However, in organic materials, the electrical charge mobility value is very low and this is related to the fact that, generally, the mobility of an electron is much lower than that of a hole. Further, the conduction mechanism is not continuous (ohm-type conduction) like in metals or inorganic semi-conductors, but rather discontinuous (we speak about "hopping" conduction-type). Thanks to intensive work on material engineering who solved a number of issues, organic electronics became a nascent technological domain encompassing a wide range of applications, including illuminants, photovoltaics, printed electronics, and batteries. The substitution of inorganic



materials with organic counterparts, particularly in processes such as the conversion of light to electrical current (photovoltaics) and electrical current to light (light-emitting diodes), promises substantial economic and ecological benefits [11].

In 1987, J. Kido and his team demonstrated the first white OLED using layered thin films of  $\pi$ -conjugate materials. The performances of this very first device were very low: External Quantum Efficacy in the order of 1% for a luminous efficacy lower than  $1 \text{ lm.W}^{-1}$  and a lifespan (in free air) of less than one day.

Since Kido's pioneering work, OLED performances enhanced to spectacular manner as shown in Fig. 3. The luminous efficacy of white OLEDs components increases almost exponentially to attain  $160 \text{ lm.W}^{-1}$  in 2020. Same observation for real OLED lighting systems: an OLED panel producing a luminous flux of 100 lm with wall-plug efficacy of  $85 \text{ lm.W}^{-1}$  is now commercially available.



**Fig. 3.** Record luminous efficacies announced since the demonstration of the 1st White OLED (1987). The red dots represent world-record efficiencies obtained by bare OLED components. The green dots correspond to lighting panels and lamps (commercially available) using OLED components. Graphics reproduced from [2] with the authorization of the authors.

That way, OLEDs became a promising candidate technology for general illumination. The technology penetrated seriously the general lighting segment in 2010's but maturity is not yet reached. It is estimated that with a broad spectrum, an OLED device can achieve a radiant efficacy of up to  $325 \text{ lm.W}^{-1}$ , with potential advancements possibly increasing this value to  $400 \text{ lm.W}^{-1}$ .

Unlike traditional light sources, such as incandescent bulbs and fluorescent lamps, OLEDs are planar light emitters with lightweight, thin profiles and peculiar broad emission spectrum. That way OLEDs represent a novel light source that enables the

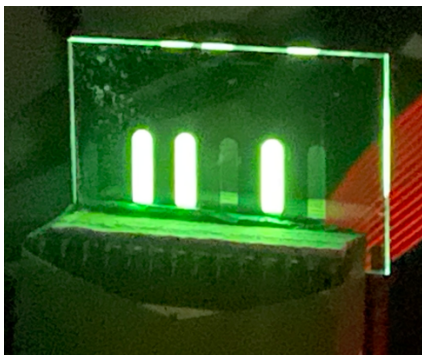
creation of large-area light sources that can be both transparent and flexible. This characteristic enables lamp manufacturers and designers to create innovative designs and striking visual effects, thereby transforming living environments in homes, offices, retail spaces, and vehicles such as cars and airplanes.

The energy-saving potential of OLEDs is comparable to that of LEDs, although the two technologies differ in several key aspects. OLEDs inherently produce UV-free light with a high Color Rendering Index (CRI), often described as "pleasant light." It is clear that the two technologies are not concurrent, but they can be foreseen as complementary. Thus, in long-term and provide that OLEDs will overcome some technical barriers, most probably the market will tend to a sustainable share between the two technologies targeting the most appropriated lighting applications in agreement with their unique characteristics.

### A. Operating principles

Organic light-emitting diodes (OLED) can be considered as a type of light-emitting diode in which the emissive electroluminescent layer consists of a film of organic compounds that emit light in response to an electric current. In reality, an OLED consists on an organic stack deposited by layers on the top of a transparent substrate (it can be glass, plexiglass, PET...) covered with a thin transparent electrode, the anode (usually ITO-Indium Tin Oxide, or more recently organic thin films like PEDOT [12]). The cathode lies on the other side of the stack usually in the form of a thin metallic electrode (made by silver, aluminum, calcium...), but, in some cases, can be made by a transparent conducting thin film. The global thickness of the stack (excluding the substrate) is of a few hundred nano-meters. For a forward voltage in the order of 10 volts, the electrical field in the organic stack is colossal ( $10^{10} \text{ V.cm}^{-1}$ ).

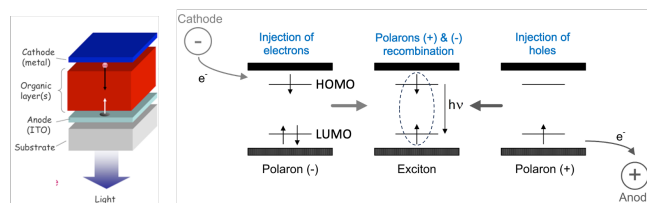
Each organic layer in the stack has a very specific role. Some of them are responsible for improving the interface between the molecules and the cathode in order to optimize the injection of charges. On the other side, for enhancing the injection of holes from the anode, a Hole Injection Layer (HIL) is usually introduced. In order to facilitate the transport of charge carriers (electrons and holes) through the organic stack, it is also possible to use layers of specific materials that will guide their motion. This is the case of the Electron Transport Layer (ETL) for electron transport and hole blocking layer (HBL). Finally, generally in the center of the component, is a layer of emissive material that will be used for the emission of light.



**Fig. 4.** OLED device using bio-sourced  $\beta$ -carotene as hole blocking layer. Courtesy H. El Housseiny, LAPLACE lab.

For the emitting organic layer, two technologies stand out today: Polymers with long carbon chains used on Polymer OLED (P-OLED); Small molecules (often organometallics) used in the most common OLEDs. They differ not only because of type of molecules used in the different layers, but also in the deposition method used. Polymers are generally deposited by spin-coating in liquid phase, while small molecules are deposited in thin films by evaporation. The latter technique requires many steps in the manufacturing process as well as the immersion of the substrate in an atmosphere-controlled chamber. As a result, small-molecule technology is much more expensive and prices soar depending on the size of the substrate. However, small molecule technology is the one used in most OLEDs available on the market today, given its higher efficiency and lifespan than P-OLED ones. Further, in the case of small-molecules, it is possible using materials coming from green-chemistry (bio-sourced) from crops, algae, etc. This will reduce dramatically the environmental impact of OLEDs. Figure 4, shows an experimental OLED device using carotene as hole blocking layer (representing 40% of the organic loaded of the component).

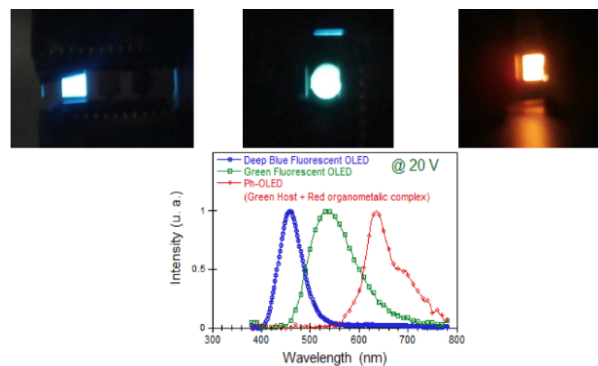
When the component is submitted to a potential difference higher than the ignition voltage, a current of electrons flows through the device from cathode to anode, as electrons are injected into the Lowest Unoccupied Molecular Orbital (LUMO) of the organic layer at the cathode and withdrawn from the Highest Unoccupied Molecular Orbital (HOMO) at the anode. This latter process may also be described as the injection of electron holes into the HOMO. Electrostatic forces bring the electrons and the holes towards each other and they recombine forming an exciton, a bound state of the electron and hole. This happens closer to the emissive layer, because in organic semiconductors holes are generally more mobile than electrons. The decay of this excited state results in a relaxation of the energy levels of the electron, accompanied by emission of radiation. The most common OLEDs use the mechanism of fluorescence for light emission, but, in that case, the efficiency of radiative recombination is not optimal: it is limited to 25%. However, other solutions exist such as the use of phosphorescence mechanisms or thermally activated delayed fluorescence (TADF) leading to the recovery of 75% of non-radiative excitons. Figure 5, illustrated schematically the full process.



**Fig. 5.** OLED operating principle: electron injected by cathode and capped by organic molecules lead to the formation of negative polarons; holes injected from the anode lead to the creation of positive polarons; positive and negative polarons recombine inside the emissive layer to form an exciton that will decay radiatively to produce photons ( $h\nu$ ). Note: vertical arrows indicate the spin of electrons involved in the process.

### B. White light emission from OLEDs

Most of OLEDs emit in the domain of visible spectrum however, the dominant emission wavelength depends on the “band-gap” of the material, defined by the difference in energy between the HOMO and LUMO and the full width at half maximum (FWHM) depends on the distribution of vibrational and rotational levels of the molecular orbitals. This last can be in the order of  $\sim 100$  nm and higher (10-times larger than the FWHM of a color LED). For this reason, an OLED emits an almost monochromatic radiation band (Fig. 6). In the specific case of P-OLEDs the dominant wavelength is shifted continuously with the polymer chain length, all colors are then possible. Further, OLED technology doesn’t suffer from the “green-gap” issue encountered in LED technology.



**Fig. 6.** Emission spectra from different OLEDs [13]

However, lighting needs white light generated to an efficient and reliable way. As for LEDs, engineers explore different techniques to obtain white light from OLEDs. These devices are called White OLEDs (WOLED).

Like in LEDs it is possible mixing yellow and blue radiation. But, for OLEDs no need to use down-conversion phosphors. At a first glance the easiest solution is to imagine flat device with a blue and a yellow OLEDs interlaced stripes like two nested combs (each OLED it is powered but a distinct driver). Of course, a more elegant solution, using a single driver, consisting on engineering molecules the first emitting on blue that can transfer partially excitation to a dopant molecule emitting in yellow (donor-acceptor principle). This can be done by



combining native color emission from blue emitting molecules with light coming from down-conversion mechanism from organic materials in the same matrix. Further, possibility of organic-inorganic molecule combination is also possible.

Of course, RGB mixing technique is also possible. In that case, two architectures are possible, one in form of stack constituted by a red, a green and a blue OLED, or, in form of flat dot matrix with RGB pixels (this technique is in use for OLED displays). In both solutions, each color-OLED need its own power supply.

The "Holy Grail" would be to reproduce native white light using a single emitter layer. This can be achieved by broadening the emission spectrum by using a mixture of molecules producing their specific spectral bands. The concept, while attractive in still in its infancy.

### C. OLED technology challenges

Organic light-emitting diodes are now on established as a mainstream technology for display applications in every day's consumer nomad electronic devices as well as for large TV sets. The penetration of the domain of lighting is more complex but possible. Today, the technology addresses mainly niche markets. Decorative lighting for high-standing premises and automotive lighting is reported to be the most promising and most mature application market for OLED lighting.

To penetrate general lighting, before the end of the decade, is an ambitious objective. To this end, engineers and scientists shall face a number of challenges: intensive research and engineering are needed in order to:

- (1) increase luminous efficacy in high current densities;
- (2) develop long-lasting blue emitters;
- (3) reduce environmental impact by developing green-chemistry, bio-sourced, molecules for the organic stack and avoid ITO or similar substances from the component
- (4) increase life span and reliability;
- (5) improve light extraction from the component;
- (6) develop custom drivers with dimming and (more difficult) color tuning capacities;
- (7) develop reliable test methods standards to establish consistency and reduce uncertainty;
- (8) develop new manufacturing facilities for high volume especially using roll-to-roll (R2R) techniques;
- (9) lower cost device and luminaire materials

An important difference from LED systems is the possibility to obtain flexible thin transparent panels. Indeed, OLEDs have excellent mechanical properties, can be flexible/bendable and also transparent, thus they can be added to any suitable surface, including glass, plastic or metal foil. That way Flexible White OLEDs (FW-OLED) can respond to consumer's higher aesthetic requirements of lighting that combines visual performance, quality-of-life and art. It is clear that FW-OLEDs have considerable potential to meet the rapidly growing requirements for lighting applications. To achieve high-performance FW-OLEDs, in addition of the above-stated challenges, transparent electrodes should be developed with outstanding optical transparency (e.g., a transmittance of >90% in the visible domain), good electrical conductivity, and

excellent mechanical flexibility to support bending. Full transparent OLEDs need to develop new reliable device architectures in order to allow light extraction from both sides of the panel without damaging the organic stack during the electrode deposition. The replace of inorganic oxide based transparent electrodes by conducting organic layers (e.g. PEDOT) can be a solution to this problem, but needs further development.

## IV. CONCLUSIONS

Since the early 2000s, SSL technology has undeniably revolutionized the world of lighting. The advent, and incredible improvement in the performance and quality, of light-emitting diodes contrasts with the "dribbles of progress" in the field of conventional light sources noted, not without resentment, by J. Waymouth in the end-80s. [14] Thus, after decades of stagnation of traditional technologies, products based on LED technology, have become, after two decades of maturation, the most efficient light sources by far that we can find on the market today. Thanks to massive investments and the profound transformation of the industry, significant state/international support programs and the adoption of bold public policies worldwide, have allowed a radical transformation of the market. It is thus expected that by the end of the current decade, LEDs will become the dominant technology in the lighting market, which is worth more than \$120 billion. [1] Moreover, provided of course that engineers find solutions to certain critical technical issues, the technology of large-surface, flexible organic light-emitting components opens up new, unsuspected horizons for the light designers of the following decade.

In addition to the contribution of SSLs to reduce electricity demand for lighting, this technology has opened the door to the era of "digital light". Thus, the quality of light and its impacts on the end-users and their environment have become major concerns for the future. Like for any technology when products arrive in maturity, innovation will led to new eras. The 4<sup>th</sup> lighting revolution is looming: the advent of intelligent and sustainable lighting systems that could transform the way we conceive of the generation of artificial light, by associating it with information and communication technologies, the Internet of Things, technologies that are transforming our society and are taking a prominent place in everyday life. This new revolution will take place for sure in the next five to ten years, perhaps even more quickly than we thought. The technological building blocks are ready and mature, while the cement that will assemble them is being consolidated and massively deployed in the form of algorithms, artificial intelligence, and communication networks. However, like any revolution, it will impose a new order. For our societies to fully benefit from it, respect for users' privacy must be guaranteed, the price of products must remain affordable so as not to leave behind the most disadvantaged in our world, the economic models of the industry must be reviewed...

In order to offer the best of this new technology and avoid that smart lighting become the "Big Eye" as called by G. Parise [16], it is necessary to call upon disciplines ranging from

fundamental sciences to engineering, from social and artistic sciences to law and economics, from standardization to public policies, coordinating them under the benevolent aegis of public decision-makers and globalized industry. A lot of exciting work to be undertaken quickly!

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