Politecnico di Torino

Politecnico di Torino

Corso di Laurea Specialistica in Ingegneria Elettronica
A.A. 2020/2021
Sessione di Laurea Ottobre 2021

Display technology

From LCD to QLED

Relatore:
Maurizio Martina

Candidato:
Gianluca Tassone

To Carmen,

My λ, my ψ, from α to ω

Contents

Introduction

In 1907 a university professor; Boris Rosing, a lecturer at the technical institute in St. Petersburg, demonstrated a primitive TV system that employed the cathode ray tube, or CRT (Cathode Ray Tube), this time accompanied by electromagnetic deflection.

The kinescope was ready; he only waited for the suitable signals to drive it to arrive, for the reproduction of the images. In the early Thirties, the systems that used the kinescope grew and improved considerably, so much so that in this decade the first television stations began to broadcast, flooding the ether with these new and wonderful transmissions.

The main problem that accompanied the cathode ray tube at that time was that of obtaining a "vacuum" pushed inside the tube itself. The technology capable of creating this vacuum in the tube had not yet reached good levels and, at the same time, the closure and sealing systems of the kinescope were not exceptional.

As time went by the technology made its progress and all these problems were overcome brilliantly. In the Fifties, the picture tubes improved considerably: excellent resolution and bright colors were achieved (in those years the first color televisions in the States were already appearing).

Since then there has been an incessant evolution and improvements in tube production, so much so that, nowadays, we have traditional flat screen (Real Flat technology) and large screen kinescopes capable of providing good quality images.

However, there were two main problems with the CRT, namely bulk and weight. A panel of the "Flat Screen" kind could represent the solution to the problem, through the LCD screen and the Plasma.

LCD panels dominate the market for electronic products with displays, but they have limitations that have dragged on since their birth: high black level, low contrast, suboptimal color rendering. For the first two there is still nothing to do today, while it is possible to significantly improve the chromatic response thanks to the quantum dots, nanocrystals inserted in the backlighting system of the LCDs, which not only allow to obtain more saturated and beautiful colors but also to reduce the energy needed to operate the display, a very important plus for portable devices.

All liquid crystal displays that use nanocrystals in the lighting system represent an important renewal of LCD technology, which in the near future will have to fight the advance of LED, the display system that promises to worthily replace the now defunct plasma.

Quantum dots are nanocrystals made of semiconductor materials, ranging in size from 1.5 to 6 nanometers, equivalent to about 10 - 30 atoms. The electronic properties of these crystals are a cross between the classic ones of semiconductors and those of single molecules and can be interpreted thanks to quantum mechanics.

The main feature of quantum dots is that they emit light when they are hit by photons or electrons, light centered on a wavelength that is directly proportional to the size of the quantum dots themselves. In other words, the smaller the quantum dot, the shorter the wavelength of the emitted photons. By varying the size of a few nanometers it is therefore possible to obtain the generation of light with a color ranging from blue to red.

In practice, by replacing the white LEDs, used in the backlight modules of today's LCD displays, with blue LEDs that illuminate quantum dots of adequate size, it is possible to obtain a white light composed of the three very pure RGB components (the blue generated by the LEDs, the green and quantum dot red), ideal for making LCDs work at their best. In fact, this technology is destined to revolutionize and give new life to the LCD for the next few years and starting from 2015 it has begun to spread in all sectors in which LCD panels are used, not only TVs and computer monitors but also tablets and smartphones.

Although the use of quantum dots in LCD panels is recent, their creation dates back to 1981 by the Russian scientist Aleksey Ekimov, who observed them as inclusions in a glassy matrix. The American researcher Louis Brus, working in a totally independent way, observed them in 1985 at Bell Labs, inside a colloidal solution. To fully understand the advantages obtainable with quantum dots, it is necessary to know the technical solutions implemented today to illuminate LCD panels.

Almost all of the displays around us (TVs, monitors, tablets, smartphones) adopt white LEDs arranged along the two largest sides of the screen, a configuration known as led edge. The problem is that the white LEDs are actually blue LEDs covered with phosphors that emit in yellow, so that the blue and yellow light appears white to our eyes. This light, however, does not adapt well to the passage through the RGB filters placed in front of the sub-pixels of the LCD display. The blue component has no problems, but the yellow part must become green and red, a transformation that involves a huge waste of photons, since only a small part of these (about 10%) can pass the green and red filters.

The process is inherently very inefficient, and the lower energy consumption of the edge LEDs compared to the old fluorescent lamps (which emitted light with a much more regular and richer spectrum in the green and red sections) is solely due to the high energy efficiency of the LEDs.

To overcome the problems of the LED edge, manufacturers sometimes resort to the full RGB configuration, in which the white LEDs give way to red, green and blue LEDs. Although the color rendering is excellent, this solution is very expensive and therefore reserved for a few professional monitors that must guarantee a very wide gamut. Yes, because the led edge is not only energetically inefficient but also makes it very difficult to obtain a gamut that meets current color standards.

Practically speaking, displays with white LEDs barely manage to cover the sRgb color space, while to satisfy the more extensive Adobe Rgb and Dci it is necessary to greatly increase the light emitted by the LEDs,

then increase the light emitting diodes and consume more current. Quantum dots replace the yellow phosphors that cover the blue LEDs and convert part of the light emitted by these light emitting diodes into green and red, with very high efficiency and precision. The obtainable advantages are both energetic and chromatic.

Since the white light produced has three well-defined peaks centered on the wavelengths of the RGB color filters, most of the photons are able to pass through, so it is possible to use less powerful LEDs and reduce current consumption. As for the gamut, designers can precisely adjust the wavelengths of photons emitted by quantum dots, so as to obtain very pure primary colors corresponding to the specifications required by the standards.

Thanks to the nanocrystals, it is therefore possible to expand the gamut to cover 100% not only the sRgb color space but also the Adobe Rgb and Dci one, up to about 95% of Rec 2020, which requires monochrome primaries.

The first appearance of quantum dots in a commercial product was in 2013, within Sony's top-of-the-range televisions, more precisely in the X9 series models. More recently, nanocrystals have been used in Amazon's Kindle Fire tablet and Asus' Zenbook NX500 notebook. At Computex Taipei 2014, Top Victory Electronics showed several monitors equipped with quantum dots produced by QD Vision, capable of displaying all the chromatic shades of the Adobe RGB color space. But it was during Ces 2015 that it was possible to get a precise idea of the wave of quantum dot screens that will overwhelm the market around the world. Changhong, Hisense, Lg, Samsung, Sony and TCL have in fact shown the new TV lines for 2015, almost all equipped with nanocrystals.

Quantum dots emit light because they are stimulated with photons produced by blue LEDs. But nanocrystals can emit light even when they are hit by electrons, so it is possible to imagine a display that does not use an LCD panel but instead consists of a grid of cells containing only quantum dots, excited with the current. These luminous elements are called QDled or

Qled. The idea of using quantum dots as direct sources of light emerged in the 90s of the last century, when researchers highlighted the efficiency of nanocrystals in the process of converting electricity to light.

The structure of a QD led panel is similar to that of an Oled one, with the quantum dots divided into cells (one for each RGB color) and enclosed between two conductive layers, which carry the electrical charges. The electrons and holes recombine within the nanocrystals, forming excitons that in turn cause the emission of photons with wavelengths proportional to the size of the quantum dots.

These represent the starting points of this work, divided into three chapters in which we will deal, respectively, of LCD technology, OLED technology, and QLED technology.

Scope of this thesis is to give a general and high level review of the main display technologies as described in literature.

1 LDC TECHNOLOGY

1.1 Characteristics and operation of the LCD

Liquid crystal was discovered in 1888 by an Austrian botanist, Fredreich Rheinizer.

The liquid crystal has the property of being neither solid nor liquid: their physical properties exhibit a behavior halfway between a crystalline solid and an isotropic liquid varying under different conditions, known as mesophases. An example of such characteristic can be liquid soap which, in fact, is not solid, but it is not completely liquid either.

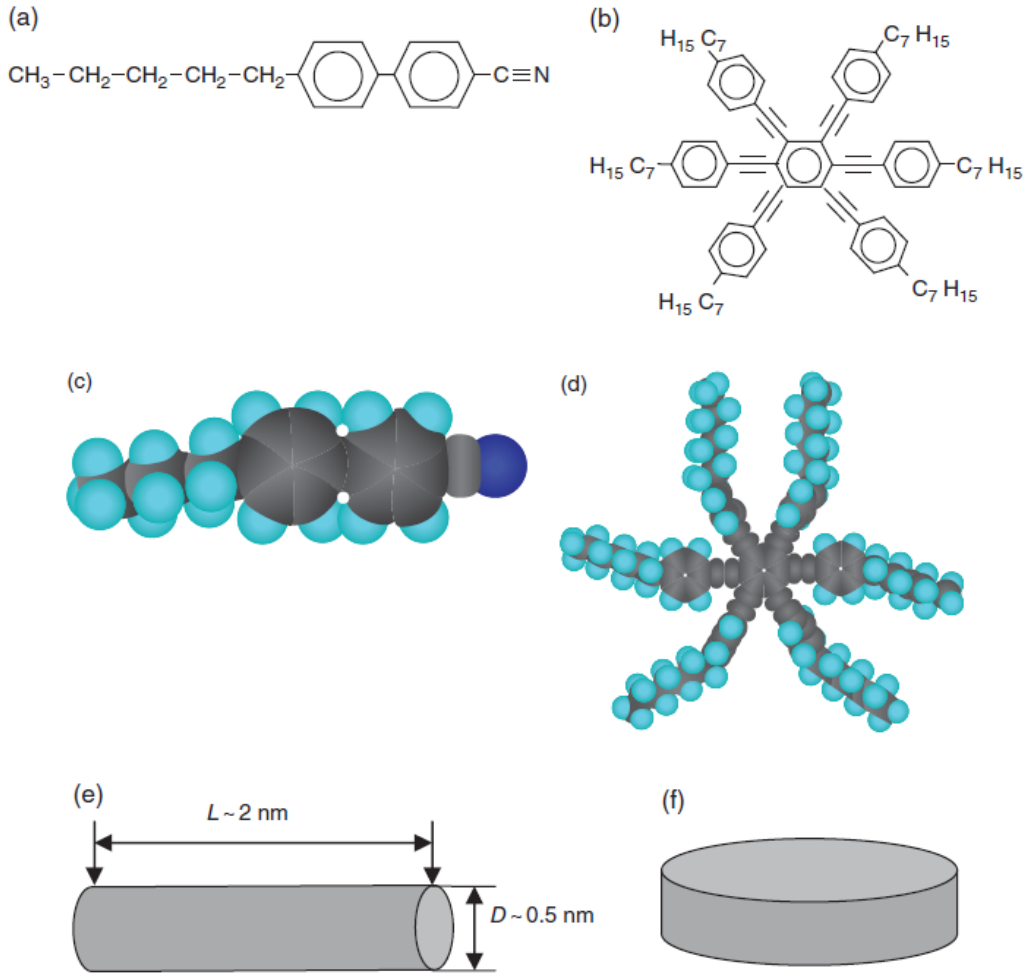
In the mid-1960s, scientists studying the properties of this matter discovered that liquid crystals stimulated by external electrical charges were able to change the properties of the light that passed through the crystals.

The first prototypes of these elements, which appeared in the late 1960s, were still too unstable for mass production. But that soon changed when a British researcher presented a truly stable liquid crystal material: biphenyl.

Two main shapes can be recognized for liquid crystal: elongated rod-like (known as calamitic) and disk-like (also known as discotic). Dimensions are in the order of degree of few nanometers and, among all the different organic compound can be used as constituent, their structure is mainly composed by a rigid core and a flexible tail as shown in Figure 1.1.

Figure 1.1 – Structure of liquid crystals

Calamitic (left side) and discotic (right side) liquid crystal: chemical structure (a & b), space-filling model (c & d), physical model (e & f)



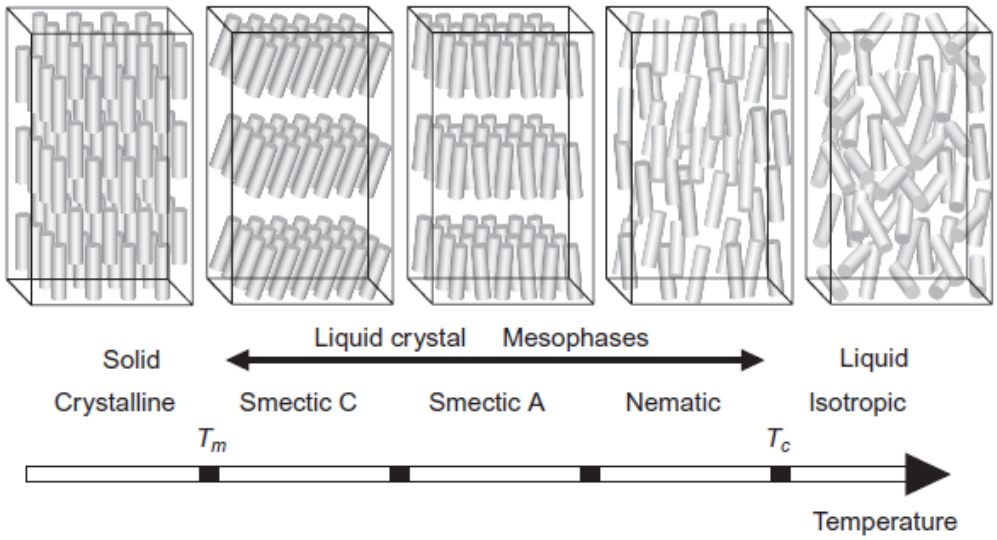
Source: Yang D.E., Wu S.T. (2015), *Fundamentals of Liquid Crystal Devices*

Such merge of characteristic allows to the system to be halfway from a complete rigid and ordered structure (crystalline solid) to an isotropic liquid (no order and totally flexible structure). Intermediate phases from the two extremes (crystal and liquid) are the most important range of application for liquid crystals and main driver for the status of the phase is the temperature. In relative low temperature scenario the liquid crystals have

very high viscosity and great orientational and positional order, making them almost solid. Increasing the temperature their phase change together with the viscosity of the system, reducing at the increasing of the temperature window passing to the Smectic phase (Smectic, from Greek: soapy). In such condition viscosity is still relatively high and molecules can move with not so fast response.

A further increase of the temperature conduct to the Nematic phase (from Greek: threadlike) where molecules have orientational order but not positional and the viscosity of the system is quite low, very similar to the isotropic liquid where no order is present and molecules can flow like water.

Figure 1.2 – Representation of the phases of rod-like molecules varying with temperature

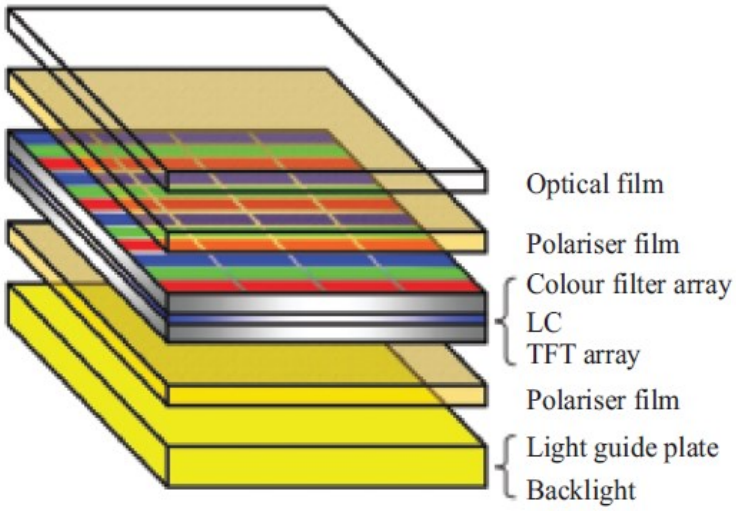


Source: Chen R.H. (2011), Liquid Crystal Displays. Fundamental Physics and Technology

Due to their nature and intrinsic characteristics the molecules have a permanent dipole moment, thus are susceptible to the action of an applied electromagnetic field. This action is capable to change the orientation of the molecules, acting as a main driver for the creation of a filter for the passage of the light.

The LCD displays inserted in today's monitors and color TVs have a sandwich structure, as shown in Figure 1.3.

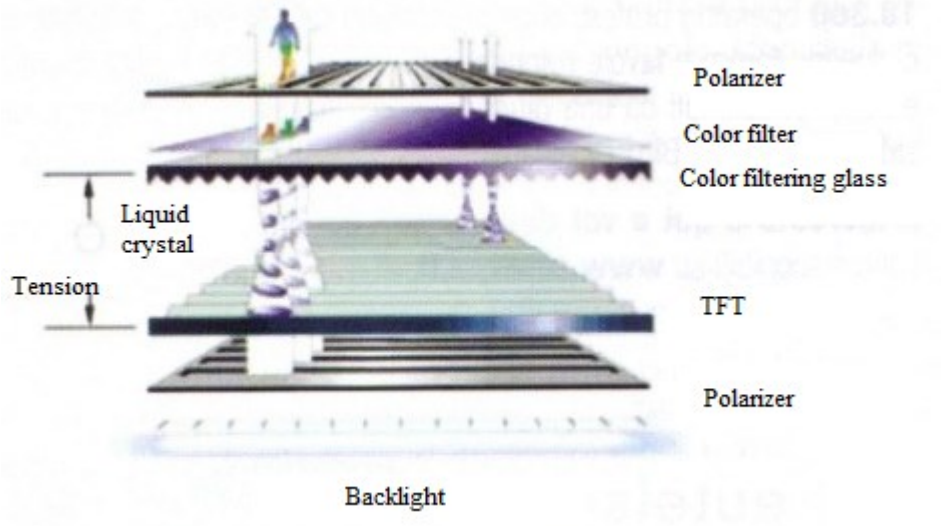
Figure 1.3 – Structure of an LCD panel



Source : Shoichi Ishihara et al,. (2019), "High Quality Liquid Crystal Displays and Smart Devices", volume 1: Development, display applications and components.

The TFT LCD (Thin Film Transistor Liquid Crystal Display) has a sandwich structure composed of various layers in which the liquid crystals are interposed between two sheets of glass. Figure 1.4 gives an idea of this arrangement.

Figure 1.4 - Layers of an LCD panel



Source: Pellini F. (2003), "Tv e monitor equipaggiati con display LCD- TFT", *Display Sat*, 9, n. 143

The first layer, called TFT Glass, has, as many TFT systems have, a certain number of pixels.

While the second layer, called Color Filter Glass, consists of a color filter that generates colors. Liquid crystals move according to the potential difference present between the Color Filter Glass and the TFT Glass. The amount of light coming from the backlight source (Back Lite) is determined by the range of movement of the liquid crystal. This provides front panel illumination and color reproduction (Tyagu & Chatterjee, 2013).

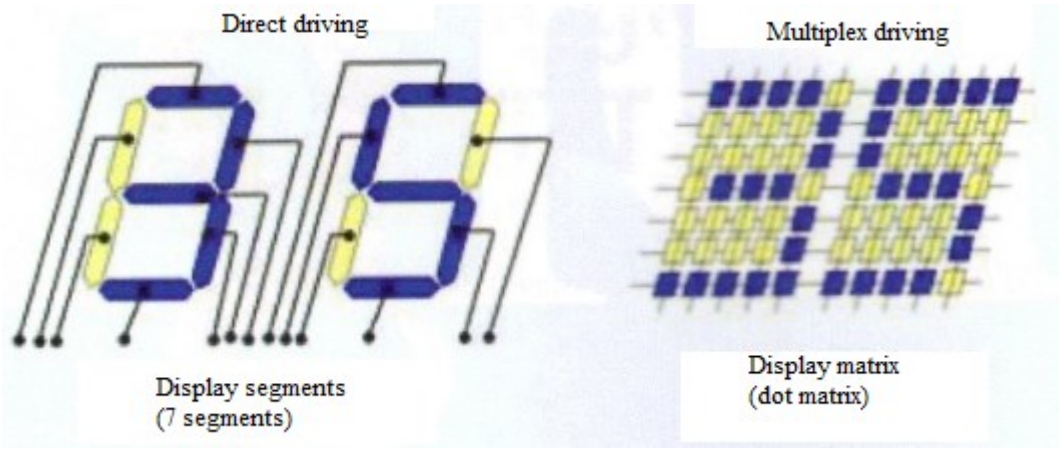
Most LCDs employ pixels formed from liquid crystal (LC) cells. These cells are able to change the direction of the polarization of the light passing through the cells themselves, according to the applied voltage. As the direction of polarization changes, more or less light is able to pass through the polarizing layer on the outside of the display. Varying the voltage results in a consequent variation of the lighting.

There are two methods of obtaining an image with these liquid crystal cells: segment driving and matrix driving. In the first case, the characters

and figures are composed of predefined electrodes in the cells themselves; in the second case, they are shown distributed in various points of the cell.

Figure 1.5 shows the comparison between the direct driving on the segments (7 segments) and the Multiplex matrix driving (dot matrix).

Figure 1.5 - Comparison between the driving on the segments and the matrix one



Source: Pellini F. (2003), "Tv e monitor equipaggiati con display LCD-TFT", *Display Sat*, 9, n. 143

The segment-driven method is used for simple representations, such as in pocket calculators. The dot matrix driving method is used for high resolution images, such as those required by laptop computers or TFT monitors (Chen, 2011).

Two driving methods are used for matrix displays. In the static or direct one, each pixel is individually connected to its own driving driver.

This is a simple method, but as the number of pixels has increased considerably, this kind of connection has become very complex.

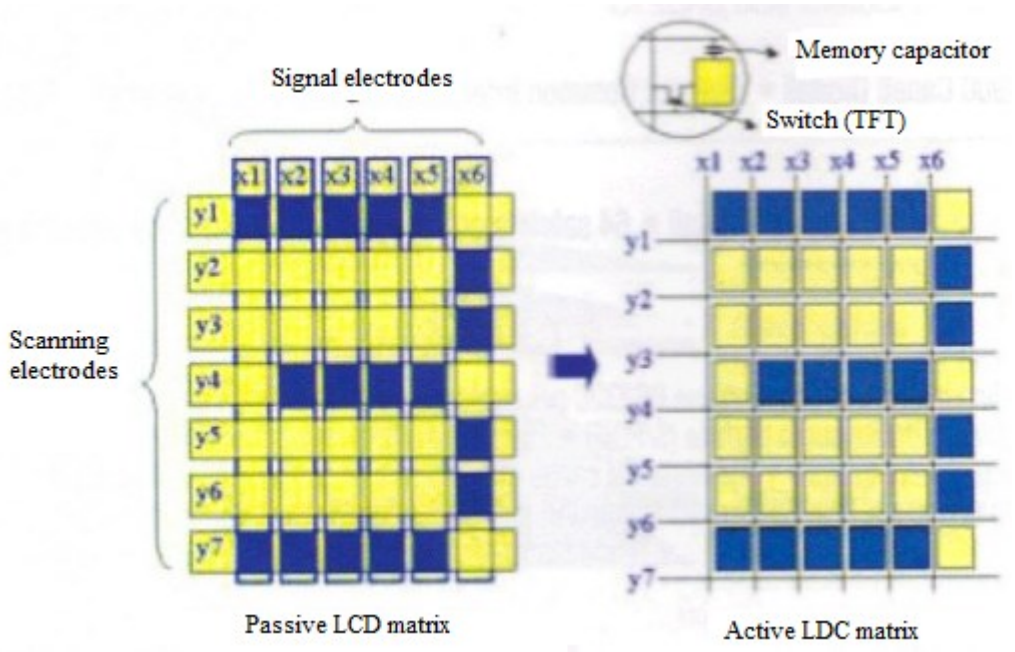
An alternative method is called Multiplex driving, in which the pixels are sorted in a matrix format.

To drive the pixels of an LCD dot matrix, a voltage can be applied to the intersections of specific vertical electrodes (signal) and specific horizontal electrodes (scanning). With this method, many pixels are driven

at the same time, by means of a pulsed drive. Consequently, this kind of driving is defined as Multiplex or dynamic.

Figure 1.6 illustrates two types of dot matrix: passive matrix and active matrix.

Figure 1.6 - Comparison between passive and active matrix



Source: Pellini F. (2003), "Tv e monitor equipaggiati con display LCD- TFT", *Display Sat*, 9, n. 143

In the passive matrix LCD PMLCD (Passive Matrix Liquid Crystal Display) there are no switching devices and each pixel is addressed several times to obtain an image. The actual voltage applied to the LC system must be distributed several times with the result of obtaining a slow response, greater than 150ms, with a reduction in contrast. The addressing of these passive matrix systems also generates a sort of cross-talk, which determines images that are not well defined because pixels that are not precisely selected are driven more than once (Tourancheau et al., 2012).

Active Matrix Liquid Crystal Display (AMLCD) LCDs have a switching device (TFT) and storage capacity. These elements are integrated into each electrode crossing point.

This active addressing method removes the limitations of multiplexing by incorporating active switching elements. Unlike passive matrix LCD systems, AMLCDs do not have substantial limitations in the number of scan lines and have irrelevant problems with regard to the cross-talk phenomenon (Den Boer, 2005).

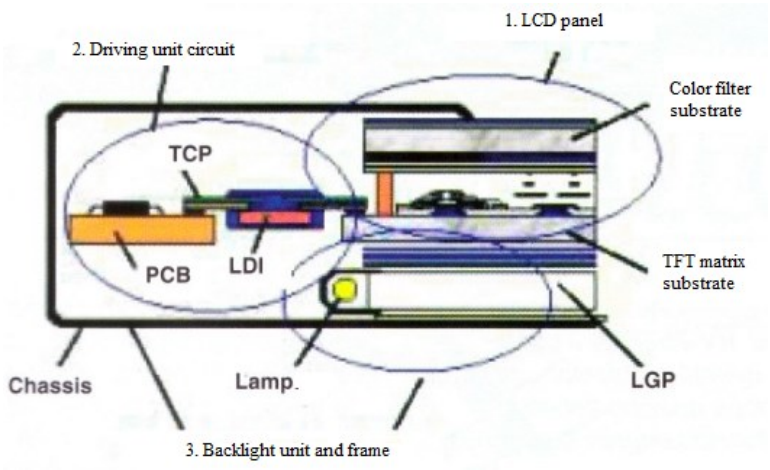
There are many types of active matrix LCDs. Most of these systems adopt switching devices composed of thin film transistors, hence the term TFT (Thin Film Transistor). The most common semiconductor layer is composed of amorphous silicon (a-Si). A-Si TFT devices are treatable on large scale fabrication using glass substrates in low temperature processes (300° C – 400° 0).

Almost all TFT LCDs are made of a-Si amorphous silicon because it is a low-priced and well-known technology.

A TFT LeD module consists of a TFT panel, a driver unit, a backlight system, an assembly chassis.

Figure 1.7 illustrates this kind of structure.

Figure 1.7 - Structure of a TFT LCD



Source: Pellini F. (2003), "Tv e monitor equipaggiati con display LCD- TFT", *Display Sat*, 9, n. 143.

The LED panel is composed of a TFT substrate and a substrate composed of a color filter. The driver unit is composed of an LDI chip, a

multilayer printed circuit, and a driver circuit. The backlight system consists of a special illuminating lamp.

A TFT LCD panel contains a specific number of pixel units often called subpixels. Each pixel unit consists of a TFT, a pixel electrode (ITO) and a capacitor Cs ().

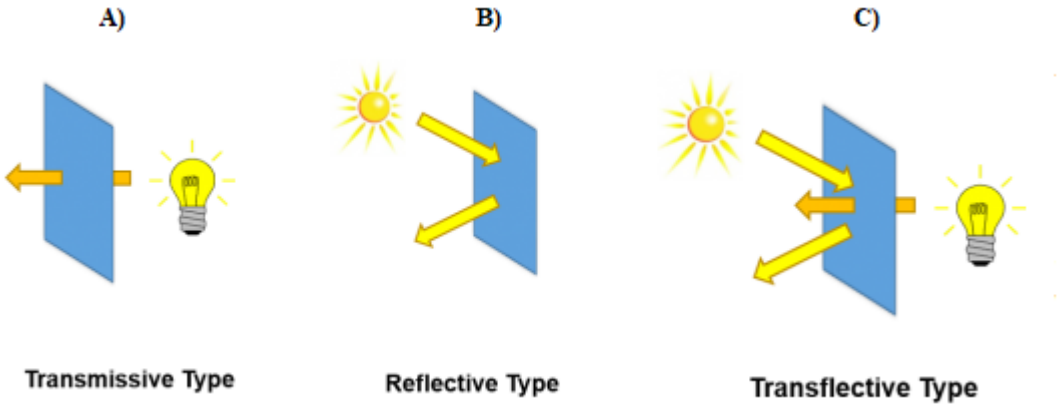
Regarding the production of colors, the color filter of a TFT-LCD television consists of three primary colors: red (R), green (G), blue (B), included in a substrate called a color filter. The elements of this color filter are arranged one by one with the pixel units of the TFT substrate. Each pixel of the LCD is divided into three subpixels, so a grouping of RGB subpixels is equivalent to every single pixel (Petrichos, Serti, 2017).

Since the three subpixels are too small to be distinguished individually, the RGB elements manifest themselves to the human eye as a three-color mixer. Each color, with its specific qualities, can be reproduced by mixing these three primary colors. The total number of color displays used in an n-bit LOI is determined by 23n, this is because each subpixel can generate 2n different transmission levels (Fang et al., 2012).

1.2 Kinds of displays

Transmissive, reflective and transflective displays

Figure 1.8 – Transmissive, reflective and transflective displays



Source: https://newvisiondisplay.com/lcd-modes/

Transmissive displays (Figure 1.8/A) receive illumination on one side and are viewed on the other. On the back of the panel a light is positioned, and the liquid crystals act as a filter, allowing only the desired chromatic component to pass through. In this way it is possible to obtain very bright displays; however, the energy expenditure of the light source can be far greater than that required by the display alone. This type of display generally has good readability in low ambient light conditions, while they become hardly visible in bright light conditions, making them particularly suitable for indoor use.

The reflective LCD displays (Figure 1.8/B) exploit the light present in the environment and reflect it thanks to a mirror placed behind the screen; unlike transmissive displays, they have a lower contrast because the light is forced to pass twice through the filter. However, one of the main advantages of reflective displays is that since there is no artificial light source, energy consumption is reduced. A small LCD display consumes so little that it can

be powered by a simple photovoltaic cell. They have a good readability in conditions of strong ambient lighting, while they are less and less legible as the external lighting decreases, an example are calculators.

The goal of transflective displays (Figure 1.8/C) is to combine the best aspects of transmissive and reflective displays. In the transflective displays behind the display there is a semi-mirror that reflects the light from the front (like reflectors), but lets the light from an illuminator placed in the back (like transmissive) pass through. This type of display is spreading rapidly, especially in mobile devices (cell phones and handheld computers), due to its good readability in all light conditions (Yang & Wu, 2015).

Active and passive displays

As previously mentioned, LCD displays with a small number of segments, such as those used in calculators or digital watches, have one electrical contact for each segment. The electrical signal to control each segment is generated by an external circuit. This type of structure becomes impractical as the number of segments increases.

Medium-sized displays, such as those in electronic diaries, have a passive matrix structure. This type of structure has a group of contacts for each row and column of the panel, rather than one for each pixel. The disadvantage is that only one pixel can be controlled at a time, the other pixels have to remember their state until the control circuit re-dedicates itself to them. The result is a reduced contrast and a certain difficulty in visualizing fast moving images well; the problem gets worse as the number of pixels increases.

For high resolution displays, such as those used in computer monitors, an active matrix system is used. In this case the LCD display contains a thin film transistor (Thin Film Transistor - TFT). This device stores the electrical state of each pixel of the display while the other pixels

are updated; this method allows for much brighter and sharper images than traditional LCDs.

The average life of LCD displays can exceed 50,000 hours; this data, together with the considerable and constant reduction of their price, makes this technology a valid alternative to cathode ray tube displays (now almost abandoned) (Yang & Wu, 2015).

1.3 Parameters of an LCD display

The main parameters that characterize an active matrix (TFT) LCD display are contrast, brightness (or more properly luminance), gray linearity, viewing angle, response time and color rendering. Furthermore, in the case of television screens, even the image scaling electronics, although not part of the actual panel, are fundamental in determining the video quality.

The relationship between the brightness of white and the brightness of black is called contrast. It is therefore a typical parameter of the panel, dependent on the ability of the liquid crystals to block the light coming from the backlight. Vice versa, the so-called "dynamic contrast" does not depend only on liquid crystals but also on the backlight: it is in fact the ratio between white, measured with the backlight at maximum intensity, and black, measured with the backlight at the minimum value. The dynamic contrast values are therefore formally much higher than the native one of the panels, on average by a ratio of at least 1 to 5.

Over time, LED backlighting technology has been developed, distinguishing two different methods for their positioning, significantly different from each other: the "lateral" backlighting, consisting of LEDs placed on the edge of the display and controllable "in block", and the "a bright carpet "(which can have a resolution equal to or even much lower than the resolution of the LCD panel), a more recent technique, which by means of a dedicated microprocessor, allows the so-called" local dimming

“, a function that acts dynamically on the various portions of the backlight, optimizing them on the basis of each single frame being reproduced, thus significantly improving the contrast. Over time, for marketing reasons, the correct term “LCD screen with LED backlight” has sometimes been abbreviated to “LED screen” but it is improper (the LEDs present have the sole purpose of backlighting).

However, strong contrasts are only necessary for use in bright light of the LCD panel; in fact, it is noted that the actually perceived contrast also depends on the ambient lighting and the surface finish of the screen (glossy/reflective or opaque/diffusing). Since in any case the screen is not a black body and reflects a part of the light that hits it, it is intuitive that the luminance of the black is altered if it is hit by a strong ambient light. Conversely, for example for watching a movie in a dark environment (the typical living room in the evening), high contrasts are generally annoying as the brighter parts of the image have a dazzling effect, reducing the perception of details in the darker parts. and increasing the perceived wake effect.

As previously said, the operation of a “liquid crystal” display provides that, with the right orientation, they can allow, or prevent, the passage of the light coming from the backlighting of the panel. The time it takes for liquid crystals to pass from a “completely closed” (black) to “completely open” (white) state, and then back to “completely closed”, is called total response time. However, some manufacturers only measure the transition from white to black (or vice versa), thus reporting to lower time values. It must also be considered that the transition from white to black can have a different duration than the inverse transition; however, it is a value that, although often praised by producers, is not really significant, because it is rare that a film goes from white to black (or vice versa); much more frequent is that you pass from one shade of gray to another and the times for the gray-gray transitions (G2G) are generally longer than the white-black ones.

The most modern displays have partially corrected the slowness on the gray-gray transition by adopting overdrive techniques (overvoltage) of the "liquid crystal" panels, which however causes an increase in image noise and/or sometimes, in particular on older panels, a reduction in reproducible colors (6 bits instead of 8, then simulated through dithering techniques).

The so-called "ghosting effect" (Tan et al., 1997; Woods & Tan, 2002) that is often attributed to LCD panels is actually only partly attributable to the response time of the "liquid crystals"; in fact, it is partly attributable to the phi phenomenon, that is, it depends on the physiology of the human eye. In fact, the perception of the wake effect is also linked to the fact that the LCD panels maintain the image between one frame and another and are continuously backlit, unlike a traditional cathode ray tube in which the image is "rebuilt" at the refresh rate of the screen (50 or 100 Hz for a TV; from 60 to 120 Hz for a computer monitor). In other words, while the phosphors of a CRT tend by themselves to "turn off" immediately after the passage of the electron brush, in an LCD-TFT (as in all active matrix, plasma or LED displays) the pixels retain their brightness "until further notice", i.e. until the next frame of the video.

However, while this is a great advantage in computer monitors as the image is stable and does not flicker, it does become a problem with moving images such as in TVs for movies.

Today's LCD displays, especially those for TVs, have a very high brightness, which if on the one hand makes them clearly visible even in strong light, on the other hand it can even be annoying for viewing in a dark or semi-dark environment. Manufacturers adopt such strong backlights as they affect the dynamic contrast.

As regards, however, the color rendering, although no type of display can reproduce all the colors perceivable by the human eye, said color rendering depends on the monochromaticity of the RGB colors (red, green and blue) of the subpixels (Wu, 2020).

Another important parameter is the viewing angle, which can be measured in various ways. When taking LCD TV screens into

consideration, the viewing angles, usually referred to, generally refer to the maximum angle under which the LCD screen can be viewed while maintaining a brightness and contrast deemed acceptable by the manufacturers (Pestov & Tomilin, 2012).

Finally, as regards the imperfection of the gray scale, it must be remembered that in the RGB system adopted by PC, DVD, DVB, high definition, etc., the gray can assume 256 levels equal to the possible combinations with 8 bits. A value of 0 corresponds to black while 255 corresponds to white. Therefore, if a display has a maximum brightness, for example, of 400 cd/m², this brightness level will correspond to white, that is to a value of 255 on the gray scale. However, the value of 128 (half scale) does not correspond to the value of 200 cd/m²; the real brightness value is generally much lower and the parameter that correlates the input signal to the light output is called gamma correction.

In other words, the gray scale is not linear at all, but follows an exponential trend with dilations and compressions; as already mentioned, for example, the black (value 0) is not completely dark, and moreover, as the RGB values increase, the brightness trend increases less markedly than one might expect, and then increases significantly towards the bottom of the scale. It is therefore possible that some neighboring gray values are not practically distinguishable from each other, especially at the extremes of the scale (low and high lights). It should also be noted that the variation in brightness and contrast is generally not linear with the angle of observation, so this issue is connected with what has been said above about the viewing angle (Xiao et al., 2011).

2 OLED TECHNOLOGY

2.1 Structure of the LED

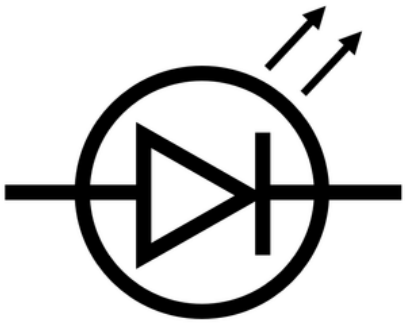
The first LED (Light Emitting Diode), of red color, was realized in 1962, then later others were developed that emitted yellow and green light. Initially they were used only in the role of optoelectronic micro-component designed for signaling. Only in the 90s were blue light LEDs made, which emit higher frequency radiation: from these it was possible to create devices that, by mixing the light with each other, could generate any color, making the LEDs suitable for wide range uses, including those relating to indoor and outdoor lighting. Their main properties, such as high efficiency, high power capacity, good color rendering capacity, high reliability, low cost manufacturability and respect for the environment, allow them to compete with traditional lighting sources, especially lamps. incandescent and fluorescent lamps.

A LED is, by definition, a diode that emits light. A diode is a two-terminal electronic device that allows the passage of electric current in one direction only, with the amount of current depending on the potential difference across the device. From a physical point of view, a LED is a chip of semiconductor material impregnated or doped with impurities to form a positive-negative junction (P-N): the positive pole of this junction is called an anode, the negative a cathode. The main feature of these devices is to let the current pass through in one direction only, like a normal diode, to which is added the ability to emit light.

Figure 2.1 shows the circuit symbol of the diode, which expresses its function: the triangle indicates the direction that allows the flow of electric current, while the bar indicates its block; arrows indicate that the diode emits

light. Having a positive and a negative terminal, the LED can only be inserted into the electrical circuit in one direction.

Figure 2.1 – LED symbol



Source: https://keystagewiki.com/index.php/Light_Emitting_Diode

To understand how a LED operates, it is necessary to analyze the structure of the materials at the microscopic level and in particular to clarify some concepts related to their ability to conduct electricity.

Semiconductor materials and band theory

The electrical properties of a material depend on its atomic structure. Electrons orbit the nucleus in energy levels or bands: they fill the bands, which are in increasing energy order as one moves away from the nucleus, in a predefined order.

Each band contains a predefined number of electrons: the first can contain a maximum of two, the second a maximum of eight; the last band that contains electrons in an atom is called the valence band, while the first empty level above the valence band is called the conduction band (Hsiang et al., 2020).

On a higher scale, it is possible to state that the valence band is the set of electrons that do not have a sufficiently high energy level to leave the atom they belong to, so they remain to orbit stably around it, while the conduction band is the set of electrons that have a sufficiently high energy level to leave the atom they belong to, giving rise to an electrical conduction.

Between these two bands may be the "forbidden band" (Pan et al., 2020), a set of energy levels that the electrons of the material cannot have because they do not correspond to either of the previous two bands.

In insulators, the forbidden band is very large, and therefore few electrons reach enough energy to pass through the conduction band, so the current is not transmitted through them. Conversely, in conductive materials, the two bands (valence and conduction) overlap, so there is no band gap and a considerable number of electrons have enough energy in this to move and therefore conduct the electric current (Pan et al., 2020).

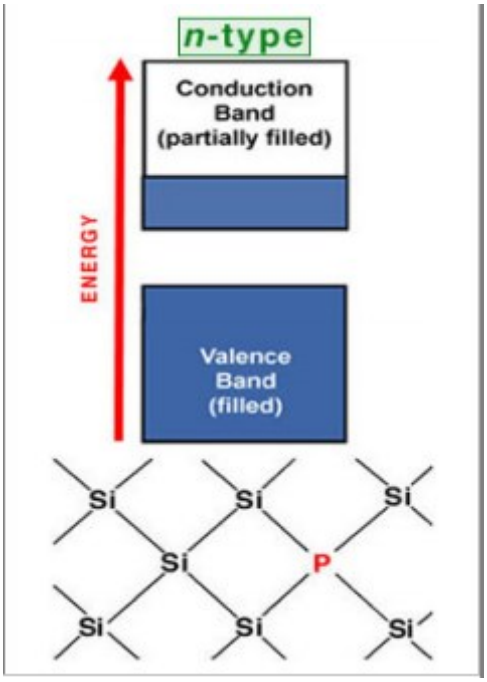
In semiconductor materials the forbidden band is small, so a rise in temperature is sufficient to bring a certain number of electrons from the valence band to the conduction band. Germanium, Silicon, Carbon and Gallium Arsenide are semiconductor materials. Each atom of these materials shares four electrons which, being attracted to the neighboring atoms, the nuclei of the various atoms, are held together by a type of bond called covalent.

Semiconductor materials and doping

Normally all the semiconductor electrons are in the valence band: that is, they remain linked to the atom they belong to and act as insulators. To conduct semiconductor materials, an operation is required, called doping (Figure 2.2 a, b, c). The doping of a semiconductor takes place by inserting atoms with valence five (pentavalents) or atoms with valence three (trivalents) inside it. The pentavalent substances include Phosphorus (P), Antimony (Sb) and Arsenic (As), among the trivalent ones Barium (Ba), Aluminum (Al), Gallium (Ga) and Indium (In) (Prakash, 2018).

By inserting a pentavalent substance inside a semiconductor four of its five electrons are used for the covalent bond, while the fifth remains free: this type of doping is called N type, because the material acquires a negative charge and the extra electrons are free to move, so this material becomes conductor (Figure 2.2).

Figure 2.2 - A schematic diagram showing the solid crystal-lattice structure and bands for silicon doped with phosphorus, an n-type semiconductor

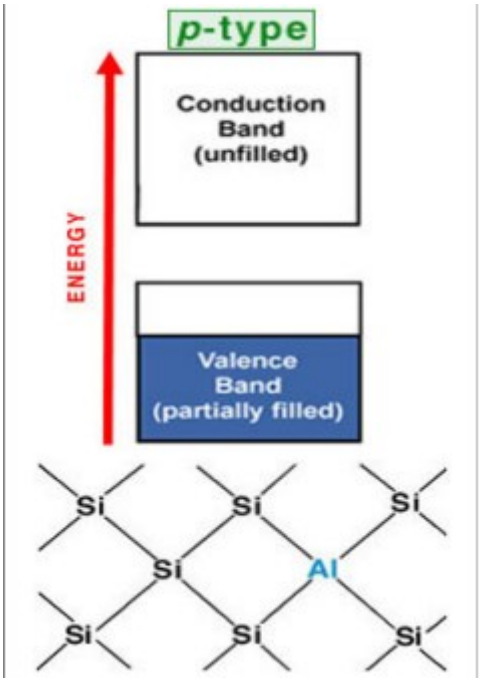


Source: Casiday R., Frey R. (2007), "Bonds, Bands, and Doping: How Do LEDs Work? Periodic Trends Experiment", Department of Chemistry, Washington University

If, on the other hand, trivalent substances are inserted into the semiconductor, the three electrons of the trivalent atom are used for the covalent bond, while an electron is missing in the valence band: this vacuum can be occupied by another electron, which in turn creates a gap in the place which he left and which can be considered a mobile positive charge, which gives rise to an electric current.

This second type of doping is called P-type (Figure 2.3) because the semiconductor material has free gaps and is transformed into a conductor (Forcolini, 2008; Scullino, 2009).

Figure 2.3 - A schematic diagram showing the solid crystal-lattice structure and bands for silicon doped with aluminum, a p-type semiconductor.



Source: Casiday R., Frey R. (2007), "Bonds, Bands, and Doping: How Do LEDs Work? Periodic Trends Experiment", Department of Chemistry, Washington University.

Furthermore, due to the temperature increase, a certain number of electrons can acquire sufficient energy to pass from the valence band to the conduction band: electron-hole pairs that are created following the increase in temperature are called minority charges; on the contrary, the electrons in the doped N-type semiconductor and the holes in the P-doped semiconductor are said to be majority charges.

P-N junction

When forming the junction of a P-type semiconductor bar with one of an N-type semiconductor, a displacement of charges occurs: the electrons and holes located in the central part of the junction are neutralized, being

charges of opposite sign. This zone devoid of charges is called the depletion region.

As soon as a certain number of electrons and holes have been neutralized, the fixed charges determine a potential difference that repels the other charges making them remain in the area they belong to: this voltage is called the potential barrier and is indicated with Vs.

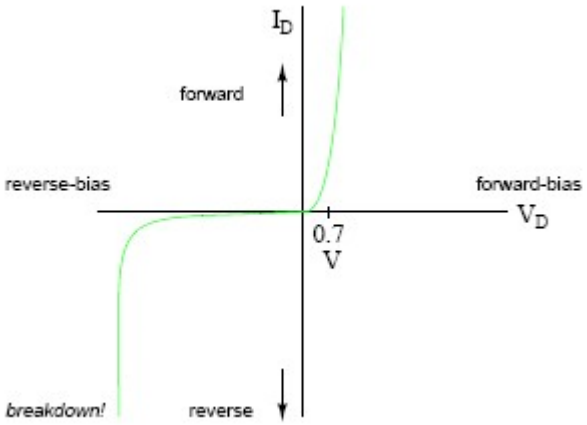
Even if the LED diode is inserted inside the circuit in the right direction, there is current conduction only when the voltage at the extremes exceeds a threshold voltage, which coincides with the potential barrier Vs. Inserted with the bias reversed there is no current conduction, except that of the minority charges, which is a very small current; for relatively low voltages instantaneous breakdown occurs.

Bias of the P-N junction

Biasing a PN junction means applying a certain voltage to its ends: we speak of direct bias when a positive charge, applied to the P-type semiconductor, repels the holes from the N-type semiconductor, while we speak of reverse bias when a negative charge applied to the N-type semiconductor repels electrons from the P-type semiconductor. The effect of the connections at the positive and negative terminals is then to push the electrons and holes towards the PN junction, lowering the potential barrier required to reduce the depletion zone of so that it becomes so thin that negative charges can pass through it by increasing the voltage. The electrons therefore begin to enter the P-type semiconductor and move from hole to hole through the crystal, making it possible for the electric current to flow from the negative to the positive pole of the battery. When an electron crosses the barrier and encounters a hole, it decays to a lower energy level, releasing the energy difference in the form of photons (Kasap, 2001). The wavelength of the light emitted, and therefore its color, corresponds precisely to the gap between the energy levels of the materials used to form the P-N junction.

Figure 2.4 shows the complete bias curve of a junction diode.

Figure 2.4 – Full characteristic curve of the junction diode in forward (quadrant I) and reverse (quadrant III) bias



Source: https://www.electroniq.net/electronic-tutorials/pn-junction.html

LED power supply

From what has just been described, it is clear that the power supply of the single LED is in direct current (CC), which is characterized by a flow of electrons of constant intensity and direction over time and can be produced starting from an alternating current (AC) with a rectification process carried out with diodes or rectifier bridges. These devices eliminate the negative component of the AC, creating a current that is not direct, but unidirectional pulsating, that is, ideally composed of an alternating current superimposed on a direct one. A capacitor then smoothes the signal, providing a current as close as possible to a continuous value. Since LEDs have a very low voltage, it is almost always necessary to calculate a resistance to be provided within the circuit. To calculate it, from Ohm's well-known law $I = \frac{V_0 - V_d}{R_0}$, where I is the current (equal to or less than that of the characteristic curve), V_0 is the voltage at the source, V_d the voltage drop at the diode, R_0 is the resistance of the circuit.

In addition to the economical but not very refined power supply method with the use of resistors, there is the possibility of using a

dynamically controlled driver, which allows you to vary the current, to make the LED pulsate, and to compensate for the effects of variation. intensity caused by temperature.

Light emission

The emission of light in LEDs is due to the phenomenon of electroluminescence, in which photons are produced in the PN junction by the recombination of electrons and holes: the light from these sources is also known as Solid State Lighting (SSL). solid, precisely because it is a solid body that emits light.

As previously mentioned, the electrons in the different orbitals have different amounts of energy, with the energy generally proportional to the distance of the orbit from the nucleus of the atom. When an electron jumps from a lower energy level to a higher one it then takes on a higher energy level.

This energy absorbed by the electric current is then re-emitted in the form of photons when the electron descends to a lower energy level. Since photons are emitted at specific frequencies, a high energy difference will produce a high-frequency photon and therefore with a short wavelength.

Although the release of energy quanta occurs in all diodes, they are visible, that is, they are photons, only when the diode consists of materials that release photons at visible wavelengths.

The P-N junction of most LEDs is made with Gallium Arsenide with Gallium Phosphorus, both materials capable of emitting light radiation when an electric current passes through them: the value of this current is generally between 10 and 30mA (Murali et al., 2014).

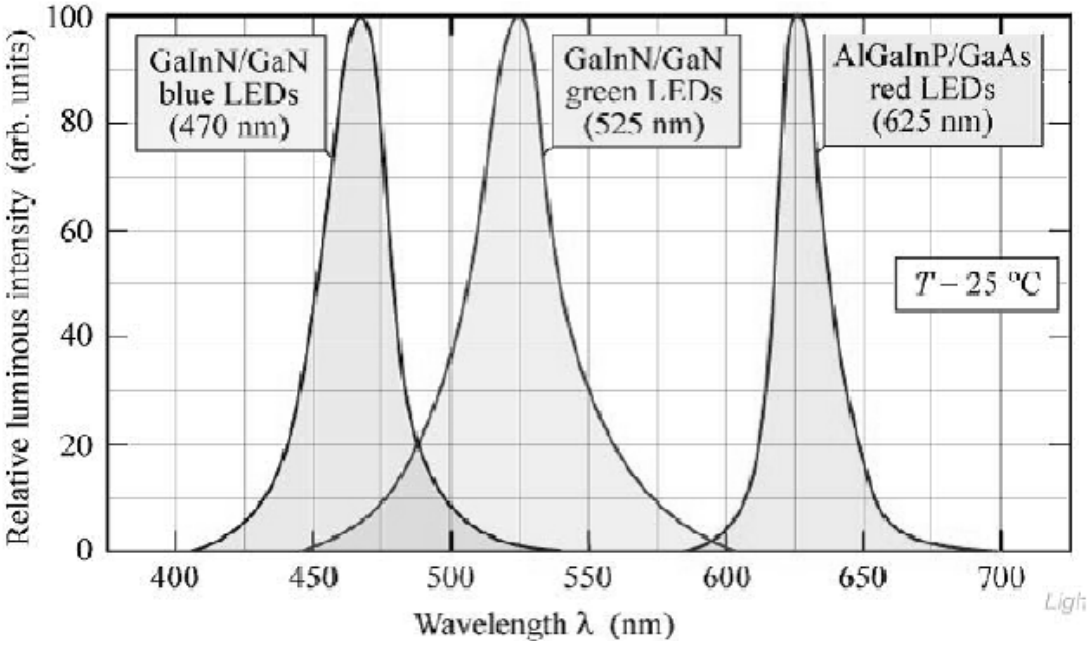
2.2 Electrical and optical properties of the LED

In Figure 2.5, the optical emission spectra of different LEDs are comparable: a red AlGaInP, a green GaInN and a blue GaInN. Comparing

them shows that the green LED has a broader emission spectrum than both the blue and the red LED, due to the technological limitations in the manufacture of Indium-rich GaInN substrates.

Furthermore, defects in the semiconductor material, for example random fluctuations in the chemical composition of the active zone, lead to a broadening of the spectrum (Schubert, 2006).

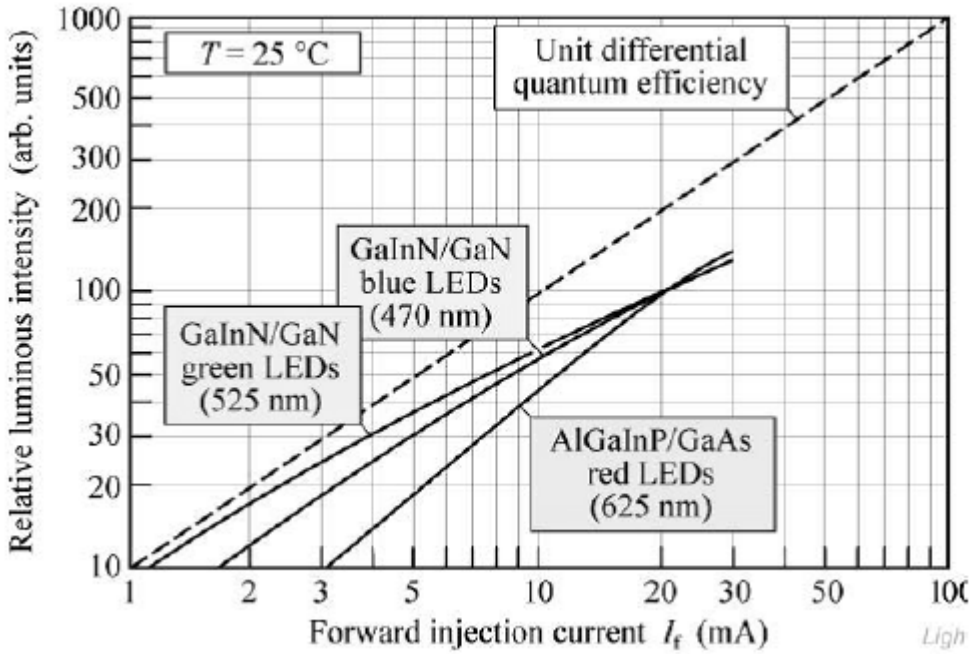
Figure 2.5 - Emission spectrum of blue, green and red LEDs at room temperature (25°C)



Source: Schubert F.S. (2006), *Light Emitting Diodes*, Cambridge: Cambridge University Press.

Figure 2.6, on the other hand, shows the graph of the injected light intensity for the same three LEDs; i unit slope (under low carrier injection conditions) as indicated by the dashed line on the graph. The red AlGaInP LED features a slope very close to the ideal one, while the GaInN LEDs have characteristics that are not very linear and have slopes that are decidedly less than one. In particular, the green LED is the one that moves further from ideal conditions to confirm the fact that the GaInN material is of too low quality, particularly with high concentrations of Indium.

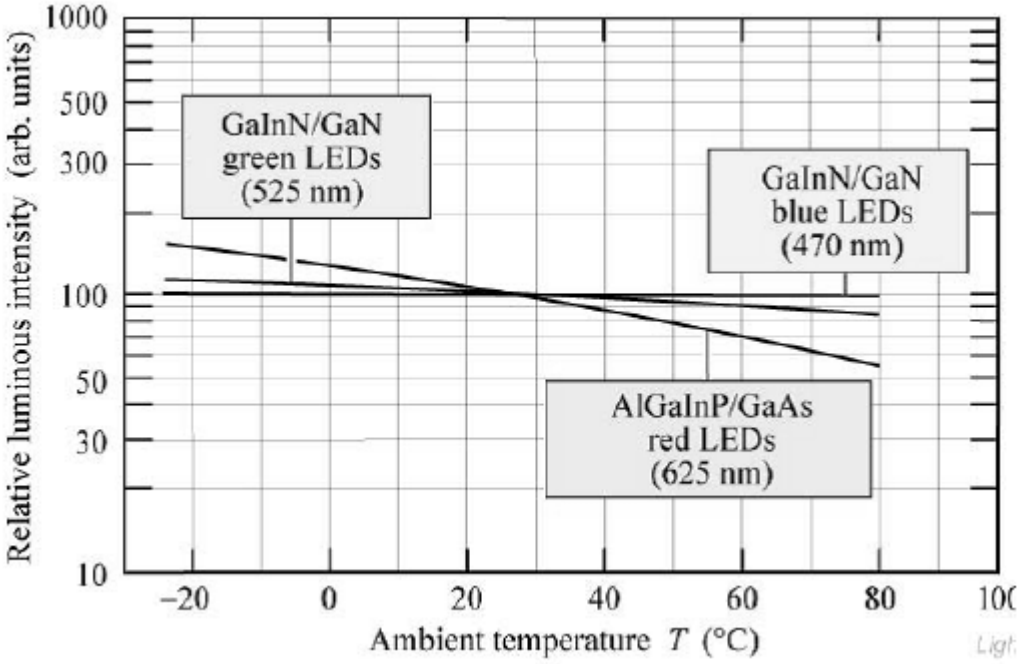
Figure 2.6 – Trend of light intensity as a function of the injection current at room temperature (25°C)



Source: Source: Schubert F.S. (2006), *Light Emitting Diodes*, Cambridge: Cambridge University Press.

The dependence of the optical power emitted on the temperature is shown in Figure 2.7. It is noted that the optical power has a much less marked temperature dependence in the GaInN LEDs than in the AlGaInP LED. This is a consequence of two facts: firstly, the potential barrier that confines the carriers is higher in systems based on GaInN / GaN and therefore the effect of the decrease in the band gap due to the increase in temperature is less marked; secondly, AlGaInP with increasing temperature is characterized by the increase in non-radiative recombination phenomena (phenomena with the absence of photon emission) which decrease its radiative efficiency.

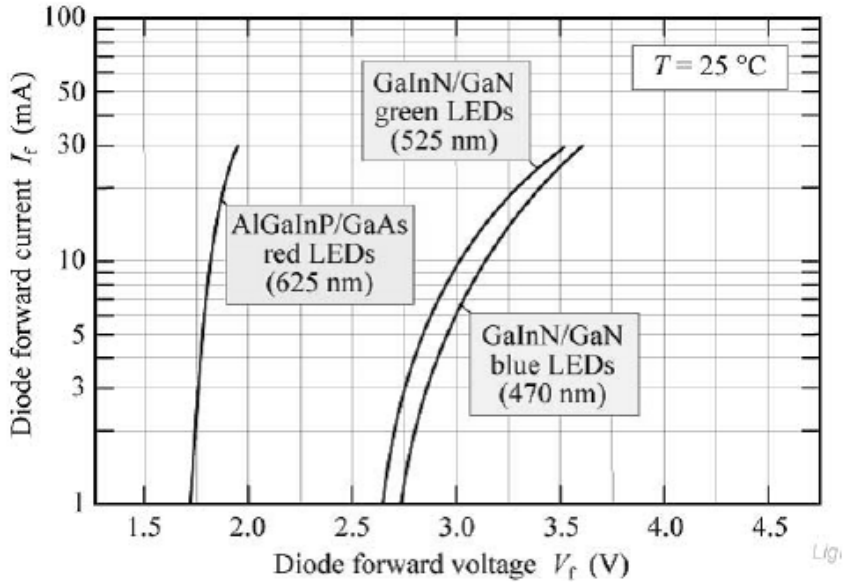
Figure 2.7 - Trend of the optical power as a function of the ambient temperature



Source: Source: Schubert F.S. (2006), *Light Emitting Diodes*, Cambridge: Cambridge University Press.

Figure 2.8 shows the current-voltage (I-V) characteristic of three directly biased LEDs: blue GaInN, green GaInN, and red AlGaInP. It is noted how the direct voltage at which the diode begins to conduct increases as the emission energy increases, that is, it is higher for LEDs that emit on lower wavelengths.

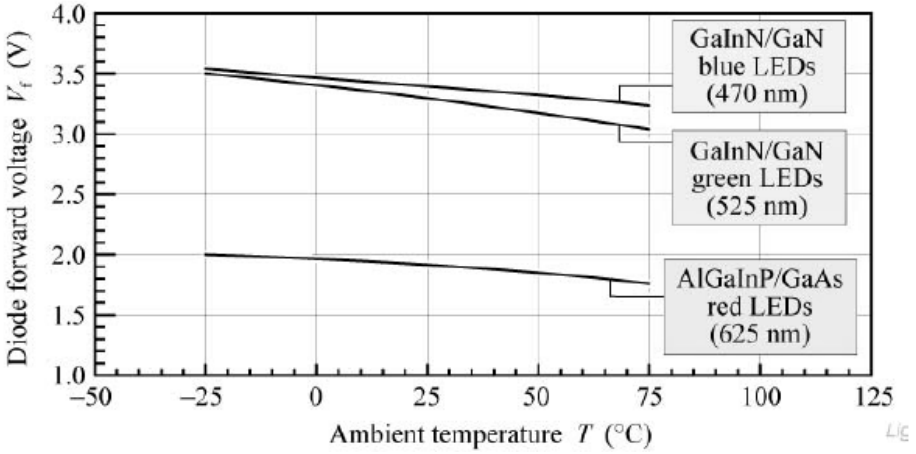
Figure 2.8 - Trend of the I-V characteristic of blue, green, red LEDs at room temperature (25°C)



Source: Source: Schubert F.S. (2006), *Light Emitting Diodes*, Cambridge: Cambridge University Press.

Figure 2.9 shows the temperature dependence of the voltage at an injected current of 30 mA. For all diodes, the forward voltage decreases with increasing temperature and the cause is the decrease in the energy gap.

Figure 2.9 - Trend of the bias voltage as a function of the temperature at a constant current of 30mA



Source: Source: Schubert F.S. (2006), *Light Emitting Diodes*, Cambridge: Cambridge University Press.

2.3 Operating mechanism of OLEDs

The evolution of organic electronics that has characterized the scientific world in recent years has influenced many fields, primarily the world of displays for smartphones. In fact, 2007 saw the birth of new screens built with a particular type of device capable of emitting light: the organic LED, or more simply OLED (Organic Light Emitting Diode). Already from the first studies of this OLED, the similarities with the common LED were evident, which shared the voltage-current characteristic with the pn junction diode, and in addition allowed the emission of light.

Like normal LEDs, OLEDs base their operation on electron-hole recombination, and on the consequent luminescence produced. Unlike diodes, however, an OLED is not made of silicon-based materials, but a carbon-based structure (polymers or small molecules).

The discovery of OLEDs, and their subsequent improvements, are still allowing a massive invasion of the market by increasingly advanced displays in terms of image rendering and efficiency, which proves to be very good. This implies low power consumption, which favors OLED applications in the field of battery-powered mobile device displays.

OLEDs can be manufactured with more or less innovative technologies depending on the materials used. Of particular note is the spin coating, a manufacturing technique mainly oriented to the creation of OLEDs based on polymers, or inkjet printing (Kim et al., 2019; Xuan et al., 2020), which allows the creation of very high definition displays in a relatively simple way and with a modest expenditure of money.

The extraordinary adaptability of OLEDs opens the door to very different fields of applications and until now only imagined by the minds of science fiction authors. OLEDs can in fact be built with materials that are almost completely transparent to the light they produce, allowing the creation of displays that, once turned off, appear as real glasses.

The elements of the success of OLED technology are to be found in much more peculiar characteristics. In the first place there is the

autonomous emission capacity of light. At the implementation level this is of particular importance because it allows you to avoid having to resort to a screen backlight, as was the case with simple LCD or LED devices. The result is a notable streamlining of the depth of the device (and, also in this case, a reduction in weight). In addition to this, the elimination of the backlight has a positive feedback also in the chromatic rendering of dark colors such as black (which can reach more considerable depths, with an improvement in contrast in the images).

From an operational point of view (and also more purely commercial and important for the average user) it is impossible not to highlight a wide viewing angle: this is a huge advantage compared, for example, to LCD screens, whose images became difficult to see if you placed yourself in certain positions with respect to the screen. Remaining on the subject of comparison between LCD TVs, Plasma TVs and OLED TVs, it should be added that the last category also sees a better overall color rendering of the devices (although this does not also correspond to an excellent naturalness of the colors) and lower energy consumption. The biggest flaw in comparison to other technologies is the average lifespan of the OLED, much lower than that of LCD TVs or PLASMA TVs (about 10000 hours against 5000-6000 hours).

An extremely important factor, as will be illustrated in more detail below, is also that of the high efficiency offered by organic LEDs, generally expressed as brightness in relation to the supply voltage. High efficiency translates into low energy consumption, an extremely relevant element in the field of displays for mobile devices. The high efficiency allows the implementation of OLEDs in the field of home or street lighting. In our historical period, characterized by the possible crisis of non-renewable energy sources, this represents a point of fundamental importance.

To understand the functioning of an organic device capable of emitting light (i.e. an OLED), it is necessary to analyze its behavior at the atomic level. A key role in this, as often happens in electronics, is played by the charge carriers (holes and electrons). In fact, it is these elementary

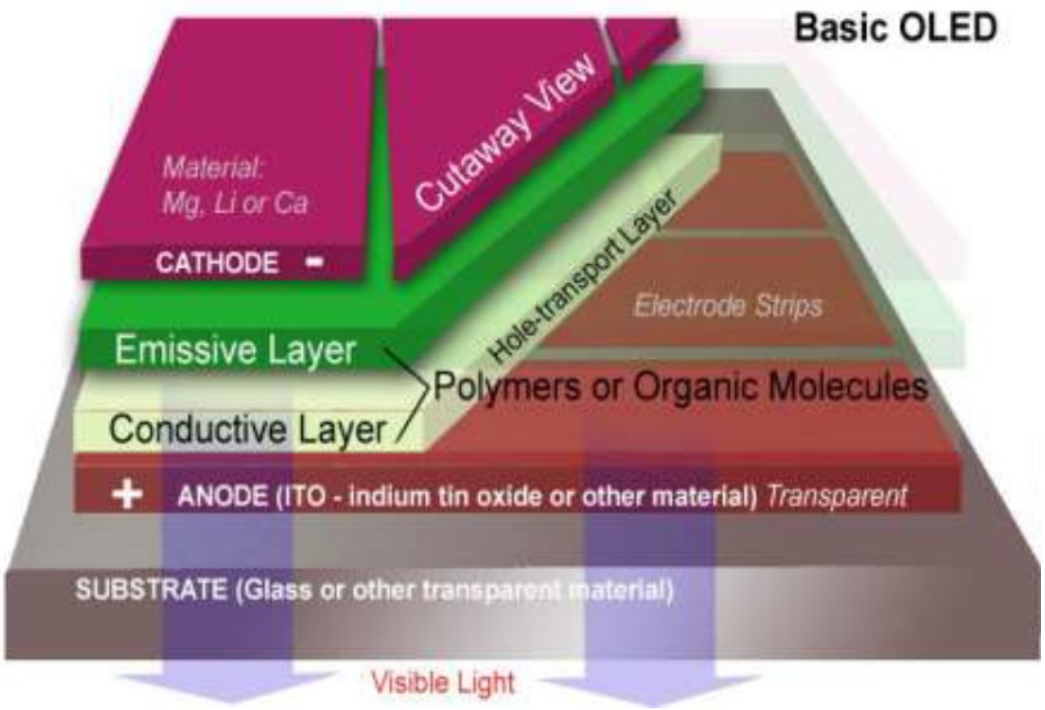
particles which, by carrying out recombination, emit energy in the form of light and allow the device to be used.

Unlike traditional LEDs, whose operation can be compared without too many problems to a normal semiconductor diode, an OLED is similar to a diode only in some respects. Looking at the microscopic, the great differences lie precisely in the materials with which they are composed and in the characteristic multi-layer structure, unlike the realization with pn junction. These discrepancies require the adoption of peculiar means for doping materials, injection of carriers, and other aspects.

OLED structure

The simplest and most schematic structure of an OLED (Figure 2.10) consists of two layers of organic type material placed between two electrodes. The purpose of the latter is obviously to inject charge carriers into the organic levels.

Figure 2.10 – OLED structure



Source: Bagher A.M. (2016), "Comparison of Led and OLED", *Scholars Journal of Engineering and Technology (SJET)*, 4(4): 206-210.

The base of the OLED is a transparent glass substrate that allows the passage of the light produced in the innermost layers. It can be made with different materials to give life to various types of OLEDs (for example flexible OLEDs, made with a plastic substrate). The shape of the substrate is fundamental for the correct emission of light and a consequent increase in efficiency.

The second layer is the anode, which is the metal responsible for injecting holes. In most cases it is an Indium-Tin oxide commonly known as ITO (Indium Tin Oxide). As in the case of the substrate, this material must also be transparent to allow the light produced in the internal layers to escape from the device.

Just above the anode take place a hole transport layer called the Conductive Layer. It should be specified that in other OLED embodiments it is possible to have a transport layer for electrons. In this case, the layer (called ETL i.e. Electron Transport Layer), is placed between the cathode and the emissive layer, and can be co-present at the Conductive Layer. This structure is called a double heterostructure.

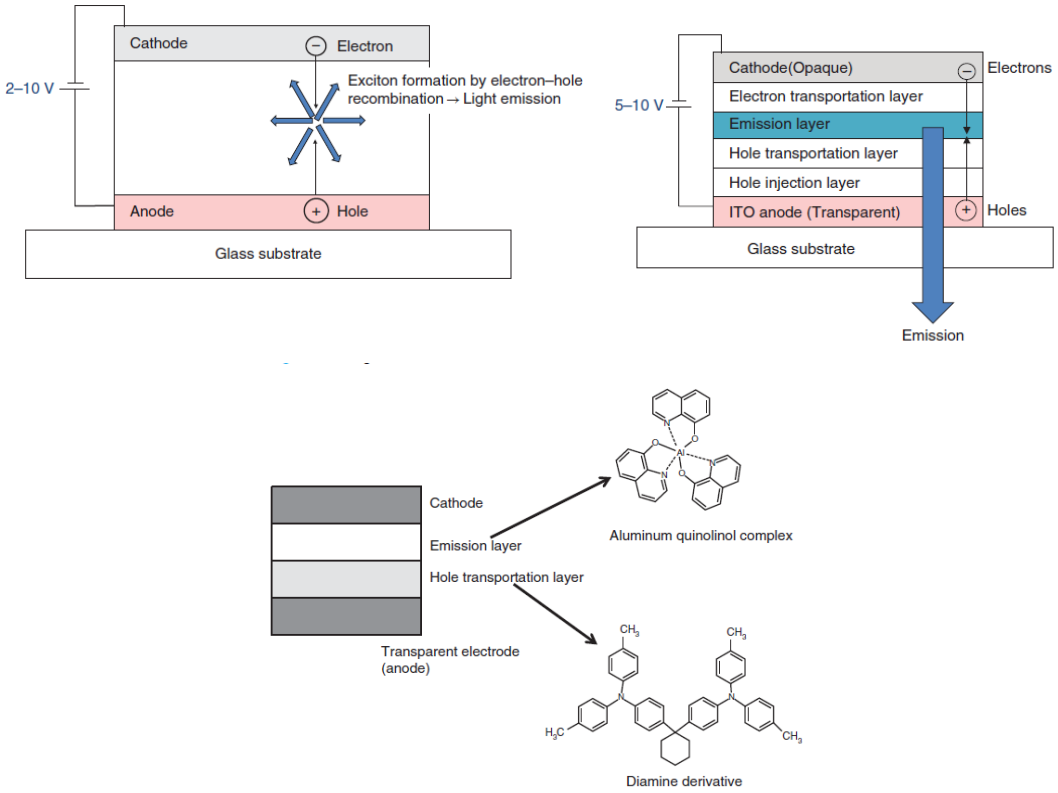
Above the Conductive Layer there is an Emissive Layer. This is where holes and electrons recombine, and this is where light is generated. With more advanced structures, one is able to concentrate the electrons in this area in order to favor the recombination of the carriers. In the vast majority of cases the role of the emissive layer is played by one of the transport layers (often from the ETL), and is sometimes specially doped. The first efficient material used for this role was an aluminum based organic molecule known as Alq_3. This material in origin is a green fluorescent emission material that can be doped to emit light in a different wavelength, such as incorporating a minimum amount of rubrene the emitted light shift to yellow/orange (Takatoshi Tsujimura ,2017)

At the other end of the device, placed at a low voltage value, there is instead a cathode. It is a metal (Lithium-Aluminum or Magnesium-Silver) or an alloy and its function is to inject electrons into the innermost organic layers. The cathode must have a low ionization energy (ie the energy to be

supplied to an atom for one of its outermost electrons to be released) in order to be able to release electrons even in response to a not too strong electric field.

The mechanism underlying the functioning of an OLED has as its pivotal event the recombination of electrons and holes. The carriers are injected into the organic layers by means of an electric field and then transported to the ETL) where they carry out the recombination with the consequent emission of light.

Figure 2.11 – OLED structure principles and particulars



Source: Takatoshi Tsujimura (2017) OLED Display Fundamentals and Applications Hoboken, Wiley

Generally, the materials with which the Organic LEDs are built are not, in their natural state, conductive materials. In fact, these are insulating materials that are unable to conduct a high level of current, especially when the applied electric field is low (less than 104V / cm).

In silicon-based inorganic materials it is used to dop the crystalline structure with acceptor and donor atoms (for example Boron and Phosphorus) in order to increase the concentration of electrons and / or holes in order to make the material more conductive. In particular, the acceptor atoms introduce holes in the material, while the donor atoms introduce electrons. The same process is unfortunately impracticable for organic materials capable of producing luminescence: the chemical doping, in fact, dampens the radiative effect of the material, making the OLED useless.

Despite the impossibility of chemically doping the organic materials of the OLEDs and the presence of insulating materials, it is still possible to reach quite high current densities (even up to 1A / cm2). This is thanks to the particular method of injection of the charges, which exploits the Tunnel Fowler-Nordheim effect, and the use of support materials that favor the injection (Liu et al., 2009;).

For quantum effects, if subjected to a sufficiently high electric field, electrons are able to penetrate the insulating material (i.e. to enter the organic layer of the OLED). Two cases are distinguished: if the current density injected n_{ci} by the electrodes is lower than the intrinsic charge density n_i inside the medium, the incoming current flow obeys Ohm's law.

Viceversa, if $n_{ci} > n_i$ (and the electric field assumes a fairly high value), the charge carriers thicken near the electrode / organic material junction, creating a space charge limited current (SCLC) region. In particular, the electron density increases near the cathode, while that of the holes increases near the anode

This non-homogeneous arrangement of the charges, obviously gives rise to an electric field that favors the one generated by the electrodes (both vectors that describe them have in fact the same direction). If we assume that the electric field due to the external potential is $E' = V/d$, where V is

the voltage between anode and cathode, and "d" the distance, we obtain that the field present inside the device is in total

$$E_{int} = E' + V/d.$$

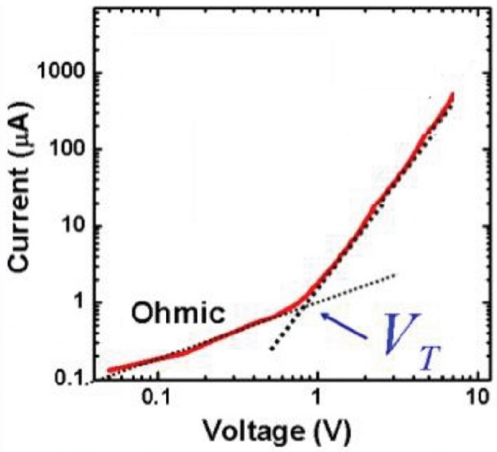
As a result of the increase in field strength, there will be a larger current flow. Although the material was not chemically doped for this purpose, therefore, it was still possible to obtain a high current density while preserving the ability to emit light through recombination.

Current density obtained as space charge limited current follow the rules

$$J = \frac{9}{8}\varepsilon\varepsilon_0\mu\frac{V^2}{d^3}$$

The two abovementioned cases for conducting polymer diode can be represented in the ideal current/voltage characteristic curve:

Figure 2.12 –Space charge-limited ideal current behavior for polymer semiconductor



Source: Syed A. Moiz, Iqbal. A. Khan, Waheed A. Younis and Khasan S. Karimov (2016): Conducting Polymers, chapter 5 page 97

2.4 Efficiency of OLEDs

High efficiency is one of the strengths of OLEDs. Thanks to various structural modifications (which will be at least partially analyzed in this

section), organic devices reach a good degree of brightness with a very low supply current (i.e., obviously, a relatively small number of carriers injected into the device).

What matters when designing an OLED to be used in displays is the amount of light emitted in the visible range: that light is nothing more than an electromagnetic wave that stimulates the human eye in cases of wavelengths between 380nm and 780nm. Of these, some have a greater impact on organ stimulation: those that have the greatest effect are the waves associated with the green color (495-570nm). Photometry deals with the measurement of waves in the visible range (unlike radiometry which deals with measuring a wider range of wavelengths).

Photometry provides different quantities for the measurement of the light:

- Luminous flux: this is the photometric quantity that measures the power of light perceived by the eye. Its unit of measurement is the lumens (lm) (the radiometric equivalent is simply the watt W).

- Luminous intensity: refers to the luminous flux emitted by a source in a unit of solid angle (the steradian, which measures 4π). The unit of measurement is the candle. Since there are 4π steradians in a sphere, the relationship between candle and lumens is $1cd = 4\pi lm$.

- Luminance: it is defined as the ratio between the light intensity emitted by a source towards a surface normal to the direction of the flow and the surface area itself. It is measured in nits, that is cd/m^2.

As for efficiency in narrower terms, three types of efficiency can be defined for an OLED.

- External efficiency ($nEXT$) indicates the ratio between the photons emitted by an OLED in the visual direction and the number of electrons injected by the cathode.

- Internal efficiency ($nINT$) corresponds to the number of photons generated inside the OLED divided by the number of electrons injected by the cathode.

- Luminous efficiency (eta_l) is measured in *cd/A*. This magnitude is equivalent to nEXT, but the luminous efficiency weighs all the incident photons according to the stimulation of the eye. So you will have $eta_l = AL/I$, where "L" is the luminance of the OLED, "A" is the active area of the device, and "I" is the injected current.

- Quantum efficiency, finally, expresses the conversion efficiency of other energy sources into light.

The increase in efficiency is achieved at the expense of several changes in both the internal and external structure of the devices. Furthermore, an appropriate choice of the materials that make up the organic layers is fundamental for a good level of efficiency of the device.

2.5 Types of OLEDs

OLEDs represent a new frontier in the evolution of displays, the most important application allowed by this technology. If initially with OLEDs it was possible to design only very low resolution monochrome displays, today we have come to produce screens capable of reproducing millions of colors at very high resolution more or less faithfully. On the other hand, OLEDs are more recently developed, capable of being transparent when switched off, while devices based on organic LEDs capable of bending or rolling up are being realized.

Full color OLED

The realization of a fairly advanced display obviously requires that the OLEDs of which it is composed are able to emit sufficiently bright colored light characterized by good saturation. Furthermore, it is necessary that the efficiency of each device is high in order to have displays that do not consume too much electricity, and have a long average life. To fix some numbers, just think that the luminance of a normal display should be around

a few hundred nits (nit is equivalent to cd/m^2), while the power supply voltage should not exceed a few volts.

During the development of organic LEDs, various methods have been implemented for the construction of color displays. Most of these methods start from a common principle, which consists in placing LEDs that emit in primary colors (red, green and blue) side by side. The combination of the three devices gives life to what is called a pixel, while the three OLEDs are called subpixels. In reality, sub-pixels are often not made up of OLEDs, but rather of filters or structures that convert light of a certain color (coming from an overlying organic LED) into another primary one. The superimposition of the three primaries guarantees the obtaining of all the colors in the visible spectrum.

The simplest realization of a colored screen involves placing three OLEDs of different colors (sub-pixels) side by side on the same substrate. This is a fairly simple solution, but it can only guarantee poor screen resolution. Furthermore, manufacturing is quite complicated due to the need to use a different organic layer for each OLED. In fact, each layer has to be grown on a very small area, causing an increased likelihood of making manufacturing errors. Each OLED must in fact be placed at a certain distance from the other, in order to allow the presence of the control circuitry.

Even the post-deposition operations could be a source of difficulties in the manufacture of the devices: it may in fact happen that the molecules used to produce the emissive layers are sensitive to certain solvents. These are essential for the removal of support layers used for the creation of the OLED (eg the photoresist). It is therefore necessary to pay great attention to the procedures faced in the realization of the devices.

For the filtering of a white OLED only an OLED that emits white light must be made. Below there are three suitably adjusted filters that allow the light produced to be broken down and only the desired component to pass (i.e. a red, a blue and a green component).

The big disadvantage of this realization lies in the damping of the light produced by the OLED after passing through the filters. As for the red color, for example, more than 90% of the light produced inside the device is absorbed before being emitted, making it too weak. To overcome this drawback it becomes necessary to make the white OLED much brighter, causing a greater flow of current into the device. This, in addition to resulting in a higher energy consumption, involves a shortening in the life of the device (already compromised by the generation of heat due to the filters arranged at the base of the white OLED).

For the conversion of blue light, the method is similar to that of producing light starting from the white LED. Although the structure is similar to that of the previous case, this time an OLED that emits blue light is used. Underneath are positioned fluorescent materials which, after absorbing the energy of blue light, emit either red or green. Note that the wavelengths associated with the two colors are both larger than that of blue. These therefore correspond to less energy. In fact, by the very definition of phosphorescent material, the light emitted has lower energy than that produced, and therefore lower luminous intensity. Also in this case it is therefore necessary to supply more current to the blue LED, in order to allow the colors produced to stand out more.

In the case of OLEDs with microcavities, the latter can be exploited in order to influence the direction of the light waves and the color emitted thanks to the fact that the emission of light becomes a function of the wavelengths of the radiation itself (Isenhart, 2019; Salehi et al., 2019).

The potential of these devices is quite scarce, even if they can be improved by slightly modifying the structure of the emissive surface in order to better disperse the light.

With a method similar to this it is possible to implement displays using stacked OLEDs. The basic idea is to stack OLEDs on top of each other with transparent electrodes emitting in red, green and blue. If their electrodes are transparent, it is possible to choose which of these three devices to activate, obtaining the desired color (this is the technique for

making SOLEDs, as will be seen in the next paragraph). Thanks to this expedient, the resolution of the implemented display can also increase by a factor of three.

The realization of a color-tunable OLED differs from the others because it does not require the use of three LEDs side by side: each LED is in fact able to emit a primary color based on what voltage is applied to its electrodes. As always, the amalgamation of the light produced by adjacent LEDs provides the desired color. Undoubtedly, this implementation allows greater integration of the devices, allowing to reach more definitions in the displays. The manufacturing complexity is also lower as there is no need to grow each OLED separately with different materials. Despite this, the control circuitry becomes more complex, which must drive each OLED in voltage (Tsujimura et al., 2016).

TOLED and SOLED

The OLED technologies presented so far are able to emit light only through one side, generally the anode (the ITO). The first OLED devices capable of emitting light from both sides (both from the cathode side and from the anode side) have already had some commercial applications. These devices, when switched off, are perfectly transparent and are therefore called Transparent OLED (TOLED) (Zissis, 2014).

Traditional OLEDs base their cathode on metals or metal alloys (such as Mg-Ag). Although these are excellent materials for electron injection, they do not allow enough light to pass through in order to obtain the desired TOLEDs. The ideal cathode for a TOLED, on the other hand, should be completely transparent, while resisting well to various types of damage, and should have a low electrical resistance to the input current. A first embodiment involved replacing the traditional cathode made of the Mg-Ag alloy with a very thin layer of similar composition and covered with ITO deposited by pulverization.

The HTL (hole transport layer) was given by 200Å of TPD (N,N′-Bis(3-methylphenyl)-N,N′-diphenylbenzidine), followed by a layer of Alq_3

with a thickness of 400Å for the transport of electrons and the emission of light. With this embodiment, only 70% of the light produced was able to emerge from the device. Furthermore, the light produced was similar to that generated by a traditional OLED based on Alq_3 as an emissive material, but the spectrum of the light exiting the cathode was slightly shifted towards the red compared to the light exiting the anode.

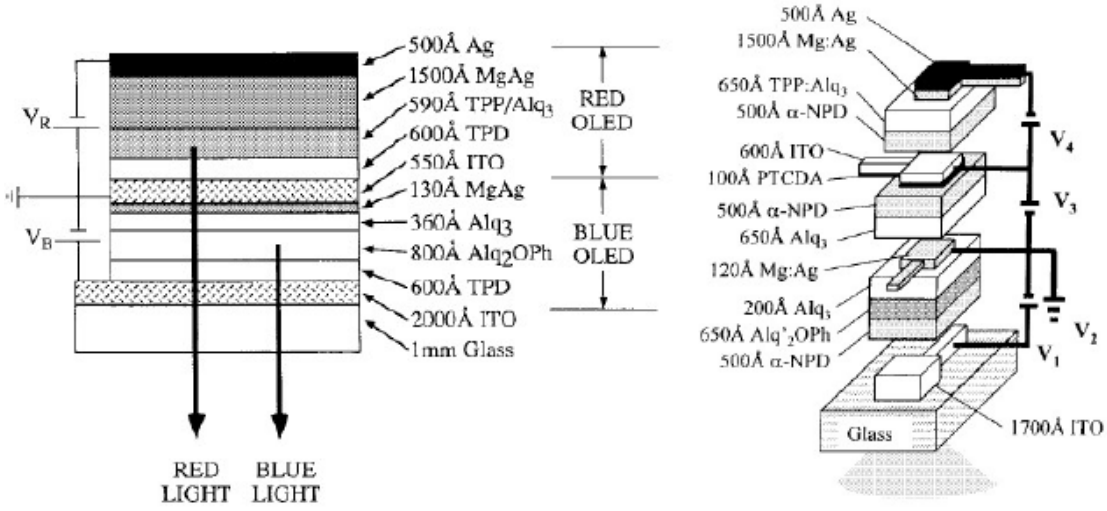
Another attempt aimed at obtaining an excellent electrode was carried out thinking about the property of ITO: the idea was to exploit a dopant that would provide it with the typical properties of cathodes. Unfortunately, we have come up with a material capable of letting only 70% of light through, and therefore unsatisfactory.

During the studies, different materials were tested in order to improve the transparent cathode, but each presented different problems. In the end, Indium oxide (InOx) was chosen, a material characterized by an excellent transmission capacity of visible light and low electrical resistance, but with a too high work function. By doping it with calcium (whose work function is equivalent to 2.63eV), however, it is possible to lower the work function to more acceptable and functional values. A new material is thus obtained, InCaOx (ICO, or indium-calcium oxide).

The ICO is deposited by thermal evaporation assisted by ion beams (the purpose of which is not to damage the sensitive internal layers of the device) and allows to reach satisfactory values of transparency in visible light, but also a good rate of electron injection.

TOLEDs can be exploited to implement another type of organic LED: Stacked OLED (or SOLED). It is an OLED consisting of one or two stacked TOLEDs, that is, built one above the other, as shown in Figure 2.13 and as seen with regard to the creation of full color displays (Kasahara et al., 2013).

Figure 2.13 – Schematic representation of two SOLEDs. The first has two elements, the second has three

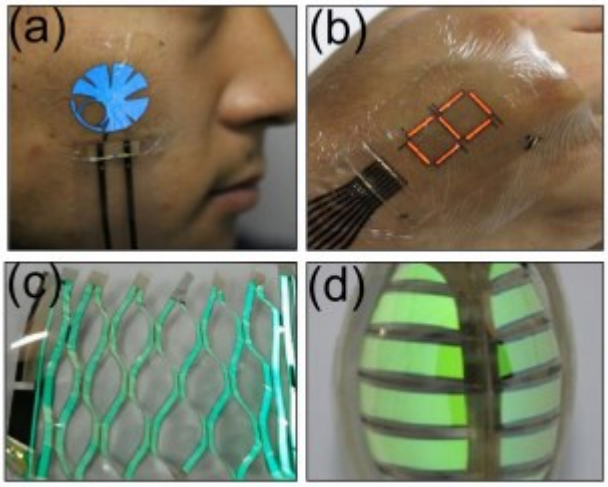


Source: Kasahara T., Mizuno J., Matsunami S., Edura T., Tsuwaki M., Oshima J., Adachi C., Shoji S. (2013), Multi-Color microfluidic Organic Light Emitting Devices using electroluminescence and electrochemiluminescence, IEEE, Taiwan

The most recent innovation of OLEDs certainly concerns flexible screens. Flexible OLEDs (FOLED) are commonly made on the plastics polyethylene naphthalene (PEN) and polyethylene terephthalate (PET), with finished devices less than 500 μm thick. The bounds of OLED technology's flexibility are being pushed with even thinner and more flexible substrates (Kim et al., 2017).

For example, Yokota et al. (2016) fabricated flexible OLED displays on ultra-thin (1.5 μm) parylene and polyimide substrates that can be worn on the body like a temporary tattoo, as shown in Figure 2.14(a) and (b). OLEDs have even been crafted into flexible 3D structures, as demonstrated by Kim et al., who fabricated OLEDs on 25-60 μm thick polyimide substrates that were cut and folded into the 3D shapes shown in Figure 2.14(c) and (d).

Figure 2.14 – Flexible OLEDs



Source: Yokota T., Zalar P., Kaltenbrunner M., Jinno H., Matsuhisa N., Kitanosako H., et al. (2016), "Ultraflexible organic photonic skin", in *Science Advances*, 2(4), e150185

2.6 OLED manufacturing techniques

There are two main techniques for the manufacture of Organic LEDs. The first is that of thermal evaporation in vacuum, while the second is that of spin coating. There are also other manufacturing methods, used only in special cases.

The construction method of each layer depends on the material used. For the deposition of polymers, for example, it is preferable to use the spin coating technique, while thermal evaporation in vacuum is more used to manufacture SMOLEDs (Small Moleculs OLEDs).

Thermal evaporation in vacuum is a manufacturing process particularly suitable for the creation of layers characterized by low molecular weights, and therefore for the realization of SMOLED.

It involves three stages:

1. Transformation of the material from solid (or fluid) to gaseous. To do this, it is necessary to convert thermal energy into mechanical energy, in

order to allow the molecules and atoms that make up the material to evaporate. One technique adopted is that of heating a resistance. In this way the material evaporates, but in doing so it loses its stoichiometric characteristics (ie it loses its original composition). In order to avoid this inconvenience, a technique called ash evaporation is used, which involves evaporating only a small number of molecules deposited on the heat source. In this way the released vapor continues to possess chemical properties similar to those of the original material;

2. Crossing of the evaporation chamber by the particles, starting from the source to reach the substrate where they can settle. The evaporation chamber is characterized by an extremely rarefied environment (ie devoid of any other atom or molecule that is not part of the material to be evaporated and condensed). A typical pressure value under high vacuum conditions is about $10^{-6} torr$, that is $1.33*10^{-4} Pa$. It has been calculated that at these pressure values a hypothetical particle of the size of 0.4nm on average would not encounter any other particle before 60m. The amount of evaporated material is expressed by Langmuir's Law: the evaporation rate ($kg/m^2 s$) depends directly on the vapor pressure P and inversely on the root of the temperature (Kim & Park, 2021).

3. Deposit of particles on the substrate. A shadow mask placed in front of the substrate is used to fine-tune the positions in which the layer is grown. It is a plate with holes in the points where the layer is to be deposited: only through these holes are the molecules able to pass and therefore deposit. The substrate is covered with a large number of absorption sites for the evaporated particles. Once here, atoms and molecules that still have enough energy can evaporate again or jump to another site. The particles that no longer have sufficient energy, on the other hand, reach the substrate and remain there, stabilizing (nucleation). These zones grow with the subsequent nucleation of further particles, creating small islands of material on the substrate. As the islands grow larger, they merge with each other to create the entire desired layer. The microstructure of the evaporated layer is controlled by factors such as the evaporation rate, the temperature of the

substrate and the chemical and physical nature of the substrate surface (Chao & Lee, 2012).

The great advantage of this manufacturing technique is the possibility of creating multiple layers in the stack, an aspect that concerns OLEDs very closely. Of great importance is also the fact that the thickness of each layer can be controlled with great precision.

Spin coating (Figure 2.15) is a widely used manufacturing technique to deposit certain types of polymers on silicon substrates. There are three main steps in the process.

Figure 2.15 – *Spin coating phases*

Source: Vazquez-Córdova S., Ramos-Ortiz G., Maldonado J.L., Meneses-Nava M.A., Barbosa-García O. (2008), "Simple assembling of organic light-emitting diodes for teaching purposes in undergraduate labs", Revista Mexicana de Física, E54(2):146–152.

A certain flowable polymer solution is deposited on the desired substrate. The second step is to rotate the substrate at low angular speed, in order to distribute the solution over the entire area. When all the substrate has been sprinkled with the solution, the angular velocity is increased in order to disperse the solution and thin the layer of material: the longer the wafer is rotated, the more the thickness of the layer is reduced (it has been

shown that the thickness is inversely proportional to the root of the rotation time).

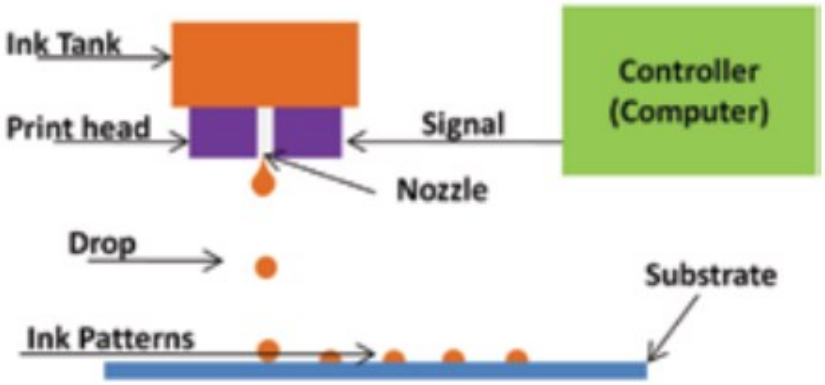
The process is particularly suitable for polymers: these cannot in fact be deposited by evaporation because during the process they can overlap or decompose, creating a layer that does not conform to the desired one. Sometimes it may be necessary to create polymeric layers of materials which, after being solutes, lose some of their properties (for example, they may lose some secondary groups linked to the main backbone of the polymer). For this reason, it is necessary to first deposit a precursor material (soluble) of the desired polymer and, subsequently, to treat this material with different techniques (for example heating at a temperature of 150 ° - 250 ° C) in order to make it the desired polymer (Vazquez-Córdova et al., 2008).

Other manufacturing methods include inkjet printing, particularly valid for the creation of high-definition displays and transparent (TOLED) or flexible (FOLED) displays, and sputtering (also called cathodic pulverization).

Inkjet printing (Figure 2.16) is a technique in which materials, in a liquid phase (solvent), are transferred onto a substrate, via a non-contact process with the application of an external signal to the printhead (Sieradzki et al., 2017). The Ink tank stores the ink that has to be printed. The print head draws ink from the ink tank and ejects droplets upon application of an external signal. The nozzle is a microchannel where a precise amount of ink passes through. The controller modifies the jetting operation. This method lead to several benefits, for instance: fast production, mask free design and minimal waste of material.

A key role is played by the ink, which physical properties (e.g. rheology) must be perfectly controlled in order to avoid impairment that could compromise the entire productive process (such as nozzle plugging or long live ligaments between the printed structures).

Figure 2.16 – Schematic of the inkjet printing process.



Source: Amruth C., et al. (2017), "Inkjet Printing Technique and Its Application in Organic Light Emitting Diodes", *Display and Imaging*, vol. 2, pp. 339–358

Sputtering (also called cathodic pulverization or spraying) is a metal deposition process initially used mainly for flat surfaces, but nowadays also used for simple three-dimensional structures. The process takes place inside a vacuum chamber, where the substrate on which the metal is to be deposited rotates in front of a cathode on which the metal to be deposited is positioned. When the high vacuum condition is reached, argon is introduced into the chamber, while the cathode is subjected to a high voltage. The positive argon ions are accelerated towards the cathode and, once they reach it, allow the metal material to release atoms which are deposited on the rotating substrate.

2.7 Materials

OLEDs are composed of layers of superimposed organic materials, which emit light when an electric current passes through them.

The materials used in an OLED device are susceptible to degradation by oxygen and atmospheric water vapor, therefore their encapsulation is absolutely necessary, i.e. the isolation of the device from the air. And while

the methods of encapsulating OLEDs on glass have now found a standard technology of application, the encapsulation of OLEDs on flexible supports is still looking for effective barrier materials and appropriate production processes (Maglione et al., 2015).

As for the electrodes, the anode is made of an Indium - Tin alloy commonly known as ITO (Indium-Tin-Oxide). The ITO is one of the reasons for the great success of OLEDs: in addition to having relatively low production costs, it has strongly contributed to the entry of OLEDs into the market thanks to the adaptability in terminals that make use of organic LEDs (especially smartphones). The ITO is transparent and highly conductive and, as already seen in the previous chapter, is often in contact with other materials (such as PEDOT, a conductive and transparent polymer) in order to improve the functionality of the final device (Tran et al., 2018).

It has been shown that the increase in oxygen content in ITO is reflected in an increase in labor function $\emptyset_{ITO}$, and therefore in an increase in efficiency (although for this purpose it is preferable to cover the anode with PEDOT). The increase in the work function of the ITO also has positive implications also in terms of brightness. The most common treatment for oxygen enrichment involves exposing the ITO film to ozone produced by a UV lamp. Due to the rapid degradation of the treated ITO, once the procedure has been completed, it is advisable to quickly lay the subsequent organic layers above the anode, otherwise the performance and life of the device will decrease (Tran et al., 2018).

The cathode is responsible for the injection of electrons and, by lowering its work function, an increase in the current injected into the device is observed (although Stossel et al. (2000) have shown that the decrease below a certain threshold (3.6 eV) does not cause significant changes in luminous efficiency). Alkaline materials would be very suitable for this purpose, but their low melting point implies a very difficult manufacturing process (based on the evaporation of the materials just mentioned).

In place of alkaline materials, materials based on calcium, barium or magnesium were then considered, which in turn have a convenient extraction job. These compositions guarantee good compatibility with some of the organic (polymeric) materials which generally constitute the innermost layers (in particular those associated with the emission of electromagnetic waves associated with green and red), but present incompatibility for others.

Because of this, we finally opted for two possible different types of cathodes: those composed of metals, or alloys, and those with a double layer (one layer made of aluminum and one of fluorides).

The most commonly used alloys are essentially two:

- Mg-Ag: it is commonly used when an ETL in Alq_3 is present at the interface. Magnesium guarantees a long life of the device and no light attenuation, while silver (in a ratio of 1 to 10 with magnesium) ensures good adhesion with Alq_3. The cathode must be manufactured under conditions of absolute vacuum: it has been experimentally proven that otherwise the I-V output characteristic of the OLED is no longer similar to that of the diodes.

- Li-Al: The cathode could be composed of only lithium due to its good properties. However, if placed in contact with Alq_3, it is subject to rapid degradation: after a few seconds of operation, in fact, the lithium diffuses into the transport layer, causing a lowering of efficiency. In order to solve this problem, a Lithium-Silver alloy was created. Its manufacture by evaporation is complicated by the difference in vapor pressure between Lithium and Aluminum. However, this problem was solved by using sputtering techniques and the insertion of a thin CuPc film (Suemori et al., 2017).

2.8 OLED displays

OLED displays can be active matrix or passive matrix. A display is composed of a matrix of pixels, that is very small regions of the screen in which there are three OLEDs side by side, each capable of emitting in red, green or blue (RGB) (Wu et al., 2020; Fröbel et al., 2018).

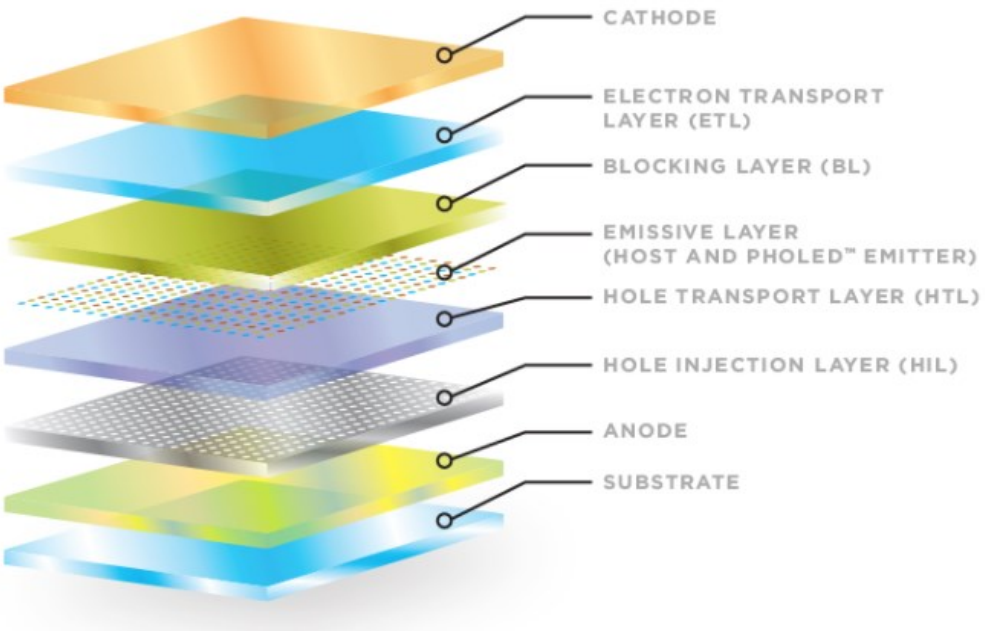
It is clear from the outset that a higher number of pixels in a display ensures better clarity of the image represented. The number of rows and columns of the pixel grid defines the screen resolution.

Resolution alone cannot be an indication of the quality of a screen. A resolution of 1280x720 on a 60-inch screen, for example, will not offer the same quality as on a 4-inch screen: in the first case the pixels should reproduce the image over a much larger area. Here then is defined another parameter characterizing the displays: the pixel density (PPI, ie pixel per inch). As the name suggests, PPIs indicate how many pixels are present within a unit of surface area of a screen, thus acquiring the meaning of density. A high PPI value indicates good screen quality, regardless of screen size.

OLEDs work thanks to the potential difference that is applied to their electrodes. As already mentioned above, they are arranged in a display according to a grid of pixels and are interconnected by means of more or less complex circuits. There are two main LED connection philosophies: the passive matrix and the active matrix. In the case of passive matrix OLEDs (PMOLEDs), the display is made up of layers of different nature shared by all OLEDs.

As shown in Figure 2.17, the innermost layers are the organic ones (the transport and emissive levels and any levels of injection and / or blocking of electrons / holes).

Figure 2.17 – Passive matrix structure



Source: Organic Light Emitting Diodes (OLEDs), Available at: https://oled.com/oleds/

Above the organic layers there are strips of material that form the cathode, while below the organic layers, where the substrate is present, the strips that form the anode are arranged orthogonally to the cathode strips. In the regions where the cathode and anode intersect, the OLED is created, which forms a pixel of the display (to be precise, a sub-pixel, depending on the realization for the color screen).

The external circuitry supplies current to the cathode and anode strips, determining which pixel should light up and which one should stay off. The intensity of the current present at the electrodes instead determines the brightness of the OLEDs.

Passive matrix displays are simple to make, but consume a lot of current due to the absence of storage capacitors that maintain certain voltage values. In a battery-powered device it would therefore not be possible to implement a fairly large or advanced screen, because the energy consumption would be prohibitive. This technology was therefore used in the past in the external screens of clamshell cell phones or MP3 players,

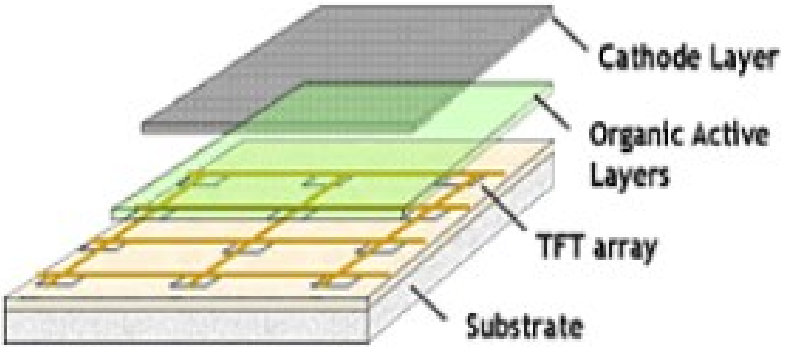
where the display had few colors and did not exceed 3 inches (Bonnassieux, 2021).

Much more advanced screens have been made using instead the active matrix technology (AMOLED). The realization of these displays is much more complex than PMOLED displays, and owes its success to thin film transistors (TFTs), i.e. thin transistors responsible for controlling each pixel, as well as the presence of parasitic capacities capable of maintaining the right voltage levels for driving (Fan, 2020).

TFTs have many advantages, such as excellent uniformity, favorable stability, and low cost, and they have been used as driving devices in AMOLEDs (;a et al., 2019; Lin et al., 2015).

The basic structure, represented in Figure 2.18 is quite simple: the TFTs (which play the role of the anode) rest on the substrate, while the organic layers (and hence the cathode) are positioned above. Each OLED is controlled by TFTs (generally one or more), responsible for charging and discharging a storage capacitor, which in turn is responsible for activating the organic LED.

Figure 2.18 – Active matrix structure



Source: AMOLED (active-matrix organic light-emitting diode), Available HTTP: http://fundunet-technology.blogspot.com/2013/08/amoled-active-matrix-organic-light.html

The active-matrix technology is more expensive than the passive matrix, but allows greater efficiency coupled to a lower supply voltage

(Bagher, 2016). It is much more attractive for displays currently on the market, because it guarantees a high refresh rate (a feature that ensures excellent image and video rendering) and excellent brightness. The light is in fact emitted from the cathode, which must obviously be transparent.

Furthermore, the anode is often made in such a way that it can reflect the light that would normally come out from its side (Oled Top-Emitting technology). This allows a good yield of the light emitted, thanks to the fact that the control circuitry is placed below the emissive layer and therefore does not dampen the light waves (Zissis, 2014).

2.9 Advantages and disadvantages of OLEDs

The main advantages of OLED screens are:

(1) The plastic, organic layers of an OLED are thinner, incomparably lighter and more flexible than the crystalline layers in a LED.
(2) Due to the fact that the light-emitting layers of an OLED are very light and thin, the substrate of an OLED can be flexible instead of rigid, thus allowing to use plastic as OLED substrate rather than the glass used for LEDs.
(3) OLEDs are brighter than LCD/LEDs, due to their intrinsic principle of emits light rather than block/filter it. Because the organic layers of an OLED are much thinner than the corresponding inorganic crystal layers of an LED, the conductive and emissive layers of an OLED can be multi-layered. Furthermore, being OLED substrate plastic base, the substrate itself can be engineered to absorb the light as minimum as possible, instead of using glass with its intrinsic absorption.
(4) OLEDs, being active components that generate by themselves the light to be emitted, do not require backlighting like LCDs, that work by selectively blocking areas of the backlight to make the images that you see. Because OLEDs do not require backlighting,

they consume much less power than LCDs. This is especially important for battery-operated devices such as cell phones.

(5) OLEDs are easier to produce and can be made to larger sizes. Because OLEDs are essentially plastics, they can be made into large, thin sheets. It is much more difficult to grow and lay down so many liquid crystals.

(6) OLEDs have large fields of view, about 170 degrees. Because LCDs work by blocking light, they have an inherent viewing obstacle from certain angles. OLEDs produce their own light, so they have a much wider viewing range (Bagher, 2017).

As for the disadvantages, they include:

(1) Reduced lifespan: usually OLED last 10,000 hours lower than LCD at least.

(2) Large quantity production of large-size screens is not available. It is therefore, only applied to those portable digital products for mass production.

(3) Problems of color purity still remains: it is difficult to display fresh and rich colors.

(4) Water can easily damage OLED.

(5) OLED display suffer to be seen in direct sunlight. Being transparent and light emitting direct sunlight may cover the image coming from the display (this is especially through for the black where a pixel is simply off).

(6) Manufacturing processes are expensive right now (Bagher, 2017).

2.10 LCD and OLED differences and advantages

As we have been able to illustrate up to this point, LCD panels are based on a profoundly different operation than OLED ones.

The layered structure allows LCD panels to be better visible outdoors (in direct sunlight) than OLEDs, although the latter have greatly improved in recent years. LCDs also reproduce colors in a more natural way (while OLEDs tend to saturate them, or to make them appear more "bright" than normal) and cost less as their production has now been widely industrialized.

OLEDs, on the other hand, have a better rendering of black because, when they have to reproduce it, they physically turn off the pixels. This also allows you to have a better contrast than LCDs (the writings can be read more clearly) and above all a lower energy expenditure. With the same uses and technical characteristics, a smartphone with an OLED screen will consume less battery than one with an LCD display. On the other hand, being a relatively new technology, it is more expensive to produce (Bagher, 2016).

Currently, liquid crystals (LCDs) and organic light emitting diodes (OLEDs) are mainly used for near-eye displays (Jang et al., 2019). Among the problems of LCDs, however, there are low response speed, poor conversion efficiency and low color saturation; for this reason the main trend at the moment is to replace them with OLED displays, characterized by advantages such as auto-luminescence, wide viewing angles, high contrast, low power consumption and fast response speeds.

In addition, the excellent flexibility and transparency of OLEDs also offers ample space for emerging electronic products, such as curved displays, smartwatches and foldable displays (Ma & Shao, 2020). However, due to the features of OLED’s materials, imperfections, such as their rapid aging, short life span, and low color purity, have been gradually exposed (Wu et al., 2018).

3 QLED TECHNOLOGY

3.1 Quantum confinement

In 2011 Samsung created a variant of LCD monitor based on quantum dots and called QLED (Quantum Dot LED). The operation differs little from that of a traditional LCD display, with which it shares much of the architecture. The main difference consists in the fact that the QLEDs exploit the quantum dots for the realization of the RGB pattern of the sub-pixels.

QLED screens are similar to OLED screens although they cannot achieve their percentage of black. Quantum dot technology supports large, flexible screens, which should not deteriorate like OLEDs. An initial application of this technology was just to filter the light from the LEDs for the backlighting of LCD screens.

The properties and performance of QLED screens are determined by the size and composition of the quantum dots. Quantum dots, ranging in size from 2 to 10 nanometers, can be both photo-active (photoluminescent) and electro-active (electroluminescent), thus allowing them to be integrated into display architectures. Screens made with Quantum dot technology are distinguished by their high "color volume", i.e. the depth of color as the brightness varies (Moore & Smart, 2020).

To explain the physical principle underlying the operation of a QLED monitor, it is necessary to introduce the concept of quantum confinement, for which it may be useful to remember how, with respect to electrical properties, materials can be classified into:

- Conductive materials;
- Semiconductor materials;
- Insulating materials.

What determines whether a material belongs to one of the three categories is the ability of electrons to move within them. The electrons of an isolated atom occupy atomic orbitals which form a discrete set of energy levels. When a large number of atoms join together to form a solid, the number of such orbitals necessarily becomes extremely large and the difference in energy that separates them is greatly reduced. The conclusion is that, in solids, the energy levels that the electrons are free to occupy form continuous bands.

However, some energy ranges do not contain orbitals, regardless of the number of aggregated atoms. These areas without orbitals form band gaps between the valence band (i.e. the set of energy levels occupied by the ground state electrons) and the conduction band (i.e. the set of empty energy levels at lower energy).

In conductive materials, such as metals, the band gap interval is significantly reduced, and the valence band and the conduction band overlap each other. Therefore, it is sufficient to provide very little energy to stimulate the electrons to pass in the conduction band (for example, it is enough to heat them to conduct electricity efficiently).

In semiconductor materials, however, the band gap increases but not excessively, remaining quite contained. If an electrical voltage is applied that exceeds the energy range of the band gap (generally some electron volts), the electrons can jump from the valence band to the conduction band.

Finally, in insulating materials the band gap is so high that the electrons do not leave the valence band.

If this behavior is general for all materials, something still different happens on the nanometer scale, which is precisely quantum confinement. This behavior is observed when the diameter of a particle is of the same magnitude as the wavelength of the electron's wave function. In other words, a particle behaves as if it were free to move only if the confinement dimension is large compared to the wavelength of the particle itself.

When this happens, the band gap remains at its original energy level, finding itself in the condition described above. However, when the

confinement size decreases and reaches a certain limit, typically on the nanoscale, the energy spectrum becomes discrete and the overlapping of the bands disappears. The main consequence is that the range covered by the band gap increases, explaining why some metals become semiconductors as their size decreases .

3.2 Quantum dots and how a QLED monitor works

QD-LED-based display technology is the ultimate choice for future generation displays because of their compelling potential advantages in terms of efficiency, power utilization, contrast ratio, lifetime, and response time (Huang et al., 2020).

Their origin can be traced back to the 1970s, when, precisely in 1972, Charles Hanry designed a heterostructure (in which layers of very thin materials with different electrical properties alternate) consisting of a semiconductor material placed between two layers of another semiconductor material but with a larger band gap. In this way the charge carriers, confined to a planar region, were no longer free to move in three dimensions with the consequent formation of a two-dimensional electronic gas. These structures were called quantum wells).

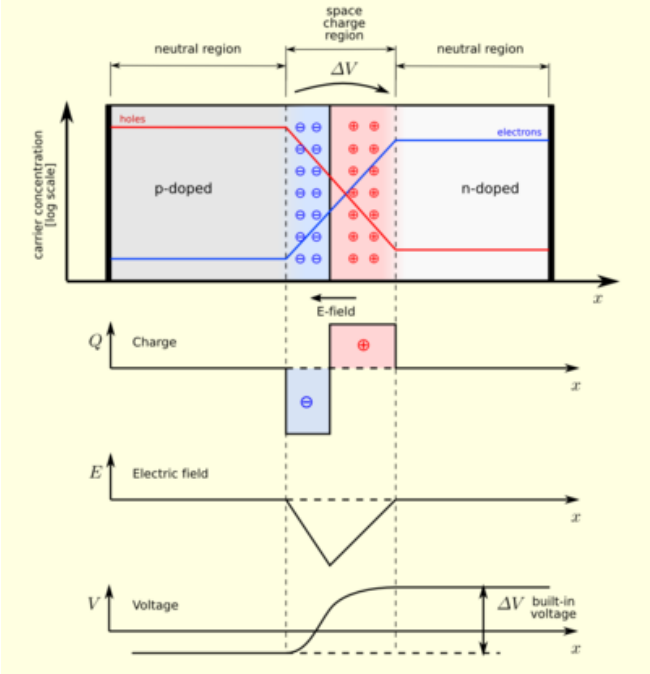
In the quantum well, if the core layer is thin enough, the energy levels are not continuous as in a bulk (massive material), but they become discrete. For example, quantum wells can be created by inserting a layer of GaAs (GaAs: gallium arsenide, semiconductor inorganic material composed of the combination of chemical elements arsenic and gallium) in a bulk of AlGaAs (AlGaAs, gallium arsenide and aluminum, semiconductor material with a large band-gap).

In 1974, Dingle experimentally confirmed what Hanry had predicted by directly observing the absorption spectrum of a quantum well. The absorption spectrum is the spectrum produced by the absorption of electromagnetic radiation of certain frequencies by a substance; to measure

it, an instrument called a spectrophotometer is used which produces a graph of the intensity of the radiation absorbed as a function of the wavelength. The emission spectrum, on the other hand, measures the radiation emitted by a body.

The following year Dingle and Hanry patented the laser diode, in which the active medium is a semiconductor material. When the *pn* junction is directly polarized, the holes in the p region (here the holes are the majority charges) are injected into the n region (where the electrons are the majority charges); similarly, electrons are injected into the p region. It is possible that the electron goes to reoccupy the place occupied by the hole; in this case we speak of spontaneous recombination and every time it happens, a photon is emitted. The energy of the photon in question is equal to the difference between the energy levels of the hole and the electron involved (Figure 3.1).

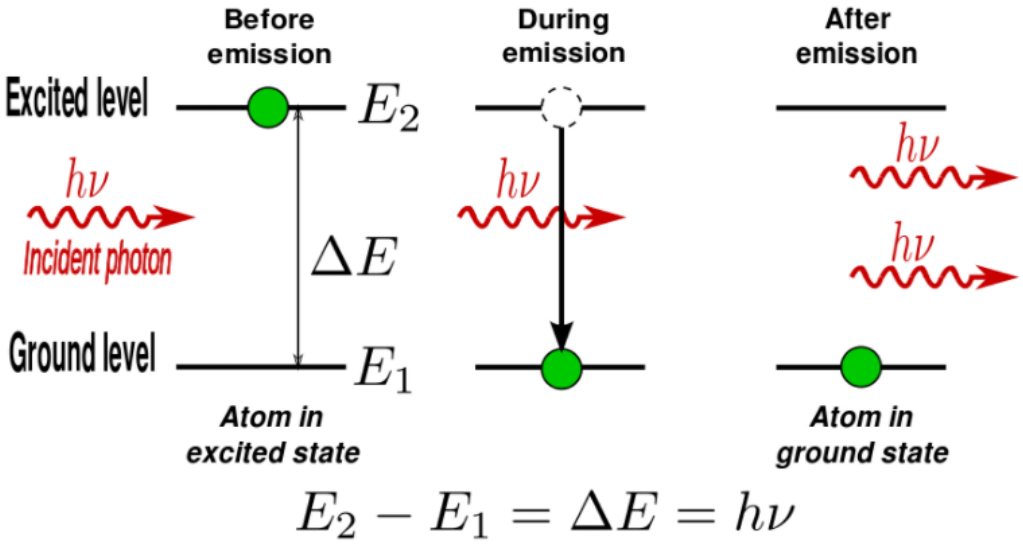
Figure 3.1 – P-N junction in thermal equilibrium with zero-bias voltage applied. Under the junction, plots for the charge density, the electric field, and the voltage are reported.



Source: "p-n junction", https://en.wikipedia.org/wiki/P%E2%80%93n_junction

Spontaneous emission is necessary in the initial phase of laser operation. We speak of stimulated emission (Figure 3.2) when a photon, with a certain direction passes close to an electron that is in a high-energy state, stimulates the recombination of this with a hole, with the consequent emission of a photon with frequency, phase and directions equal. At the end of the process there will be two photons with the same frequency, phase and direction.

Figure 3.2 - Schematisation of the spontaneous emission phenomenon



Source: “Stimulated emission”, https://en.wikipedia.org/wiki/Stimulated_emission

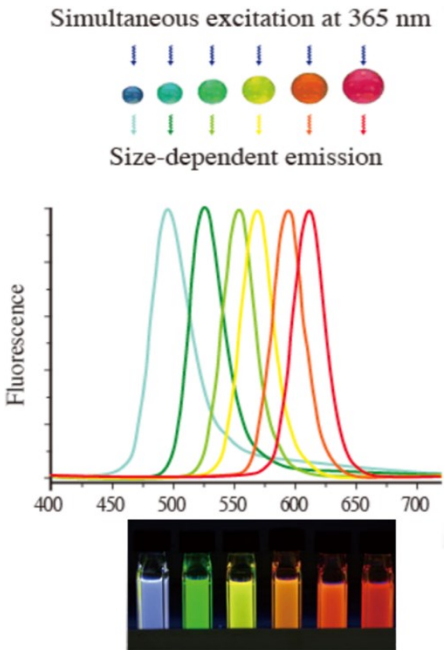
By the late 1980s, most of the knowledge on heterostructures and quantum wells was well established and studies began to move towards smaller structures: quantum wires and quantum dots. The complete reduction of the two "infinite" dimensions of quantum wells to atomic values allowed to confine the excitons (a quasi-particle describing the excited state of a solid; in a semiconductor it can be seen as a bound state of electron and hole interacting through the Coulomb force) in all three dimensions; this fact has altered the classic model of allowed energy states which are no longer continuous but discrete.

In a bulk semiconductor the conduction and valence bands are separated by a certain “energy gap” and the density of the electronic states

in the valence (and conduction) band is continuous; a quantum dot on the other hand is characterized by discrete states such as those of an atom, with energies that depend on the edge of the quantum dot.

Quantum dots are crystals about 10 nanometers in diameter, made from a semiconductor material, in most cases cadmium selenide. Their size is so small that they are able to influence the quantum properties of their electrons, in particular their energy gap (i.e., the energy needed to push electrons into a higher energy band) on which the color of the electrons depends on the light that the material can emit. Because a bulk semiconductor is limited to emitting a single color of light, researchers can adjust the precise color that a quantum dot can take on and re-emit by adjusting its size.

Figure 3.3 – Quantum dot spectral characteristics



Source: Jian Chen, Nanosys, Inc (2012), "Quantum Dots, The Future of LED Display Technology" IEEE Santa Clara Valley Consumer Electronics Society

Although the discovery of quantum dots dates back to 1981, their technological application only began in 2002, when the Quantum Dot Corporation of Hayward, California, began selling them to cell biologists, who rewarded them as fluorescent labels for proteins and other biological molecules (Bourzac, 2013).

Quantum dots are characterized by unique electronic and optical properties that are different from those of the bulk semiconductor materials. QDs have discrete electronic states, like those of natural atoms, and their electronic wave function is somewhat analogous to that of a real atom. This is why they are frequently referred to as artificial atoms (Ashoori, 1996; Banin et al., 1996; Kastner, 2000).

Due to such peculiar properties, quantum dots are being used in numerous modern-day technologies such as solar cells (Han et al., 2014; Hsu et al., 2018), photodetectors (Konstantatos & Sargent, 2009), photodiodes (Pal et al., 2012), field-effect transistors (Koh et al., 2011), biological systems (Marchuk et al., 2012), and light-emitting diodes (Chen et al., 2015; Lin et al., 2015; Liu et al., 2017).

For display technology purpose quantum dots find their best suitable scope as color down-converters for light-emitting diodes (LEDs): such application grant to have an efficient illumination source together with high-quality displays. Both electrically and optically pumped quantum dots are used with LEDs (Shirasaki et al., 2013).

In addition to the transfer of radiative energy from the LEDs to the quantum dots, another mechanism involves the transfer of energy by Forster resonance (FRET), on which the transfer of non-radiative energy from the LEDs to the quantum dots depends. FRET, also known as non-radiative resonant energy transfer (NRET) is strong enough to be observed when the quantum emissive wells of the LED are in close contact with the QD phosphor layer.

Researchers used innovative ideas to build better performing QD-LEDs. The availability of multiple material choices for QDs indicates their variability between different reports. QD electroluminescence (EL) based

displays have higher capacity than QD photoluminescence PL or liquid crystal-based OLED technologies to provide the best solution of wide gamut and pure black color.

The QD EL display ("QD-LED display" and also called "QLED" or "EL-QLED" display) has electrons and holes pumped into QDs where they recombine to directly produce photons for the main red, green, or blue (Smeeton et al., 2019).

In QD LED-based lighting sources and display devices, energy is transferred from the active LED to the quantum dots via radiative energy transfer and NRET.

In the direct transfer of radiative energy, there must be correspondence between the absorption spectrum of the acceptors, i.e. the quantum dots, and the emission spectrum of the donors, i.e. the active LED, unlike what happens in the NRET, where donors and acceptors must be in close contact (Zhang et al., 2012).

These two energy transfer mechanisms can generate electron-hole pairs in quantum dots thus resulting in radiation. An efficient QD-LED device must be designed so that both of these mechanisms can contribute to the energy transfer process with minimal losses. Quantum dots that absorb ultraviolet (UV) / blue wavelengths and emit blue, green and red colors are used with a UV, or blue LED for making QD LEDs.

Recently, QD-LED TV screens with edge-lit lenses have promoted the first solution to quantum dots in consumer displays. They use a quantum dot dispersion in a polymer embedded in a glass tube positioned at the edge of a screen, above an LED strip. One major drawback of this technique, however, is the decrease in temperature output. It proved difficult for early QDs who suffered from thermal runaway problems; including a very heavy hermetic tube to ensure continued reliability of operation.

The current technology of choice for QD-LCD televisions involves inserting quantum dot films into displays. In this case the process proceeds with the superposition of quantum dots to a blue LED backlight, incorporating everything in an LCD matrices, with an improvement in

chromatic performance. Being higher performing with luminous efficiency and wide range, CdSe based quantum dots are commonly used in recent years., QDs made of InP or perovskite were investigated and are currently exploited as alternative base device due to the fact that CdSe compounds are quite toxic and dangerous for environment and people.

The latest industry standard solution for producing QD on screens is cadmium-free film, although there is still consensus that next generation color filters QD (QDCF) are still an imminent stop on the research journey and QD development.

Among the various types of QDs, such as CdSe and InP, perovskite quantum dots (PQDs) exhibit several notable optical characteristics, such as a high photoluminescence quantum yield, tunable emission wavelength, high color purity (Leng et al., 2018; Li et al., 2016; Nedelcu et al., 2015; Sun et al., 2016).

Thus, PQDs have been under study in recent decades for their quantum confinement effect and resistance to various defects. Several synthetic routes have been attempted to find a method capable of reliably producing stable and defect-resistant perovskite quantum dots.

There are two main ways of synthesis, namely:

1. room temperature synthesis, which involves mixing cesium halide (CsX) and lead halide (CsX2) in a good solvent such as dimethyl sulfoxide (DMSO) or N, N-dimethylformamide (DMF) followed by the addition of hood ligands such as oleic acid and oleylamine with vigorous stirring. The mixture is then added to a vigorously stirred flask containing a poorer solvent such as toluene, so that the perovskite quantum dots begin to precipitate and can be further separated by centrifugation;

2. "hot-injection", a method involving the preparation of cesium oleate in 1-octadecene (ODE) under argon at 150° C by stirring cesium carbonate and oleic acid. Lead halide is separately dried in ODE by heating under vacuum and capping ligands including oleic acid and oleylamine under argon are added to dissolve it completely. Then the cesium oleate

solution is stirred for 5-10 seconds at 150 ° C before it is precipitated, which is further separated by centrifugation.

Compared to quantum dots that depend on CdSe and InP, PQDs have several advantages, such as tunability of emission wavelengths from blue to red, narrow full width to half the maximum (FWHM), easy fabrication, etc. (Swarnkar et al., 2015).

However, the PQD has a number of problems in terms of presentation as a color converter for display applications. Environmental factors such as heat, humidity, high-energy radiation can easily compromise the optical properties of PQDs, altering their surface properties and long-term stability (Sinatra et al., 2019).

Furthermore, in order to evaluate the stability of quantum dots, it is also important to consider how they are configured, as the composition and interaction between the atoms determine the properties and stability of the QD optical (Sinatra et al., 2019).

Furthermore, as reported in the literature, inorganic PQDs show superior properties for optical visualization compared to other types of PQD in terms of low PL quenching and PL peak shifting at high temperature (Sinatra et al., 2018, 2019).

Although the optical properties of PQDs are excellent, their visualization applications are limited to green emitting CsPbBr3 PQDs. Furthermore, they are not suitable for display applications as they do not withstand the highest temperatures, showing stability problems in these cases.

In the literature, surface and mass defects that can induce surface traps and ionic migration respectively are reported as causes of this problem (Azpiroz et al., 2015; Koscher et al., 2017).

Therefore, these problems need to be overcome so that PQDs can be successfully introduced for visualization applications without stability issues.

Among the various approaches proposed to solve these stability problems, those of Sinatra et al. (2018, 2019) are considered.

The first approach focuses in particular on halide vacancies, improving the synthesis condition by inserting additional halides into the system (Wu et al., 2019).

The second approach involves treating PQDs with strong ligands. In most PQDs, oleic acid and oleylamine act as ligands for the synthesis of PQDs and are likely to detach from the surface because the bond with the surface at higher temperatures is weak, which causes surface defects.

In the third approach, protection is applied to the PQDs in a post-treatment method by providing precursors of thin inorganic oxide. Other similar methods, aimed at improving the stability of PQDs, are compositional engineering, surface engineering, matrix encapsulation and device encapsulation (Wei et al., 2019).

The instability could also be caused by the movement of protons between oleic acid (OA) and oleylamine (OLA), which results in a significant loss of ligands. Addressing this problem, Li et al. (2016) reported improved stability by suppressing inter-ligand proton transfer and applying a polystyrene coating, in which oleylamine (OLA) has been replaced with cetyltrimethylammonium bromide, which cannot be protonated; thus, the transfer of protons between the ligands was suppressed with improved stability in the PQDs.

Additionally, to improve humidity and thermal stability, PQDs can be further compounded with carboxy-functionalized polystyrene (cPS) via chemical interactions.

Furthermore, Lv et al. (2019) proposed several encapsulation techniques (e.g., the sol-gel method, the model-assisted method, the physical method and the microencapsulation method) to improve the stability of metal halide PQDs by inhibiting light-induced decomposition, and focusing on improving chemical and thermal stability (Lv et al., 2019).

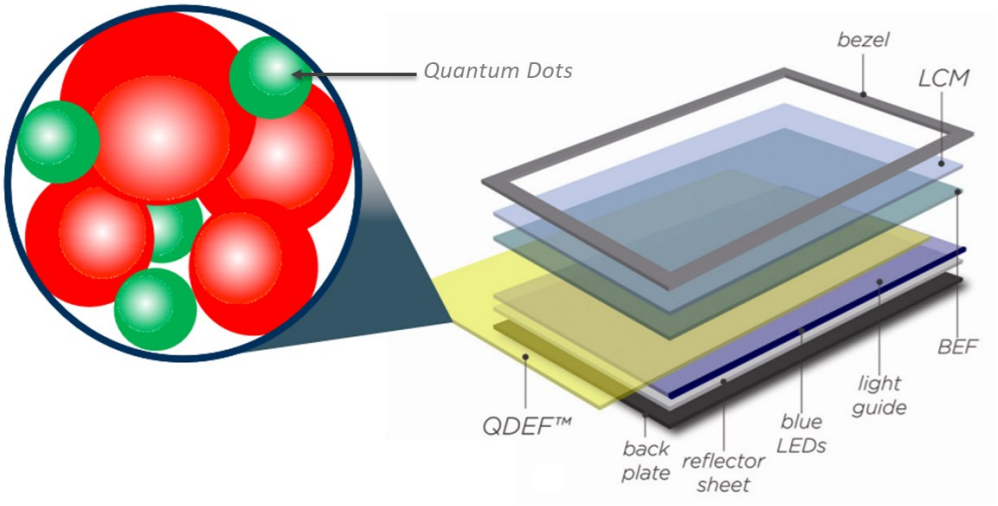
However, further performance improvement of these encapsulated PQDs is still needed to meet the growing demand for various practical applications (Huang et al., 2020).

As far as the structure of a QLED is concerned (Figure 3.4), it is not so different from the OLED technology discussed in previous chapter; however, in the case of QLED screens, the light emitting centers are, as said, cadmium selenide (CdSe) nanocrystals, or quantum dots.

As already anticipated, a layer of cadmium-selenium quantum dots is sandwiched between layers of organic materials that carry electrons and holes. An applied electric field allows the displacement of electrons and holes in the quantum dot layer; here the quantum dot captures and recombines them, emitting photons, whose emission spectrum is narrow, and characterized by its full width at half the maximum value.

QD-LEDs can be fabricated using two main techniques, namely phase separation and contact printing. QLEDs are a reliable, energy efficient and color tunable solution for display and lighting applications that reduce manufacturing costs, using ultra-thin, transparent or flexible materials (Bagher, 2017).

Figure 3.4 – *Quantum dot display structure*



Source: Bagher A.M. (2017), "Quantum Dot Display Technology and Comparison with OLED Display Technology", *International Journal of Advanced Research in Physical Science (IJARPS)*, 4(1): 48-53

Quantum dot screens are quite different in that the technology is based on small conductive nanocrystals, usually in the range of 2 to 10

nanometers in diameter. The color of the light produced or filtered by a point is based on its diameter and using some of these could produce all the colors needed. As with OLED screens, light and colors can be supplied on request and the QD-LEDs can be very bright. However, current quantum dot screens rely on a blue LED backlight which is then converted into a white light before passing through the familiar LCD color production layer.

One of the main advantages of OLEDs over LCDs is that they allow for a wider range of colors, and therefore a sharper viewing experience given the more accurate color reproduction. Conversely, LCD screens, which depend on a pseudo-white backlight, consisting of blue LEDs with a yellow phosphor coating, do not return the same color and gamma accuracy in most cases.

However, the highly accurate nature of Quantum Dots means that developers can use a pure blue backlight, and the presence of accurate red and green filters allow for the return of true white light, filterable into sharper colors (Bagher, 2017).

In screens based on quantum dot technology, however, the inaccuracies of white light lose importance, and require less compensation than the LCD filter layer, with a consequent increase in color brightness and gamma. These factors make screen QDs equal, if not in any case even superior to OLEDs, in terms of color accuracy (Derlofske et al., 2013).

However, since quantum dots are dependent on backlighting, deep black accuracy and contrast ratio exhibit a range of issues similar to LCD screens, which helps make OLED screens more suitable when it comes to contrast and contrast images. high contrast, dynamic range (Bagher, 2017).

Another benefit that QLED screens share with LCDs is the reduction in manufacturing costs. The presence of a quantum dot filter layer does not represent a significant cost or complexity to produce a screen, as it is just a mixed assortment of red and green dots and an intricate matrix.

However, reduced production costs do not always correspond to equally competitive sales costs, and it is this factor that still makes LCDs

the main choice on the market today. (Jang et al., 2010; Coe-Sullivan et al., 2013).

Quantum dots can be created using four methods: ion implantation, epitaxy growth, colloidal synthesis, molecular seeding. The first system requires the use of advanced lithographic techniques, an evolution of those used for the construction of electronic chips.

Epitaxy is based on the growth of nanocrystals through the deposition of thin layers on a support (also crystalline) which acts as a base. Both methods are slow and expensive, suitable for creating laboratory samples, not for mass production.

The third system, colloidal synthesis, is purely chemical and allows the growth of quantum dots in a colloidal solution kept at a temperature just below 350 ° C. The size of the nanocrystals can be precisely adjusted by varying the synthesis conditions, i.e. the concentration of the reagents, the temperature and the reaction time. This method is easily scalable, relatively fast and inexpensive, allows the production of many kilograms of nanocrystals per reaction cycle and therefore lends itself well to the needs of a world-class market.

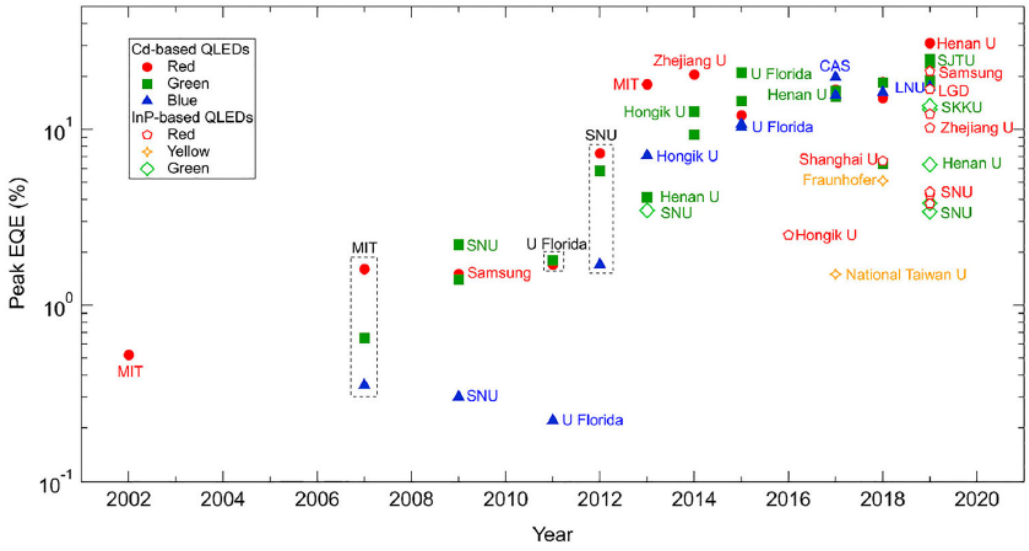
A continuous flow variant of the colloidal synthesis has also been developed, which allows to further increase the amount of nanocrystals produced and which, moreover, allows for the elimination of quantum dot size variations between one cycle and another.

The fourth system, molecular seeding, is also well suited for mass production. It is based on a crystalline growth process that does not require high temperatures and is particularly suitable for indium-based quantum dots, which are much less polluting than those with cadmium. The growth of quantum dots is regulated by periodically adding reagents at a moderate temperature, until the desired size is reached (Martello, 2015).

3.3 QLED: recent developments

In the last decade, the attention of researchers has focused in particular on the synthesis of QDs of colloidal nanocrystals (QDs) and their application to QLEDs, by virtue of the unique optical and electrical properties that such QDs exhibit. The quantum photoluminescence yield (PLQY) of QDs has approached unity thanks to advances in synthesis methods, resulting in an overall improvement in performance, as reported in Figure 3.5.

Figure 3.5 – EQEs of the Cd- and InP-based QLEDs



Source: Jang H.J., Lee J.Y., Kim J., Kwak J., Park J.H. (2020), "Progress of display performances: AR, VR, QLED, and OLED", *Journal of Information Display*, vol. 21(1), pp. 1-10.

Cd-based QLEDs

The main advantages of CD-based QDs (cadmium-based quantum dots) are narrow emission (FWHM <30 nm) and high stability, thanks to which it is possible to increase external quantum efficiency (EQE) of this type of screen. Recently, an EQE> 30% has been reported through control of shell growth and modification of the surface ligands of red-emitting Cd-based QDs. As shown in Figure 3.4 and Table 3.1, the maximum EQEs of

QLEDs emitting red, green and blue reached 30.9, 25.04, and 19.5%, respectively (Song et al., 2019; Yang et al., 2019; Wang et al., 2017).

Table 3.1 – Device performances of Cd-based QLEDs

	QD structure	Peak wavelength (nm)	FWHM (nm)	Max. luminance (cd/m^2)	Max. EQE (%)	Max. CE (cd/A)
Red	CdSe/CdS	640	28	42,000	20.5	–
	CdSe/CdZnSe/ZnSe	631	21	30,000[a]	15.1	15.9
	CdZnSe/ZnS	624	25	54,669	18.5	31.36
	ZnCdSe/ZnSe/ZnS	602	27	334,000	30.9	72.0
Green	CdSe/ZnS	515	38	218,800	5.8	19.2
	CdSe/ZnS	526	27	90,000[a]	21	82.0
	ZnCdSe/ZnS	532	20	78,000	16.5	70.1
	CdSe/ZnS/ZnS	515	26	460,000	6.4	–
	CdSe/ZnS/ZnS	522	19	106,400	24.8	98.2
	CdSe/ZnS/ZnS/ZnS	524	21	70,650	25.04	96.42
	CdZnSeS/ZnS	538[a]	20[a]	1,680,000	16.6	75.3
Blue	ZnCdS/ZnS	443	21.5	7600	10.3	1.9
	CdSe/ZnS	468	20	4890	19.8	14.1
	ZnCdSe/ZnS/ZnS	479	34	14,100	16.2	11.8
	CdZnS/ZnS	452	24	7993	17.4	2.0[a]

Source: Jang H.J., Lee J.Y., Kim J., Kwak J., Park J.H. (2020), "Progress of display performances: AR, VR, QLED, and OLED", *Journal of Information Display*, vol. 21(1), pp. 1-10.

From the viewpoint of brightness, a QLED which exhibits an extremely high value of >1,600,000 cd/m2 was achieved by improving the heat dissipation through the use of sapphire as a substrate as sapphire has higher thermal conductivity than the glass substrate (Sun et al., 2019).

InP-based QLEDs

Since cadmium is highly toxic, researchers are investigating colloidal QDs devoid of this element, and the most studied element for red and green emitters is indium phosphide (InP), with all its derivates and compounds. Such solution showed during rigorous tests a way lower cytotoxicity compared to the Cd-based quantum dots (Tarantini et al. 2019).

The performance of InP-based QLEDs has reported also significant improvements in recent times. As of November 2019, an EQE> 20% was reported for red-emitting InP-based QLEDs by removing the defective oxide layer on the surface of the InP core and engineering the shell thickness and ligand length (Won et al., 2019).

High brightness of ~ 100,000 cd / m2 and longer operating life was also reported. Bright and efficient green emission InP QLEDs with narrow spectral bandwidths (FWHM <40 nm) have also been reported by introducing an intermediate layer suppressing holes with a superior emission structure (Lee et al., 2019), and by adopting the composition-tailored ZnMgO nanoparticles as the ETL (Moon et al., 2019).

The device performances of the selected InP-based QLEDs are summarized in Table 3.2.

Table 3.2 - Device performances of InP-based QLEDs

	QD structure	Peak wavelength (nm)	FWHM (nm)	Max. luminance (cd/m^2)	Max. EQE (%)	Max. CE (cd/A)
Red	Inp/ZnSeS/ZnS	619	63	2849	2.5	4.2
	InP/ZnSe/ZnS	607	48	1600	6.6	13.6
	InP/ZnSeS	623	38	27,800	4.4	8.5
	InP/ZnSe/ZnS	618	42	10,000	12.2	14.7
	InP/ZnSe/ZnS	630	35	100,000	21.4	–
Yellow	InP/ZnSeS/ZnS	545	56[a]	10,490	1.5[a]	4.44
	InP/ZnSe/ZnS	565	65	1900	5.1	18.0
Green	InP/ZnSeS	518	64	3900	3.46	10.9
	InP/GaP/ZnS//ZnS	527	58	2938	6.3	13.7
	InP/ZnSeS	539	37	17,400	3.4	21.6
	–	531	34	13,900	13.6	–

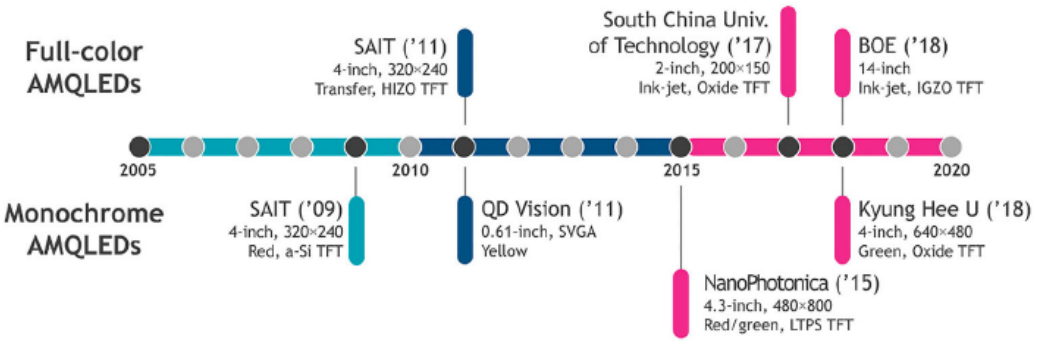
Source: Jang H.J., Lee J.Y., Kim J., Kwak J., Park J.H. (2020), "Progress of display performances: AR, VR, QLED, and OLED", *Journal of Information Display*, vol. 21(1), pp. 1-10.

Active-matrix QLED displays

The implementation of active-matrix QLEDs (AMQLEDs – Figure 3.6) is highly meaningful for the realization of QLED displays (Cho et al., 2009; Coe-Sullivan et al., 2011;; Yang et al., 2015; Kim et al., 2018).

In the case of monochromatic AMQLEDs, the QD layer can be formed through spin-coating, while for the full-color AMQLEDs, the main technologies are QD patterning methods, such as pick-and-place transfer and inkjet printing (Kim et al., 2011; Jiang et al., 2017; Li et al., 2018).

Figure 3.6 - Demonstration of monochromatic and full-color AMQLEDs



Source: Jang H.J., Lee J.Y., Kim J., Kwak J., Park J.H. (2020), "Progress of display performances: AR, VR, QLED, and OLED", *Journal of Information Display*, vol. 21(1), pp. 1-10.

The size of the display screen, with the evolution of the technology, has also progressively improved: a well-known display company showed its 14-inch full-color AMQLED display driven by indium gallium zinc oxide (IGZO) thin-film transistors (TFTs) in 2018. Only Cd-based QDs have been used to date, but the InP-based AMQLEDs are expected to be demonstrated in near future (Jang et al., 2020).

3.4 Advantages and disadvantages of QLEDs

In order to fully understand the advantages that can be obtained with quantum dots, it is necessary to know the technical solutions implemented today to illuminate LCD panels. Almost all the displays around us adopt white LEDs arranged along the two major sides of the screen, a configuration known as led edge.

The problem is that white LEDs are actually blue LEDs covered with phosphors that emit in yellow, so that the blue and yellow light appears white to our eyes. This light, however, is poorly suited to pass through the RGB filters placed in front of the subpixels of the LCD display. The blue

component has no problems, but the yellow part must become green and red, a transformation that involves a huge waste of photons, since only a small part of these (about 10%) can pass the green and red filters.

The process is inherently very inefficient, and the lower energy consumption of led edge compared to old fluorescent lamps (which emitted light with a much more regular and richer spectrum in the green and red sections) is due solely to the high energy efficiency of the led. To overcome the problems of the led edge, manufacturers sometimes resort to the full RGB configuration, in which the white LEDs give way to red, green and blue LEDs. Although the colour rendering is excellent, this solution is very expensive and therefore reserved for a few professional monitors that must ensure a very wide gamut. In other words the LED edge is not only energy inefficient but also makes it very difficult to obtain a gamut that meets the current colour standards. In practice, displays with white LEDs can barely cover the sRgb colour space, while to meet the more extensive Adobe Rgb and Dci it is necessary to greatly increase the light emitted by the LEDs, then increase the number of light emitting diodes and consume more current.

The quantum dots replace the yellow phosphors that cover the blue LEDs and convert into green and red part of the light emitted by these light-emitting diodes, with a very high efficiency and precision. The achievable advantages are both energetic and chromatic. Since the white light produced has three well-defined peaks centred on the wavelengths of the Rgb chromatic filters, most of the photons can pass, so it is possible to use less powerful LEDs and reduce power consumption.

With regard to the gamut, designers can precisely adjust the wavelengths of the photons emitted by the quantum dots, so as to obtain very pure primary colours corresponding to the specifications required by the standards. Thanks to nanocrystals, it is therefore possible to expand the gamut to cover 100% not only the sRgb colour space but also the Adobe Rgb and Dci colour space, up to about 95% of Rec 2020, which requires monochromatic primaries (Martello, 2015).

The main disadvantages of QLED are mostly inherited from the general LCD technology:

(1) QLEDs do not produce light by themselves but use backlight unit for illumination. The use of backlighting prevents deep blacks and washes out darker tones of colors

(2) QLED screens suffer from "light bleed" effect which is visible in certain scenes, thus resulting into slight haze around bright objects which blurs lines which should be usually sharp.

(3) With QLED based display screens, best viewing angle is dead center. Poor picture quality in both color and contrast when viewer moves side to side or between up and down.

(4) Less saturated blue. Furthermore, blue quantum dots require highly precise timing control during the reaction because of their small size (Bagher, 2017).

Conclusions

As illustrated in this paper, LCD screens dominate the market of electronic products with displays (TV, monitor, tablet, smartphone) but have limits that have dragged on since their inception: high black level, low contrast, color rendering. not optimal. For the first two there is still nothing to do today, while it is possible to significantly improve the chromatic response thanks to the quantum dots, nanocrystals inserted in the backlighting system of the LCDs, which not only allow to obtain more saturated and beautiful colors but also to reduce the energy needed to operate the display, a very important plus for portable devices.

This improvement will be evident even in the eyes of the most distracted user, unlike what is happening with the Ultra HD TV screens, presented to the public as an important step forward in display technology but which failed to trigger the replacement of the TVs. hoped by the producers, both for the lack of Ultra HD content and for the objective inability to appreciate a visual improvement when looking at a small Ultra HD screen, perhaps even from an excessive distance.

Quantum dot displays (which always remain LCD displays since the liquid crystal screen does not change in any way) and more generally all liquid crystal displays that use nanocrystals in the lighting system represent an important renewal of LCD technology, that in the near future will have to fight the advance of the OLED, the visualization system that promises to worthily replace the now defunct plasma.

Quantum dots are nanocrystals made of semiconductor materials, ranging in size from 1.5 to 6 nanometers, equivalent to about 10 - 30 atoms. The electronic properties of these crystals are a cross between the classic ones of semiconductors and those of single molecules and can be interpreted thanks to quantum mechanics. The main feature of quantum dots is that they emit light when they are hit by photons or electrons, light centered on a wavelength that is directly proportional to the size of the quantum dots themselves. By varying the size of a few nanometers, it is therefore possible

to obtain the generation of light with a color ranging from blue to red. Practically, by replacing the white LEDs, used in the backlight modules of today's LCD displays, with blue LEDs that illuminate quantum dots of adequate size, it is possible to obtain a white light composed of the three very pure RGB components (the blue generated by the LEDs, the green and red from converted by quantum dots), ideal for making LCDs work at their best.

This technology is destined to revolutionize and give new life to the LCD for the next few years with its widespread diffusion in all sectors in which LCD screens are used, not only TVs and computer monitors but even tablets and smartphones. The forecasts for the industrial sector dedicated to the production of quantum dots are rosy from the very beginning: already in 2013, when mass production began, worldwide revenues were over 120 million dollars, with a forecast for 2016 of 1, 1 billion, a figure that was expected to rise to 3.1 billion in 2018, with an estimated year-on-year growth of around 90%.

In the comparison between OLED and QLED, it was highlighted how the displays with QLED technology have a structure similar to that of an OLED, with the quantum dots divided into cells (one for each RGB color) and enclosed between two conductive layers, which carry the electric charges. The electrons and holes recombine within the nanocrystals, forming excitons which in turn cause the emission of photons with wavelengths proportional to the size of the quantum dots.

The architecture described closely resembles that of the new OLED TVs and in fact follows most of its features: absolute black because the subpixels can be turned off completely, practically infinite contrast, high brightness, no trail or drag, very low power consumption, extremely thin and possibly also flexible screen.

Compared to OLEDs, QDleds are better performing in terms of color purity, given that the dispersion of the wavelengths of the three RGB primaries is very low, furthermore the quantum dots are more efficient and

therefore consume less despite having a higher brightness. It is no coincidence that currently the QDleds can cover 95% of the Rec 2020 color space, while the OLEDs stop (at least for now) at 80%.

Of course, QDleds also have a number of disadvantages, the first of which concerns the higher costs, although it can be expected that in the future, with mass production, the price will decrease. Another difficulty concerns the creation of quantum dots that emit blue light that require very small dimensions, about 1.5 nm, at the limit of current production technologies. Furthermore, the useful life is limited to a few thousand hours, due to the high temperature to which they are subjected during operation. Finally, they are subject to a reduction in the current-to-light conversion efficiency due to eddy currents.

It's worth to take in consideration one additional point regarding the environmental and safety problems related to the QDleds: current best performers in terms of efficiency and color response are the nanocrystal based on CdSe. Such compound is heavily detrimental for environment and people. Research is going forward to find efficient substitutes with way less HSE side effects: InP based quantum dots represents a promising solution for the future but overall performances, apart from the peak of EQE, need to improve to pair with Cd-based QDleds.

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A conclusione del mio percorso universitario, vorrei ringraziare il mio Relatore, Professor Maurizio Martina, per la grande disponibilità e la possibilità di concludere questo lungo percorso. Grazie a lui sono riuscito a realizzare il mio desiderio di laurearmi e per questo gliene sarò sempre riconoscente.
Ringrazio la mia famiglia che mi ha fatto iniziare questo percorso e con cui posso celebrare questa giornata.
E non potrò mai ringraziare abbastanza Carmen che mi è stata vicino durante il lavoro di stesura e che non capirà mai la dedica iniziale.