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# Organic Light Emitting Diodes operation and application in displays

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**ABSTRACT**

**Purpose:** The aim of this work is to perform the review of the recent most important results of experimental and theoretical investigations connected with the organic light emitting devices (OLEDs).

**Design/methodology/approach:** The recent achievements in the field of designing, fabricating and clarification of the OLEDs operation have been presented. The possibilities of numerous, present and future applications of these devices have been pointed out.

**Findings:** We show that fundamental differences among organic and inorganic devices result from differences between inorganic and molecular semiconductor materials. No charges are present in OLED devices without charge injection. Emission is due to radiative transitions from the neutral excited states to the ground states. We pointed out the important role that the OLEDs play in display design (even the flexible ones).

**Research limitations/implications:** The main disadvantage of OLEDs is reported to be short their lives (particularly the blue OLED) and weak resistivity to moist but improvements are advancing.

**Originality/value:** Our review concerns the most recent experimental and theoretical publications in the OLED investigation. We also show some recent examples of OLEDs application.

**Keywords:** LED, OLED; Displays; Organic materials; Optoelectronics

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**RESEARCH PAPER**

## 1. Introduction

Organic materials are of great interest for electronics applications, as they have many advantages over their inorganic counterparts**.** They may often be solution-processed, allowing the fabrication of devices such as circuits**,** displays**,** and radio-frequency identification devices on plastic substrates, and deposition by unconventional means, such as screen and inkjet printing**.** The most attractive prospect, however, is the incorporation of functionality by design. The versatility of organic synthetic techniques and the wide spectrum of commercially available building blocks allow seemingly infinite flexibility in tuning molecular structure, and therefore the corresponding molecular packing and macroscopic properties. Already, organic solids such as pentacene and rubrene have surpassed amorphous Si in performance, of thin film transistors (TFT) and light emitting devices creating organic light emitting diodes (OLEDs) which are used by the former. An OLED is a thin-film solid state device, which makes it easier to apply to flexible displays because of its relatively simple fabrication process and reduced distortion according to the geometric form of display.

Table 1.
History of investigations in the field of electroluminescence organic materials

| Year | Authors & references | Materials, structure and emission |
|---|---|---|
| 1953 | Bernanose *et al*. [10] | Blue emission from LED on Li complex |
| 1963 | Pope *et al.* [11] | EL from antracene crystals |
| 1976 | Kalinowski *et al.* [12] | EL from tetracene crystals |
| 1983 | Partridge [13] | EL from polymers |
| 1987 | Tang and Van Slyke [14] | Double-layer organic solid LED |
| 1990 | Burroughes *et al*. [15] | Single-layer PLED |
| 1993 | Greenham *et al*. [16] | Double-layer PLED |
| 2007 | M. Hack *el al.* [17] | Technology Flexible OLED display |

The purpose of this article is to review the recent most important papers concerning investigations on OLEDs and AMOLEDs. Recently, some reviews have appeared on this subject, just to mention the papers [1-9]. History of fundamental investigations in the field of electroluminescence organic materials, OLEDs and display is presented in Table 1 [10-17]. As it can be seen since over 50 years, researchers are interested in study of this subjects. Additionally, the metal-free transparent OLEDs should be mentioned. Theirs original fabrication and interesting properties have been reported by Parthasarathy et al. [18]. Furthermore, importance of the quasi-monochromatic colour and white light emitting devices should be indicated. For example, quasi-monochromatic OLEDs based on rare earth ion emission, particularly on Eu and Tb organic complexes, emitting in pure red and green and also the highly efficient white-light emitting devices based on single dopant emitters of a mixture of molecular, excimer and exciplex phosphorescence have been reported by Kalinowski *et al*. [19].

OLED displays may be operated in two basic architectures: passive matrix (PM) and active matrix (AM) displays. The AM architecture is expected to be the main technology on which advanced OLED displays will be based (steering them by TFT which could be the organic or inorganic). Now the used displays are CRT (Cathode Ray Tube), PDP (Plasma Display Panel) ELD (Electro Luminescent Display), LCD (Liquid Crystal Display) and OLED (Organic Light Emitting Diode). These two architectures are concurring OLED technology that resembles LCD technology and uses such procedures as vacuum evaporation of thin films (including shadow mask processes), lithography and etc. The others are described in paper [20]. Organic thin film transistors (OTFTs) are required for fabrication of plastic-based AMOLEDs, as conventional Si-based TFTs cannot be directly fabricated on plastic substrates. In general, organic solids are thermally evaporated to form a polycrystalline active layer. Many details of this fabrication procedure in technology OLED, such as surface treatment, temperature, material purity, device structure, and testing and deposition vacuum conditions, dramatically affect the performance of thin-film devices. Displays based on OLEDs have an apparent advantage over LCDs due to their superior inherent properties such as viewing-angle independence and fast response time. Especially in mobile applications, OLED displays are already competing with LCDs as there are many devices available, which use simple PM OLED displays instead of LCDs. One candidate for AM backplanes TFT is amorphous silicon (a-Si), which is commonly used in AMLCDs. However, the threshold-voltage shifts of a-Si TFTs caused by the bias stress voltage are a serious problem for OLED displays. Compensating for the threshold-voltage shift by using driving scheme has been investigated, but it is not yet good enough to apply it to TV displays; accordingly, a new TFT with a small enough threshold-voltage shifts has to be developed. Another approach is the use of microcrystalline silicon (a-Si). The other method is the use of low-temperature polycrystalline silicon (LTPS) which has the highest carrier mobility and extremely small threshold-voltage shift. In order to realize the feasibility of this new technology as described above, Sony has developed a 27-in. OLED-display prototype with full-HD resolution (1920 x l080 RGB) [9]. Recently, prototypes have been demonstrated based on a-Si, including a 20-in. display by IBM/GMO in 2003[21] and a 40-in. display by Samsung Electronics in 2005[22]; however, even with these demonstrations, the majority of AMOLED prototypes continue to be made on crystallized Si TFT backplanes (e.g., CMO demonstrated a 25-in.-diagonal AMOLED in 2006 based upon an LTPS backplane), primarily because of the stability problems associated with a-Si. Almost all OLED displays produced today use the evaporation of organic small molecules [23].

The display market of the future demands ubiquitous devices that are more portable, fashionable, and environmentally friendly [24]. Display manufacturers need to advance their technologies to build lighter, slimmer, more rugged devices that consume low amounts of power while at the same time improve the picture quality. The emerging technology of flexible active-matrix displays is being developed in order to fulfil these needs. Currently, there are active research projects in reflective-type flexible liquid-crystal displays (LCDs) [25], flexible electrophoretic displays (EPDs) [26], and emissive type flexible OLED displays [17]. Today, EPD technology is considered as the most desirable flexible-display technology because of its simple fabrication process and very low power consumption. An AMOLED, on the other hand, is an emissive-type display device that promises better picture quality - including brightness, colour, contrast ratio, viewing angle, and response time - compared to active-matrix liquid-crystal displays (AMLCDs). However, in general, AMOLED displays still have to overcome numerous technological obstacles for mass production [27]. AMOLEDs hold great promise for use inflexible displays [28]. LG Display has presented a full-colour 4-in. flexible AMOLED prototype on an 80-μm-thick stainless-steel foil substrate, achieving a curvature of 5-cm bending radius.

## 2. OLEDs, theirs structure and operation

### 2.1. Structures of OLEDs

OLED (organic light emitting diode) is a monolithic, thin-film, semi conductive device that emits light when a voltage is applied to it. Various ways of light are generated by applying an electric field to organic materials, without involving any intermediate energy forms - the phenomenon known as organic

electroluminescence (EL). EL is the result of the electric field–imposed formation of emissive states without recourse of any intermediate energy forms, such as heat.

In its most basic form, an OLED consists of a series of vacuum-deposited, small-molecule organic thin films that are sandwiched between two thin-film conductors. The following figures show most often met constructions of this device. In Fig. 1 is presented one of the possible simple structures of OLED. Here emission of EL occurs in the electron and hole transmission layers. However, in more complicated but also more efficient OLED is shown in Fig. 2, the emission takes place in a separate layer.

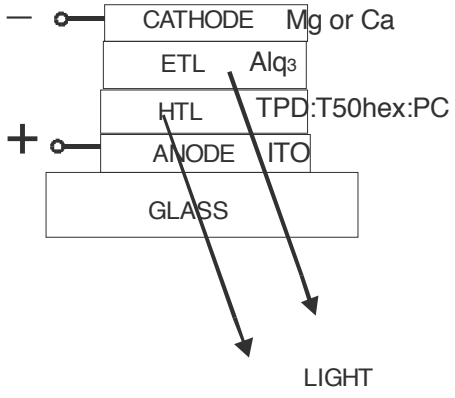


Fig. 1. An OLED is a monolithic, thin-film, solid-state device. Schematic of a simple real OLED structure. ETL – electron-transport layer, HTL – hole-transport layer

Sometimes the application requirements force to construct the different configurations of OLEDs, examples of these are shown schematically in Fig. 3. The output of the EL light can go through the anode, cathode or through the both electrodes as well.

The ETL has the function of assisting the injection of electrons from a metal cathode and their transport throughout the bulk film. Recombination of holes and electrons occurs at the boundary regions between two organic layers. When the recombination region is located within an ETL, the ETL behaves as an emissive layer (EML). When the recombination occurs within the HTL, on the other hand, the HTL can behave as an EML. Thus these devices are classified into two types: ITO/HTL/ETL(EML)/Metal and ITO/HTL(EML)/ETL/Metal. In three-layer structure shown in Fig. 2, an independent thin EML is sandwiched between HTL and ETL (ITO/HTL/EML/ETL/Metal), in case bipolar materials (which have ability to transport both electrons and holes) are available. Figure depicts this typical device structure. In its most basic form, an OLED is a monolithic, solid-state electronic device consisting of a series of vacuum-deposited organic thin films sandwiched between two transparent thin film conductors. When voltage is applied across the device, these organic thin films emit light. This light emission is based upon a luminescence phenomenon wherein electrons and holes are injected and migrate from the contacts toward the organic heterojunction. When these carriers meet, they form excitons (electron-hole pairs) that recombine radiatively to emit light of a certain wavelength (e.g., red, green or blue for flat panel displays) according to the specific organic materials employed.

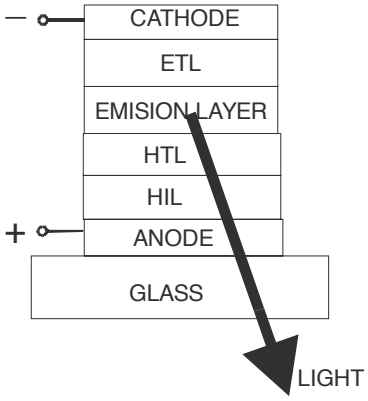


Fig. 2. A typical OLED multilayer device. ETL – electron-transport layer, HTL – hole-transport layer, HIL – hole-injection layer

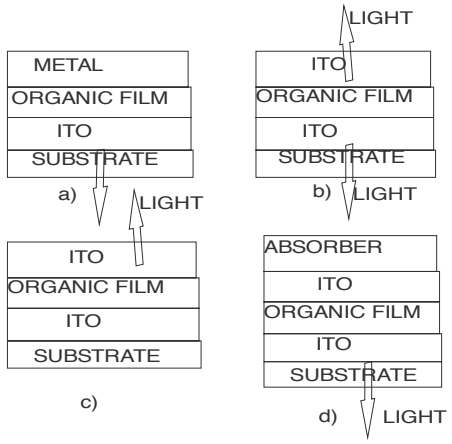


Fig. 3. Schematic of (a) a standard OLED with a reflective top cathode, (b) a TOLED with a transparent both, the top cathode and the substrate, (c) a TOLED built on an opaque substrate, and (d) a TOLED with an absorber on top (T – transparent)

In its most common structure, known as a "single heterostructure," an OLED device consists of a hole transporting layer (HTL) and an electron transporting and light emitting layer (ETL/EL) sandwiched between two transparent electrodes. Transparent OLEDs (TOLEDs) enable new features: transparency, directed top emission, enhanced contrast ratio, and multi-stacked devices. Transparency paves the way for displays to be used in new places in the automobile. In applications where maintaining vision area is important, TOLEDs have the potential to be integrated with the windshield for navigation and warning systems, and with the other windows for entertainment and telecommunication. TOLEDs can also be designed into a novel rear-view mirror and head-up information systems, and also be used as transmitters with the other display systems or backgrounds. In addition, because TOLEDs are transparent, they may be built on opaque as well as transparent surfaces. This means that a display may be built on metal roll stock, for example, for potential use in exterior automotive parts. Moreover, it also creates a number of new, and as yet, unimagined product opportunities.

Good HTL materials should satisfy one or more of the general requirements given below.

1. Materials are morphologically stable and form uniform vacuum-sublimed thin films.
2. Materials have small solid state ionization potential.
3. Materials have high hole mobility.
4. Materials have small solid state electron affinity.

These requirements can be used as general guiding principles for screening new hole transport materials. Several metal chelates have been proposed and used as ETL materials. Tris (quinolin-8-olato) aluminum ($Alq_3$) and its analogues are known to be one of the most robust ETL materials. An oxadiazole derivative, 2-(4′-biphenyl)-5-(4″-tert-butylphenyl)-1, 3, 4-oxadiazole (t-Bu-PBD) was used as an ETL material in blue-emitting OLEDs, where light emission from the hole transporting layer was demonstrated. One of the best examples for a systematic molecular design lies in the success of the distyrylarylene development. OLEDs are generally characterized by the material used in the emissive layer: Either small molecules such as $Alq_3$, poly (methyl methacrylate) (PMMA) and bisphenol-A-polycarbonate (PC), $C_{60}$ and pentacene can be used or polymers such as poly (para-phenylenevi-nylene) (PPV), poly (3-alkylothiophenes) (P3ATs), poly (P-phenylene thynylenes) (PPEs). Often, a polymer layer is spin coated on top of ITO to provide a smooth surface for the following layer stack.

## 2.2. Basic phenomena in OLEDs

OLEDs made of small molecules behave very similarly to conventional inorganic LEDs, but the fundamental difference exists between conventional inorganic semiconductors and the "so-called" molecular semiconductors. This difference originates primarily from two intrinsically different electronic and optical characteristics between conventional inorganic and organic semiconductors.

First, all solid films made of small molecules useful for OLEDs are wide-energy-gap semiconductors. As early studies on EL in anthracene single crystals clearly indicate, anthracene has a high resistivity of $10^{20}$ Ωcm. Vacuum-sublimed films have resistivities typically on the order of $10^{15}$Ωcm. This means that no charges are present in OLED devices without charge injection and attention should be paid only to the behaviour of injected charges from the electrodes. In other words, OLEDs are not treated under electrostatic equilibrium but rather under dynamic charge equilibrium when devices are in operation. All charges are assumed to behave as space charges in solid molecular films, and no local charge neutrality is expected within the films.

Secondly, neutral molecules in the excited states, i.e., singlet and triplet excitons, are produced by charge recombination, and emission is due to radiative transitions from the neutral excited states to the ground states. There is no experimental evidence on the radiative recombination of positive and negative charges in OLEDs, which typically occur in inorganic LEDs. It should be emphasized here that estimating the EL quantum efficiencies becomes quite simple once these two basic assumptions are made.

The elementary processes that take place upon charge injection into an OLED including recombination of holes and electrons, radiative decay from the electronic excited states, and output coupling of the emitted light. The external EL quantum efficiency and internal EL quantum efficiencies are connected by the extraction efficiency of photons. An external EL quantum efficiency, $\eta_\varphi$ (ext) is defined as the ratio of numbers of emitted photons outside a device divided by the number of charges injected into a device. The internal quantum efficiency, $\eta_\varphi$ is the ratio of the number of photons produced within a device divided by the number of charges injected.

The power conversion efficiency in emissive devices is frequently expressed in terms of the luminous power efficiency (lm/W). A better measure of the power conversion efficiency, may be given in terms of the electric-to-photon conversion efficiency ($W_E$/W) expressed by the ratio of the power of the emitted light to the input electric power. The relationship between the power efficiency (internal) $\eta_E$, which is defined by the ratio of the emitted light power inside a device and the applied electric power (JV), and the quantum efficiency (internal) $\eta_\varphi$ is given by Equation (1) where $\varepsilon_p$ and eV express the photon energy of the emitted light eV, obtained by averaging the entire electroluminescence spectrum, and the applied voltage, respectively. The major factor determining the power conversion efficiency is $\varepsilon_p$/(eV). In a

$$\eta_E = \eta_\varphi \frac{\varepsilon_P}{eV} \tag{1}$$

hypothetical situation when the average photon energy $\varepsilon_p$ is equal to the electronic potential provided by the applied voltage, eV, the ratio $\varepsilon_p/(eV)$ is 1.0. Usually this factor is assumed to be far less than unity, because several steps lead to the decrease of the potential *eV* before the production of the thermally relaxed emissive excitations. Voltage losses due to energy barriers to charge injection, voltage drops due to charge transport resistance, dissipation of electronic energy corresponding to a binding energy of electron-hole pairs at charge recombination, and excess energy due to the thermal relaxations of the hot emissive excitations to the lowest electronic excited state are the main origins for lowering the value of the $\varepsilon_p$/(eV) factor below unity. Recently, the introduction of high-conductivity doped layers between the cathode/anode and the organic ETL/HTL have led to a drastic decrease in the driving voltage of OLEDs. In general, carrier injection into organic materials has been described using thermionic emission and Fowler–Nordheim tunnelling, and modifications of the above models by taking the interface recombination current, polaron effects, and disorder into account. While accurate determination of the recombination coefficient including all processes is still not readily available, it has been proposed that the Langevin recombination mechanism generally applies to the organic systems. Based on the Langevin formalism, the recombination coefficient is proportional to the carrier mobility in the following way: OLED materials can probably be classified as either semiconductors or insulators. Their typical band gap is about 3 eV, and the device is usually undoped in terms of conduction type. Thus, the current carriers have to be injected from the electrodes. Conduction features can be understood by considering the case where only one kind of carrier (say, holes) is injected. When traps are not present, the current–voltage relationship obeys the classic Child's square law: This relationship deviates from the linear form because the carrier distribution is not a constant in the solid; rather, it decays rapidly into the solid from the injecting electrode. There is a so-called space charge build-up near the electrode, giving the process the name space charge limited conduction (SCL). In this case, the space charge consists of conducting carriers. When significant traps are present, the trapped charge concentration can be many orders of magnitude larger than that of the conducting carriers. There will

also be space charge build-up near the electrode; however, in that case, the dominant space charges are the trapped charges. The conduction process is thus called TCL conduction, in order for it to be distinguished from the previously mentioned trap-free SCL case.

A great deal of progress in the understanding of organic EL has been made using EL cells based on single organic crystals. The sandwich cell EL structures involve a single crystal and at least one semitransparent electrode. The study results made clear that the emissive states are mostly molecular singlet excitons formed in the bulk recombination of electrons and holes injected from electrodes; that is, type III of the EL underlies the electric field–imposed emission from organic single crystals. However, in some early works, they have been interpreted in terms of impact ionization excitation by primary electrons injected from a metal contact.

The EL spectra of relatively thick (>5 μm) organic crystals can differ from their photoluminescence (PL) spectra for several reasons: (1) different reabsorption effects caused by a difference in spatial distributions of the emitting states generated by the exciting light in PL and by charge carrier recombination in EL, (2) the presence of bulk dopants or defects acting as more efficient recombination centres than acceptors in energy transfer processes, and (3) the splitting the insulator electronic levels at the interfaces. Interestingly, the difference in the trivial reabsorption effect between PL and EL spectra allowed the spatial distribution of excited states to be inferred, and revealed the role of traps and excitonic interactions.

The study of EL in powder-type dielectric cells has been extended to organic films prepared by vacuum evaporation, melting, and recrystallization or solution cast, sandwiched between carrier injecting electrodes. EL diodes have been fabricated on polycrystalline and amorphous anthracene and other organic compounds. The crucial role of charge injection at electrodes has been realized. An important model, also employed in EL of single crystals and used currently to explain optical and electrical characteristics of vast variety of organic LEDs. EL is due to generation of excited states via the recombination of primary electrons and holes injected at two oppositely placed electrodes, and moving against each other across the luminescent material. Other mechanisms such as impact ionization excitation by primary electrode-injected electrons in local strong electric fields, however they could not be excluded conclusively. The strong field has been located in the depletion layer, developed parallel to the metal contact. Injection-recombination mechanism becomes more appropriate to explain the functioning of thin film EL devices. The injection-limited-currents have been shown to impose nonlinear brightness-current characteristics.

Present state-of-the-art PPV-based EL devices approach the efficient $Alq_3$-based LEDs, showing luminance up to $10^4$ Cd/m$^2$ and lifetime over 10.000 h. Both the EL and PL spectrum as well as their EL efficiency depend on degree of the monomer–polymer conversion.

Molecularly doped polymers (MDPs) having a base on electronically inert polymeric binder are of particular interest because they allow us easily to select a variety of dopant molecules with diversified electronic functions. The guiding principle for choosing the right composition of an MDP for an EL device is that energetic position of the HOMO/LUMO (Highest Occupied Molecular Orbital/Lowest Unoccupied Molecular Orbital) of a hole/electron-transporting dopant incorporated into such a binder should be as high/low as possible in order to eliminate trapping by accidental impurities of the possible inert binders. The optical and electronic properties of isolated small molecules can be simply described according to a molecular orbital picture. Electrons are localized on molecules and the optical properties of the molecular solids are roughly approximated with this localized electron model. The important point, however, is that electrons and holes move within molecular solids producing large electric current. The movement of electrons and holes in molecular solids is described as a hopping process from one molecular site to another (Fig. 4).

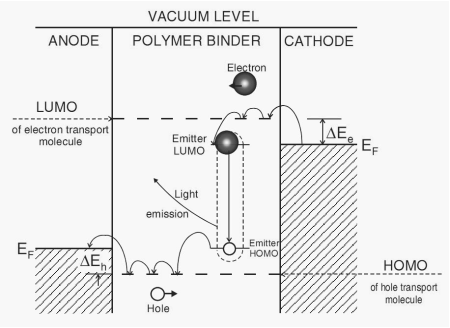


Fig. 4. Schematic emission mechanism diagram responsible for EL effect in an OLED device

The organic stack consists of a series of individual organic materials tailored for specific functionality, e.g., light emission and carrier transport. When voltage is applied across the device, these organic thin films emit light based upon a luminescence phenomenon wherein electrons and holes are injected and migrate from contacts toward each other. When these carriers meet, they form excitons (electron-hole pairs) that recombine radiatively to emit light, the colour, efficiency and intensity of which are characteristic of the specific organic materials employed. A variety of colours have been demonstrated. OLEDs offer bright emissive light, excellent contrast ratio, low power consumption, wide viewing angle and fast response time requisite for video rate applications. Additionally OLEDs are current-driven devices (i.e., brightness is proportional to current), brightness can be varied over a very wide dynamic range.

## 2.3. Model of electroluminescence

In order to obtain the EL effect carriers should be injected from the electrodes into the organic material. Usually diodes are fabricated on ITO coated glass substrates. The model assumes that injection of charges from the electrode into the organic semiconductor is governed by thermionic emission. The thermionic emission occurs across the energy barrier that is formed between the work function of the injecting electrode and the HOMO or LUMO of the organic semiconductor depending on whether hole or electron injection, respectively, is considered. The current density $J$ across this energy barrier can be modelled using the general diode equation

$$J = J_0\left(\exp\left[\frac{qV}{nkT}\right]-1\right) \quad (2)$$

where $J_0$ is the saturation current density is given by the equation

$$J_0 = AT^2 \exp\left(-\frac{\Phi_B}{kT}\right) \tag{3}$$

where A is the Richardson constant and $\phi_B$ is the injection barrier for charges. Once the charges have been injected, they have to travel across the organic semiconductor to the opposite electrode. It has been shown for organic materials that this drift current is a SCLC and follows the equation

$$J = \frac{9}{8}\mu\varepsilon\varepsilon_0\frac{V^2}{L^3} \tag{4}$$

where $L$ is the thickness of the sample. Furthermore, the mobility in an organic material is given by a simplified equation:

$$\mu = \mu_0(T)\exp(\beta\sqrt{\frac{V}{L}}) \tag{5}$$

In the case of single-crystal anthracene, with anthracene cation and anion containing electrolyte solutions as anode and cathode, respectively. Many research results indicate that the EL emission intensity depends linearly on the injected current density. This result is quite valuable and it provides clear-cut evidence for a charge-injection process. The emission arose predominantly from a region near the positive electrode (anode), indicating that electrons are injected from the cathode and transported through the crystal to meet the holes entering from the opposite electrode and then due to the recombination process EL occurs. The development of stable solid state contacts with good injection characteristics for both electrons and holes is an important area deserving further attention.

In molecular systems, which have very low carrier densities, the injected positive and negative charges (referred to as electrons and holes for simplicity) are expected to exist as space charges with no local charge neutrality. This case is clearly different from inorganic semiconductor LEDs, in which minority charge carrier injection at a n-p junction recombine with the majority charge carriers and the junction determines the charge recombination process. The performance of OLEDs critically depends on the balanced injection of holes and electrons into the emitting layer from the anode and cathode. Since lowering the injection barrier at the electrode/organic junction would facilitate effective carrier injection, a natural approach to enhance carrier injection is to use n-type or/and p-type injection layers. Extensive research on the applications of n-type injection layers, such as Li:4,7-diphenyl-1, 10-phenanthroline [29,30] (BPhen) and $Alq_3$, [31] and p-type layers, such as 4,4', 4'' tris(3-methylphenylphenylamino) triphenylamine (m-MTDATA): 2,3,5,6-tetrafluoro-7,7,8,8,-tetracyanoquinodime thane ($F_4$-TCNQ), [28,29] $CuO_x$, [32] and $SiO_2$, [33] have been reported. Recently it has been reported that junctions between suitable n- and p-type injection materials can be effectively used as connecting units to join two or more emitting units in series. [34–39]. The luminance intensity of such "tandem OLEDs" generally increases a number of stacking emitting units. As expected, the connecting unit plays a crucial role on the device performance. In addition to the efficient injection of oppositely charged carriers into the adjoining organic layers, the connecting unit must also possess a high optical transparency and a low electrical conductivity. To date, a variety of connecting units have been introduced, which include Cs:2,9-dimethyl-4,-7-diphenyl-1,10-phenanthroline (BCP)/ITO, Cs:BCP, Li :BCP/V2O5 [35], Li :$Alq_3$, Li:1,3,5-tris(N phenylbenzimidazol -2-yl) benzene (TPBI) /$FeCl_3$ :N,N(-bis)1-naphthyl(N,N)-diphenyl-1,1(biphenyl-4,4)-diamine (NPB) [39], Mg:$Alq_3$ /$WO_3$.

When tandem OLED has been applied, as it is shown in paper [40], the device performance is significantly improved. For instance, at a luminance of 100 cd/m$^2$ (typical brightness for display application), the current density required is only 6.2 mA/cm$^2$ for the tandem OLED, much lower than that required for the conventional single-emitting-unit device (17.1 mA/cm$^2$). Similarly, at a current density of 100 mA/cm$^2$, the current efficiency of the conventional OLED is 0.63 cd/A, while that of the tandem OLED is-increases to 1.47 cd/A. These values clearly demonstrate the effectiveness of the two-emitting-unit tandem architecture on improving the current efficiency. However, the notable weakness of the tandem devices is their high driving voltages. This is attributed to the larger series resistance of the thicker organic layers in the former. It should be mentioned that the device efficiency may depend on the purity of chemicals used and the fabrication conditions.

## 3. Application

The tremendous strides have been made in the science and technology of organic electroluminescence (EL). Most of this progress has been applied in developing flat panel displays. If this rate of progress can be sustained into the next decade, organic EL technology has the potential to exert an impact not only on displays, but also on general lighting applications. In particular, a large-area white-light-producing organic light-emitting device could potentially provide a solid state diffuse light source that could compete with conventional lighting technologies in performance and cost. The vision of solid state lighting has largely been driven by the desire to reduce energy consumption. Organic electroluminescent displays on rigid or flexible substrates are envisioned to play a significant if not major role in the area of flat panel displays. They may eventually dominate the market in just a few years. Small, passive, and active matrix organic light-emitting displays that are relatively inexpensive already have penetrated the commercial market in a significant way. Organic electroluminescent displays can be small, such as hand-held or head-mounted devices, or large, such as flat panel screens that can be rolled up or hung flat on a wall.

OLED devices offer many advantages for flat panel display applications:

1. Very thin solid-state device (less than 300 nm thick),
2. Light weight,
3. High luminous power efficiency,
4. Fast response time that makes animations and motion crisp and entertaining,
5. Wide viewing angle without brightness or image loss (170+ degrees),
6. Self-emitting, which eliminates the need for a back-light illumination source,
7. Colour tuning throughout the entire visible spectrum for full-colour displays,
8. Flexibility.

OLEDs that have these merits in addition to their temporal stability are expected to have many applications. Devices that are very thin and lightweight and have low power consumption are especially suitable for portable equipment (e.g., wireless phones, PDAs, view finders for digital cameras) and other portable imaging devices. Monochrome, multiple-colour, and full-colour display technologies using OLEDs, as are future directions relating to applications based on the needs in the multimedia era.


Fig. 5. Picture of 40-in AMOLED display fabricated on the a-Si TFT substrate matrix from Samsung

Fig. 6. Photograph of the flexible AMOLED display driven by pentacene TFTs

Samsung Electronics announced full-colour AMOLED displays 40-in (Fig. 5) [41] based on a white emitter with an RGB colour-filter array which have been reported as an alternative technology to those displays with patterned RGB emitters due to their relatively higher cost. However, RGB displays based on a white emitter have a disadvantage in power consumption because part of energy of the white light is absorbed by the colour filters. Recently, a white-emitter based AMOLED display with an RGBW pixel format has been demonstrated. It consumes approximately one-half the power of an analogous white-emitter based RGB display. The RGBW pixel format developed by Samsung to achieve high luminescence and a high contrast ratio for AMLCDs has been applied to the AMOLED display for the first time. It works by using unfiltered white subpixels with a relatively high efficiency to replace the combined emission from the lower efficiency RGB subpixels. Several pioneering studies have demonstrated flexible green monochromic AMOLED driven by OTFTs that employ a conventional bottom-emission structure on a plastic film [42, 43]. An effective way to achieve a full-colour pixel structure is to employ a top-emission structure. Unlike bottom-emission structures, a top-emission OLED does not require a transparent substrate, allowing a wider selection of plastic substrates to be used. Top-emission structures are thus advantageous for producing flexible OTFT-OLED displays. Full-colour pixel structure with a pixel resolution of 80 ppi in a flexible OTFT-OLED has been reported. The pixel structure can be achieved by using a combination of top-emission OLEDs and finely patterned OTFTs, resulting in the world's first demonstration of full-colour imaging on a flexible OTFT-OLED are presented in the paper [44]. In the paper [45] the presented top-emission structure is divided into two parts; namely, the pixel OTFT circuit and the OLED: The OLED is formed on the OTFT circuit. In this structure, the pixel size can be reduced by fabricating OLEDs on top of the OTFT circuit. A full-colour pixel structure with a resolution of 80 ppi, corresponding to a main pixel size of 318x318 μm, is designed based on the above design concept. Small-molecule fluorescent RGB OLEDs are formed on the flexible OTFT backplane by shadow-mask evaporation, followed by formation of the common cathode and encapsulation of the OLED. Finally, the backplane including the OLED layers are assembled with a 100-μm-thick cover film using a sealing resin. Fig. 6 shows a photograph of the fabricated flexible display. The OTFT backplane makes the display thin and lightweight. The thickness and the weight of the display can be reduced to 0.3 mm and 1.5 g, respectively. The backplane also makes the display mechanically flexible, and the display specifications are maintained even when the display is subjected to bending. Operation of the display is possible at a bending radius as small as 20 mm wide viewing angle and a high contrast ratio of OLEDs supports a clear visibility in a bending condition. These results demonstrate that the combination of OTFTs and OLEDs is a promising candidate for the flexible displays.

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