

A bright future for organic light-emitting transistors

Cees Draaijer, Armin Palavra & Ellen Schallig

18th July 2013

1 Introduction

Field-effect transistors are emerging as useful devices for efficient light generation from a variety of materials. In this progress article from Muccini [2006], the focus lies on organic light-emitting field-effect transistors and the role played by the material properties, device features and the active layer structure in determining device performance.

Since the separate patenting of the field-effect transistor (FET) in the early 20th century, by Lilienfeld in 1926 and then by Heil in 1934, no practical applications arose before the transistor effect was observed and explained by Shockley in 1947.

Recent advancements in organic science induced the development of a broad range of devices, such as organic light-emitting diodes (OLEDs), solar cells, and organic field-effect transistors (OFETs). This has economic viability since they can be produced as low-cost, large-area, lightweight and more flexible devices than their inorganic counterparts.

Organic light-emitting field-effect transistors (OLETs) are an example of more integrated devices, combining the electrical switching functionality of a field-effect transistor and the capability of light generation into a single device. This is important because steps required to construct highly integrated opto-electronic systems of separate devices affect the simplicity of the system architecture and production cost.

Moreover OLETs offer an ideal structure for improving the lifetime and efficiency of organic light emitting materials by different driving conditions than standard OLEDs (section 3.3). Also they can achieve optimized charge-carrier balances (section 3.4).

In the article several recent advances of FET architectures to achieve light generation from different organic materials are reviewed. First it presents an overview of comparable inorganic devices, such as those based on silicon and direct-bandgap semiconductors. Next the emission properties of single-walled carbon nanotube FETs are discussed. They have potential for use as highly integrable nanoscale light sources. OLETs based on organic thin films are discussed for their low production cost and ease of integration on virtually any substrate. Finally possible directions of development are examined.

First however, a short recap is given on the basics. Transistors and p - n junctions are discussed, and a comparison between organic and inorganic semiconductors is given.

2 Aspects from the course

In this part the basics are discussed. In order to understand the recent developments in LET technology, first the field effect, and transistor and LED technology must be understood. A short introduction to LETs is also given, and brief consideration to why development of organic semiconductors is important.

2.1 Transistors

The ability to on a large scale produce transistors has been one of the biggest advancements in the 20th century. Transistors and derived devices are necessary components in every modern electronic device. They can amplify currents or switch them off completely. To make these transistors, one needs a material that has both conducting and insulating characteristics, to be able to not only conduct currents, but also switch them off. These materials are called semiconductors, which have a band gap between the valence band and the conduction band. An intrinsic semiconductor material is not a good conductor. Without thermal assistance its valence band is completely filled and its conduction band is empty. Combined with its band gap, good conduction requires doping of the material.

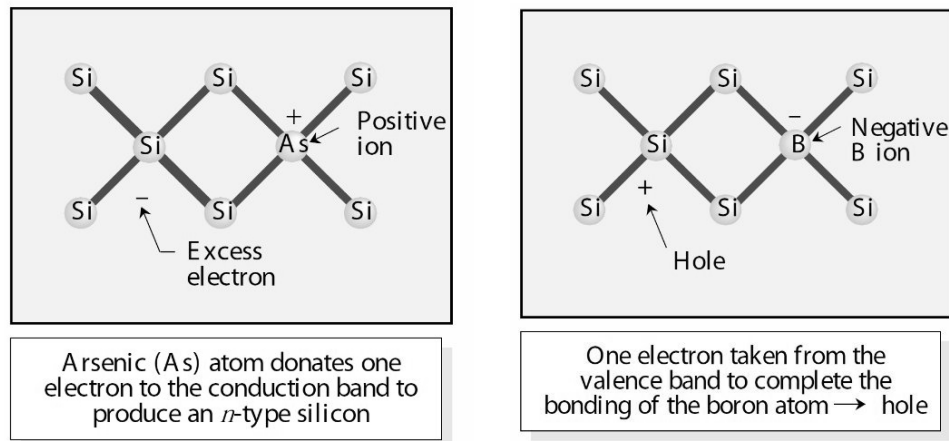


Figure 1: *n*-type doping and *p*-type doping. From van Wees [2013].

Doping (figure 1) introduces either extra electrons (*n*-type doping) or extra holes (*p*-type doping) in a material. This is done by putting atoms with different covalent bond forming properties in the crystals. With silicon, which forms 4 covalent bonds, to introduce extra electrons a material which forms 5 covalent bonds (e.g. arsenic) should be used. The extra electron is now relatively free to move. For *p*-type doping a material that only forms

3 covalent bonds (e.g. boron) should be used. The ‘empty’ place is a hole which can travel relatively easy through the material.

Field-effect transistors are made of a combination of n -type and p -type semi-conductors. The field effect refers to the control of the electrical conductivity of a material by the application of an external electric field. The working of a junction-FET (JFET) illustrates how this field effect is used. There are other transistor designs that use the field effect in a similar way, a few of which are the MOSFET, MESFET, and the organic OFET.

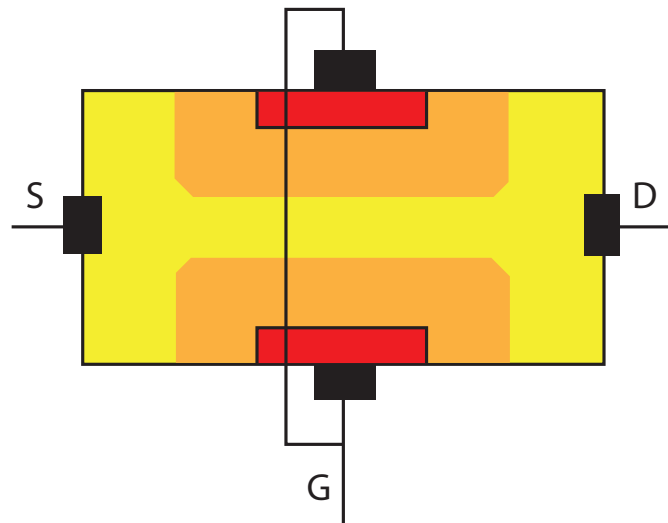


Figure 2: A junction field effect transistor, with the position of source (S), drain (D) and gate (G) shown. Red is the substrate, yellow is the channel. Orange is the depletion zone influenced by the gate voltage.

In figure 2 a diagram of a JFET is shown. In this example the channel through which the charge carriers flow (with a voltage difference between source and drain), is made of a p -type semiconductor, and the surrounding substrate is made of an n -type semiconductor. Therefore the mobile charge carriers in the channel are holes. When the mobile electrons in the substrate are pulled away by a positive voltage applied to the gate, only the static positive charges remain, which forms the depletion zone. This induces a positively charged electric field, which penetrates into the channel and repels the holes there, effectively narrowing the channel. With a high enough gate voltage the channel can be completely ‘pinched off’, resulting in a voltage-controlled switch.

2.2 Diodes

Not only the transistor has had a big impact on society, the field of light-emitting materials has also seen much progress. From indicator lamps to replacements for incandescent light bulbs, the light-emitting diode (LED) has gained a lot of ground.

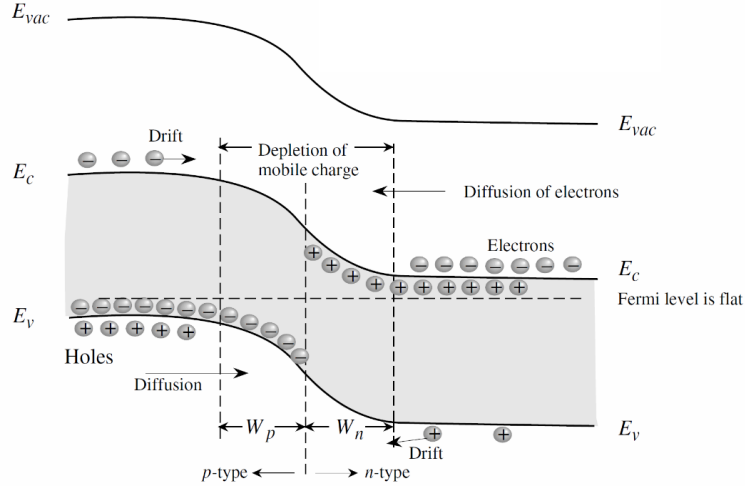


Figure 3: p - n junction. From van Wees [2013].

To make an LED, one needs a p - n junction. This is a piece of p -type semiconductor and n -type semiconductor put together. There is a difference in electron and hole densities across the junction, which results in the diffusion of holes from the p -side and electrons from the n -side. These recombine and near the junction only the static charges remain, which is called the depletion zone. In this region an electric field exists that repels the electrons and holes that enter the region.

If the p -type is connected to the positive terminal of a battery, and the n -type to the negative terminal (called forward bias), holes from the p -side and electrons from the n -side are pushed to the depletion zone. The width of the zone is reduced and with enough voltage difference the electrons and holes can go through the depletion zone and recombine with the charge carriers on the other side. Photons with the energy of the band gap of the materials are emitted. This is called electroluminescence and is the basis for an LED.

2.3 LETs

A light-emitting field-effect transistor (LET) is a device that couples the electrical characteristics of a FET to the controlled radiative recombination

of the electrons and holes, which are injected into the channel via the source and drain contacts [Muccini, 2006]. As seen in figure 4, the LET also has characteristics similar to a LED. Important is that the materials are able to sustain both electron and hole currents and efficient electroluminescence emission, to get a high quantum efficiency.

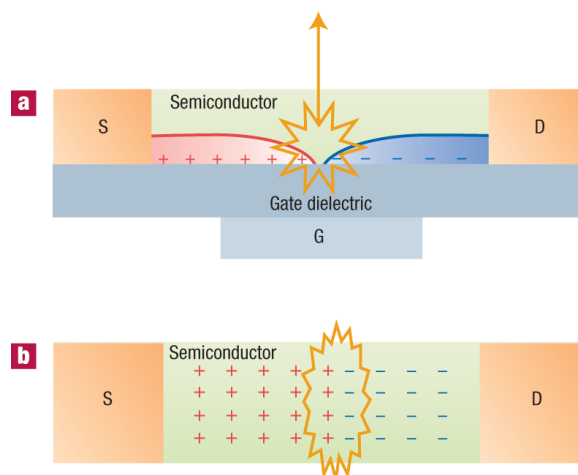


Figure 4: Scheme of LET. (a) Side view. (b) Top view. The device can be thought of as a sort of forward-biased p - n junction. Electrons and holes are injected from the drain (D) and source (S) contacts and recombine within the channel in a position controlled by the gate (G). From Muccini [2006].

2.4 Organic Semiconductors

In the previous sections the general structure of different devices were discussed, but not much was said about the materials that can be used to make these devices. Only silicon was talked about, however, there are many other suitable materials.

A considerable amount of time and effort has been put into the development of organic semiconductors, and not without success. They are made from polymers, a base building block repeated many times. Often these building blocks are variations on the benzene ring. Organic semiconductors have many advantages over inorganic semiconductors, as summarized in the opto-electronics part of the course [Loi, 2013]. Unfortunately organic semiconductors also have disadvantages, which are surmountable depending on the purpose of the devices.

Inorganic semiconductors require an expensive and complicated production method which involves several steps, including photo-lithography, etching, and metallization. Organic semiconductors on the other hand can be easily

P13/ α -quinquethiophene (T5) (ref. 50)

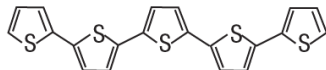


Figure 5: Example of polymeric material. From Muccini [2006].

printed from a solution, and on many different types of (cheaper) materials such as glass, metal foils, and plastics, which as a bonus gives the possibility of producing flexible semiconductors. The organic semiconductor material itself is also much cheaper and more widely available.

With bulk inorganic semiconductor material it is not possible to change the band gap considerably, which for LEDs restricts the wavelength of the light that comes out. One way to overcome this is by making nanocrystals: the size controls the wavelength. For organic semiconductors however it is much easier to change the band gap. Most of the organic materials have a relative complex molecular structure compared to inorganic materials, and therefore there are more possibilities to adjust the molecule slightly resulting in different properties.

Against the major advantages that organic semiconductors have, there are a few disadvantages as well. For OLEDs the carrier mobility is about five orders of magnitude lower than of inorganic LEDs [Muccini, 2006]. Even though the mobility for OLETs can be four orders of magnitude higher than OLEDs, it is still lower than that of inorganic materials. This means that the device reacts more slowly, which is not preferable.

Although the efficiency of organic devices continues to increase, for high brightness it still is not at the level of inorganic devices. The efficiency is described by the quantum efficiency η : the fraction of excited carriers that recombine radiatively. The corresponding equation is:

$$\eta = \frac{R_r}{R} = \frac{\tau_{nr}}{(\tau_{tr} + \tau_{nr})},$$

with R = total recombination rate, R_r = radiative recombination rate, τ_{tr} = radiative lifetime, and τ_{nr} = non-radiative lifetime. The goal is to have an as high as possible radiative recombination rate, because only those recombinations emit light.

Finally the lower lifetime of organic semiconductors is worth some consideration. Their lifetime is lower compared to inorganic semiconductors, and they are more vulnerable to the environment. This is because organic materials react more easily with water or oxygen.

3 Main messages of the article

This progress article by Muccini [2006] is a treatise on the progress made in the field of light-emitting field-effect transistors, and describes the situation from 2006. Since then, the field has again advanced a lot and this will be elaborated on in section 5. In the following subsections the article is summarized.

3.1 LETs based on inorganic semiconductors

Silicon is the most well known and most successful material in the field of electronics. However, its current use in opto-electronics is limited because of its poor light-emitting properties. This is because silicon is an indirect-bandgap semiconductor, which makes it unfavourable for light emission. For each radiative electron-hole recombination, a phonon is needed to conserve momentum. This causes dominance of non-radiative recombination mainly occurring at lattice defect sites, such as dislocations, impurities, cluster defects and precipitates.

This problem is overcome by using silicon nanocrystals instead of bulk silicon. For nanocrystals hole and electron diffusion is limited by the size of the crystals. This way defect sites become isolated and radiative emission is the dominant recombination pathway. Emission from nanocrystals can therefore be rather high, up to a quantum efficiency of 10%. Additionally, the emitted light can be tuned by the exact size of the nanocrystals, from near-infrared to the visible range.

To achieve such electrically driven bright emission, an efficient way to inject opposite charges into the nanocrystals is required. The most successful approach has been a FET structure in which nanocrystals are embedded into the gate oxide. Electrons and holes are injected by tunnelling through the oxide under application of an alternating electric field. This induces sequential accumulation of electrons and holes in the nanocrystals, and light is generated at each cycle.

In this FET structure the electric field required to generate light is lower than in the LED ‘sandwich’ structure. This shows why silicon still has great potential to be explored.

However, direct-bandgap inorganic semiconductors are better for applications where opto-electronic performance faces more severe constraints. Materials such as gallium arsenide (GaAs) and indium phosphide (InP) can generate much brighter luminescence and allow higher modulation speeds than silicon. LETs based on an InGaP/GaAs heterojunction have been demonstrated, showing that LETs based on inorganic semiconductors could be used

for display and communication purposes. In a further development the In-GaP/GaAs LET was designed as a transistor laser.

Although the performances of inorganic semiconductor LETs and transistor lasers are the best achieved to date, their fabrication process is rather complicated, compatibility with other technology is limited and they are relatively expensive. Hence, it is useful to look at different devices.

3.2 LETs based on carbon nanotubes

To prepare nanoscale light sources for use in fully integrated opto-electronic circuits, there are several methods. One of them is the engineering of light-emitting nanowires made of direct-bandgap semiconductors. Duan et al. have made advancements in this field by assembling *p*-doped and *n*-doped nanowires to form a *p-n* junction. Gudiksen et al. achieved this by fabricating nanowire superlattices. Unfortunately for achieving high performance levels, with these methods ease of fabrication is lost as well.

A different approach is to use semiconducting single-walled carbon nanotubes as the active component in a field-effect transistor. Carbon nanotube FETs of *n*-type, *p*-type and ambipolar character have been fabricated. The ambipolar charge transport is achieved by simultaneous injection of holes and electrons via thermally assisted tunnelling through the Schottky barriers formed at the source and drain contacts. Under biasing conditions suitable for ambipolar transport with balanced hole and electron currents, infrared optical emission is generated as the result of electron-hole recombination in the nanotube. This is illustrated in figure 6.

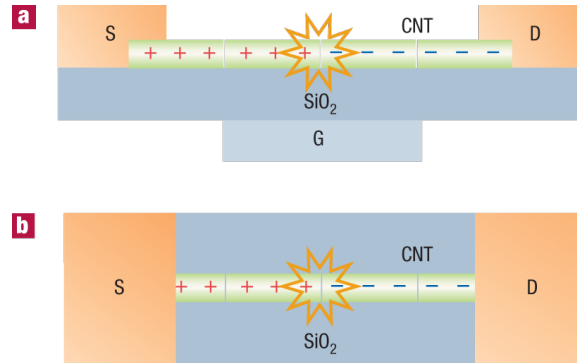


Figure 6: Device structure of a carbon nanotube. (a) Side view. (b) Top view. Infrared emission is generated by the recombination of electrons and holes flowing in the nanotube. From Muccini [2006].

The infrared radiation emitted by the carbon nanotube FET has some special properties. Due to the elongated shape of the tube, the light is polarised

parallel to the tube axis. This resembles a linearly polarized dipole radiation source. As the bandgap of the nanotube is inversely proportional to its diameter, it is expected that the wavelength can be tuned by changing diameter sizes. Although this is still to be explored, carbon nanotube LETs offer significant potential as nanoscale photon sources that could easily be integrated in opto-electronic devices.

3.3 LETs based on organic thin films

One of the most appealing properties of organic materials is that they can be deposited on many different types of surfaces, such as a CMOS or cheap materials like plastic and glass. This, in turn, enables easy and cheap fabrication, which is of course an important driving factor for further developments.

Organic materials can be produced with low-cost, large-scale industrial production processes such as direct printing, ink-jet and other solution based techniques. Organic thin film structures, which only require small amounts of material, are ideal for markets where low-cost production is of high importance, and performance does not require inorganic devices.

Also organic materials can sustain multiple functionalities when synthesized, and may be used to create multifunctional devices. The OLET represents a step towards this possibility, combining electron and hole field-effect transport, light emission, and electrical switching.

OLETs enable electroluminescence in the same materials as OLEDs, though with different driving schemes. The vertical structure of OLEDs enables low-voltage-driven light emission and charge transport occurs perpendicular to and through the plane of different layers. In OLETs charge transport occurs parallel and through the plane. A schematic representation is shown in figure 7.

The mobility of the charge carriers in this OLET geometry can be up to four orders of magnitude higher than in the OLEDs. The OLET has a potentially higher electroluminescence quantum efficiency, which is inherent to the device structure.

For OLETs, the distance between the exciton formation region and the metal electrodes is much larger. Therefore they are less affected by electron-metal quenching. This effect is further reduced by the availability of a third electrode that balances electron and hole currents. These structural advantages make OLETs more favourable for high-brightness electroluminescence and highly integrated devices. These advantages however do rely on the further development of organic materials.

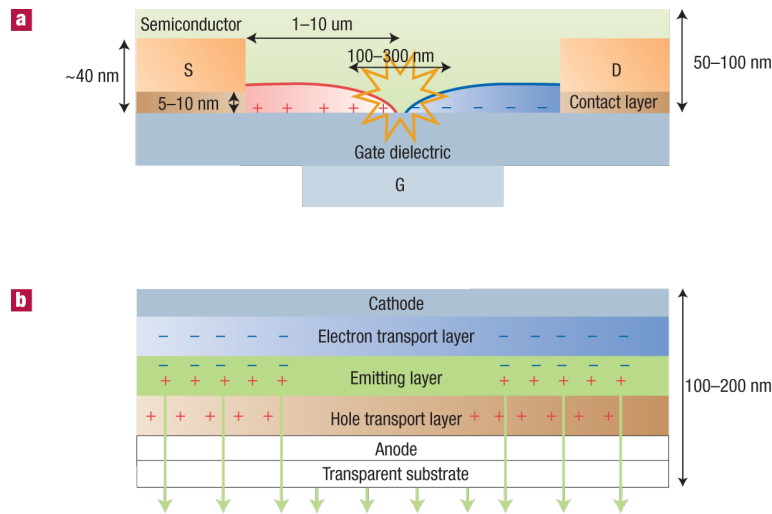


Figure 7: Schematic representation of OLET and OLED. (a) Horizontal charge transport in OLETs. (b) Vertical charge transport in OLEDs. From Muccini [2006].

A possible disadvantage for OLET devices is the distance the charge carriers need to travel before recombining radiatively. For typical ambipolar OLETs the distance is in the order of hundreds of nanometres or more, in OLEDs the distance the minority carriers travel are only in the order tens of nanometres. This requires stricter charge transport properties of OLET materials.

3.4 Unipolar OLETs

OLETs were first demonstrated by Hepp et al. using a tetracene thin film. Tetracene is the four-ringed member of the series of acenes, a class of organic compounds and polycyclic aromatic hydrocarbons made up of linearly fused benzene rings. Moreover, it is a molecular organic semiconductor.

Typical current carriers in organic semiconductors are holes and electrons in π -bonds. Almost all organic solids are insulators. But when their constituent molecules have π -conjugate systems, electrons can move via π -electron cloud overlaps, especially by hopping, tunnelling and related mechanisms. Also polycyclic aromatic hydrocarbons work with this mechanism.

To make the first OLET, Hepp used interdigitated gold source and drain electrodes, fabricated on a Si/SiO₂ substrate before deposition of the organic active layer. The charge transport and light emitting layer is the tetracene, configured as a polycrystalline film. The resulting electrical characteristics are typical of a *p*-type FET. Light emission from the tetracene indicates that electrons and holes are simultaneously injected into the active layer.

The electrons cannot move through the tetracene, so they are trapped at the gold/tetracene interface. At this interface they then recombine with the holes, emitting light.

One important issue that can be relevant for other materials under the same driving scheme, is that electrons are injected from gold into tetracene over an theoretically unexpected nominal barrier of 2.7 eV. This points to the actual structure of the gold/tetracene interface, where a composite layer could be formed. Thus it is no simple matter of considering the different materials' energy levels separately.

A number of investigations were done to optimize this first device and to make it ambipolar. Yet never electron transport was observed in the tetracene thin films. The primary limiting process for achieving high-brightness emission is singlet-triplet quenching. This was concluded after numerical simulations looking at exciton processes. Triplets appear to be most dominant in quenching singlets. It prevents pure tetracene films, when provided with a realistic optical feedback structure, to reach the threshold for stimulated emission.

OLETs' electroluminescent and electrical properties are, among other things, dependent on the transistor channel length. On decreasing the channel length, both electron injection and electroluminescence efficiency are improved. This unfortunately holds up only to a certain point. The contact resistance from a typical metal/organic interface tends to dominate the electrical characteristics of the transistor, hindering further improvement. Unfortunately the external quantum efficiency is still very low, so that there are no practical applications.

Organic materials with both efficient electroluminescence and transistor characteristics are needed. The application of well-established OLED materials is not straightforward, as most of them have low FET-performance. Their strong molecular packing that allows high mobility, increases non-radiative decay.

As an alternative spin-coated polymers have been used as active layers in LETs with bottom-contact device structures as in figure 4. The polymers used are among the most commonly used LED polymers. In addition to extending OLET concepts to polymers, experiments show a clear increase in light-emission efficiency on using metals for source and drain electrodes that have a workfunction more suitable for holes and electrons injections respectively.

As mentioned before, to fabricate large-area and low-cost devices, the good solubility of the organic semiconductor, which would allow printing and casting processes, is important. A new molecular system was devised which is suitable for drop-casting onto a pre-patterned FET structure to produce

OLET devices. Although the transistor characteristics are less than if produced by vacuum sublimation, most likely due to morphological characteristics of the solution-processed films and to the lower degree of molecular ordering, it widens the range of processing techniques and again points to the crucial role played by synthetic chemistry in tailoring the processing conditions and functional properties of materials.

3.5 Ambipolar OLETs

In unipolar devices only one type of charge carrier is transported efficiently across the transistor channel and light generation is restricted to an area close to the minority carrier injection electrode. Ambipolar organic semiconductor devices do not have this limitation. This means that they can be used in the fabrication of complementary logic circuits with a single active layer.

Ambipolar charge transport is crucial in LETs for maximizing exciton recombination through electron-hole balance as well as for adjusting the position of the recombination region in the channel by tuning the gate voltage. The consequent decrease of exciton quenching leads to improved quantum efficiency of device.

In principle, pure organic semiconductors should support both electron and hole conduction equally. However in practice most of the organic semiconductor films only display unipolar charge transport. Of these the majority is *p*-type, so holes are more mobile than electrons. Ambipolar field-effect charge mobility of electroluminescent organic thin films seems to be limited and their opto-electronic response in a device structure remains to be explored.

For instance, the field-effect mobility determines the switching time of the OLET device and is a critical parameter for those applications where light emission is to be modulated by the applied voltage, e.g. for active matrix displays and frequency-modulated nano-scale light sources.

In view of the limited number of electroluminescent materials with good ambipolar mobility values, alternative approaches to achieve high ambipolar transport in OLETs have been explored. The first ambipolar OLETs were demonstrated using a bulk heterojunction as the active component of the device. Like previously applied in LEDs, solar cells and FETs, this uses the mixing of two materials with complementary properties.

The most important requirement that the two materials must comply with, is that the relative positions of the HOMO and LUMO must allow exciton formation and recombination in the material with the smaller energy gap.

Given this restriction, the approach of the bulk heterojunction can be extended to other materials in the search for higher-brightness OLET devices. The electroluminescence intensity is also determined by the relative concentration of materials and by the structural features of the bulk heterojunction. However, the absolute mobility values are low.

OLETs based on two-component layered structures have been realized. Here growth compatibility between the n -type and p -type materials is essential in forming a continuous interface and in controlling the resulting optoelectronic response of the OLET. Therefore the sequence of the deposition of the layers is important for determining the device characteristics. The optimum performance is not necessarily achieved by using materials with the highest mobility values in single-layer devices.

To date, the bilayer approach provides the highest balanced mobility values in ambipolar OLET devices. However the separation between the electron transport layer and the hole transport layer, in spite of the electron-hole attraction, drastically reduces the probability of electrons and holes meeting to form excitons inside the device channel. When charges are accumulated at the interface between the dielectric substrate and the organic material, near the drain top electrode, the superposition of gate contact/bilayer/drain contact is likely to form an LED structure at the origin of the light emission, which is therefore confined next to the drain metal electrode as in the case of unipolar OLETs.

Recently it was shown that in the polymer-based ambipolar LETs the emission zone can be scanned across the transistor channel on changing the gate bias. This was done with low-workfunction metals for the electron-injection electrode and high-workfunction metals for the hole-injection electrode. In addition, trap-free dielectrics were used to avoid electron trapping and enable ambipolar transport.

The observation of a spatially resolved recombination zone whose location in the transistor channel is controlled by the applied bias, demonstrates the coexistence of electron and hole channels, and therefore the ambipolar nature of charge transport. The recombination zone is located at the centre of the channel when electron and hole currents are balanced. The electroluminescence quantum efficiency can be as high as that of LEDs based on the same material.

At present, the drawback of the ambipolar polymer-based LETs remains the mobility values. However, the latest results, together with the continuous development of the knowledge of the chemical and physical properties of the relevant interfaces in the device, and the possibility of chemically tailoring the active materials, open exciting perspectives for the full realization of the scientific and technological potential of OLETs.

3.6 Directions and opportunities

OLETs are of high interest as they can be used in many different applications, from communication systems to solid-state lighting, and provide a novel device architecture to investigate fundamental optoelectronic properties in organic materials. The in-plane architecture of OLETs allows for direct probing and observation of various fundamental aspects of organic material science, as opposed to the OLED technology.

OLETs may be the key element for the next-generation organic active matrix display technology. They can provide effective solutions for the brightness and lifetime of the electroluminescent pixels, through the high degree of control of charge injection and accumulation in the organic layer. The integration of light-emitting and electrical switching in one element reduces the amount of other elements to be produced, which results in a cheaper fabrication of the active matrix display.

The in-plane OLET structure can be a valid alternative for the vertical OLED structure for an electrically pumped organic laser. These lasers have many advantages over the III-V semiconductor lasers, such as lower cost and wider range of possible lasing emission. However exciton quenching and photon losses are still major problems, which have prevented the realization of the electrically pumped organic laser to date.

The LET configuration can prevent exciton quenching and photon losses by moving the metal electrodes away from the region of exciton formation and light emission. The high mobility of carriers in a FET configuration minimizes the required charge-carrier densities, which also reduces exciton quenching and photon absorption. These key advantages make the field-effect transistor approach the most favourable for achieving the organic laser.

OLETs have potentially higher light-emission efficiency and brightness than OLEDs, which opens the market of low power consumption solid state lighting. OLETs also can be fully compatible with well-established other technologies which may allow for the development of optical communication with OLETs as a key active element. Finally, OLETs can be solution processed and fabricated on plastic surfaces. This is a gateway for the printing on large-area and flexible substrates.

4 Relevance of the devices

Given the title of the article, “A bright future for organic field-effect transistors”, it is clear that the devices in general sense are deemed very important. Yet there is still a lot of work to be done, so that the article has to differentiate in different device generations and design concepts. There is an important role for synthetic chemistry in tailoring the processing conditions and the functional properties of materials. In many cases there is a trade-off between high performance and ease of fabrication.

The general objective is to allow the fabrication of multifunctional organic devices using extremely simple device structures. This has strong economical relevance. OLETs represent a step forwards.

As compared to OLEDs, a clear advantage is their potentially higher electroluminescence quantum efficiency. Moreover they can be used to investigate fundamental opto-electronic properties in organic materials, and can be used in all kinds of applications, ranging from display technology to electrically driven organic lasers. In these applications they may enable the development of next-generation technologies, such as organic active matrix display technology.

As OLETs are fully compatible with many well-established electronic and photonic technologies, they can have a huge impact on society, especially because they can be fabricated on plastic substrates in combination with solution processing. This enables relatively low-cost production, which makes the economic driving forces huge.

5 Future

The article mostly focuses on the discoveries made in the OLETs field and future possibilities. It shows a bright future for OLETs, mainly praised for their low-cost and very favourable production methods. The possibility to make flexible devices creates a whole new range of possible applications.

However most of the achievements are obtained in laboratory environments, to take advantage of the low-cost possibilities it is necessary to produce OLETs on an industrial scale, which was still not the case in 2006.

Nowadays organic photonic devices are mass-produced. Only these are not OLETs but OLEDs. Many mobile phones that are produced contain an OLED display that match the performance of inorganic displays while the price is in the same range. Full size OLED television screens are also available on the consumer market, but the price is almost ten times higher than that of inorganic (LCD) displays. The expectation is that the prices of big OLED displays will drop further.

Also in the field of OLETs, a lot of progress has been made since 2006. Capelli et al. [2010] published a paper on OLET performance. They report improved OLET devices that are more than 100 times more efficient than equivalent OLEDs and more than 2 times more efficient than the optimized OLED with the same emitting layer. The devices are 10 times more efficient than any other reported OLETs. The device has a very high quantum efficiency of 5% compared to OLEDs (2.2%) and previous OLET designs (0.6%).

Nevertheless, despite the article's title, one of the remaining weaknesses that needs improvement is the brightness.

References

- R. Capelli, Toffanin S., Generali G., Usta H., Facchetti A., and Muccini M. Organic light-emitting transistors with an efficiency that outperforms the equivalent light-emitting diodes. *Nature Materials*, 9:496–503, June 2010.
- Prof. dr. M. A. Loi. Device Physics Lecture Notes: Optoelectronic Devices. *Groningen University*, 2013.
- M. Muccini. A bright future for organic field-effect transistors. *Nature Materials*, 5:605–613, August 2006.
- Prof. dr. ir. B. J. van Wees. Device Physics Lecture Notes: Semiconductor Physics. *Groningen University*, 2013.