Perspectives on organic light-emitting diodes for display applications

R. U. A. Khan* · C. Hunziker · P. Günter

Abstract Herein, we describe a number of key issues that concern the commercialization of organic light-emitting diodes for display applications. We will firstly outline the historical and market contexts that show the potential for organic electronics as a viable display technology. Next, we will discuss the chemical structures for a range of both small-molecular and polymer organic semiconducting compounds, and how the electronic properties are governed thereof. Also we will briefly discuss various common film deposition and device fabrication strategies. Then, we will describe two factors that are highly relevant for commercially viable organic light-emitting diodes, namely charge balance, and device degradation. Finally, we will outline some methods for achieving the high-volume throughput of organic electronics via well-established technologies that are used in the printing industry.

1. Introduction

Organic electronics has been highlighted as an area with real-world commercial potential [1–3]. Nowadays, it is possible to create a wide variety of organic materials, some of which are conductive, some insulating and some semiconducting. Within these broad classifications, there are a myriad of variants according to their band gap and electronic properties, which can be modified by varying the nature of one or more key functional groups of the compound, and also by exter-nal factors such as doping. Furthermore, by fine-tuning the chemical structure of these materials it is possible to obtain a wealth of different results. This opens up avenues of flexibility that hitherto have not been found in other fields of research within optoelectronics and photonics, and in practical terms has allowed the realisation of items such as the full-color display. In addition, due to the fact that these materials are formulated using well-established chemical processes, their costs remain low.

At the moment, the most promising applications for organic electroluminescent devices are backlights for liquid crystal displays, simple alphanumeric displays, and ultimately full-color active matrix displays. Organic light-emitting diode (OLED) technology is used already for small displays in various consumer devices such as cell phones, digital cameras, in-car hi-fi, and watches. Since OLED based displays do not have to be back-lit, they have the potential to be thinner and lighter than conventional LC displays. Furthermore, since only the pixels that are switched on will emit light, power consumption can be greatly reduced compared to LCDs where the entire panel must be backlit constantly. OLED displays also have the clear potential to provide higher contrast and truer colors, higher brightness, wider viewing angles, better temperature tolerance, and faster response times than LCDs.

There are several additional reasons why the use of organic materials is attractive. Clearly, there exists a far greater potential for large-area and low-cost applications for organics as compared to their inorganic counterparts. Organic electronic materials can be deposited at room temperature using simple, industrially applicable techniques such as spin-coating, inkjetting, and printing (e.g. flexo, microcontact, gravure). Using such techniques, it is also possible to print organic electronic materials, onto a wide variety of substrates including flexible foils. The combination of these advantages

R. U. A. Khan (✉)* · C. Hunziker · P. Günter
Nonlinear Optics Laboratory, Swiss Federal Institute of Technology, ETH-Hönggerberg, CH-8093 Zurich, Switzerland

*Present address: Advanced Technology Institute, University of Surrey, Guildford, Surrey GU2 7XH, United Kingdom
e-mail: r.khan@surrey.ac.uk

means that organics have particular relevance for the fabrication of low-cost, lightweight, mass-produced electronic items (well-documented products include E-paper and RFID tags).

Even though the first products using organic displays have been introduced onto the market, there remains a wide scope of scientific activity in the field. One significant challenge in using organic materials is that devices (particularly OLEDs) commonly degrade over short timescales compared to their inorganic counterparts. This means that the achievement of commercially practicable organic-based devices, that possess suitable lifetimes, may well require a parallel development of additional technologies; e.g. encapsulation and gettering. Other important goals include higher device efficiencies and lower operating voltages.

2. Historical perspective

Today, conventional non-conjugated polymers ("plastics") are widely used for a myriad of industrial and household applications. Polymers are attractive for use as substitutes for structural materials such as wood or metals because of their high strength and light weight. The first studies of semiconducting organic materials focused on small molecular crystals. In 1960 photoconductivity was observed in crystalline anthracene [4]. Interestingly, from the measurement of the time evolution of the transient photocurrent, a hole mobility of 0.3 cm^2 V^{-1} s^{-1} was deduced, which is still large by modern standards. Soon afterward, electroluminescence in anthracene was reported by Pope in 1963 [5]. However, until the early eighties, organic semiconductors were merely considered to be a scientific curiosity and little potential for any applications in the electronics sector could be foreseen at that time. A significant step forward for organic electronics was achieved by the fabrication of efficient double-layer small molecular OLEDs by Tang and VanSlyke in 1987 [6]. On the other hand, during the late seventies, research was extended from small molecules to include conjugated organic polymers as conducting materials [7]. The discovery of electroluminescence from sandwich structures containing thin films of poly(phenylene vinylene) (see later, Fig. 3(a)) [8] was, however, the turning point that suggested the applicability of polymers as well as small molecules for organic displays.

Over the last several years, the primary motivation for all efforts in research in the area of organic electronics is its potential for new and low-cost applications not accessible to conventional inorganic semiconductors. Recent advances in OLED research have largely addressed the fundamental challenges of emission color, efficiency and lifetime [2]. Organic thin films have also been extensively researched for the fabrication of thin-film transistors (TFTs) [9] and solar cells [10]. Developers envisage organic TFTs to be used in wide ranging, low-performance applications such as product labeling
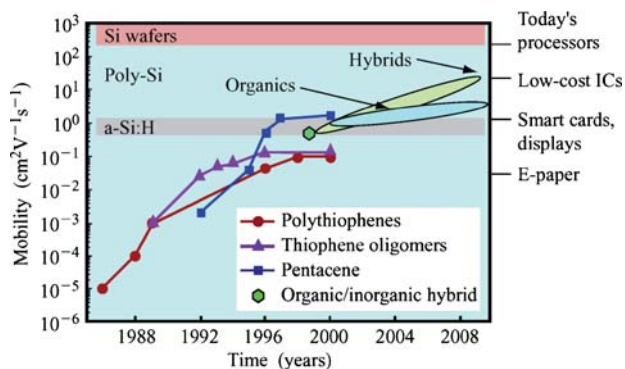
Fig. 1 The organic electronics roadmap: achieved and expected carrier mobility values for various organic semiconducting materials. Also shown are common mobility values that are achieved using silicon-based technologies. Reproduced with permission from [11]

and smart cards, as well as backplane drivers in OLED and LCD displays, where information processing at relatively low speed, but on large-areas is required. Organic TFTs as building blocks for functional circuits have been investigated for many years, but only recently has their performance been sufficient to attract serious attention from industry. Figure 1 shows the advances in charge carrier mobility that have been achieved by various organic semiconductors over the past few years [11]. It is clear that the hole mobility of pentacene has in fact *surpassed* that of the current leader in the large-area device sector, namely amorphous silicon.

3. Market considerations

Organic electronics clearly dovetails with chemical and semiconductor industries, in which competition is fierce. However, academic institutions, larger companies and smaller enterprises have contributed greatly to the growth of what is widely recognised to be a commercial prospect with immense potential. The display analysis firm iSuppli speculates that the market revenue for OLEDs in applications including mobile phones, media players and televisions will rise to $2.9 billion in 2011, up from $408 million in 2005. OLED unit shipments will rise to 60 million units in 2005, nearly double the 31 million units in 2004. The present makeup of research into organic electronics includes firms such as Philips, Merck Chemicals, Sumitomo, Cambridge Display Technology, Dupont-Teijin, Agfa, Microemissive Displays, Plastic Vision, Thales, Optrex, Siemens, Infineon, ST Microelectronics, Konarka, Molecular Vision, Plastic Logic, Osram, Elam-T, VTT, Qinetiq, IBM, Samsung, Sony, Sharp, Kodak, Epson, and Aixtron. This is a testimony to the wealth of potential in this field, and also demonstrates the closeness to commercialisation of several types of organic-based devices.

An ever-expanding base of knowledge has furthermore resulted in large gains in performance and lifetime. Examples

of technologies that may be introduced or will benefit from these materials are free-form advertising signs, pricing labels, PDAs and displays for the telecommunication and automotive industry, as well as security applications. As there has been rapid growth in terms of material choice, the opportunities for this field have not yet been fully exploited. Nevertheless, commercial products using organic semiconductors have now appeared on the market, including small molecule based segment color displays (Pioneer), monochrome passive matrix displays (Philips), and full-color active matrix displays for digital cameras (Kodak/Sanyo). Prototypes have also been shown of large area displays, e.g. a 17" inkjet printed RGB (Toshiba) and a 20" vacuum deposited RGB display (IBM/Chi Mei), and of plastic transistor driven electrophoretic (Philips/E-Ink, Polymer Vision and Plastic Logic/Gyricon) and liquid crystal (Philips, Plastic Logic) displays. Many other developments are underway e.g. related to displays and including electrochromic modes of operation (NTera).

Finally, of note: the fact that the charge carrier mobility of pentacene has now surpassed that of amorphous silicon (see Fig. 1) is a commercially significant achievement. Amorphous silicon is at present the dominant technology for backplane drivers in active-matrix LCDs (as well as being heavily utilized in other large-area electronic devices, such as solar cells) and currently occupies the second largest position in the global electronic materials market, behind crystalline silicon but well above photonic materials such as gallium arsenide and nitride. On paper therefore, it has been proved that organic electronics have the real potential to supplant current amorphous silicon technology if the hurdles of device reproducibility, volume/large-area production, cost, and lifetime are overcome.

4. Current OLED design and fabrication strategies

4.1. Molecular/polymer structure

The molecular structures of a range of common organic semiconducting small molecules are shown in Fig. 2, and various conjugated polymers are displayed in Fig. 3. In the past, it has been common practice to distinguish between those materials that are hole-transporting and those that are electron-transporting. It is not always easy to define what constitutes good charge transport, but we may say generally mobilities that are greater than 10^{-4} cm^2 V^{-1} s^{-1} and no carrier trapping (although dispersive materials that exhibit shallow trapping on a similar timescale to the charge carrier transit time may still be good hole transporters). Examples of materials that possess good hole transport are the triphenylamine derivative molecule TPD [12] and 4,4′,4″-tris(3-methylphenylphenylamino)
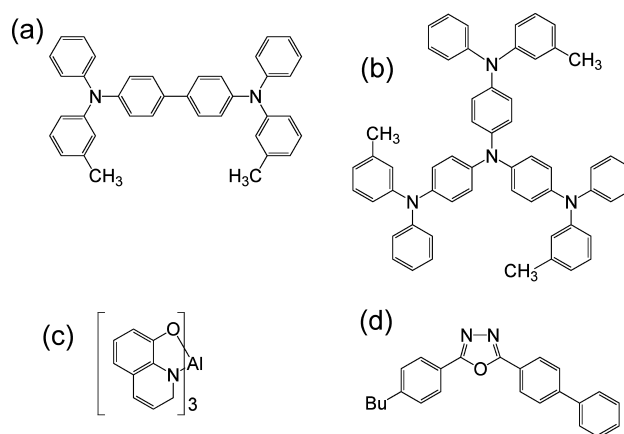
Fig. 2 Common small-molecular organic semiconductors: (a) N,N′-diphenyl-N, N′-(3-methyl-phenyl)-1, 1′-biphenyl-4, 4′-diamine (TPD), (b) 4,4′,4″-tris(3-methylphenylphenylamino) triphenylamine (MT-DATA), (c) aluminium 8-hydroxyquinoline, (d) 2-(4-biphenylyl)-5-(4-*tert*-butylphenyl)-1,3,4-oxydiazole (PBD)
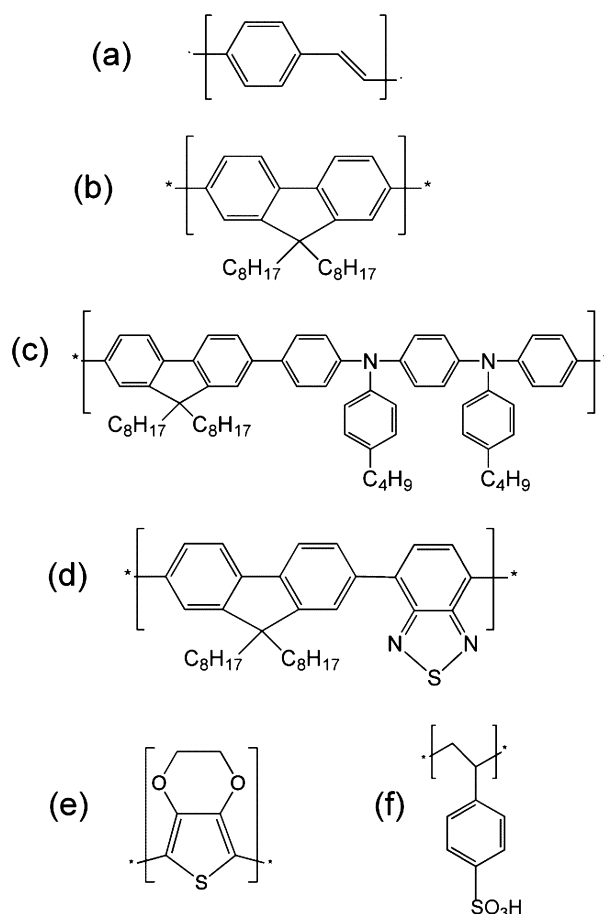

Fig. 3 Common organic semiconducting polymers: (a) poly(phenylene vinylene) (PPV), (b) poly(9,9-dioctylfluorene) (PFO), (c) poly(9,9-dioctylfluorene-*co-bis*-N,N-(4-butylphenyl)-*bis*-N,N-phenyl-1,4-phenylenediamine) (PFB), (d) poly(9,9-dioctylfluorene-*co*-benzothiadiazole), (e) poly(ethylene dioxythiophene) (PEDOT) which is commonly doped with (f) poly(styrene sulphonic acid) (PSS)

triphenylamine (MTDATA) [13] (Fig. 2(a) and 2(b)) and the conjugated polymers poly(9,9-dioctylfluorene) (PFO) (Fig. 3(b)) [14] and poly(9,9-dioctylfluorene-*co-bis*-N,N-(4-butylphenyl)-*bis*-N,N-phenyl-1,4-phenylenediamine) (PFB) (Fig. 3(c)) [15]. Excluding PFO, the common feature within these compounds is the incorporation of nitrogen atoms into the conjugated network; the donor functionality of the N lone pair generally results in an enhancement of hole transport. This has the additional effect of lowering the ionization potential of the compound and therefore facilitating the hole injection process.

Notable molecular materials that are commonly utilized as electron transporters are aluminium 8-hydroxyquinoline (Alq) [16] and 2-(4-biphenylyl)-5-(4-*tert*-butylphenyl)-1,3,4-oxydiazole (PBD) (please see Fig. 2(c) and Fig. 2(d)) and the conjugated polymer poly(9,9-dioctylfluorene-*co*-benzothiadiazole) (Fig. 3(d)) [17]. Although Alq is well-utilized as an electron transport layer, its charge transport properties are unexceptional, with mobilities typically ranging between 10^{-5} and 10^{-6} cm^2 V^{-1} s^{-1} and it generally displays significant electron trapping [16]. For the other compounds, the oxydiazole and thiadiazole-rings are electron deficient, which results in improved electron transport within these compounds.

It was previously thought that the goal of both good hole and electron mobility within a single material was unachievable and that, in particular, good electron mobility was hard to obtain. Historically, the range of electron transporters has been conspicuously smaller than that of hole transporters. However, it has been reported that the electron trapping within Alq is greatly reduced if the material is extensively purified prior to deposition, and the electron mobility is measured in the absence of atmospheric contaminants (particularly oxygen) [18]. The electron injection from a Mg/Al electrode into Alq is ohmic but the addition of oxygen results in a Schottky barrier being formed [19]. It has also been observed that the electron mobility of C$_{60}$, an excellent electron transporter, reduces by three orders of magnitude upon the exposure of oxygen [20]. Recent studies of organic transistors have furthermore demonstrated that n-type conductivity within conjugated polymers is possible if electron trapping at the semiconductor(dielectric interface is minimized by use of a hydroxyl-free dielectric [21] [22]. Indeed, within a range of materials that were previously considered simply good hole-transporters, including PFO, *ambipolar* charge carrier mobility (i.e. similar mobility values for both electrons and holes) was observed. This observation has attracted interest within the community, as it suggests that the reason why most organic electronic materials transport holes rather than electrons is an extrinsic rather than an intrinsic property. It also allows the realization of novel devices, e.g. light-emitting transistors.
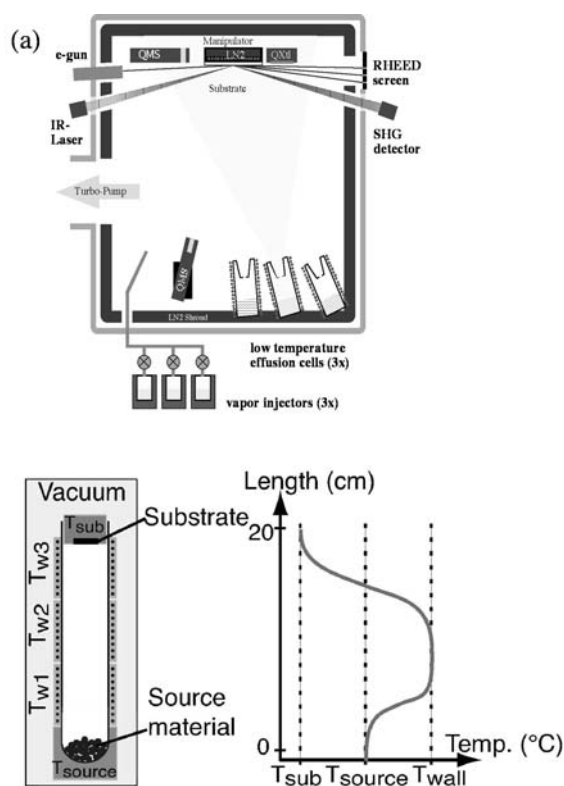
Fig. 4 (a) Organic molecular beam deposition apparatus. (b) Configuration of hot-wall deposition

4.2. Deposition methods

Conjugated polymers are commonly deposited by dissolving in an organic solvent such as toluene, xylene, chloroform or chlorobenzene followed by spin-coating or drop-casting. The details of these experimental procedures are not outlined here but generally, the resulting films are amorphous. For small molecules, the most commonly utilized method is organic molecular beam deposition (OMBD) (see Fig. 4(a)) whereby organic molecules are evaporated onto a thermally stabilized substrate under high or ultrahigh vacuum (UHV) conditions [23]. An alternative technique where small molecules are deposited onto a range of substrates is organic vapor-phase deposition [24] where the molecules are transported to the substrate by means of a carrier gas. One significant advantage for this technique is that ultrahigh vacuum conditions are not required.

The deposition of crystalline organic thin films, however, is of considerable interest as the charge carrier mobilities are likely to be greatly improved as compared to their amorphous counterparts. The standard method to deposit crystalline thin films is organic molecular beam epitaxy (OMBE), which requires lattice-matched growth conditions and a careful control of factors such as deposition rate and temperature [25]. However, an interesting but less researched technique

for the deposition of ordered organic thin films is hot-wall deposition (HWD) [26]. Figure 4(b) shows the configuration used to deposit thin films using this technique. As in OMBD, the source material is sublimed but the main feature is a heated liner that is used to enclose and direct the vapor to the substrate. The effect of this liner is to obtain better control of the thermodynamic equilibrium between the incident molecules and the substrate, which facilitates crystal growth of the resulting thin film. Hot-wall epitaxy (HWE) on well-ordered substrates represents one simple and promising alternative to conventional OMBD, and has also been shown to be appropriate for Van der Waals epitaxy, as demonstrated by the growth of organic molecular thin films comprising e.g. oligomers and fullerenes [27].

4.3. OLED device structure

An organic polymer LED (PLED) consists of at least one undoped semiconducting layer that is sandwiched between two electrodes, as depicted in Fig. 5(a). The hole-injecting anode must be transparent for the light to emanate and is usually made of indium tin oxide (ITO). Most commonly, poly(ethylene dioxythiophene) (PEDOT, see Fig. 3(e)) doped with poly(styrene sulphonic acid) (PSS, see Fig. 3(f)) is used as the hole-injecting electrode within PLEDs as it facilitates

Fig. 5 : (a) Common device structure for polymer-based light-emitting diodes (PLEDs). (b) Band diagram for PLED operation

hole injection into the organic emitting layer [28, 29]. The cathode normally consists of a low work function metal, commonly Ca, in order to minimize the electron injection barrier to the organic layer. The band diagram for a typical single-layer (i.e. polymer) OLED is shown in Fig. 5(b). Charge carriers, electrons and holes, are injected from either electrode on each side, by applying a voltage, and both carrier types drift towards each other in the applied field. The incumbent holes and electrons form excitons (binding energy typically 0.3 eV [30]), which then recombine to produce light. For vacuum-deposited small molecular OLEDs (SMOLEDs), the device design is similar although PEDOT:PSS is normally not used as a hole-injecting layer, and instead SMOLEDs typically consist of an amorphous thin film heterostructure of an undoped hole-transporting layer (HTL) and an electron-transporting layer (ETL). Recombination takes place at the interface between these two layers. The most common bi-layer SMOLED device consists of TPD as the HTL, and Alq as the ETL and recombination layer [6].

5. Performance aspects

There are clearly several competing factors that govern the output efficiencies of organic light-emitting diodes. Crucial points include: optimizing the luminescence quantum efficiency and lifetime (control of photophysical processes), singlet versus triplet emission [31] (spin statistics will play a vital role in governing the internal quantum efficiency of an organic device), and the outcoupling of the emitted light. However, herein we will only focus on two issues that are also critical; charge balance, and degradation.

5.1. Charge balance

The efficiency of an organic LED is clearly critical for both sufficient brightness and also low power consumption. Balanced hole and electron currents are essential in order for the device efficiency to be maximized, by ensuring that the recombination zone is kept towards the center of the device. If the emission zone exists close to either of the electrodes, the radiative evanescent electric field has been shown to be dissipated by dipole-image dipole coupling with the metallic electrode [32]. Drift-diffusion simulations of the charge carrier densities of both holes and electrons have been particularly useful in identifying the position of the recombination zone within organic LEDs [33]. Especially in the case of single-layer PLED devices, the correct balance of holes and electrons is very difficult to achieve because it requires a compromise of the four interplaying factors of hole barrier height, hole mobility, electron barrier height, and electron mobility. This is further complicated if the
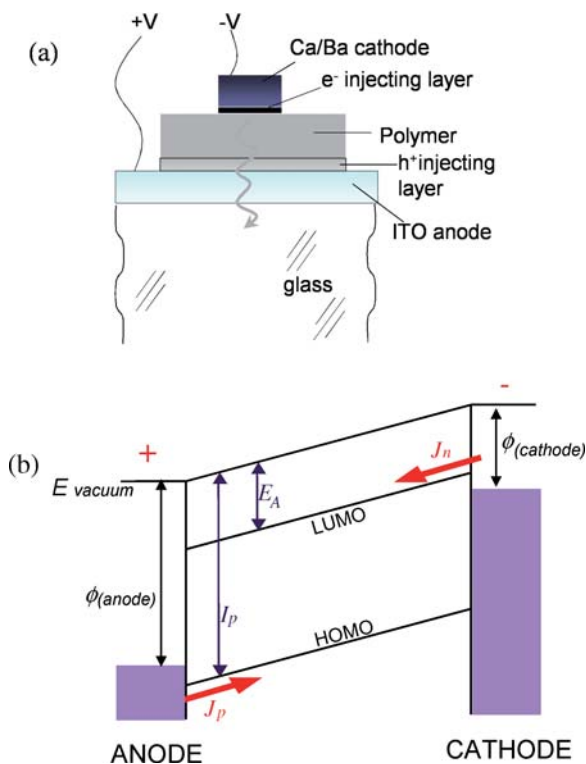
mobilities are highly field-dependent as is the case for several materials.

We will discuss these factors with relevance to the common electrode materials used in PLEDs. PEDOT:PSS (Fig. 3(e) and Fig. 3(f)) is a common hole-injecting material and possesses a work function of 5.2–5.4 eV [28]. Organic semiconductors that possess an ionization potential (I_p) that is significantly greater than this value will form blocking (Schottky-type) contacts with PEDOT:PSS. Conversely a common electron-injecting material is calcium that possesses a work function of 2.8 eV. Values of electron affinity (E_a) well below this value will result in a blocking contact for electrons into the material. So as our first example, PFB (Fig. 3(c)) possesses a fairly large hole mobility (greater than 10^{-4} cm^2 V^{-1} s^{-1} as previously mentioned). But, electron transport within this material is very poor as the carriers are trapped within a very short range, and furthermore, the barrier to electrons is large, owing to the low electron affinity of PFB (taking the HOMO energy of PFB as 5.1 eV [15] and an approximate figure of bandgap of 3.0 eV, the electron affinity will be close to 2 eV). The second example is BT (Fig. 3(d)) that possesses a large electron affinity of approximately 3.2 eV and a reasonably large electron mobility of 10^{-4} cm^2 V^{-1} s^{-1} [17]. However, it possesses a large ionization potential of approximately 6.0 eV. The large barrier to hole injection has tended to make BT considered unsuitable for use in isolation within LEDs. The third example is PFO (Fig. 3(b)), which possesses a relatively large hole mobility (10^{-4} cm^2 V^{-1} s^{-1}) but conversely hole injection into the material is poor due to its large ionization potential (5.8 eV) [34]. We note that previous measurements have shown that the bulk electron transport within PFO sandwich structures is quite poor. But, we refer the reader to the previous discussion of n-type FET operation that has been observed recently in PFO, amongst other polymers (Sec. 4.1). Clearly, there is some ambiguity in the exact nature of electron mobility in organic semiconductors, but it appears that electron transport is highly sensitive to trapping which depends on the purity of the organic semiconductor, and is reduced by the elimination of oxygen and moisture (also remember that FETs conduct charge only over a few monolayers close to the gate dielectric, so the results may not be directly related to bulk measurements of mobility within an organic thin film).

There are some strategies for improving charge balance within these materials. For PFO, it has also been shown that one may increase the hole current, and hence improve the electroluminescence efficiency, by blending the polymer with a molecule which possesses a lower value of ionization potential, which facilitates better hole injection into the polymer [35]. Conversely, it is possible to improve charge carrier balance within PFO devices, by reducing the hole mobility of the material. This has been achieved for example by doping the polymer with a hole-trapping small molecule [36].

As a consequence of the importance of charge carrier balance, low hole mobilities have been shown to be required for high values of electroluminescence quantum efficiency to be achieved. Within poly(p-phenylene vinylene) (PPV)-based OLEDs (see Fig. 3(a) for the chemical structure of PPV), the optimum hole mobility for high electroluminescence efficiency was shown to be approximately 10^{-7} cm^2 V^{-1} s^{-1} [37].

5.2. Degradation

Critically, the performance characteristics for organic LEDs have historically been hindered by poor device lifetime. Particularly in the case of blue-emitting organic diodes, lifetimes of less than 10 000 hrs have largely prevented the usage of organic LEDs in commercial environments. However, recent strides have improved the operating lifetime of organic polymer devices to more industrially applicable levels.

Thermal instabilities within the organic thin film have been demonstrated to be a common cause of device failure. Variations in morphology due to low glass transition temperatures and/or crystallization upon device operation are clearly causes of degradation [38]. But, chemical oxidation is also likely to be a candidate for any degradation process occurring within these types of material, and indeed, various studies have demonstrated the presence of a reaction between the organic semiconductor and oxygen in degraded devices [39, 40]. However, the conflicting and possibly co-related mechanisms of aggregation/morphological changes and chemical oxidation may be difficult to separate. Historically, there has been some controversy concerning these degradation processes. For example within polyfluorene devices, a consequence of the degradation process is a broad and featureless green emission band (the so-called "g-band") [40]. This emission has been ascribed generally to the formation of fluorenone defects, due to the oxidation of the C-9 site where long alkyl (or other) substituents are added in order to promote solubility. However, there has been some conjecture as to whether the existence of the g-band is due to emission from fluorenone-based excimers (excited state dimers that arise due to close proximity of electronically excited aromatic systems) or in fact simply localized (i.e. intrachain) fluorenone π-π^* transitions [41, 42]. It has recently been shown that the g-band may be suppressed by the matrix isolation of the oxidized polyfluorene chains by dispersion in an inert polymer matrix [43], indicating the former; that interchain interactions are required for the appearance of the g-band.

Another clear indication of a degraded device is the existence of non-emissive "black-spots". Earlier studies suggested that these may be formed by the development of individual sites where local electrical breakdown of the bulk of the film occurs [44] but later it was shown that in the case
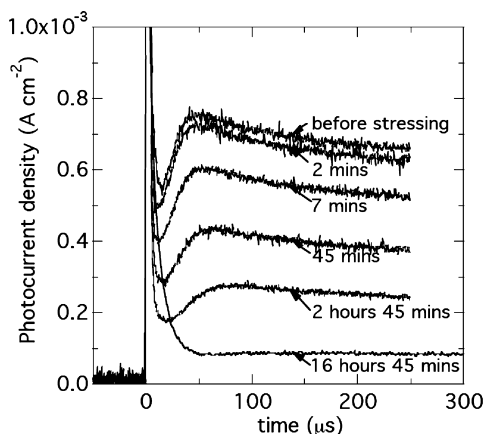
Fig. 6 Current transient curves for hole injection from PEDOT:PSS into a blue-emitting conjugated polymer, for different stressing times at an applied step voltage of 60 V. Reproduced with permission from [46]

of devices that contained a PEDOT:PSS hole-injecting layer, the PEDOT was locally dedoped with a concurrent local oxidation of the metal cathode [45]. We observed [46] that, within PEDOT:PSS-containing devices, there was an reduction of the hole current following strong electrical driving that was attributable to the loss of ohmic hole injection. Figure 6 shows the evolution of the dark injection (DI) transients after increasing periods of electrical stress. It is observed that the magnitude of the injected current decreases as the device is stressed. Before stressing, the DI transient shows a characteristic current peak that implies that the hole-injecting contact is initially ohmic so that the space-charge limit is attained [47]. As the device is stressed, however, the magnitude of the dark injection current peak decreases, and its temporal position shifts to longer timescales. Separate time-of-flight measurements showed that the bulk mobility within the device did not change as a consequence of stressing. Therefore, the changes in DI transients correspond to a loss of ohmic injection into the film. Furthermore, electroabsorption measurements that probed the built-in field within the device confirmed that there was the concurrent development of an interfacial resistance. These findings were consistent with the dedoping of the PEDOT:PSS layer upon strong electrical driving. We may conclude that the development of hole injection materials with better stabilities compared to PEDOT:PSS will be required in order to overcome these issues.

6. The future - printable electronics

The most significant future development of organic LEDs will ultimately be industrialization: primarily to reduce costs and increase throughput whilst not compromising on device performance or lifetime. Printable electronics has the potential to achieve this, as it will enable vast existing markets

(devices, displays, PCBs, and so on) to be merged. Major funding institutions support this effort: For example, the EU Framework VI Information Societies Technologies programme contains several organic printing-based collaborative projects e.g. POLYAPPLY, ROLLED and CONTACT.

There has also been significant progress in the *inkjet printing* of electronic materials through research carried out within both large and small enterprises. It is now possible to realise the fabrication of transistors and full-color displays using this technique. However, the disadvantages of inkjetting are that it is slow and the materials are required to be carefully adapted in order to print correctly. Furthermore, to e.g. achieve a display resolution of 0.1 mm, it is necessary to pre-pattern the substrate, which negates some of the cost benefit. However, a more recent development is the advent of microcontact printing. It is an adaptation of a technique known as flexography, which is well-established within the printing industry. A process for the realisation of transistors has been established but not on an integrated device scale (less than 0.1 mm line widths in structures extending over tens, or hundreds of square centimetres) that would be needed for the fabrication of printed integrated circuits with a reasonable functionality.

Current projects often build on other traditional forms of printing. As an example, the CONTACT project addresses the usage of *gravure* contact printing of complete organic electronic devices (transistors in this case, but the technology could be adapted for the printing of OLEDs) layer-by-layer. Contact printing is an area that has not received significant attention in the past, and this is in large part due to the unavailability of test and experimentation gear of sufficient quality. The project is based upon the usage of the commercially available gravure printer known as the LABRAT-ESTER (please see Fig. 7): this is an inverted geometry precision sheet printer, i.e. the substrate sheet is cylindrical and mounted on the roller, that is capable of printing at a wide range of pressures and speeds (up to 1 ms^{-1}) using custom-made flat gravure plates. The machine can also be reconfigured to test flexo. It needs minimal amounts of ink (around 0.5 mL per sheet), structures from 20 μm to 500 μm scale have been printed, and it also needs minimal amounts of training.
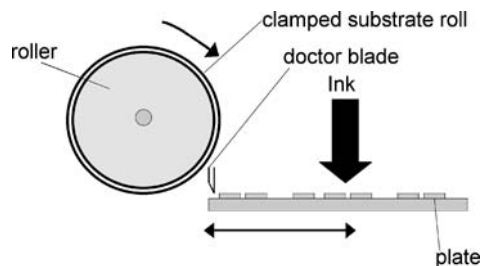
Fig. 7 Configuration of LABRATESTER for the gravure printing of organic electronic devices onto flexible substrates

7. Conclusion

Although this review is not exhaustive, it does illustrate some recent developments within the organic electronics community that have the greatest relevance to the future of organic displays. Both small-molecular and polymer based organic light-emitting diodes will have their own respective roles to play in perhaps different market segments. It appears that the solution-deposition and printing capabilities of conjugated polymers will stand them in better stead for the realization of a wide range of marketable products. However, several of the most recent commercialized products have been based on small-molecular thin films. Clearly, further gains in device efficiency, coupled with further breakthroughs in both understanding and countering the problem of device degradation, will be crucial to the success of the field within the industrial sectors. Finally, the co-fabrication of both organic light-emitting diodes and organic transistors as their backplane drivers will help to allow a single unified technology platform to evolve, and compete more strongly with the current amorphous silicon/polysilicon based LCD market.

References

1. Friend, R.H., Bradley, D.D.C., Holmes, A.B., Phys. World **5**, 42 (1992)
2. Friend, R.H., Gymer, R.W., Holmes, A.B., Burroughes, J.H., Marks, R.N., Taliani, C., Bradley, D.D.C., Dossantos, D.A., Brédas, J.L., Lögdlund M., Salaneck, W.R., Nature **397**, 121 (1999)
3. Forrest, S., Burrows, P., Thompson, M., IEEE Spectrum **37**, 29 (2000)
4. Kepler, R.G., Phys. Rev. **119**, 1226 (1960)
5. Pope, M., Kallmann, H., Magnante, P., J. Chem. Phys. **38**, 2042 (1963).
6. Tang, C.W., Vanslyke, S.A., Appl. Phys. Lett. **51**, 913 (1987)
7. Chiang, C.K., Fincher, C.R., Park, Jr. Y.W., Heeger, A.J., Shirakawa, H., Louis, E.J., Gau, S.C., Macdiarmid, A.G., Physical Review Letters **39**, 1098 (1977)
8. Burroughes, J.H., Bradley, D.D.C., Brown, A.R., Marks, R.N., Mackay, K., Friend, R.H., Burns, P.L., Holmes, A.B., Nature **347**, 3819 (1990)
9. Burroughes, J.H., Friend, R.H., Phys. World **1**, 24 (1988)
10. Nelson, J., Curr. Opin. Solid State Mater. Sci. **6**, 87 (2002)
11. Shaw, J.M., Siedler, P.F., IBM Journal of Research and Development **45**, 3 (2001)
12. Stolka, M., Yanus, J.F., Pai, D.M., Journal of Physical Chemistry **88**, 4707 (1984)
13. Giebeler, C., Antoniadis, H., Bradley, D.D.C., Shirota, Y., Appl. Phys. Lett. **72**, 2448 (1998)
14. Redecker, M., Bradley, D.D.C., Inbasekaran, M., Woo, E.P., Appl. Phys. Lett. **73**, 1565 (1998)
15. Redecker, M., Bradley, D.D.C., Inbasekaran, M., Wu, W.W., Woo, E.P., Adv. Mater. **11**, 241 (1999)
16. Kepler, R.G., Beeson, P.M., Jacobs, S.J., Anderson, R.A., Sinclair, M.B., Valencia, V.S., Cahill, P.A., Appl. Phys. Lett. **66**, (1995) 3618
17. Campbell, A.J., Bradley, D.D.C., Antoniadis, H., Appl. Phys. Lett. **79**, 2133 (2001)
18. Malliaras, G.G., Shen, Y., Dunlap, D.H., Kafafi, Z.H., Appl. Phys. Lett. **79**, 2582 (2001)
19. Kiy, M., Biaggio, I., Koehler, M., Günter, P., Appl. Phys. Lett. **80**, 4366 (2002)
20. Tapponnier, A., Biaggio, I., Günter, P., Appl. Phys. Lett. **86**, 112114 (2005)
21. Chua, L.-L., Zaumsell, J., Chang, J.-F. Ou, E.C.-W., Ho, P.K.H., Sirringhaus, H., Friend, R., Nature **434**, 194 (2005)
22. Dodabalapur, A. Nature **434**, 151 (2005)
23. Khan, R.U.A., Kwon, O.-P., Tapponnier, A., Rashid, A.N., Günter P., Adv. Funct. Mater. **16**, 180 (2006)
24. Burrows, P.E., Forrest, S.R. Sapochak, L.S., Schwartz, J., Fenter, P., Buma, T., Ban, V.S., Forrest, J.L., J. Cryst. Growth **156**, 91 (1995)
25. Schlesser, R., Dietrich, T., Sitar, Z., Gitmans, F., Kündig, A., Eng, L., Münch B., Günter P., J. Appl. Phys. **78**, 4943 (1995)
26. Lopez-Otero, A., Thin Solid Films **49**, 1 (1978)
27. Andreev, A.Y., Matt, G., Brabec, C.J., Sitter, H., Badt, D. Seyringer, H., Sariciftci, N.S., Adv. Mater. **121**, 1379 (2000)
28. Carter, S.A., Angelopoulos, M., Karg, S., Brock, P.J., Scott, J.C., Appl. Phys. Lett. **70**, 2067 (1997)
29. Brown, T.M., Kim, J.S., Friend, R.H., Cacialli, F., Daik, R., Feast, W.J., Appl. Phys. Lett. **75**, 1679 (1999)
30. Alvarado, S.F., Seidler, P.F., Lidzey, D.G., Bradley, D.D.C., Physical Review Letters **81**, 1082 (1998)
31. Baldo, M.A., O'Brien, D.F., You, Y., Shoustikov, A., Sibley, S. Thompson, M.E., Forrest, S.R., Nature **395**, 151 (1998)
32. Becker, H., Burns, S.E., Friend, R.H., Phys. Rev. B **56**, 1893 (1997)
33. Scott, J.C., Karg, S., Carter, S.A., J. Appl. Phys. **82**, 1454 (1997)
34. Janietz, S., Bradley, D.D.C., Grell, M., Biebeler, C., Inbasekaran, M., Woo, E.P., Appl. Phys. Lett. **73**, 2453 (1998)
35. Sainova, D., Miteva, T., Nothofer, H.G., Scherf, U. Glowacki, I., Ulanski, J., Fujikawa H. Neher, D., Appl. Phys. Lett. **76**, 1810 (2000)
36. Campbell, A.J., Bradley, D.D.C., Virgili, T., Lidzey, D.G., Antoniadis, H., Appl. Phys. Lett. **79**, 3872 (2001)
37. Blom, P.W.M., Vissenberg, M.C.J.M., Huiberts, J.N., Martens, H.C.F., Schoo, H.F.M., Appl. Phys. Lett. **77**, 2057 (2000)
38. Qiu, Y., Qiao, J., Thin Solid Films **372**, 265 (2000)
39. Cumpston, B.H., Parker, I.D., Jensen, K.F., J. Appl. Phys. **81**, 3716 (1997)
40. Bliznyuk, V.N., Carter, S.A., Scott, J.C., Klarner, G., Miller, R.D., Miller, D.C., Macromolecules **32**, 361 (1999)
41. Gaal, M., List, E.J.W., Scherf, U., Macromolecules **36**, (2003) 4236.
42. List, E.J.W., Guenter, P., De Freitas, P.A., Scherf, U., Adv. Mater. **14**, 374 (2002)
43. Sims, M., Bradley, D.D.C., Ariu, M., Koeberg, M., Asimakis, A., Grell, M., Lidzey, D.G., Adv. Funct. Mater. **14**, 765 (2004)
44. Lin, K.K., Chua, S.J., Wang W., Thin Solid Films **417**, 36 (2002)
45. Kim, J.-S., Ho, P.K.H., Murphy, C.E., Baynes, N., Friend, R., Adv. Mater. **14**, 206 (2001)
46. Khan, R.U.A., Bradley, D.D.C., Webster, M.A., Auld, J.L., Walker, A.B., Appl. Phys. Lett. **84**, 921 (2004)
47. Lampert, M.A., Mark, P., in Current Injection in Solids (Academic Press, Cambridge, 1970).