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Conjugated polymer electroluminescence: technical aspects from basic devices to commercial products

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Conjugated polymers have achieved much attention as light-emitting and charge transporting active layers in light-emitting polymer (LEP) devices. So far, the main focus of research and development in this area has been to improve device efficiency and to achieve different emission colours. For a successful commercialization of the technology, however, a variety of other aspects are equally great important. The dominant issues are device operating life and shelf life but other challenges arise in the areas of, for example, substrate conditioning, large scale coating of thin polymer layers and electrodes, encapsulation and environmental testing. This paper will address a selection of these engineering issues.

1. Introduction

The discovery of light-emission from the conjugated polymer poly(*p*-phenylene vinylene) (Burroughes *et al.* 1990) has initiated large efforts world-wide to investigate and exploit this effect of electroluminescence from conjugated polymers (see, for example, Braun *et al.* (1994)). This work has demonstrated emission colours from deep blue to near infrared, emission from flexible devices on plastic substrates, internal quantum efficiencies (photons per injected electron-hole pair) of close to 10%, resulting in power efficiencies of several lm W^{-1} , high resolution (less than $5 \mu\text{m}$ pixel size), fast switching (below μs) and low voltage operation in DC (less than 3 V). Other key advantageous features of the light-emitting polymer technology include lambertian emission (wide viewing angle), the possibility of using passive matrix addressing (May 1996), ease of device manufacture and patterning and the efficient escape of the generated light out of the device (low refractive indices of the polymers and substrates). LEP devices are typically very thin (less than 1 mm), light-weight, robust, flexible and formable; these features are in principle only limited by the substrates and encapsulation and those can be thin sheets of glass, sheets or rolls of plastic or metal foil. The basic device design/structure is very simple (Burroughes 1990) and material cost and consumption is low; thus it is anticipated that the LEP technology can be of low cost.

2. Basic device operation

Figure 1 shows the key elements of an LEP device before connectorization and encapsulation. When a voltage is applied between the two electrodes, positive and

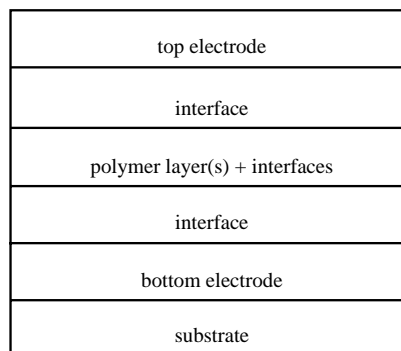


Figure 1. Schematic drawing of an LEP device.

negative charge carriers are injected into the polymer layer(s) above a threshold voltage. Some of the positive and negative charge carriers recombine to form excitons which decay radiatively with a certain efficiency to emit light. The exact nature of the electrodes and interfaces, the polymer layer structure and thicknesses, the properties of the polymers and the drive scheme determine the device-dependent carrier injection efficiency, balance of positive and negative charge carriers, recombination efficiency, drive voltage, efficiency for radiative decay of the excitons, internal quantum and power efficiency.

A typical device might have the following structure: glass/ITO/conjugated polymer/Al. One of the ‘striking beauties’ of the LEP technology is its simplicity and the ease with which an LEP device can be constructed successfully to emit light; a simple laboratory process using off-the-shelf commercial glass/ITO and simple spin-coating of a suitable conjugated polymer with a final evaporation of Al gives reasonably high yields of working devices.

3. Commercial requirements

To be commercially viable, even simple products which require only a few hundred to a few thousand hours operating life at low brightness (few tens of Cd m^{-2}) have to withstand, for example, the following testing regimes: continuous testing at $-20 \rightarrow +65^\circ\text{C}$ (powered), $-40 \rightarrow +85^\circ\text{C}$ (unpowered), a burn-in test at 85°C (powered) for at least tens of hours, thermal shock testing from $-40 \rightarrow +85^\circ\text{C}$ in repeated cycles and at different frequencies from cold to hot, testing at elevated temperatures greater than 50°C in relative humidities above 90% (powered), prolonged exposure to UV light and electrical shock testing.

These tests ensure acceptable product shelf life and operating life in different environmental conditions. In addition, the products that meet these specifications have to be manufactured at low cost. In the following discussion we will address a few of the aspects of the development of LEP devices which address these requirements.

4. Some engineering aspects of light-emitting polymer devices Substrates and bottom electrode

(a) Smoothness

There are many important aspects with respect to substrates for LEP devices. These include smoothness, barrier properties and resistance to processing conditions.

ITO-coated glass is generally used as the LEP substrate. Taking into account that the active polymer layer(s) in LEP devices are typically only about 1000 Å thick, it is apparent that microscopic smoothness of the glass/ITO is important. Figure 2 shows an atomic-force microscope (AFM) scan of what a commercial glass/ITO substrate can look like. Although the underlying smoothness of the surface is very good and reflects the generally high quality of the glass, ‘spikes’, which in the case of figure 2 are up to 100 Å high, are present. These spikes can originate from the ITO deposition process and can, in particular if they are very narrow, be catastrophic for LEP devices. If the polymer layer thickness above such a spike is reduced, and hence the local electric field under device operation is increased, hot spots can occur. These hot spots may result in simply brighter emission spots, local ‘burn-out’ of the polymer or complete shorting of the device such that it is no longer usable. It is now also widely recognized that the current densities in such hot spots can be so high that, locally, the top electrode is evaporated off. This results in pin holes in the top electrode and non-emissive ‘black spots’. The pin holes then provide channels for the ingress of oxygen and, particularly important, moisture which induces amongst other things corrosion of the top electrode around the pin hole and growth of the black spots (see, for example, Burrows *et al.* 1994). Fortunately, ITO deposition techniques exist which minimize or avoid such spikes.

A transmission electron microscope (TEM) cross-section of an LEP device on a glass/SiO₂/ITO substrate with a conjugated polymer layer and Al top electrode is shown in figure 3. In the case of figure 3, the conjugated polymer was poly(*p*-phenylene vinylene), PPV. HCl is released during the conversion of the precursor polymer to PPV and this HCl is a potent etching reagent for the ITO. The TEM studies were originally performed to look at electromigration of electrode material into the polymer layer after prolonged operation at high current densities and to look at the ITO–PPV interface. It can be seen that the polymer–Al interface is very smooth and that the roughness in the ITO can be reflected in a variation of the polymer thickness. In addition to this, TEM can also give very useful information on the morphology of the electrodes (see below).

Although less apparent, the macroscopic smoothness of substrates and the bottom electrode is also very important. Small LEP devices for research and development, typically only up to a few cm² large, tend to be fabricated by spin-coating the polymer layers and macroscopic smoothness is not really an issue. When larger scale manufacturing is considered, the methods of choice are, for example, continuous or batch-type blade or meniscus coating but also spin-coating; tolerances on the macroscopic smoothness (‘buckling’) are tighter here. For example, in a typical blade coating process, a dilute solution of a conjugated polymer would be deposited on a 14 inch square and 0.7 mm thick glass/ITO substrate with a substrate-blade distance of about 50 µm to give, after evaporation of the solvent a polymer film thickness of the order of 1000 Å. If the viscosity and shear properties of the polymer solution, its concentration, the substrate-polymer wetting–adhesion properties and the film drying process cannot be sufficiently well matched such that surface tension guarantees a uniform polymer film thickness, then a macroscopic buckling of the substrate of, say, 10 µm can result in intolerable polymer film thickness variations.

(b) Barrier properties

LEP devices, incorporating conjugated organic materials and cathodes which undergo corrosion, must be protected from the ingress of oxygen and moisture. Glass

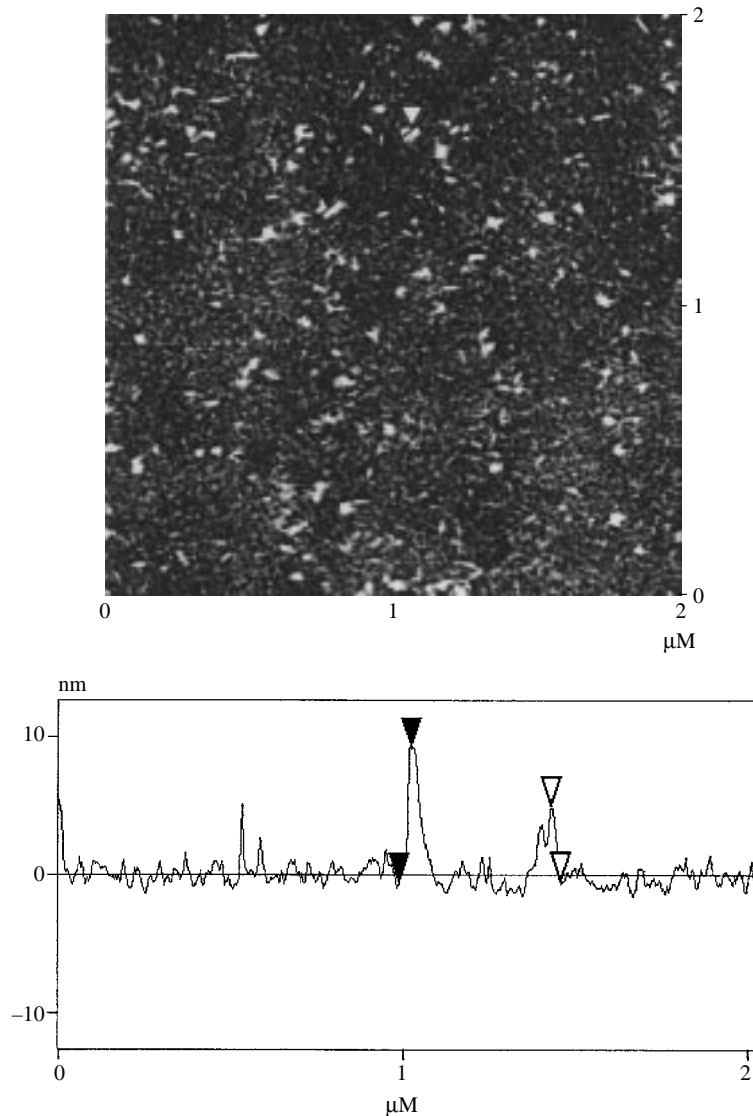


Figure 2. AFM image and line scan of a glass/SiO₂/ITO substrate. The bright spots in the areal image are spikes in the ITO coating. The image was taken with a very fine ‘supertip’ in order to improve lateral resolution.

as a substrate, even when used as thin flexible glass as little as 30 μm thick, is, for all practical LEP purposes, totally impermeable to oxygen and moisture and is thus ideally suited. This, however, throws away some of the key attractive features of the LEP technology, namely flexibility and formability and large scale low cost manufacturing employing roll-to-roll techniques. Although ITO-coated thin, flexible glass is available commercially, its cost, availability in volume and ‘residual’ brittleness impede its use.

The first choice for flexible substrates for LEP devices are, and have been, commercial ITO-coated polymer films such as polyester, PET. We have fabricated LEP devices on commercial PET/ITO which have been in continuous operation for, in

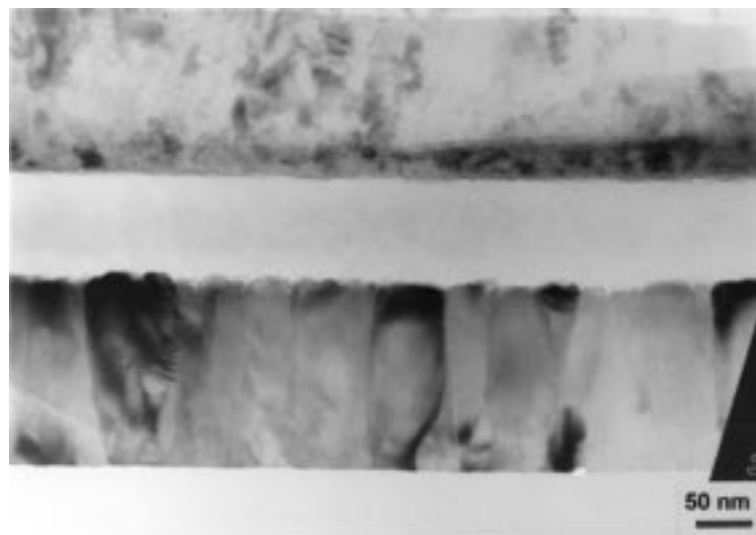


Figure 3. TEM cross-section of a glass/SiO₂/ITO/PPV/Al LEP. The Al is on top.

the best case, over 3000 h. This was achieved by encapsulating the device with glass on both sides to prevent ingress of oxygen and moisture. This, therefore, serves as a proof of principle that plastic LEP devices will have the performance of glass devices if substrates with adequate barrier properties can be found. Our AFM studies have shown that plastic substrates with ITO coatings of sufficient surface quality can be obtained and the ITO sheet resistance and transparency is also good. Great care has to be taken in the handling of the PET/ITO sheets because the thin brittle ITO layer can easily crack on the soft PET. The cracks can increase the sheet resistance, show up as ridges on the ITO surface and provide diffusion channels for ambient oxygen and moisture. By careful processing of the PET/ITO substrates, the problem of washing out low molecular weight compounds and polymer additives from the PET and water and oxygen dissolved in the substrate can be minimized.

The overriding development challenge to using plastic substrates for LEP devices is thus the high permeability for oxygen and moisture. PET itself has relatively high permeabilities for water and oxygen and typical values for PET and other systems are given in table 1. To our knowledge, the best barrier polymers presently available are liquid crystalline polymers, LCPs. We have been investigating PET and several other plastic substrates with thin transparent coatings of dielectrics and metals, including multilayers, and our findings are that carefully handled commercial PET/ITO itself had the best barrier properties. It should be pointed out here that for commercial PET/ITO, the deposition of stress-free/minimized and well-adhered ITO has been optimized.

Very importantly, we have been able to retain, and in some cases even improve, the good barrier properties of PET/ITO after the deposition and conversion of precursor PPV. Any etching or patterning of the ITO on plastic substrates would obviously be detrimental and any additional barrier layers, for example oxide films between the polymer substrate and the ITO, need to be deposited very carefully indeed; otherwise any extra strain during deposition, handling and thermal cycling can trigger cracking in the oxide layers, including the ITO, and result in higher gas transmission, as the examples in table 1 show. This is not only an important issue in the

Table 1. *Oxygen and water barrier properties of some substrate systems*

(The permeability values should only be taken as rough guides (see, for example, Packaging Strategies International, USA, 15 January 1996). The unit for water is $\text{gm} \cdot \text{x}/\text{m}^2 \cdot 24\text{h} \cdot \text{atm}$ and, for oxygen, $\text{cc} \cdot \text{x}/\text{m}^2 \cdot 24\text{h} \cdot \text{atm}$; x is the film thickness given in the table. The thicknesses of the ITO, PPV or SiO_2 coatings is typically of the order of 1000 \AA .)

polymer or polymer + coating	water permeability	oxygen permeability
polyester, PET	~ 10 at $25 \mu\text{m}$	~ 100 at $25 \mu\text{m}$
liquid crystal polymer, LCP	< 0.1 at $25 \mu\text{m}$	< 1 at $25 \mu\text{m}$
PET/ITO	< 0.01 at $175 \mu\text{m}$	< 0.01 at $175 \mu\text{m}$
PET/ITO/PPV	< 0.01 at $175 \mu\text{m}$	~ 0.04 at $175 \mu\text{m}$
PET/ SiO_2 /ITO	~ 0.2 at $100 \mu\text{m}$	~ 0.05 at $100 \mu\text{m}$

cases where the conjugated polymers themselves need a heat treatment; it should be borne in mind that resistance to thermal cycling is required for any product. In the same sense, the thermal expansion coefficient and glass transition temperature of the employed polymer substrate are very important. Contraction of the polymer substrate on outgasing of dissolved volatile compounds, such as oxygen and water, may also be an issue due to the requirement of vacuum depositing a top electrode onto the LEP device.

(c) *Estimates of plastic LEP lifetimes*

We have performed some calculations taking into account the solubility of water and oxygen in PPV and their transmission through a PET/ITO substrate, the reaction rate of PPV with water and oxygen, operation of the device at an efficiency of about 1 lm W^{-1} and driven at a brightness of a few tens of Cd m^{-2} and have assumed that the device is not operational once 50% of the conjugated segments have reacted with oxygen and/or water. Together with the exposure of the device to normal ambient daylight for five years and the absorption of light of energy greater than the band gap of the conjugated polymer in the substrate (use of absorption filters), we estimate that, with respect to oxygen, our best PET/ITO/PPV devices would meet about 3000 h half life. Moisture and its ingress into the device is a more severe problem due to the generally higher permeability of water vapour compared to that of oxygen (smaller size of molecule, polarizability, etc.). To achieve the same device performance when the ingress of water is taken into account, substantial reductions in the overall water permeability are still required. Fortunately, it turns out that the conjugated polymers can be designed and synthesized such that the reaction rate with water, when excited states generated by ambient light or created within the device under operation, can be very substantially reduced (see below). However, even if the conjugated polymers are not susceptible to reactions with water, the protection of the polymer–cathode interface and the cathode itself against corrosion still remains to be solved.

To summarize this aspect of polymer substrates, it seems that plastic LEP devices which meet commercial requirements are presently not yet feasible. On the other hand, many of the engineering issues outlined above have a large unused potential for improvement and optimization. For example, ‘hybrid’ LEP devices in which flexible substrates are used to take benefit from manufacturing advantages could be

fabricated and then laminated to glass. Or, as pointed out above, the quality of additional dielectric barrier layers can be improved much further in respect of adhesion, stress and cracking.

5. Conjugated Polymers for LEP devices

One of the outstanding advantages of the LEP technology is the potential to make use of a wide spectrum of organic and polymer syntheses to design polymeric semiconductors with different functionalities including emission wavelength, transport properties and solubility. This enormous flexibility in the design of the active semiconductors, which is unmatched in the field of inorganic semiconductors, has only been exploited to a small extent but has already resulted in devices giving emission over the whole visible spectrum (see, for example, Burroughes *et al.* 1990; Grem *et al.* 1992; Braun *et al.* 1991, 1994) and, for example, made use of band gap engineering tricks to increase device efficiency (Greenham *et al.* 1993). However, from the synthesis of an electroluminescent semiconducting polymer to an LEP device which fulfills commercial requirements, many more polymer aspects must be taken into consideration.

Melting point and glass transition temperature, as well as intrinsic thermal stability of the organic materials in an LEP device, are important; charge transport and luminescence properties, gas diffusion and solubility, device stability when operated or stored at elevated temperatures and other properties may change as the morphology of the polymer changes. Fortunately, it has turned out that many conjugated electroluminescent polymers, and certainly the rigid planar systems based on the phenylene-vinylene backbone structure, show no significant problems in respect of a strong temperature dependence of the morphology-related properties. General temperature dependent morphological effects in the active organic layers are particularly important when blends are used (phase separation, etc.). For example, it is well known that oxadiazole compounds in a polymer matrix placed under the cathode can dramatically increase LEP device efficiencies, but at the same time the morphological instability (recrystallization) of this layer makes it practically useless for commercial products.

Furthermore, there are several general synthesis aspects to be considered. For instance, purity issues are paramount—e.g. a certain amount of catalyst residual can be irrelevant for device performance whereas the same residual amount of a different catalyst can be detrimental. It is a feature of the technology that, due to the thinness of the polymer layers, materials requirements are very low indeed; for example, *ca.* 1 lit of a *ca.* 0.4% solution, i.e. only about 5 g of conjugated polymer, would be sufficient to coat 5–10 m² with *ca.* 1000 Å of polymer, economic blade coating and *ca.* 50% wastage of material taken into account. The importance of the rheological properties of the polymer solutions to achieve uniform coatings has been indicated above.

Above all of the already mentioned required polymer ‘engineering’ properties stands the requirement of conjugated polymer stability in the presence of high concentrations of singlet and triplet excitons, positive and negative charged states and radicals during device operation and storage ‘on the shelf’ and at different temperatures and humidities. In this respect, the stability against reactions with oxygen and moisture, as well as the polymer solubilities and permeabilities for oxygen and moisture, are very relevant. First, the polymers have to be intrinsically stable in

the absence of oxygen and moisture. Second, the polymers should have low solubilities and permeabilities for, and low reaction rates with, oxygen and moisture. In this sense, for example, it would be better to have very compact, more crystalline polymers; these, however, tend to have lower luminescence efficiencies.

The area of polymer stability and polymer degradation is much too wide to discuss here in detail. We would only like to point out that one should not forget that common knowledge in this area is normally confined to thermal and photostability and therefore it is not taken into account that conjugated polymers in LEP devices are, in addition, subject to high concentrations of charge carriers, i.e. undergo reduction and oxidation at a very high rate.

6. General electrode issues, cathode top electrode

Needless to say that the choice of the electrodes and, in particular, given that transparent conducting inorganic oxides such as ITO or SnO are obvious choices for the anode, the top electrode (cathode) is very important. The first relevant parameters are the work function and reactivity of the electrodes, as well as the ability to use a simple deposition process.

This really is only a small list of relevant electrode issues. The work function has to be stable under operation and on the shelf, i.e. any long term interface reactions and segregation effects can change the effective work function (carrier injection) over time and hence change the electrical device characteristics. Electrodes have to adhere well (and polymers have to adhere to electrodes) otherwise delamination and interface diffusion can be a problem. Silver, for example, is used to improve the adhesion properties of magnesium in organic light-emitting devices (Tang, this volume). The adhesion between electrodes and adjacent polymers depends also very much on the way surfaces are prepared/cleaned/treated before electrode deposition and on the deposition process itself.

Corrosion of the electrodes and, in particular, the lower work function cathode and issues such as catalytic reactivity and electrochemistry with the adjacent polymer layer are extremely important, as is electromigration or doping and diffusion of the electrode material into the adjacent polymer layer (Salaneck, this volume). Alloys and inter-metallic compounds of low work function elements with more stable metals can be used, but in this case the deposition process itself, as well as metallurgy, phase separation and surface segregation, should be carefully considered.

The deposition process of the electrodes, in particular the top electrode/cathode, also has interesting engineering aspects to it. To give a simple example; a standard evaporation of Al onto an LEP device in a standard laboratory, i.e. no clean room, will often lead to films full of small pin-holes which can be readily seen by holding the device in front of an intense lamp. As discussed, this may easily lead to growing black spots. Putting a little drop of water onto the top electrode or to its edge under a microscope can give very useful clues as to what can happen in respect of pinholes and adhesion.

The morphology of the electrode films can also be very important as it will influence microscopic diffusion, sheet resistance, etc. Figures 4*a, b* give examples of this. Figure 4*a* shows a TEM image of a film of evaporated Al (thermal evaporation at about 2×10^{-6} mbar at a rate of about 5 \AA s^{-1} , with the substrate at room temperature). The film is about 1000 Å thick and it can be seen very clearly that the average grain size of the aluminium is of the same order; therefore, there exist many

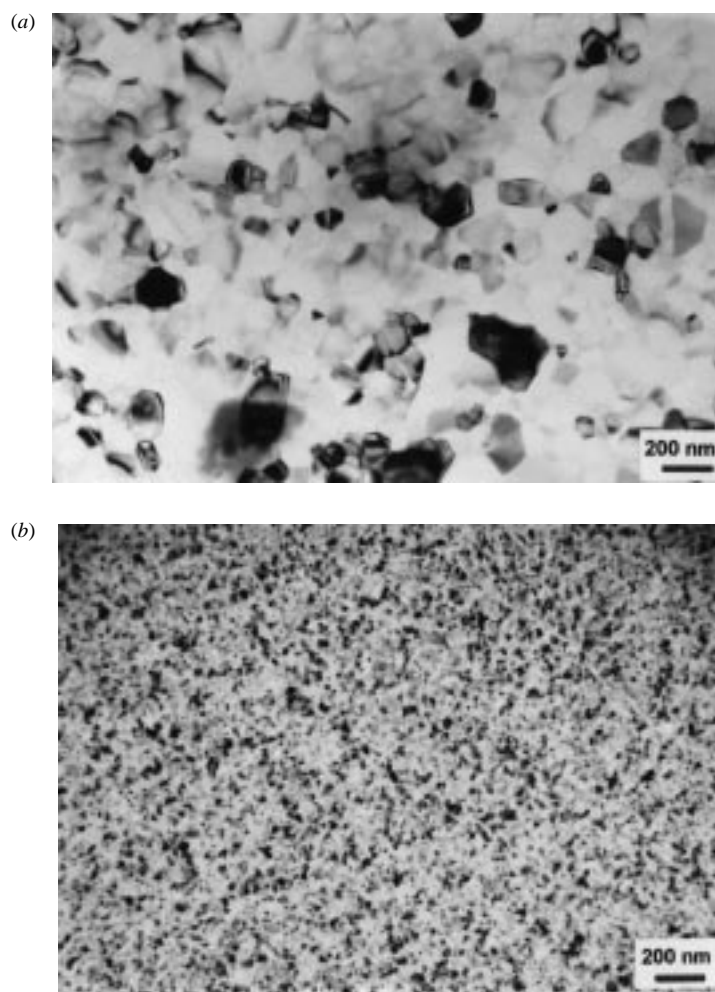


Figure 4. (a) TEM micrograph of an evaporated Al film on PPV. (b) TEM micrograph of a sputtered Al film as deposited onto PPV.

effective diffusion channels for ambient gases to penetrate to the polymer–cathode interface. A TEM image of another aluminium film which has been improved in this respect is shown in figure 4*b*. This film is much more compact.

7. Some stability data on precursor poly(*p*-phenylene vinylene)

We have been intensively investigating poly(*p*-phenylene vinylene), PPV, prepared via the precursor route, as an active charge transporting and light-emitting layer in LEP devices. PPV has some very attractive features. The basic synthesis is reasonably straightforward, monomer synthesis and availability of catalysts are not a problem and good purification methods exist. The precursor has advantageous rheological, viscosity, wetting and adhesion properties. For example, we have been able to coat large areas (so far about $20 \times 30 \text{ cm}^2$, limited only by the size of our present equipment) with high viscosity and low concentration precursor solutions and achieved very uniform film thickness after thermal conversion. Water or alcohol-based sol-

vents can be used for the precursor. PPV is insoluble, intractable and infusible and temperature stability is not an issue; this also makes it amenable for use in multilayer devices.

At CDT, we have been developing a proprietary precursor PPV which can be converted at greater than or equal to 150 °C (therefore it can be used with a range of plastic substrates) in gas atmosphere and the conversion time is in the range of tens of minutes to a few hours. These conversion conditions have not yet been optimized and we believe that they can be relaxed much further. This precursor gives us a form of PPV which has a photoluminescence efficiency of 50–60% with yellow–green emission.

The figures 5*a–c* show some photostability data of this PPV, measured as change in optical absorption. All measurements were performed on plain PPV films on glass substrates with the PPV (unencapsulated) placed straight under an intense fluorescent tube (*ca.* 4000 Cd m⁻², including UV light) at room temperature and in a controlled atmosphere.

Figure 5*a* shows that this PPV is intrinsically very stable, i.e. there is no photodegradation in the absence of water or oxygen. Often, photoluminescence is a more sensitive measure of polymer degradation. Figure 6 shows the photoluminescence over time of a film of PPV similar to those in figures 5, but encapsulated and illuminated at 65 °C in air; this film has now been looked at for over 20 months and, as can be seen, there is no observable change in the photoluminescence over time. When we expose films such as shown in figure 5*a* to light in the presence of either moisture or oxygen or both, there is rapid bleaching of the conjugated polymer, with oxygen being more effective in attacking the conjugated polymer backbone. For example, the film in dry air and under the same light conditions would bleach to about half of its original peak absorption value in about one day and the same degree of bleaching in moist nitrogen (no oxygen) would take about 10 days.

The photodegradation in dry air is dramatically reduced when external light above the band gap of the polymer is excluded/minimized by using a cut-off filter in front of the PPV (this is the situation in an operating LEP device in which internally created light is of energy below the band gap and in which ambient high energy light is blocked by a filter in or on the substrate). Figure 5*b* demonstrates this; the remaining photooxidation is likely to be due to residual above band gap light leaking through the cut-off filter. Figure 5*c* shows the equivalent experiment, i.e. use of a cut-off filter, but with moist nitrogen. Such types of experiments are very useful indeed in order to get an understanding of potential degradation mechanisms of conjugated polymers, combined obviously with other techniques such as IR spectroscopy.

Using PPV prepared by the same precursor route in simple ITO/PPV/cathode single layer devices (which we often use to look at polymer stability in device conditions), we could show that the polymer can also withstand high current densities in continuous operation for many thousand hours.

Figure 7*a* shows an ITO/PPV/Al device which was fabricated and encapsulated and is driven in normal laboratory conditions, i.e. in air. The device is driven in constant current mode (DC) at about 30 mA cm⁻², at about 3 V and outputs about Cd m⁻². The device is still running and it is apparent that all voltage, current and light output are very stable. Although the efficiency of this device and its brightness is not high, it demonstrates clearly that high current densities can be sustained without degradation of the polymer itself and the polymer–electrode interfaces. A similar device, but with Ca as the cathode, is shown in figure 7*b* and again the device

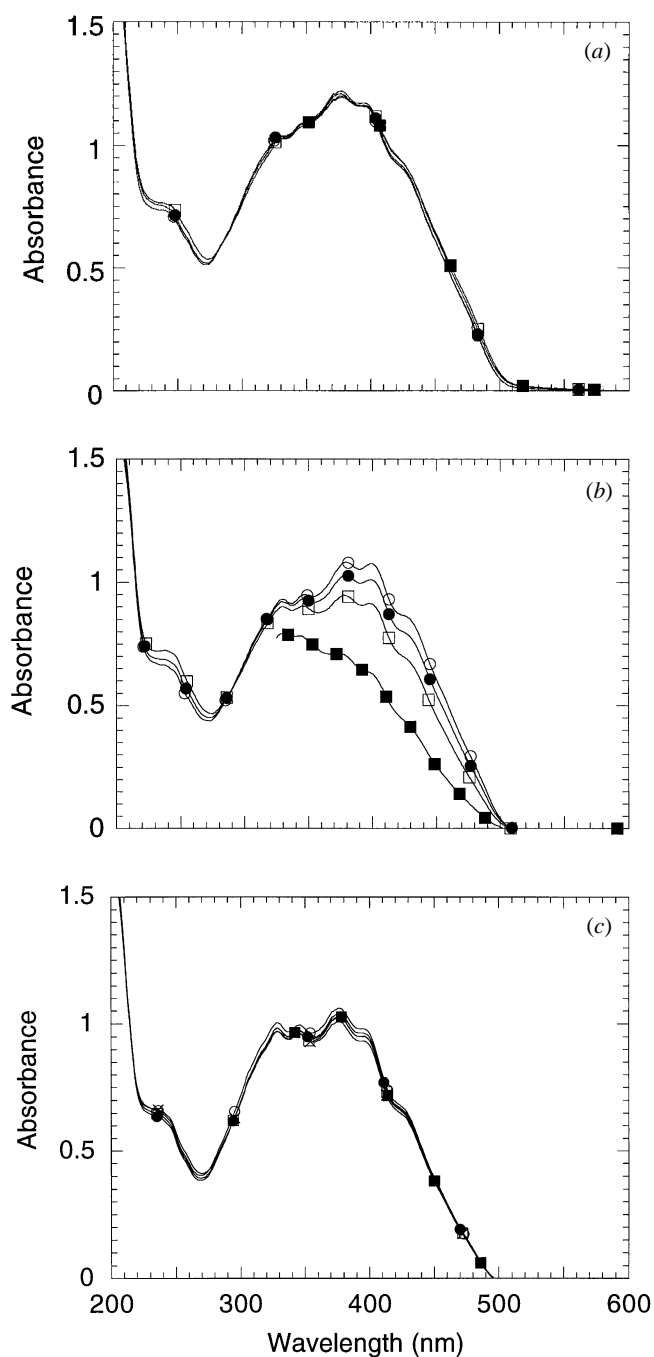


Figure 5. Absorbance of an un-encapsulated PPV film in dry nitrogen, at room temperature and exposed to unfiltered light from a high intensity fluorescent lamp. The different spectra were taken over a light exposure period of 62 days. (b) As in (a), but with oxygen and a 500 nm cut-off filter between the lamp and the PPV. The spectra were taken at zero (open circles), 5 (full circles), 14 (open squares) and 26 days (full squares) of light exposure. (c) As in figure 5a, but with moisture and 500 nm cut-off filter between the lamp and the PPV. The spectra were taken over a period of 35 days.

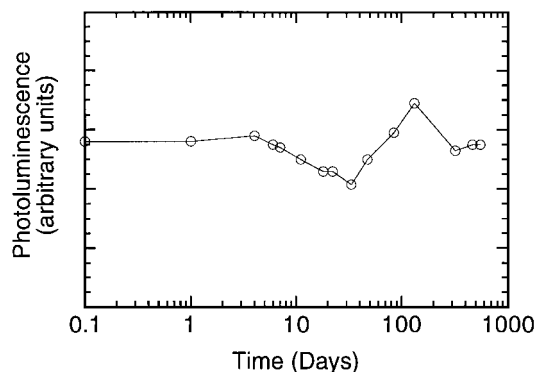


Figure 6. Photoluminescence of encapsulated PPV over time with the film in air, at 65 °C and placed under a high intensity fluorescent lamp. The kink is an artefact of the photoluminescence measurement.

is very stable and still running (in air, encapsulated). There are no observable signs of a decay of the cathode; emission is completely uniform to the eye and the few dark spots are microscopic, indicating the integrity of the encapsulation.

We currently have of the order of fifty other devices running encapsulated in air in the range of 1000–5000 h of continuous operation; at different temperatures, current densities, voltages or currents, driven at different current densities and brightnesses (presently up to about 100 Cd m⁻²) and DC or pulsed at different duty cycles. All this work has not yet shown up any intrinsic limitations in the technology with respect to operating and shelf life. In fact, the normal failure mechanism of our ‘good’ devices is an abrupt shortage or burn-out which we believe is almost certainly due to imperfect processing, say, for example, a spike in the ITO, some local polymer impurity or top electrode imperfection.

8. Summary

Although the discussion above outlined several of the many issues to be considered for the fabrication of commercially viable LEP devices, it has also been demonstrated by examples that these problems can indeed be solved. We have presented LEP devices which are still running very stable beyond 6000 h of continuous operation and have not been able to identify any major technology hurdles. In addition to the work presented here, there have recently been several public reports of stable LEP device operation of greater than 2000 h in air (see, for example, Yang 1996; Staring, this volume). Many basic aspects of the technology have been addressed and solved and it is now time to put a strong emphasis on the ‘engineering side’ of the technology.

The author would like to point out that since the Discussion Meeting was held, very considerable improvements in the light-emitting polymer field have been achieved. For example, the device shown in figure 7*a* is now running at about 11 000 h, still without any observable signs of decay. Devices of the type shown in figure 7*b* have been running up to greater than 7000 h without decay. More importantly, device efficiencies of several lm W⁻¹ with brightness well above 100 Cd m⁻² at drive voltages of less than 4 V are now regularly achieved in red and green emitting devices and with operating lifetimes well in excess of 1000 h. These more recent advances by Cambridge Display Technology and other groups do indicate very clearly that the

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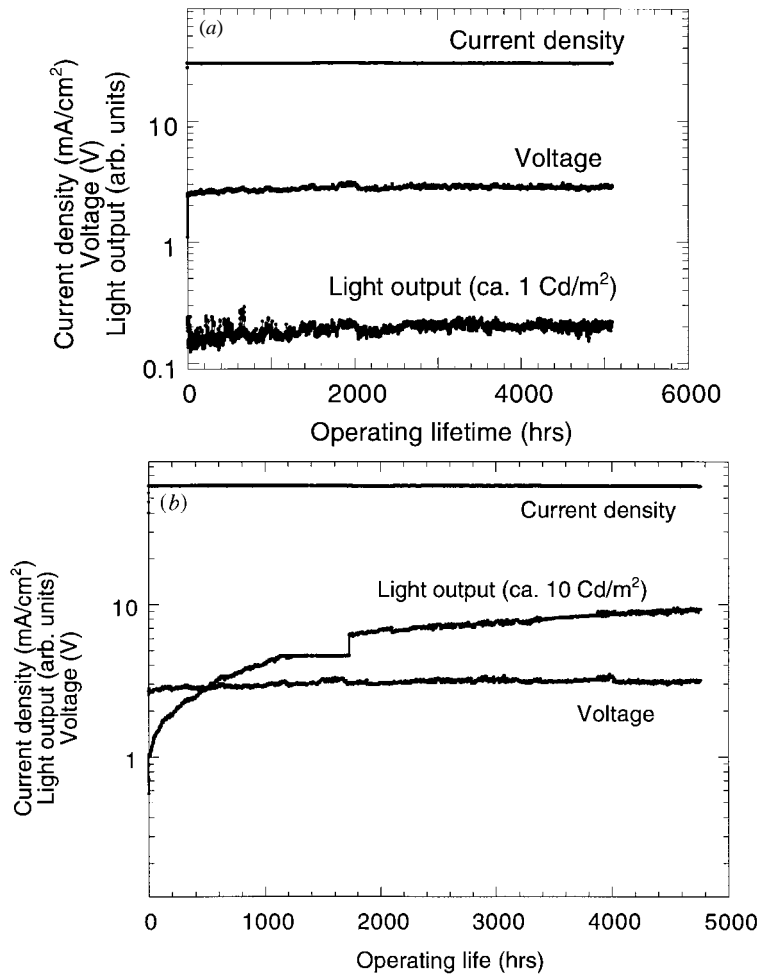


Figure 7. (a) Current density, voltage and brightness over time of a glass/ITO/PPV/Al device. The device was fabricated and encapsulated in air and is driven in DC mode in air. The device is now running at greater than 6000 h. (b) Current density, voltage and light output over time of a glass/ITO/PPV/Ca/Al device. The device is encapsulated and is driven in DC mode in air. The kink in the light output around 1500 h is an artefact of the measurement. The device is now running at greater than 6000 h.

light-emitting polymer technology will be a serious contender in the display and sign markets.

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Discussion

D. D. C. BRADLEY (*Department of Physics and Centre for Molecular Material, University of Sheffield, UK*). Dr Pichler has described the ability to perform standard photolithography on precursor-route poly(phenylene vinylene) films. We have demonstrated that the technique may also be used readily to pattern micron scale features on top of dialkoxy phenylene vinylene polymers. It thus appears that polymers generally are accessible to this method of device fabrication. Would he please comment on this?

K. PICHLER. I do fully agree with Professor Bradley's view that conjugated polymers are accessible to photolithography for device fabrication and patterning and the results his group has achieved with a soluble dialkoxy phenylene vinylene polymer in this respect is very impressive. However, we do believe that the insoluble PPV obtained via a precursor route has additional advantages due to its much reduced interactions with wet chemicals which are generally used in lithography. We have clear indications, therefore, that standard photolithographic techniques can be used in conjugated polymers devices, whereas it is widely believed that the equivalent organic light-emitting devices using sublimed molecular films are not, or much less, compatible with lithography.

A. VECHT (*School of Chemical and Life Sciences, University of Greenwich, UK*). In view of the considerable press publicity that organic EL panels have received, and although we fully realize that the claims made that the organic EL will replace the cathode ray tube are unrealistic, would Dr Pichler like to predict when the relatively simple 1000 character displays will be available on the market?

K. PICHLER. One of CDT's current demonstrator devices is a 16 × 16 pixel dot-matrix display. These can be made quite reliably and in a low-cost process. Unfortunately, I am not able to tell you reliably when such LEP displays will be on the market.