Organic Light-Emitting Devices for Solid-State Lighting

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Abstract

Organic light-emitting devices (OLEDs) have been widely developed for flat-panel displays, but only recently the efficiency of white OLEDs has risen to the point where they can be considered for solid-state lighting (SSL) applications. In this review, we discuss the requirements of solid-state lighting as they relate to OLEDs. We focus on how the color, efficiency, and cost requirements of general illumination differ from those of displays and how these differences might have an impact on the design of organic SSL. We then present some recent developments in large-area fabrication techniques that might be appropriate for solid-state lighting applications. Finally, we review recent results in the development of organic materials, device architectures, light extraction schemes, and fabrication techniques that can lead to cost-effective OLED lighting.

Introduction: The Potential for OLED lighting

The development of organic light-emitting devices (OLEDs) has a long history. Electroluminescence from small-molecule OLEDs was reported 45 years ago[1] and that from polymer OLEDs 25 years ago.[2] It was the development of thin-film heterojunction devices using molecular materials[3] that rekindled interest in the field in the late 1980s, and it was the ability to fabricate large-area devices with high yields that led to the more recent widespread commercialization of OLEDs in displays. The rapidly accelerating deployment of OLED displays in portable electronic devices and the introduction of an 11-in.-diagonal, 3 mm-thick OLED television[4] indicate that many of the manufacturing issues are finally under control.

A flat-panel display requires high-resolution patterning of red, green, and blue light with good efficiency and color saturation at a brightness of ~200 candelas per square meter (cd/m^2). The possibility of making OLED displays extremely thin is a further advantage over liquid-crystal displays, which are their main competition but which require polarizers, a backlight, and color filters in addition to the image-generating layer. Because the total thickness of the light-emitting organic layers and electrodes is only a few hundred nanometers, the minimum thickness of an OLED is limited only by the thickness of substrate and encapsulation that will result in mechanical robustness.

For portable devices, however, improved display efficiency also leads directly to longer battery lifetime, and achieving the highest possible efficiency is therefore very important. This has led to green OLEDs with an efficacy well in excess of 100 lumens per watt (lm/W) and operating lifetimes projected to be 100,000 hours. Although such numbers still lag behind the achievements of white inorganic LEDs based on InGaN, the improvement in OLED efficiency with time has been remarkably steep, and there seems to be no fundamental reason why 150 lm/W OLEDs should not be achievable. It is these results that have inspired major lighting companies worldwide[5] and the U.S. Department of Energy[6] to turn their attention toward the energy-saving potential of organic solid-state lighting (SSL).

The figures of merit for a lamp, however, are far different from those relevant to flat-panel displays. Whereas an excellent display can be constructed using three monochromatic emitters, a high-quality light source must accurately render *all* colors that it illuminates. This requires a broad spectrum similar to that emitted from a blackbody across the visible spectral range. This color-rendering ability is quantified in the color-rendering index (CRI). Total lumen output, not brightness per unit area, becomes an important figure of merit. A typical office lighting fixture emits about 5,000 lm, which corresponds to about 1,600 cd from a Lambertian emitter (that is, one that obeys the cosine law of emission, so that it has the same apparent radiance when viewed from any angle). The optimal angular distribution of the light output depends on the application: general illumination requires a broad "batwing" distribution, whereas task lighting or spotlights call for a narrower beam of light. Regardless, unless the brightness at which OLEDs have long operating lifetimes (typically 1,000 cd/m^2) increases by several orders of magnitude, it is difficult to project OLED lighting to be anything other than a large-area (~1 m^2) product. In all but niche applications, such a product will need to sell profitably for a few dollars. This is in stark contrast to inorganic LEDs, which are made from small chips of expensive materials. These form point light sources that are usually assembled into multichip packages to provide sufficient light output and need external diffusers to prevent glare.

A successful OLED product that improves the efficiency of general illumination will therefore likely be of low profit margin but very high volume, in terms of both unit shipments (the U.S. market alone is currently about 2 billion lamps per year) and volume of component materials (as each lamp will be of relatively large area to achieve a usable lumen output). Niche products with lower lumen output or relatively short lifetimes could still be commercially lucrative but would not have a significant positive impact on, and could even increase, the overall energy consumption of lighting. Cost limitations on everything from materials and deposition processes to encapsulation and packaging will inevitably be extremely challenging, and it is here that organics have a key advantage: Produced in sufficient volume, the carbon-based materials and noncrystalline substrates that comprise an OLED *should* be amenable to low-cost manufacturing. Different materials and device designs will be required for success in such a demanding field, thus providing significant new opportunities for leadership in materials science.

Requirements for Lighting

There is enormous commercial potential for SSL across a range of lighting

sources, but the highest energy impact lies in general illumination, which consumes more than 20% of the electricity generated in the United States. General illumination requires good quality lighting, which is primarily described by three parameters:

- The lumen output indicates the luminous flux. A 100-W incandescent lamp emits ~1,500 lm. A standard office fixture containing four fluorescent lamps behind a diffuser emits ~5,000 lm.
- CRI is an arbitrary measure of the ability of a light source to reproduce the true color of objects being lit by the source. Blackbody sources such as incandescent lamps have CRI values close to 100, whereas monochromatic sources such as low-pressure sodium lamps have CRIs approaching zero (although they can achieve an efficacy of 200 lm/W). A source with a CRI of <70 is unacceptable for interior lighting applications.
- The correlated color temperature (CCT) is the temperature of a blackbody spectrum closest to the color of the light source. The CCT of incandescent light bulbs is ~2700 K, called "warm white." A higher CCT, called "cool white" because it includes more blue light, is less desirable because it is not what the consumer is used to seeing, even if it achieves a high CRI.

Incandescent lamps are still commonly used for residential lighting because of their low price and high lighting quality, despite their low efficiency, which results from the use of a heated filament to generate light. In contrast, OLEDs generate light with a color defined by the exciton energy characteristic of the molecular emitter. Achieving high-CRI white light generally requires the use of two or more light-emitting molecules emitting at different wavelengths, either co-doped into a single layer or vertically stacked in multiple light-emitting layers. Either architecture adds complexity to an OLED lamp but also provides the flexibility to tune the color temperature of a lamp by controlling the relative intensity of the emitters used. The CRI of such a white OLED can easily exceed 90.

Most importantly, in OLEDs, light is generated by the radiative decay of excitons with very little associated heat, whereas conventional lighting technologies all use energetic routes such as high temperature or plasma (in the case of fluorescent lamps) that generate light only as a by-product of the primary excitation process. Table I provides a summary of existing lighting technologies. It should be noted that Universal Display Corporation has recently demonstrated a white OLED with a projected lifetime of 100,000 hours at 30 lm/W. Although the table represents the best data that can be gleaned from the literature, there are no industry standards for the testing of organic lighting, so reported values can vary widely. It is also possible to dramatically increase the efficacy of a white light source by reducing the CRI below the optimum.

Based on laboratory results, organic SSL can clearly achieve sufficient lighting quality for general illumination. Affordability might be a more challenging goal. Although the cost of ownership is an appropriate economic metric for judging the cost of lighting, it is safe to assume that few consumers will pay more than a few dollars for a light bulb regardless of its efficiency. No organic SSL is currently on the market, and to achieve commercial viability, it must therefore be cost-competitive with other forms of lighting. Figure 1, an example of this moving target, shows the evolution of lumens per module and cost per lumen for *inorganic* LEDs. With the improvement in luminous efficacy of these devices over the past four decades, the cost has diminished from $20/lm to about 1¢/lm today. Although a 1,500-lm (100-W) incandescent light bulb can be purchased for less than 50¢, representing a cost per lumen of <0.03¢, the higher efficiency and operating lifetime of LEDs already make them more competitive than their purchase price would suggest. Given the increasing worldwide emphasis on energy efficiency, the future of inefficient conventional lighting seems somewhat dim. (For example, several countries have already introduced legislation to ban the sale of incandescent lamps.) To compete with other replacements such as LEDs, however, the luminous efficacy of white OLEDs clearly needs to be above 100 lm/W, and the cost must be below 1¢/lm.

To put this requirement in the context of an OLED lighting panel, if we assume that the published[5] luminous efficiency of 64 lm/W can be manufactured as a 1-ft^2 (0.09-m^2) panel operating at a brightness of 4,000 cd/m^2, the flux per panel would be 1,200 lm, assuming a Lambertian light distribution. A reasonable cost point for such an OLED panel to achieve significant market penetration would therefore be

Table I: Summary of Lighting Technologies.

Light Source	Efficiency (lm/W)	CRI	Lifetime (h)
Incandescent lamp	10–15	>90	1,000
Fluorescent tube	40–80	70	10,000
High-pressure sodium lamp	140	<10	10,000
Light-emitting device (LED)	>80	80	>10,000
Organic light-emitting device (OLED)	65	>90	10,000

Note: CRI is color rendering index.

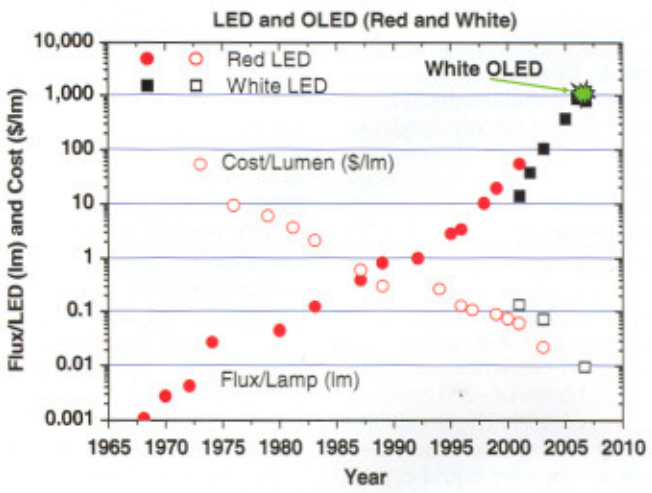


Figure 1. Flux per module and cost per lumen for inorganic LEDs over time. The data point for white OLED is based on a 64 lm/W panel emitting at 4,000 cd/m^2 and shows the marketplace challenges faced by OLEDs. *Note:* No cost per lumen point exists for LEDs because such lighting products have not yet been manufactured.

below $10. This requirement directly leads to limitations on OLED SSL materials and designs. For example, display-quality glass is too expensive to be a suitable substrate material. Very low-cost float glass might be an option if the surface quality and impurity diffusion could be cheaply controlled. Plastic is similarly too expensive once requirements for dimensional stability, glass transition temperature, and extremely low moisture permeability are taken into account. Batch coating techniques, whether using vacuum sublimation or solution-based methodologies, are unlikely to achieve the high throughput required. A fast, continuous coating process must be developed. Roll-to-roll coating seems to be an ideal fit here, but any technique capable of coating large areas with a short cycle time should be considered.

Most OLED development to date has been targeted at relatively high-value-added flat-panel displays. The unique requirements of SSL demand a different approach but also create opportunities for OLEDs to dramatically lower the manufacturing costs:

- A significant portion of the cost of an OLED display lies in the active-matrix backplane. A lamp does not need one.
- High-resolution patterning is not required. Some pixilation of the large area required to generate >1,000 lm will likely be necessary to achieve a good yield, but this will be on a scale orders of magnitude greater than that needed for a display.
- The saturated colors required in displays, which are challenging to achieve given the broadening effects of intramolecular phonons in organic molecules, are not needed; in fact, broad spectra are ideal.
- The most efficient OLEDs emit green light, the spectral region in which InGaN semiconductor devices suffer their lowest quantum efficiency. The "warm" white that consumers expect from a lamp uses more of these wavelengths, where OLEDs achieve their peak efficiency, and relatively little blue light, which remains the weak area of the OLED spectrum.
- OLEDs require minimal power conditioning because they behave more like bulk resistors than true diodes. (A current-limiting circuit will still be required.) They can therefore operate from high-voltage ac household supply by connecting several devices in a series, whereas LEDs require low-voltage dc power conversion.
- A lamp can tolerate dark spots and defects because it is rarely observed directly; only the lumen maintenance with respect to time is important. In contrast, a single dark spot can ruin a display. This could reduce the strict yield requirements set by display manufacturing.
- Top-emitting OLEDs on low-cost metal-foil substrates have already been demonstrated. The materials cost per unit area is low, in contrast to that of InGaN LEDs, which must be grown on crystalline sapphire or SiC.

Leveraging the lessons learned in OLED display manufacturing could substantially reduce the development time of OLED SSL. Compared to a projected worldwide market for flat-panel displays of ~76 million m^2 per year, the two billion light bulbs sold each year in the United States alone represent a potential market volume, which—even at a low profit margin—should provide a powerful incentive for both science and business to address the new set of constraints and opportunities presented by the specific demands of the lighting market.

White-Light Architectures for Organic SSL

There is really no such thing as a correct "white" light; the CCT of even "natural" sunlight can vary from <3000 K at sunset to >10000 K for a clear blue sky. All solid-state white-light devices, both organic and inorganic, currently use one of two approaches to generate a broad, white-light spectrum (Figure 2):

- a combination of two, three, or even four single-color subelements, either side by side or in a vertically stacked geometry; or
- a blue or ultraviolet device that stimulates fluorescence or phosphorescence in other materials, the combination of which leads to white light of acceptable quality.

Both of these approaches have advantages and challenges. The subelement approach adds complexity to the device that will likely increase cost, whereas the single blue device coupled to a downconversion phosphor promises a simple structure but gives up efficiency to the Stokes shift in the downconversion process. Furthermore, blue OLEDs currently have shorter lifetimes than green or red emitters. Stacked or laterally patterned, multicolor devices can achieve the highest possible efficiency while also allowing user control of lighting color. The combination of many relatively narrow spectra can come close enough to an ideal blackbody spectrum to give very high efficiency and CRI. Active control of the color elements might be necessary, however, to compensate for differential aging caused by the different operating lifetimes of different colors. Although it is also possible to create a white OLED by combining three dopants in a single layer, very careful control of dopant concentrations is required to prevent transfer of all of the exciton energy to the longest-wavelength emitter, and the advantage of independently addressable color components is lost.

Materials for Organic Solid-State Lighting

The materials challenge for OLEDs to obtain the efficiency required for general

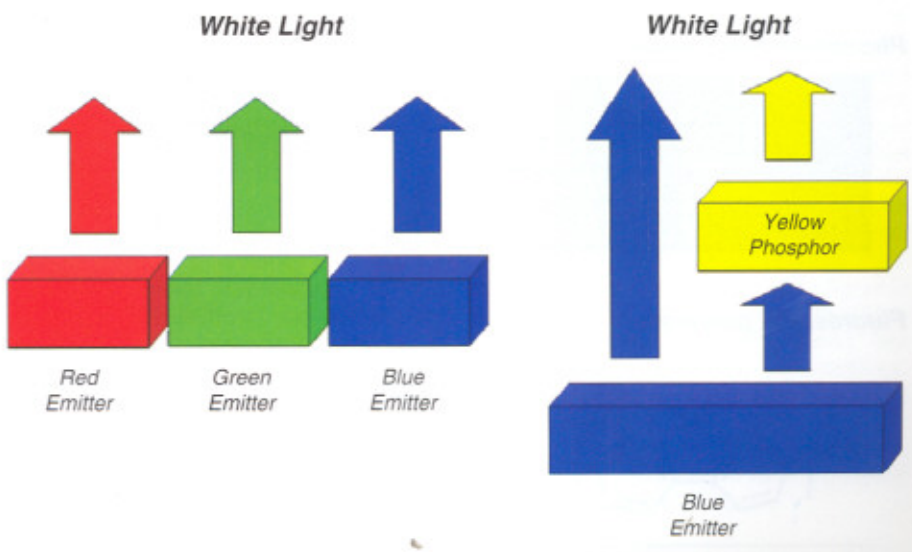


Figure 2. Two approaches to generating white light from an OLED: direct combination of red, blue, and green light (left) using either lateral patterning or vertical stacking of three emitters, partial downconversion of blue light (right) using fluorescent or phosphorescent layers on the substrate.

illumination can be simply stated: to achieve close to one photon generated per electron injected with no large barriers to charge injection and transport. The first low-voltage OLEDs[6] consisted of merely an organic bilayer sandwiched between an anode and a cathode, but to achieve the target efficiency for lighting, many more layers are required, most of which are now composed of at least two and possibly more[7] different materials.

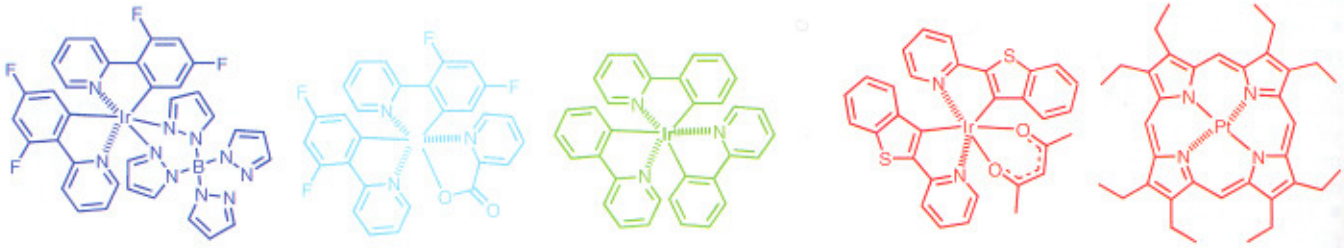
The optical properties of organic semiconductors are dominated by strongly bound excitons. In contrast to inorganic semiconductors, therefore, the spin of injected charge carriers is important, as quantum mechanical factors allow only excitons with zero net spin to radiatively recombine. If simple spin statistics apply, only 25% of the excitons generated by electrically injected charges can give rise to light. This is because the ground state of most organic materials consists of a pair of electrons with zero net spin. Random injection of electrons and holes into an organic semiconductor yields only 25% of excitons with opposite spins on the constituent electron and hole.[8] These "singlet" excitons can directly recombine to give light without violating spin conservation rules. The remaining 75% of the excitons are in high-spin "triplet" states, and direct recombination to the ground state is therefore forbidden by the conservation rules of quantum mechanics. Triplet excitons are therefore usually nonemissive.

Phosphorescent organic small molecules[9] incorporate a heavy metal ion that couples with organic ligands,[10] resulting in a metal–ligand charge-transfer state. Excited states in these molecules retain enough metallic characteristics to enable spin selection rules to be violated, leading to OLEDs with 100% *internal* quantum efficiency (IQE). Figure 3 shows some common high-efficiency small-molecule and conjugated-polymer emitters for OLEDs. External quantum efficiencies of around 20% have already been experimentally demonstrated in green[11] and blue-green[12] devices and more recently in the aforementioned white devices.[15,17] The difference is that IQE is defined as the number of photons generated in the light-emitting layer per electron injected whereas EQE is the number of photons that escape from the device per electron injected. Total internal reflection and waveguiding effects in the substrate and organic layers account for most of the difference.

In a simple planar device, the light coupled out is only about 20% of the total, and the demonstrated EQEs of 20% therefore already represent close to 100% IQE. It is relatively simple to increase the outcoupling by up to a factor of two using simple roughening or laminated microlens techniques, but getting close to the 100% outcoupling efficiency demonstrated in inorganic LEDs (achieved by removing the substrate and shaping the die) is not yet feasible. Doing so over large areas at low cost is yet more challenging.

Significant challenges also remain, moreover, in maintaining such a high IQE at the high brightness required for general illumination, where multiexciton quenching effects become significant. These effects can be lessened by vertically stacking multiple devices of each color, thereby increasing the brightness at a given drive current.[13]

Minimizing the operating voltage of an OLED requires the addition of a charge-transfer dopant to increase the charge-carrier density in an organic layer.[14] This can both increase the conductivity of the



Phosphorescent small molecules

Fluorescent polymers

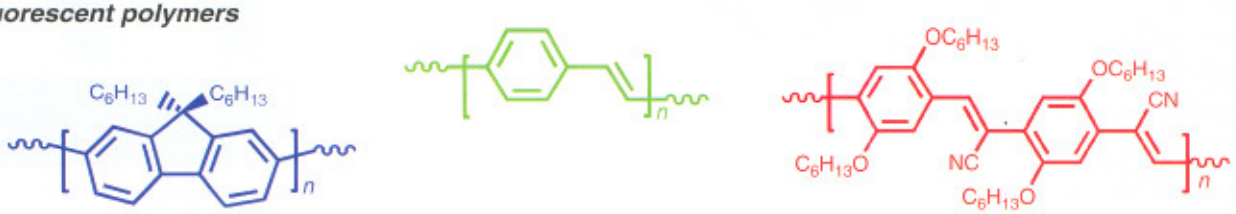


Figure 3. Common small-molecule and polymer emitters for OLEDs. Phosphorescent small molecules (top) from left to right: bis(2-(4,6-difluorophenyl)pyridinato-N,C$^{2'}$)tetrakis(1-pyrazolyl)borate iridium(III), bis(2-(4,6-difluorophenyl)pyridinato-N,C$^{2'}$)picolinate iridium(III), *fac*-tris (2-phenylpyridinato-N,C$^{2'}$) iridium(III), bis[2-(benzo[*b*]thiophen-2-yl)pyridinato-C^{3},N]acetylacetonate iridium(III), and 2,3,7,8,12,13,17,18-octaethyl-21H,23H-porphyrin platinum(II). Fluorescent polymers (bottom) from left to right: poly(9,9-dihexylfluorenyl-2,7-diyl), poly(*p*-phenylene vinylene), and poly(2,5-di(hexyloxy)cyanoterephthalylidene).

organic layers and set up interfacial dipoles between layers to facilitate charge injection. Laboratory results, however, show that bright devices operating barely above the bandgap voltage of the light-emitting molecule are indeed possible. Most approaches that increase the device efficiency, however, also increase the device complexity, which again pushes against the cost constraints of general lighting

Conjugated polymers have also been used to make OLEDs. High-resolution displays using polymers have been demonstrated by companies such as Seiko Epson and DuPont. A typical polymer OLED device consists of an indium tin oxide (ITO) anode, a hole-injection layer such as poly(3,4-ethylenedioxythiophene) (PEDOT) oxidatively doped with poly(styrene sulfonic acid) (PSS), a light-emitting polymer layer, and a low-work-function cathode. Because polymer devices in general do not have carrier-blocking layers to confine the injected carriers, imbalanced transport will lead to the creation of a recombination zone at either the cathode or anode interface, resulting in luminescence quenching. Balanced transport in polymer OLEDs requires extreme care to control the charge injection and transport by chemistry and is often difficult to achieve. Today, the best polymer OLEDs have performance comparable to that of the best fluorescent small-molecule devices.

Compared to phosphorescent small-molecule devices, however, the efficiency of conjugated-polymer devices is significantly lower. Because of their low triplet energies, most conjugated polymers are not suitable for phosphorescent light-emitting devices. Recently, several groups have made solution-processable OLEDs by dispersing small-molecule dyes into a nonconjugated-polymer binder such as poly(vinylcarbazole) (PVK). External quantum efficiencies greater than 10% have been achieved. Specifically, high-efficiency blue-emitting devices have been demonstrated by dispersing blue phosphorescent dyes along with an electron-transporting moiety into a PVK binder. The balance of transport in dye-dispersed polymers can be tuned by controlling the number of electron- and hole-transport moieties in the polymer binder. By tuning the electron-transport properties of the polymer blend, the current efficiency can be increased from about 2 cd/A to 23 cd/A.[15] This example shows how the balance of carrier transport affects the OLED device performance. With a downconversion phosphor layer, the device emits white light with a luminous efficiency of 25 lm/W. This approach might be interesting because high-efficiency phosphorescent devices can be fabricated using solution processes.

A recent development that would improve the economics of white OLEDs is a *single* material that efficiently emits high-quality white light. Recently, emission from organic materials that form excited aggregates in the solid state, called excimers, and then dissociate to smaller molecules have been shown to be capable of achieving very high quantum efficiencies with broad spectral widths.[16–18] Further development of such materials might significantly reduce the complexity of an organic SSL device by reducing the number of phosphorescent dopants and therefore the cost of the device.

Another new class of materials is under development in an attempt to combine the efficiency of small molecules with the solubility of polymers. These solubilized or dendritic phosphors[19–21] might enable high-efficiency organic SSL deposition in a process at atmospheric pressure. Processes using nanoparticle clusters have also been developed to permit even insoluble small molecules to be formed into thin films without the use of vacuum.[22]

Light Extraction

Because of the mismatch in index of refraction between the organic layers, the glass substrate, and air, a portion of the emitted light is trapped in the organic layers and in the glass substrate as a result of total internal reflection. The external quantum efficiency, η_{ext}, is given by $\chi\eta_{int}$, where η_{int} is the internal quantum efficiency and χ is the light extraction efficiency. Based on the classical ray optics model, the light extraction efficiency is estimated to be about 20%, and most of the light generated is lost in the organic layers and the substrate.[23] Various light extraction schemes have been used to enhance the light outcoupling efficiency of OLEDs. These methods can be divided into two approaches. The first approach is to introduce light scattering centers in the glass substrate[24] to enhance light extraction. The second approach is to use various optics elements, including photonic crystals,[25] mesa formation,[26] and microlens arrays,[27] to enhance light extraction. However, to date, most of the light extraction schemes have provided less than a twofold enhancement in light extraction efficiency. It should be noted that the classical ray optics model might not provide an accurate estimation of the light extraction efficiency because it ignores microcavity effects in the OLEDs. It is evident that the light extraction efficiency is strongly dependent on the device geometry and might actually be higher than what is estimated by the ray optics model. An important challenge for these outcoupling enhancement techniques is to fabricate the structures over a large area at very low cost.

Fabrication Techniques for Organic Solid-State Lighting

Batch deposition techniques, either liquid- or vapor-based, are unlikely to achieve the large device areas and low unit costs required for general illumination. Continuous vacuum processes operating at very low cost, however, are well-known in applications such as food packaging and architectural glass coatings. Commercial vacuum thermal deposition systems have already been used to deposit OLEDs over at least a 370 mm × 470 mm (or so-called "Gen 2") substrate size in the display industry. Such systems should be adaptable to a continuous-feed process on either rigid or flexible rolled substrates because only very coarse patterning is required for organic SSL. Alternatively, advanced deposition techniques such as organic vapor-phase deposition[28,29] (OVPD) might prove favorable. OVPD uses a heated carrier gas to transport the starting materials into a hot-wall deposition chamber. There, the starting materials deposit only on the cooled substrate using a showerhead assembly to promote large-area uniformity. The potential advantages of OVPD include a vacuum requirement only in the millitorr range and efficient materials usage.

Printing is a well-established manufacturing process that can, in some cases, also be competitive with large-area processing. Several companies such as General Electric, Seiko Epson, and Cambridge Displays have demonstrated printed OLEDs. Two approaches have been used: For flat-panel displays where high-resolution printing is required, inkjet printing is commonly used; however, the throughput is probably too low for lighting manufacturing. Another approach is to use reel-to-reel gravure printing. With this technique, small pits are engraved on the printing cylinder. During the printing process, the cylinder is inked, and high pressure is applied to the substrates. The line resolution of the gravure printing technique is about 200 μm, which is sufficient for lighting panel fabrication. A schematic diagram of such a printing process is shown in Figure 4.

Conclusions

Laboratory results suggest that organic SSL is indeed feasible. Achieving a sufficiently low cost, however, remains a significant challenge. Since the invention of

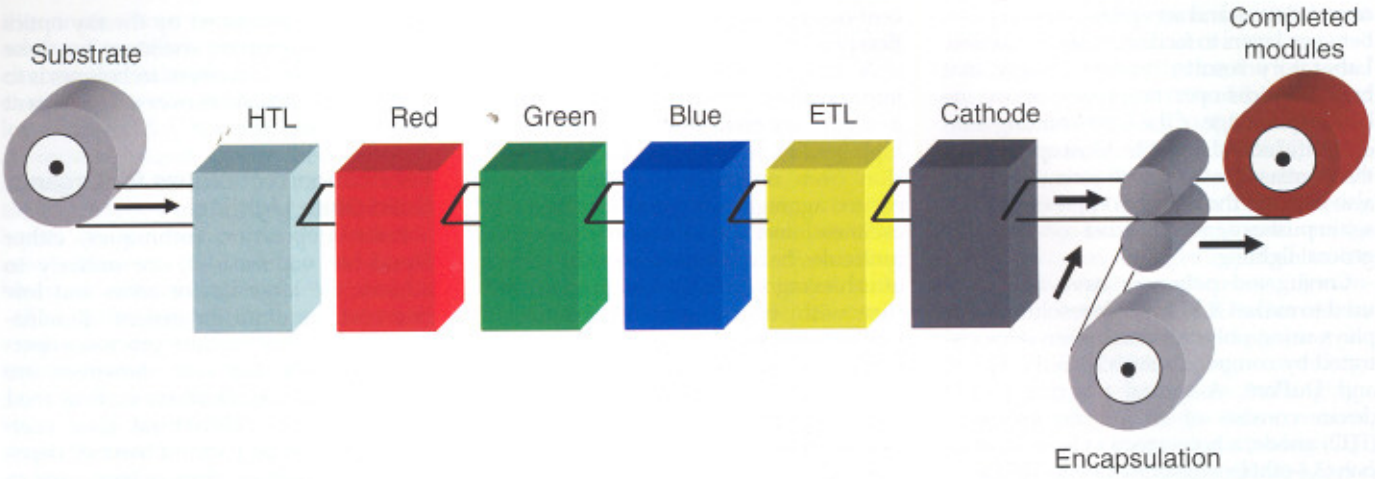


Figure 4. Schematic diagram showing the manufacturing process of white OLED panels using reel-to-reel gravure printing. HTL and ETL are the hole-transporting layer and electron-transporting layer, respectively, and the intervening layers are composed of materials that emit the indicated colors.

the OLED, the device structure has been made steadily more complex in order to achieve high efficiency and long lifetime at high brightness. Now, the challenge is either to demonstrate a high-throughput manufacturing process that is capable of making such structures with good yield and at very low cost or to use what we have learned to simplify the OLED structure without sacrificing performance. Recent progress in OLED lighting has been encouraging. Prototyping of large-area OLED panels has been demonstrated by the Research Institute of Organic Electronics in Japan. Figure 5 shows five sets of OLED panels, operating at 5,000 cd/m^2 with a luminous efficiency of 20 lm/W, in a form factor that would be difficult if not impossible to fabricate efficiently using other lighting technologies.

Because of their low efficiencies and limited operating lifetimes relative to the other colors, blue OLEDs remain the weakest component of organic SSL. Operating lifetime itself is still a poorly understood subject. Although it has been shown that some phosphorescent OLEDs degrade chemically during device operation,[30] there are also proofs of concept for 10^7-hour lifetimes using similar phosphors.[31] It is still unclear what structure–property relationships govern these very different materials performances. Indeed, there are indications that charge imbalance and injection in OLEDs might lead to significant degradation,[15] which suggests that the stability of OLEDs might be limited not only by the emitter layer but by the surrounding layers used to optimize charge injection and transport. Furthermore, injection of charge into an OLED generates chemically distinct species such as charged radicals. To achieve long operating lifetimes at high brightness, it will be necessary to understand the entire device as an electrochemical system, as well as a light-emitting semiconductor before organic SSL becomes a commercial reality.

The cost arguments we have presented are specific to general illumination products. They are important because of their potential impact on electricity consumption.[32] There will, however, doubtless be a market for OLEDs at much lower efficiency and higher cost solely because of their unique form factors. Higher-value-added products such as flat (and flexible) backlights and low-performance novelty lighting products might well provide lucrative niche markets for early developers of organic SSL, and as volumes ramp up, costs will subsequently decrease, perhaps to the point where OLEDs indeed become competitive for general illumination.

Figure 5. Recent demonstration of 140 mm × 140 mm OLED lighting panels. The panels had an operating efficiency of 5,000 cd/m^2 and a luminous efficiency of 20 lm/W.

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