Patterning Approaches and System Power Efficiency Considerations for Organic LED Displays

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Abstract

In this paper we will focus on the various issues which reduce the power efficiency of a complete display system vs. that of a single isolated organic LED, and then discuss the impact of these issues on display integration and design. Critical issues are the necessity of an active matrix design for high definition displays, and the desire for a power-efficient approach for full color. Both dry-etching and ink jet printing will be described as options for achieving patterned films.

Introduction

There are now many groups pursing both polymer and small molecule organic light-emitting devices (LED's) for the fabrication of large area displays [1-4]. General system attributes for both types of devices are a high system power efficiency, full color, and low-cost. Although isolated device efficiencies are now over 10 lm/W, the need for high contrast and the need to individually address pixels in large displays can reduce the system power efficiency to well under 1 lm/W. In this range, we will show that the self-heating can be a significant limitation to system performance, even for monochrome displays. The problem will be even worse for color displays unless a power-efficient approach towards full color can be found. Because patterning organics is attractive for full-color, both dry etching and ink jet pattering approaches will be described.

Self-Heating of Flat Panel Displays

For any future OLED-based flat panel display, it is highly desirable that it be cooled passively, i.e. without a fan. Furthermore, for large displays, it is unlikely that heat can be conducted laterally out of the display, but it will have to be dissipated out of the front and back surfaces. The mechanisms for heat transfer from a flat surface to an ambient are radiation and convection. Basic modelling of these mechanisms yielded the results shown in Fig. 1 for the surface heat transfer coefficients for these mechanisms (k, in W/cm^2 per

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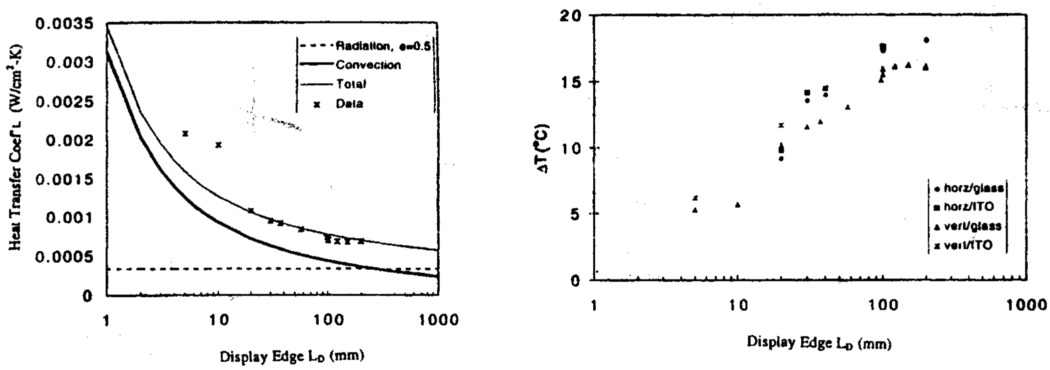
degree of temperature difference from the surface to the ambient, ΔT) for vertically oriented plates. The results for horizontally oriented plates are similar. The details of the modeling and further experiments can be found in Ref. 5. We see that for small plates, convection is efficient, but that it rapidly becomes less efficient as the display size becomes larger. This is because of the increased distance air must flow across the face of the display. Superimposed on Fig. 1(a) are experimental points of measured heat transfer efficiencies for vertically oriented square plates, which represent the sum of radiation and convection. For sizes above 1 cm^2, which are those of technological interest for displays, the models well represent the data. At smaller sizes, there is lateral conduction of heat through the display, so that the temperature rise is even less than that calculated by one-dimensional models.



(a) (b)

Figure 1 (a). Surface heat transfer coefficient for convection and radiative (ε = 0.5) processes for a vertically-oriented display plate, and (b) temperature rise vs. edge size for a vertically oriented plate at 220 W/cm^2 with two-sided passive cooling.

Fig 1 (b) shows the measured temperature rise in a display as a function of size for a fixed power density of 220 W/cm^2. Note that the data on the front and back of the plate are similar, and that there is little difference between horizontal and vertical displays. Note that displays of size ~10 cm on an edge have temperature rise nearly an order of magnitude larger than that of displays of a size of a few mm. This is critical because the reliability of OLED's, which is a critical system concern, is expected to be poorer at higher temperatures [6-9]. Further, most reliability measurements today are made on small devices, whereas this data shows that larger displays products will be hotter if operated at the same brightness (same power density).

Based on the model results shown in Fig 1 (a), a simple relationship between the power density (P/A) and the temperature rise (ΔT_D, in K) of a vertical display of edge L (given in meters) with two sided cooling with average emissivity ε was developed [5]. The expression should be valid for L > 1 cm and for a $\Delta T_D \cdot L^3$ product between 10^{-4} and 10^1 $K \cdot m^3$, which encompasses most range of technological interest.

$$P/A = \pi L / \eta_L = 2.6\,(4.7\,\varepsilon + ((\Delta T_D/K) / (L/m))^{0.25})\,(\Delta T_D/K) \quad W/m^2 \qquad (1)$$

The temperature rise predicted by this expression is shown in Fig. 2 for a brightness of 100 cd/m^2 (assuming a Lambertian angular distribution) as a function of display size for different display power efficiencies. For sizes less than 1 cm, the temperature rise is substantially less than that shown by the model due to lateral heat transport. The results show that a system efficiency of 2 lm/W is probably acceptable, but that a system efficiency of 0.2 lm/W is not.

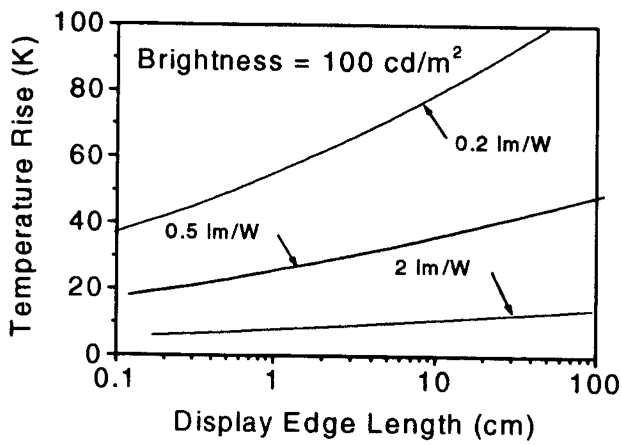
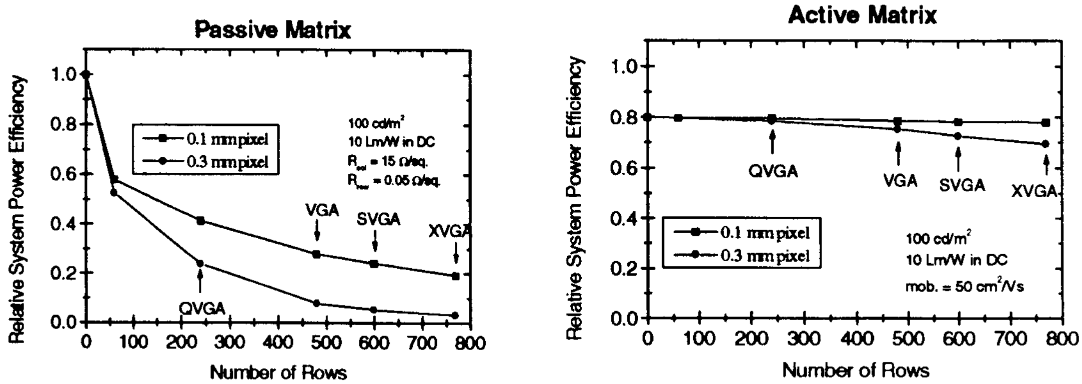


Figure 2. Temperature rise as a function of display size for a brightness of 100 nits based on Eq'n. 1 [5]. No intentional edge cooling is assumed.

Active vs. Passive Matrix System Power Efficiencies

For display-level brightnesses, some of the better power efficiency numbers which have been reported for isolated OLED's are on the order of 10 lumens/Watt. However, OLED's are inherently reflective devices because of the general reflective nature of the top cathode. To achieve a very high contrast ratio, a solution of a circular polarizer or neutral density filter in front of the display is often discussed. In typical applications, the resulting transmitted light from the OLED is reduced as well, typically to only about 40 % of its original value, with a corresponding reduction in the display power efficiency. A much further loss of power efficiency can occur from the addressing method used to address individual pixels in a display. For example, in a passive matrix display with N rows, each device is on for a duty cycle of at most only 1/N, so that the device must be operated at N times its average brightness over this time. Because of the relatively slow turn-on of OLED's, for a passive matrix display of ~200 rows, the drive voltage will typically increase by a factor of 2, e.g. from 4 V to 8 V. Further losses in the system power efficiency are incurred by the power dissipated during the large current pulses due to the resistance in the row and column lines. As shown in Fig. 3, these electrical factors can easily reduce the efficiency by a factor of 5 for high information content displays. Further power efficiency losses of roughly a factor of two result from the required voltage compliance on the current drivers which drive the column lines. Taken together, these factors can easily reduce the virgin device efficiency of 10 lumen/W to an efficiency for the final product of 0.2 lumen/W. Because of system heating considerations, with such a system efficiency it would be very difficult to build a bright passively-cooled large-scale display.



(a)

(b)

Figure 3. Comparison of decreases in system power efficiency of passive and active matrix OLED display designs due to electrical considerations for square pixels of sizes 0.1 and 0.3 mm. A virgin device efficiency of 10 lm/W and a brightness of 100 cd/m^2 are assumed. Current source compliance factors in the passive matrix are not included. Row and column line sheet resistances are 15 Ω/square and 0.05 Ω/square, respectively.

In an active matrix design, a minimum of two transistors per pixel are required for current mode devices such as OLED's. Typically, one functions as a sample and hold device to capture data from the data line (during the short cycle during which a row is addressed), and a second transistor is used to translate the stored data into a DC drive current through the OLED. In this way, the high OLED drive voltages, I^2R drops in row and column lines, and the problem of DC power dissipation in the column current sources in passive matrix displays can be avoided. Some power must be dissipated in the transistors, however. In a polysilicon TFT process with a mobility >> 10 cm^2/Vs, this minimum value is set by gray scale resolution effects, and is probably on the order of 1 V (Fig. 3 (b)). Combining the effect of a contrast-enhancing plate with the transistor power dissipation, a system power efficiency of 2-3 lm/W should be achievable, consistent with the requirements for low self-heating in large-area displays.

Patterning by Dry-Etching

The above calculations of system power efficiencies for passive and active matrices assumed a monochrome display. In practice, color integration may further reduce energy efficiencies, resulting in yet more severe problems with self heating. For example, one scheme towards full color involves a display of all blue emitters followed by color conversion modules to convert blue light to green or red light [10]. However, such conversion processes have an inherent energy inefficiency. An alternate approach would fabricate white emitters, with color filters to achieve red, green, and blue, an approach which would lower energy efficiency by a factor of three. The advantage of these approaches is that one needs to make only a single type of OLED. Microcavities can also be used to tune the color of a single broadband emitting layer, but have poor properties for off-axis viewing [11]. In principle, to achieve the ultimate power efficiency for color integration, one would want the ability to place individually optimized red, green, and blue emitting devices next to each other on a substrate. This is difficult since both spin-coating and evaporation produce blanket coatings, and the organic films are easily damaged by conventional patterning techniques like wet photoresist processing. Furthermore, evaporation of small molecules through a shadow mask is not realistic for a large scale display with many fine pixels.

Therefore we have developed two methods for the pattering of organic films for the color integration of OLED's. The first of these is based on dry etching. Previously, we have demonstrated the three color integration of molecular-doped polymer LED's. These were single layer devices using PVK doped with both emitting centers (dyes) and electron transport agents [12,13]. In that work, after the spin-coating of a uniform film, a patterned cathode was evaporated through a shadow mask. The metallic cathode was then used as a mask for an oxygen plasma to etch the organic film where it was not protected by the cathode. The edges of the devices were made electrically inert by a patterned nitride layer deposited before the organic layer. This allowed us to then repeat the spin-coating process for the next organic layer, which was itself patterned by the same cathode evaporation and dry-etching process. In this way red, green, and blue emitters could be integrated onto a single substrate [12], with no degradation of the individual

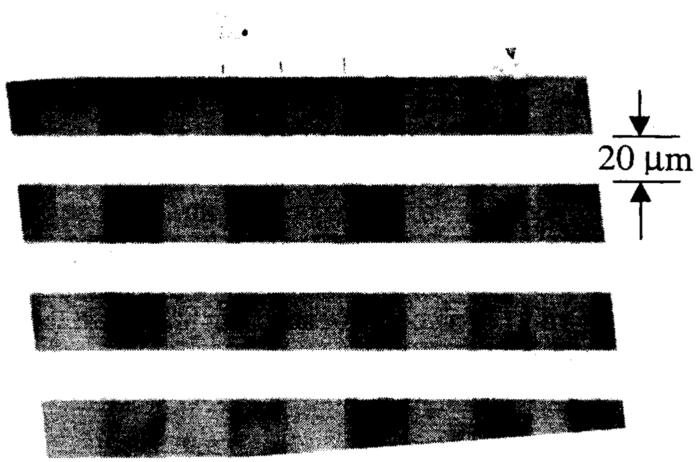


Figure 4. Aluminum cathode lines (white horizontal lines) patterned by photolithography and dry-etching on top of PVK on top of ITO lines (vertical).

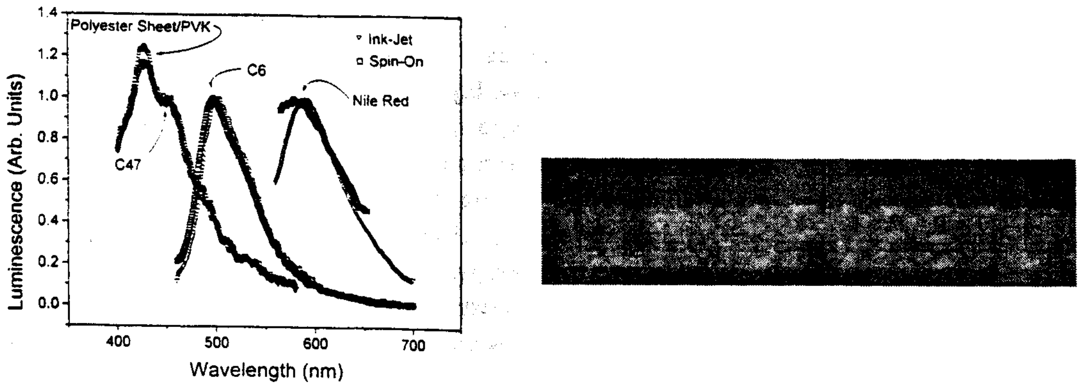
devices due to the integration process. While this work showed the feasibility of etching organic layers, it still relied on the formation of large-area cathode patterns by shadow-mask evaporation.

More recently, we have overcome this drawback and developed the ability to fabricate arbitrary patterns in aluminum-based cathodes on top of polymer films using photolithographic processing. After the organic layer was spin-coated, a blanket aluminum-based cathode was deposited by evaporation. Conventional photoresist patterning was then performed on top of the aluminum, which protected the organic film from the photoresist processing. To prevent damage to the PVK film during the process, and to prevent the cathode from peeling from the PVK, it was essential that the cathode be deposited without any pinholes. The cathode was then dry-etched using a Cl-based plasma, with no visible damage to the organic layer. Dry-etching was necessary since wet etching destroyed the structure. Figure 4 shows an aluminum-based cathode which was patterned by such an etching process (on top of PVK on top of ITO lines patterned by conventional wet etching). The width of the Al lines was 20 μm and the pitch was 40 μm. OLED's fabricated with such a process had turn-on voltages and quantum efficiencies similar to those of simultaneously fabricated devices using cathodes defined by conventional shadow masks. With the capability to photolithographically define cathodes and thus OLED's to a size << 100 μm, it should now be possible to integrate optimized R, G, and B devices within the required pixel sizes for high information content displays.

Patterning by Ink-Jet Printing

As opposed to patterning films after blanket deposition, it is also attractive to consider the direct patterned deposition of organic films for achieving full color integration. By using direct patterned deposition, the etching of the organic films could be avoided. Because polymer films are deposited from solution, in principle they can be deposited in a local fashion by ink-jet printing, whereby local microdroplets of the polymer solution are applied to the substrate. We therefore investigated the ink-jet printing of local patterns of polyvinylcarbazole doped with the dyes of coumarin 47 (C47, blue photoluminescence), coumarin 6 (C6, green), and nile red (orange-red). While in the work presented here the emitting polymers were directly deposited by ink-jet printing, work has also been done using ink-jet printing to pattern hole-injecting layers before blanket deposition of the emitting layers by spin-coating [15].

The work was done using a commercial ink-jet printer designed for printing ink on paper. It was of the piezoelectric type and had a nozzle opening of 65 microns. The substrates were 175-μm polyester foils coated with indium tin oxide. The PVK was dissolved in chloroform at a ratio of about 10 g/l, and the dye concentration was 0.1 g/l. Using a hand-held syringe, the PVK solution was injected into the ink-reservoir in place of the usual ink in the printer. We were able to successfully print individual droplets of polymer using this method [14], although the control of the droplet size was not good. The droplet size ranged from 150 to 200 um in diameter, and the height of the polymer islands ranged from 40 to 70 nm. The photoluminescence spectra of the materials fabricated by inkjet printing were similar to that fabricated by spin-coating (Fig. 5 (a)). A ultraviolet-fluorescence image of a series of letters composed of individual dots doped with nile red is shown in Fig. 5 (b). The letters appear "double" because of the "bold" mode of the printer.



(a) (b)

Figure 5. (a) Photoluminescence spectra of PVK films doped with C47, C6, and nile red deposited by both spin-coating and ink-jet printing. Also, (b) UV-fluorescence image of printed letters consisting of dots of PVK doped with nile red. The height of the letters is 3 mm [14].

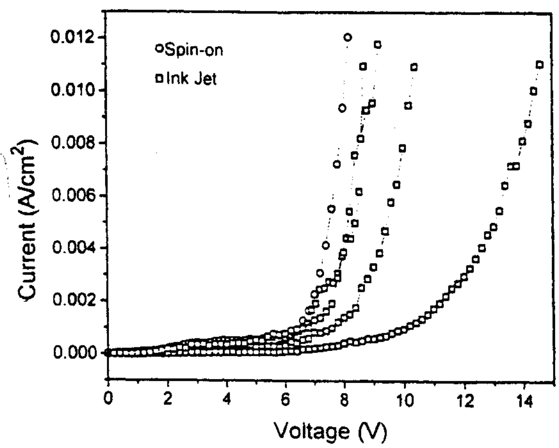


Figure 6. Current voltage characteristics of OLED's with 250-μm diameter Mg:Ag cathodes on top of 50 nm C6-doped films deposited either by ink-jet printing (4 devices) or spin-coating (1 device).

It was not possible to fabricate OLED's on top of individually printed dots due to the difficulty in placing a cathode on top of a single dot. Therefore to test the quality of the ink-jet printed material, the printer was operated in a mode to print a continuous sheet of PVK with a nominal thickness of 50 nm, rather than isolated dots. Cathodes were then evaporated using standard shadow-mask techniques. The I-V curves of the devices, along with that of a control device made on a dye-doped PVK film fabricated by conventional spin-coating, also with a 50 nm thickness, are shown in Fig. 6.

Except for one ink-jet printed device, the turn-on voltage of the two types of devices were similar, although the variation in the turn-on voltage of the devices fabricated on ink-jet printed films was substantially larger than that we typically observe in devices in spin-coated films. We think this is due to variations in the thickness of the film deposited by ink-jet printing. The quantum efficiency of both types of devices was poor (< 0.1 %), probably because no electron transport material was used. When a proper amount of an electron transport molecule is added to the solution before spin-coating to make a three-component blend, in single-layer spin-coated devices with this material system we typically observe external quantum efficiencies approaching 1% [13]. Further work is necessary to improve the film thickness uniformity and also to develop solutions which do not damage the many plastic parts found in commercial ink jet printers.

Summary

The power efficiency of an OLED-based display is not only important because of battery life in potential applications, but because self-heating of the display may limit the viability itself of the product. There are many considerations which cause the power efficiency of a complete high definition display system to be far lower than that of an isolated device, and a difference of over a factor of ten can easily result, especially if a passive matrix scheme is adopted. Because of the power dissipation issue, methods for achieving full color without sacrificing power efficiency are important. Both the patterning of blanket deposited films and cathodes using photolithography and dry-etching, and the direct patterned deposition of polymers using ink-jet printing are attractive alternatives towards this end.

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