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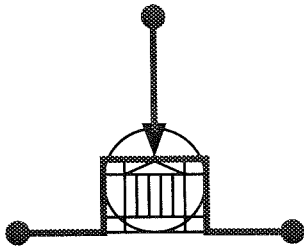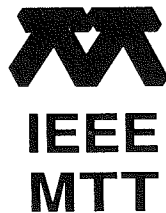
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Processing and Integration Issues in Organic Light Emitting Diode Displays

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Abstract

The impact of system issues such as power dissipation and full color capability on process and device integration is examined. Power dissipation is especially important because of the self-heating of the display. Specific areas which have been examined are the integration of TFT's and OLED's together to form an active matrix, rugged substrates, and methods to integrate different patterned organic layers onto a common substrate

Introduction

Since the seminal work of Tang and Van Slyke [1] there has been an increasingly strong interest in developing flat panel displays based on organic LED's (OLED's), either based on polymers or small organic molecules [2,3,4]. While most research has focused on improving the performance or stability of isolated devices, consideration of the final display product as a system introduces new issues to be considered. Using the system drivers of power dissipation and full color, we show that the ability to integrate both optimum organic layers for individual red, green, and blue devices and thin film transistors (TFTs) for an active matrix architecture is highly desirable for a system. We then examine several issues in these areas from a process technology point of view.

System Motivation

The system power efficiency is especially important for displays based on OLED's because the stability of the organic materials and interfaces and the device reliablity are critical issues which depend on temperature [5-8]. Therefore the self-heating of devices must be understood. We have measured and modelled the self-heating of flat panel displays as a function of their power dissipation density, orientation, and size [9]. The experimental results for a power density of 220 W/m^2 are shown in Fig. 1 for plates of both horizontal and vertical orientation. Note that for a fixed power density, the self-heating rises sharply as the display size increases. Modeling shows this effect to be due to a rapid drop in convection efficiency at larger dimensions [9]. Because OLED device efficiencies are typically on the order of several lumens/Watt (assume 3 lm/W), operating at a typical brightness of 100 cd/m^2 implies a power density of only 105 W/m^2. However, to achieve high contrast in a system, a circular polarizer or other plate (with < 50% transmission) may be used, doubling the required power to 210 W/m^2. Any further substantial power inefficiencies would be highly undesirable because of the resulting self-

heating of the devices would be on the scale of many tens of degrees, leading to premature device degradation.
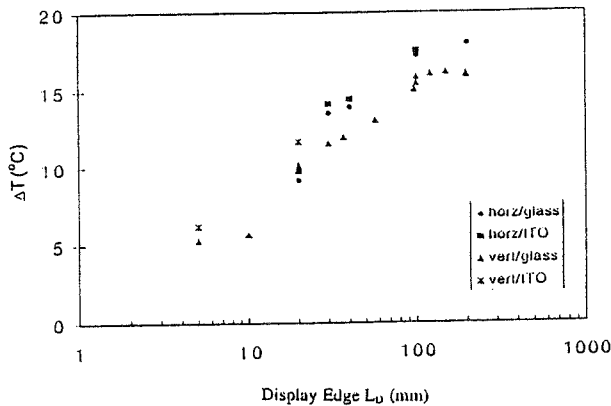

Fig. 1. Measured temperature rise of glass flat panels (on both front and back sides) as a function of edge dimension for both horizontal and vertical orientation for a power density of 220 W/m^2 [9]
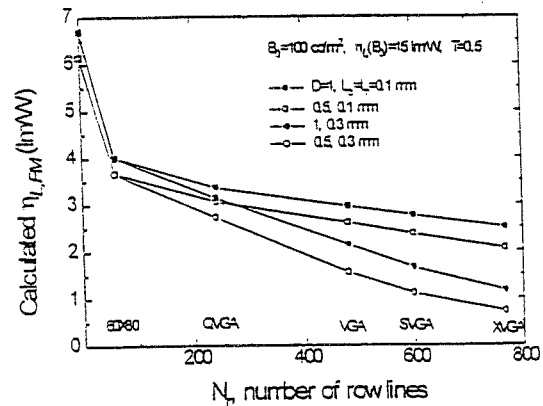
Fig. 2. System power efficiency for a passive matrix display as a function of the number of lines, assuming ITO data lines of 10 Ω/sq, Al row lines of 0.05 Ω/sq, pixel size 0.1 x 0.1 or 0.3 x 0.3 mm^2, device efficiency of 15 lm/W, system brightness of 100 cd/m^2.

In OLED display systems demonstrated to date, the passive matrix addressing approach has been chosen for addressing pixel elements [10,11]. This implies driving them at low duty cycles for very high brightness. Due to the higher OLED voltages and power dissipation in the data and select lines, a much higher drop (easily as large as 4 X) in the system efficiency can occur (Fig. 2). Because such an efficiency drop, and the resulting device temperature increase may be unacceptable, the integration of TFT's with the OLED's for an active matrix (AM) architecture is highly desirable. This solution yields a display with far higher power efficiency, but requires the integration of TFT's and OLED's. Furthermore, many approaches to achieve full color involve inherent energy efficiencies, such as white OLED's followed by color filters. Because of the excessive heating this implies, the ability to integrate different organic layers for optimum R, G, and B devices for color is also highly desirable. Finally, unbreakable substrates (as opposed to glass) would be highly desirable.

TFT Integration on Stainless Steel Foil Substrates

An active matrix architecture allows devices to be operated close to DC, as opposed to the low duty cycles of a passive matrix. The TFT choices for large area applications include amorphous silicon (a-Si) with a μ of ~1 cm^2/Vs and polysilicon (p-Si) with μ ~ 30 cm^2/Vs. To demonstrate that a-Si TFT's are capable of providing appropriate current levels for OLED's, we integrated a-Si TFT's and OLED's onto a common substrate. In place of glass, we chose thin stainless steel foils (thicknesses from 25 to 200 μm) because of their rugged and flexible nature, and because they more easily withstand the process temperatures of a-Si TFT fabrication than plastic substrates. Fig. 3

shows the device structure, in which a standard a-Si TFT is first fabricated on the steel foil. The organic used was the polymer PVK doped with electron transport agents and a dye, a combination which has demonstrated brightnesses in excess of 10,000 cd/m^2 [12]. Because the foils are opaque, a top emitting OLED structure was used with a semi-transparent top contact [13,14]. The transistor W/L ratio was 18 and the OLED diameter was 0.25 mm.
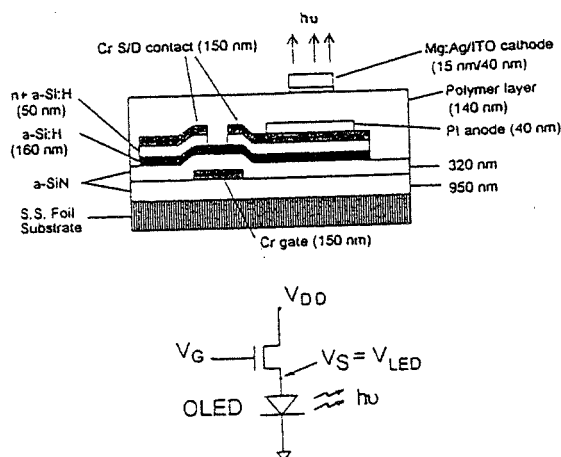

Fig. 3. Cross section of integrated TFT/OLED structure on flexible stainless steel foils.

Fig. 4. Current vs voltage of isolated LED (LED voltage), isolated TFT (V_{GS}) and TFT-OLED combination (V_G).

Fig. 4 shows the I-V curve of the isolated LED, isolated TFT, and of the TFT driving the LED in series. The TFT, which was operated in saturation mode, can clearly provide currents densities to the OLED of mA/cm^2, which is typical of that used in OLED applications. Furthermore, because of the rugged nature of the substrates, dropping the foils from a height of 10 m onto concrete had no effect. The 25-μm foils could also be wrapped around a pencil with no change in TFT characteristics.

Full Color Integration

The most power-efficient route towards full color would be direct integration of optimized R,G, and B devices onto a single substrate. This is difficult in OLED technology, however, because the sensitivity of the organics to solvents and water makes their patterning by conventional etching and photolithographic processes problematic. Furthermore, with polymer-based devices, the spin coating of a second polymer layer can cause the dissolution of a previously formed layer. Therefore we have developed the process shown in Fig. 5 which allows us to integrate and pattern multiple organics by spin-coating onto a single substrate [15]. The organic layer is deposited onto a substrate with a patterned insulator, and then patterned by dry-etching using the metal cathode as a self-aligned mask. The sidewall of the device is then coated with metal to seal the edges so that it is stable to further spin-coating and processing. Fig. 6 shows I-V and L-V curves both of a virgin PVK/Alq/nile red device and of the same device after green and blue devices were subsequently integrated onto the same substrate. Note there is no
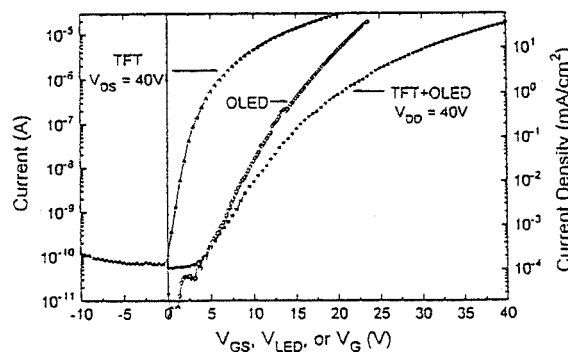
degradation of the device from the subsequent processing, and operation of the optimized integrated RGB devices has been demonstrated [15].
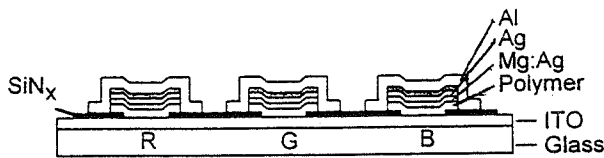

Fig. 5. Structure for integration of multiple organics on a single wafer by spin-coating, using a patterned nitride and metal sidewall sealing.
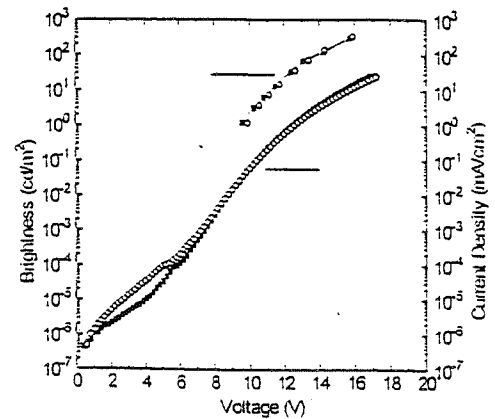
Fig. 6. L-V and I-V curves of both a virgin isolated PVK/PBD/nile red device (squares) and the same device after the fabrication of green and blue devices on the same substrate (circles).

Summary

Key motivations from a system point of view in OLED displays are high system power efficiency (for low self-heating), full color, and ruggedness. These require the integration of TFT's for an active matrix architecture, novel substrates, and novel approaches for the patterning of organic-based devices. This work has been supported by NSF (in part through its Research Experience for Undergraduates Program), the NJ Comm. on Science and Tech., and DARPA (USAF-TPSU-PU-1464-967).

1. C.W. Tang and S.A. Van Slyke, Appl. Phys. Lett. **51**, 913 (1987).

2. J.H. Borroughes, D.D.C. Bradley, A.R. Brown, R.N. Marks, R.H. Friend, P.L. Burn, and A.H. Holmes, Nature **347**, 539 (1990).

3. D. Braun and A.J. Heeger, Appl. Phys. Lett. **58**, 1892 (1991).

4. C. Adachi, S. Tokito, T. Tsutsui, and S. Saito, Jap. J. Appl. Phys. **27**, L269 (1988).

5. S.A. Van Slyke, C.H. Chen, and C.W. Tang, Appl. Phys. Lett. **69**, 2160 (1996).

6. J.C. Carter, I. Grizzi, S.K. Heeks et al, Appl. Phys. Lett. **71**, 34 (1997).

7. P. Burrows, V. Bulovic, S.R. Forrest, L.S. Sapochak, D.M. McCarty, and M.E. Thompson, Appl. Phys. Lett. **65**, 2922 (1994).

8. C. Adachi, K. Nagai, and N. Tamoto, Appl. Phys. Lett. **66**, 2679 (1995).

9. J.C. Sturm, W. Wilson, and M. Iodice, IEEE J. Spec. Topics Quant. Elec., to be published.

10. C. Hosokawa, M. Eida, M. Matsuura, K. Fukuoka, H. Nakamura, and T. Kusumoto, Digest of the Society for Information Display, 1073 (May, 1997).

11. T. Tohma, Conf. Record of the Int. Disp. Res. Conf., p. F-1 (Sept., 1997).

12. C.C. Wu, J.C. Sturm, R.A. Register, J. Tian, E.P. Dana, and M.E. Thompson, IEEE Trans. Elec.Dev. **44**, 1269 (1997).

13. C.C. Wu, S.D. Theiss, G.Gu, M.H. Lu, J.C. Sturm, S. Wagner, and S.R. Forrest, IEEE Elec. Dev. Lett, **18** (Dec., 1997).

14. E.Y. Ma, S.D. Theiss, M.H. Lu, C.C. Wu, J.C. Sturm, and S. Wagner, Tech. Dig. IEDM (1997).

15. C.C. Wu, J.C. Sturm, R.A. Register, and M.E. Thompson, Appl. Phys. Lett. **69**, 3117 (1996).