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# Organic smart pixels

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The fabrication and characteristics of organic smart pixels are described. The smart pixel reported in this letter consists of a single organic thin-film field effect transistor (FET) monolithically integrated with an organic light-emitting diode. The FET active material is a regioregular polythiophene. The maximum optical power emitted by the smart pixel is about 300 nW/cm$^2$ corresponding to a luminance of $\sim$2300 cd/m$^2$. © *1998 American Institute of Physics.* [S0003-6951(98)01528-9]

Organic and polymer light emitting diodes (LEDs) have been investigated for a number of years for possible use in backlighting and display applications.[1–4] Recent advances in both small molecule and polymer based LED technology have led to dramatic increases in device lifetime, which have paved the way for their commercialization.[5,6] Attention has also been paid to addressing issues of high information content displays based on such LEDs. Passive [7] as well as active addressing schemes have been proposed and/or demonstrated. The active addressing schemes involve one or two field-effect transistors (FETs) in each pixel. Such FETs act as LED drivers and can, in principle, improve the performance of high information content displays. In recent reports, FETs with polycrystalline Si (Ref. 8) and amorphous Si (Ref. 9) active channel materials have been integrated with organic LEDs. The concept of organic/polymer LEDs being integrated with silicon transistor technology was pioneered by Kim *et al.*[10]

Organic FETs have attracted attention for use in a number of large area applications where high switching speeds are not essential. Field-effect mobilities $>0.1$ cm$^2$/V s have been obtained with several organic materials.[11,12] FETs have also been realized using printing methods, demonstrating the compatibility of such materials with various types of printing techniques.[13,14]

The monolithic integration of organic transistors and LEDs has never before been demonstrated. It is expected that such an integration will be simpler and cheaper from a processing perspective when compared to silicon-FET based approaches. In this letter, we describe the characteristics of polymer FETs and organic LEDs fabricated on the same substrate (glass). We also describe the characteristics of an integrated organic smart pixel, in which a LED is the active load of a FET. Key issues regarding system performance of displays with smart pixels comprising organic FETs are briefly discussed.

The active channel material used in the FETs in the smart pixel is regioregular poly(3-hexyl thiophene) (PHT), which has been shown to result in FETs with field-effect mobilities as high as 0.046 cm$^2$/V s.[15] These relatively high mobilities are a result of the molecular ordering of PHT on most substrates which is such that high mobilities are achieved along the plane of the interface with the substrate on account of the direction of current flow being same as the $\pi$-stacking direction.

The organic LED materials are triphenyl diamine (TPD), a hole transporter, and 8-hydroxyquinolinato aluminum (Alq), an electron transporter and emitter. When used in a bilayer configuration, these materials result in LEDs with external quantum efficiencies in excess of 1% (photons/electron). Higher efficiencies can be obtained through the use of more complicated device structures and fluorescent dopants such as a coumarin,[1] pyrromethene,[4] or a modified quinacridone.[16]

The smart pixels were fabricated on indium tin oxide (ITO) coated glass substrates. The substrates were first patterned to define the ITO LED anode regions. Gold FET gates were then photolithographically defined, followed by the deposition of $Si_3N_4$ (thickness $\sim$180 nm) which functions as the gate insulator. Vias were etched in the $SI_3N_4$ to address the individual gates. Source and drain regions (Au) were defined above the $Si_3N_4$, with the sources each connected to a probe pad while the drains were connected to the ITO. The transistor active material (PHT) is then solution cast over the substrate. To complete the fabrication of the smart pixel diamine and Alq (of thickness $\sim$100 nm each) were sublimed over the anode regions and, finally, Al cathodes of circular shape (and diameter = 0.03 cm) evaporated. A schematic of the cross section of the smart pixel is shown in Fig. 1.

The characteristics of the individual FETs are shown in Fig. 2(a) for enhancement-mode operation. The FETs operate in both enhancement and depletion modes and had a channel length, L, of 5 $\mu$m and a W/L ratio of 200. The field

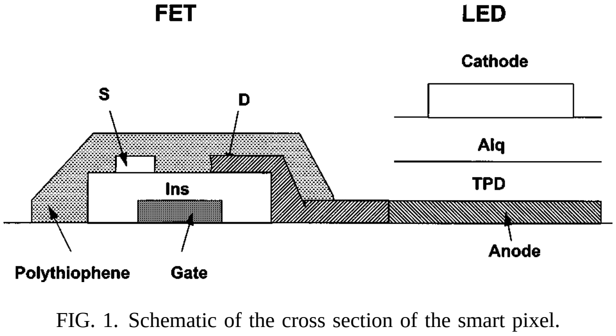

FIG. 1. Schematic of the cross section of the smart pixel.

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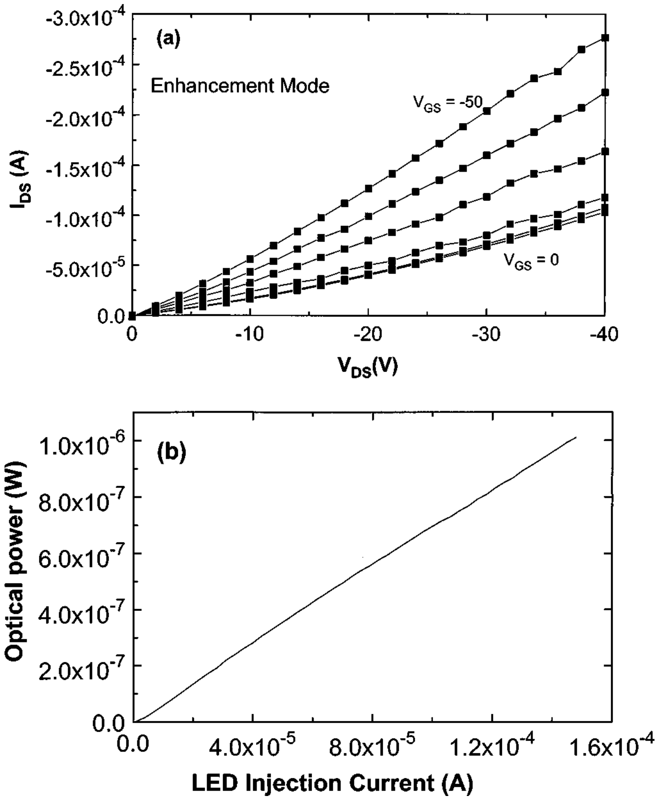

FIG. 2. (a) Enhancement-mode current–voltage characteristics of a polythiophene FET tested without the LED load. The gate voltage step is −10 V. (b) Light–current characteristics of an individual Alq/TPD LED with an Al cathode and no doping.

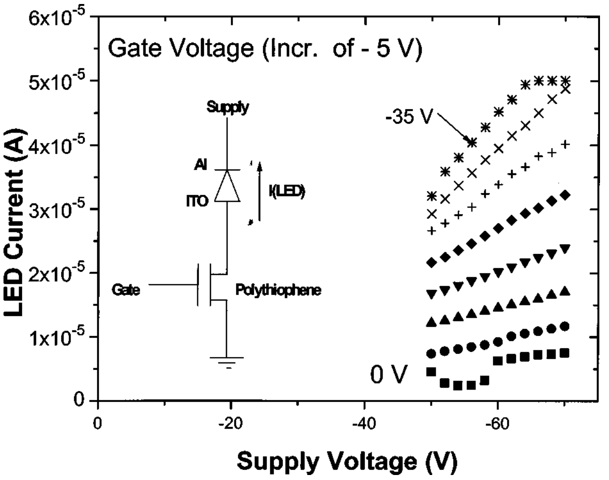

FIG. 3. Electrical characteristics of the smart pixel. In the inset is shown the equivalent circuit. The light output of the pixel is proportional to the current flowing through the LED.

effect mobility extracted from the device characteristics is $1-3\times10^{-2}$ cm$^2$/V s. The operating voltages can be lowered by employing a thinner gate insulator. The nonideal saturation characteristics and off current are a result of the gate dielectric employed-deposited $Si_3N_4$; with other gate dielectrics PHT FETs have been shown to possess good saturation characteristics and high on/off ratios.[15] The values of field-effect mobility reported above are among the highest for solution-deposited organics/polymers. The light–current characteristics of a discrete LED are shown in Fig. 2(b). The measured external quantum efficiency is 0.3%–0.45%. The external QE can be further improved by employing dye-doped emissive layers and low-work function cathodes.

The electrical characteristics of the smart pixel are shown in Fig. 3. The light output of the pixel is proportional to the LED current [see Fig. 2(b)]. The maximum LED current measured is 50 $\mu$A, which corresponds to a current density of 72 mA/cm$^2$. The maximum luminance of the smart pixel is estimated from the optical power and a conversion factor of 485 L/W to be ~2300 cd/m$^2$. The conversion factor was calculated by combining the electroluminescence spectrum of Alq with the wavelength dependent luminous efficiency.

In the fabrication sequence described above, it does not really matter if the polythiophene is also deposited over the LED anode regions, although it required only between the source and drain regions of the FET. Indeed, such a coverage of the anode may actually help hole injection from the ITO to the LED active layers. The natural compatibility of LED and FET materials will be further elucidated in a future publication.

Let us briefly consider the utility of smart pixels based on organic FETs and LEDs from a system perspective. We expect that the integration of organic FETs and LEDs will be of great benefit in two categories of displays: (a) in ‘‘small’’ displays in which a single FET drives a LED in each subpixel, and in which the introduction of FETs facilitates addressing, simplifies drive circuitry, reduces cross talk, and offers an alternative to cathode patterning to define pixel size, and (b) in ‘‘large’’ displays where each subpixel will consist of a circuit with two or more transistors driving a single LED, and which would greatly simplify addressing.

The size (both physical dimensions and number of lines) of displays containing a single FET in each pixel (or subpixel) will be limited by the current drive capability of the FET. If such a display is driven a line at a time, the FET must possess a sufficiently high transconductance so as to drive the LED to emit at several times the brightness required for indoor viewing (typically 100 cd/m$^2$). For a pixel size of L, the area of the LED (and the current drive requirement) will be proportional to L$^2$, while the channel width (and current drive capability) of the FET will scale with L. Ideally, one would want to keep L$^2$/L small so that the FET can drive the LED to a sufficient brightness during the time of single line is selected. It is easy to see how small dimension displays are favored from this perspective.

In larger displays where the pixel area, L$^2$, is larger, there will be enough room in each pixel to have a simple circuit consisting of two or more FETs. This circuit will convert the line signal to a drive current for the LED. In this case, although the addressing may be a line at a time, the LED can be kept on for the duration of the entire frame by the FET circuit. This will relax the mobility requirements on the organic FETs.

We next consider the question of processing methods that are likely to be useful in realizing displays based on organic smart pixels. While conventional photolithography-based patterning may be useful in the smallest displays where the feature sizes are also correspondingly small (<10 $\mu$m), it is expected that low-cost printing based approaches will be particularly advantageous for small as well as larger displays. There have been recent demonstrations of discrete FETs[13,14] and polymer LEDs[17,18] fabricated wholly or partially with printing methods. The fabrication of large smart-pixel based displays by printing methods is technologically promising. Our group has taken the first steps in that direction by demonstrating good performance with discrete polythiophene FETs fabricated by screen printing[14] and stamping.[19] Additionally, we have realized good performance with sublimed organic semiconductors such as pentacene on plastic substrates. The pentacene FETs were fabricated on Mylar® substrates with a printed polyimide gate dielectric. Mobilities of up to 0.1 $\mathrm{cm}^2/\mathrm{V\,s}$ and on/off current ratios $>7\times10^4$ were obtained for gate voltage modulation between 0 and $-100$ V. This demonstration indicates that, in addition to solution processible materials such as polythiophene, useful devices can be realized with a combination of printing and large area sublimation of small molecule organic semiconductors on plastic substrates.

In summary, we have demonstrated the first organic smart pixel, which consists of an organic FET monolithically integrated with an organic LED. The FET had an active semiconducting layer consisting of regioregular polythiophene and the LED was based on the Alq/TPD bilayer system. The maximum brightness achieved from the LED in the smart pixel is $\sim 2300$ $\mathrm{cd/m}^2$. This demonstration is the first step in realizing displays based on smart pixels and in developing novel fabrication methods for such displays.

*Note added in proof:* We have learned that H. Sirringhaus *et al.* of Cambridge University, UK, have recently succeeded in integrating polymer TFT's and LED's.

[1] C. W. Tang, S. A. Van Slyke, and C. H. Chen, J. Appl. Phys. **65**, 3610 (1989).

[2] J. H. Burroughes, D. D. C. Bradley, A. R. Brown, R. N. Marks, K. Mackay, R. H. Friend, P. L. Burn, and A. B. Holmes, Nature (London) **347**, 539 (1990).

[3] D. Braun and A. J. Heeger, Appl. Phys. Lett. **58**, 1982 (1991).

[4] For a recent review, see, A. Dodabalapur, Solid State Commun. **102**, 259 (1997).

[5] J. M. Shi and C. W. Tang, Appl. Phys. Lett. **70**, 1665 (1997).

[6] R. F. Service, Science **273**, 878 (1996).

[7] Y. Kimima, N. Asai, N. Kishii, and S. Tamura, IEEE Trans. Electron Devices **44**, 1222 (1997).

[8] M. K. Hatalis, M. Stewart, C. W. Tang, and J. Burtis, Proc. SPIE **3057**, 222 (1997).

[9] C. C. Wu, S. D. Theiss, G. Gu, M. H. Lu, J. C. Sturm, S. Wagner, and S. R. Forrest, IEEE Electron Device Lett. **18**, 609 (1997).

[10] H. H. Kim, T. M. Miller, E. H. Westerwick, Y. O. Kim, E. W. Kwock, M. D. Morris, and M. Cerullo, J. Lightwave Technol. **12**, 2107 (1994).

[11] H. E. Katz, J. Mater. Chem. **7**, 269 (1997).

[12] Y. Y. Lin, D. J. Gundlach, S. F. Nelson, and T. N. Jackson, IEEE Trans. Electron Devices **44**, 1325 (1997).

[13] F. Garnier, r. Hajloui, A. Yassar, and P. Srivastava, Science **265**, 1684 (1994).

[14] Z. Bao, Y. Feng, A. Dodabalapur, V. R. Raju, and A. J. Lovinger, Chem. Mater. **9**, 1299 (1997).

[15] Z. Bao, A. Dodabalapur, and A. J. Lovinger, Appl. Phys. Lett. **69**, 4108 (1996).

[16] T. Wakimoto, Y. Fukuda, K. Nagayama, A. Yokoi, H. Nakada, and M. Tsuchida, IEEE Trans. Electron Devices **44**, 1245 (1997).

[17] T. R. Hebner, C. C. Wu, D. Marcy, M. H. Lu, and J. C. Sturm, Appl. Phys. Lett. **72**, 519 (1998).

[18] J. Bharathan and Y. Yang, Appl. Phys. Lett. **72**, 2660 (1998).

[19] J. Rogers, Z. Bao, and V. R. Raju, Appl. Phys. Lett. (in press).