Monochrome and Full-Color Polymer Light-Emitting Displays Fabricated by Ink-Jet Printing

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Abstract

One of the first commercial applications of "plastic" or polymer electronics will be in the field of display technology. Polymer Light-Emitting Displays (PLEDs) are emissive, have a wide viewing angle and high contrast. They are also very thin and lightweight. Several companies are already in advanced stages of commercial develop-ment. These first display products will be monochrome, but will soon be followed by full-color versions. These full-color displays are likely to be fabricated using ink-jet printing techniques. This paper discusses some of the technical issues.

Introduction

The emerging technology based around PLEDs promises to have many advantages over existing electroluminescence technologies.[1-5] They are ideally suited for use in portable, battery operated electronics applications as a result of their crisp, high-contrast, easily readable images and because of their low weight, and low power consumption. Displays with tens of thousands pixels have been fabricated and have shown themselves to be excellent for displaying moving text and graphical images. They are likely to find use in a wide range of portable electronics where high readability is an issue, such as cell-phones and pagers.

The market for small displays in consumer applications is projected to be worth several billion dollars in the early part of the next century. Of particular interest is the market for portable telephones and pagers. Presently, this market is supplied by inorganic LED displays or by LCD displays. Both of these technologies have limitations. Pixilated displays fabricated from *inorganic* LEDs are not able to achieve the pixel count or resolution that is becoming necessary. Liquid crystal displays have the problem of poor contrast and viewing angle, as well as slow response speed, particularly at low temperatures. Another big disadvantage is their non-emissive nature, which makes low light-level viewing difficult. This can be surmounted by the addition of a backlight but this then leads to significantly increased power consumption.

PLEDs are much easier to read than liquid-crystal displays (LCDs) as a result of a very wide viewing angle (> 160°), a high contrast (> 100:1), and no image latency so they can handle moving graphics or scrolling text much more smoothly.

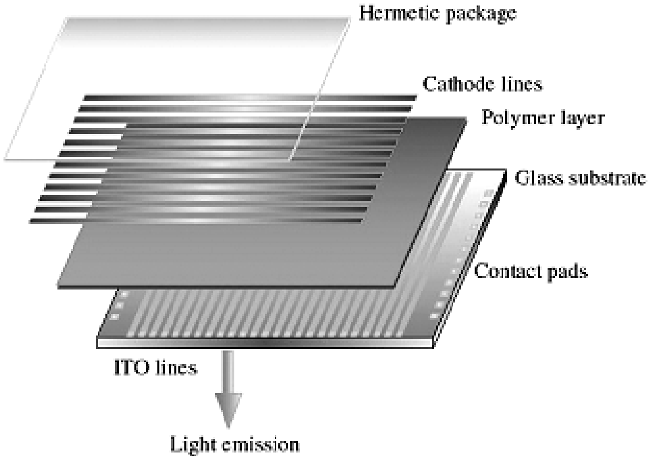

Figure 1. Schematic of a monochrome PLED.

The active material in a PLED is a light-emitting polymer film, approximately 0.1 μm thick, sandwiched between two electrodes, which can be stimulated to emit high intensity light by application of low voltages (< 10V typically). The structure of a typical monochrome display is shown in Fig. 1.

The two electrodes are typically indium-tin oxide, (ITO), the positive electrode, which is usually supplied ready coated onto the glass substrate, and calcium (with a protective aluminum overcoat) as the negative electrode which is usually applied in a vacuum deposition process.

For a monochrome display, the polymer layer is typically deposited by a spin-coating process. However, for full color displays this approach cannot be used since the individual sub-pixels of Red, Green and Blue polymer cannot be differentiated. Recent work by from several groups has focused on the use of an ink-jet printing approach to pattern these individual colors.

Ink Jet Printing of Light-Emitting Polymers

Unfortunately, most existing ink-jet printers cannot handle the requirements for printing displays. There are several reasons:

i) Light-emitting polymer inks are not water-based. Most ink-jet printing equipment is intolerant of the necessary organic solvents.
ii) Most ink-jet printing equipment is designed to print onto flexible substrates not large, rigid, breakable glass substrates.
iii) The usual techniques for printing ink "dots" to create the image (e.g. Fig. 2a) are inappropriate for our needs. We must create continuous polymer layers without any gaps, since gaps will allow the two elec-trodes to "short" together and prevent the displays from working. This is shown more clearly in Fig. 2b. Different colors for the pixel are achieved by simul-taneously operating all three sub-pixels at different intensities, in much the same way as a TV operates.
iv) The drop placement accuracy for fabrication of displays needs to be around 5 µm. This is a combined accuracy of the stage positioning and the drop trajectory accuracy. Most current ink-jet printers cannot achieve this.

Formulation of Polymer Ink for Printing PLEDs

The polymer inks used for PLED production are of fairly high molecular weight (typically ~ 500,000), and are soluble in organic solvents (e.g. toluene, xylene, anisole etc.), but not aqueous solvents.

These high molecular weights, and solvent choices, gives rise to significant visco-elastic properties of the solution, and as a consequence, rather pronounced ligament formulation. An example is shown in Fig. 3. This ligament formation is undesirable since the drop placement accuracy on the substrate is less well defined. It also limits how close the print-head can approach the substrate, further limiting drop-placement accuracy.

Several ink-jet manufacturers produce multi-nozzle heads capable of printing these materials, including (but certainly not limited to) Spectra, Xaar/MIT, Ink-Jet Technology and Epson. Drop sizes are typically in the range of 30 – 100pL at this stage, although smaller drop heads are under development. These next-generation heads, with drop-sizes down to ~ 10pL are necessary for controlling the film thickness of the polymer layers with the required accuracy (remember, they are only ~ 0.1µm thick once dried, and need to have a high degree of uniformity).

The use of organic solvents has other complications. Typically the solvents are relatively volatile, which gives rise to latency problems, misfiring of the nozzles, directional inaccuracy or dropout. Solvent choice becomes critical, and blends are frequently used. However, choice is somewhat limited by the relatively narrow window for the viscosity and surface tension requirements to get good droplet formation. Typical values for the viscosity window are 5 - 20 cps. Once the ink has hit the display substrate, it is very important that it spreads to fill the well and then dry to form a flat, uniformly thick film. Non-uniform thicknesses will give rise non-uniform light emission from the sub-pixel, and undesirable electrical operating characteristics.

Unfortunately, this is rather difficult to achieve. Most of these polymer ink solutions show significant mass transport, and Marangoni effects as they dry, giving rise to dry films that are far from flat. Examples of this are shown in Fig. 4 for unconstrained drops on a microscope slide, in a 3-D view and also a vertical cross-section.

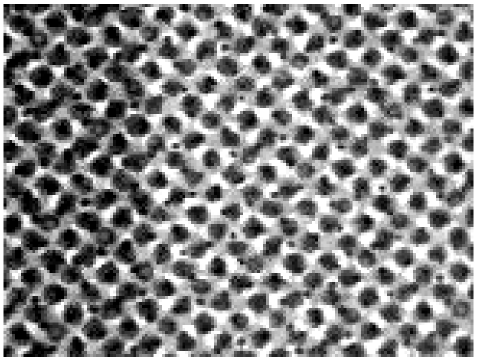

Figure 2a. Traditional color printing relies on creating a "dot" pattern of inks, often multiple layers of different colors, in order to create a full-color gamut. Applying no ink creates areas of "White".

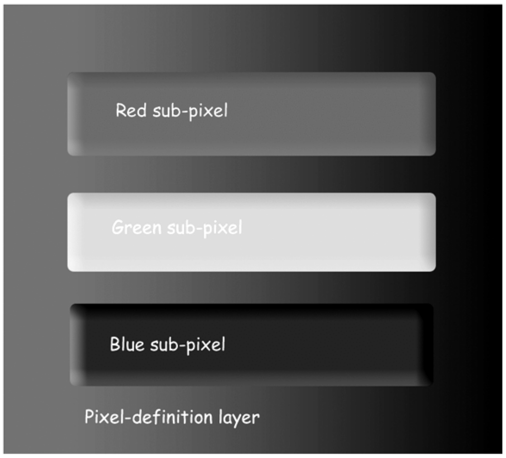

Figure 2b. For color PLED displays, a "pixel-definition" layer is applied to the substrate to create "wells" into which the polymers are printed. These wells must be completely filled to avoid electrical shorts in the display. The sub-pixels in this figure are typically 100 x 300 µm. Simultaneously operating all three sub-pixels creates areas of "white" emission.

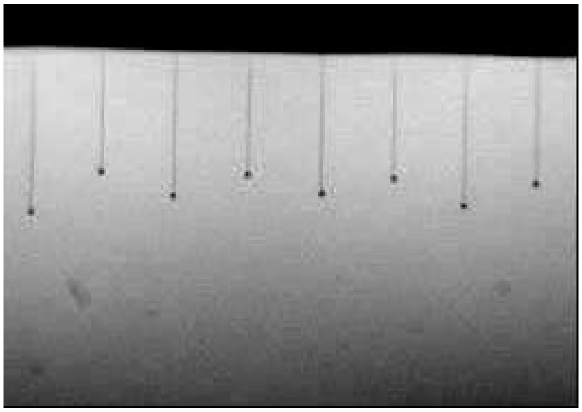

Figure 3. Jetting of polymer inks showing pronounced ligaments, in this case over 600 μm long.

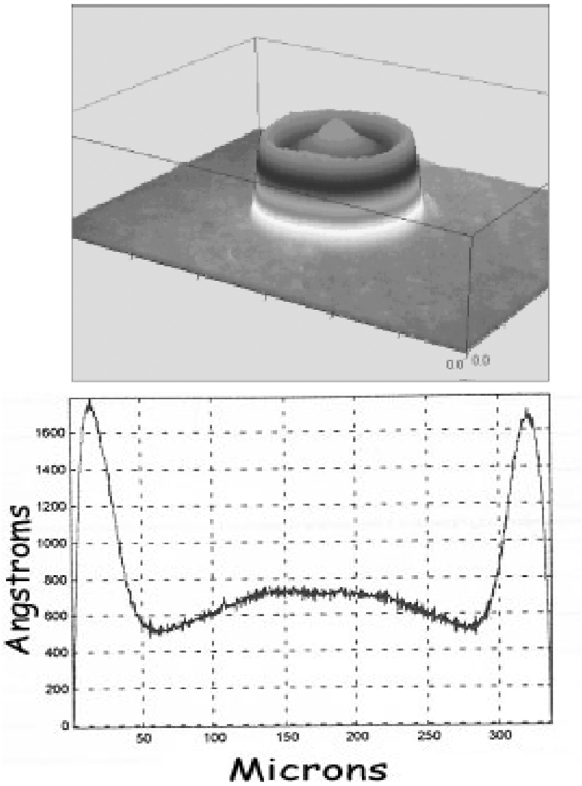

Figure 4. Examples of the tendency for these inks to dry as non-uniform films. The upper figure shows a 3-D image of the dried polymer drop, the lower figure shows a vertical profile. Mass transport to the edge of the drying drop is clearly seen.

Adding to the complication is the fact that, unlike typical ink formulations for office use (for example), we usually cannot add humectants, surfactants or other solution modifiers, since these generally degrade the light-emitting properties of the polymer layer.

The development of a palette of colored inks with good printing parameters, film-forming properties and good light-emitting performance remains one of the biggest challenges to date.

Examples of a Full Color Display Fabricated Using Ink-Jet Printing Techniques

Despite the large number of complications associated with printing these polymer inks, it is possible to make high quality displays. Fig. 5 shows an example of a full-color active-matrix display. This displays required several passes through the printer, with each color being deposited sequentially. Fig. 6 shows a close-up of a section of the display with the individual red, green and blue sub-pixels clearly visible. Each sub-pixel in this display is 85 μm wide giving a 100 dpi display pitch.

Figure 5. An example of a full-color, active matrix display with 230,000 sub-pixels. It is a 4” diagonal QVGA format (320x240xRGB), with NTSC video input and 100 dpi color pixel resolution.

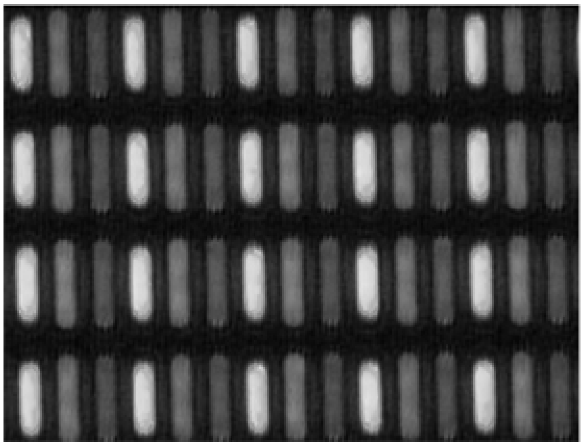

Figure 6. A section of a full-color display showing the sub-pixels.

Remaining Issues and Future Possibilities

Early results from the use of ink-jetting techniques for production of PLEDs look very promising. However many issues remain to be fully resolved. Production equipment needs to be developed to handle large, fragile glass substrates, with a very high degree of positional accuracy, in combination with highly accurate heads. Such equipment is just becoming commercially available (e.g. Litrex Corp. and Epson).

Multi-nozzle print heads with 10 pL drop sizes, tolerant of organic solvents, need to be fully developed. These are also under development by several companies.

Polymer ink formulation issues remain to be fully understood. Since the molecular structure of the polymers themselves is still under development, these formulation requirements are not yet fully defined.

Clearly, this technique would easily adapt itself to fabrication of flexible PLEDs made on plastic substrates. This is a very exciting possibility for mass production on a roll-to-roll basis. However this is realistically several years away as existing plastic substrate material is not yet of sufficient quality.

Conclusion

Ink-jet printing techniques are being developed to fabricate flat-panel displays from light-emitting polymers. The solution-processible properties of these polymers are well suited to ink-jetting techniques, although full-scale production will require the development of new types of printing equipment and a better understanding of the morphological properties of the jetted polymer films.

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Biography

Ian Parker received his B.A. degree in Physics from Cambridge University in England in 1985 and a Ph.D. in Solid State Physics (also from Cambridge University) in 1989, followed by postdoctoral work at University of California, Berkeley. Since 1992 he has worked at UNIAX Corp. (now known as DuPont Displays) His work has primarily focused on development processes for fabrication of PLEDs, as well as basic understanding of their operating and failure mechanisms.