XGA resolution full video microdisplay using light emitting polymers on a silicon active matrix circuit

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ABSTRACT

Capable self-emissive polymers are being developed for use as emitting materials for a variety of display applications. This paper describes the use of standard CMOS integrated circuit silicon wafer technology along with a spin-cast polyfluorene-base polymer emissive layer, to demonstrate an XGA resolution, full video microdisplay. The silicon chip drive circuitry (Analog Pixel-APIX) is described along with results from our efforts to optimize the reflective anode, the semitransparent cathode process, and emissive cell construction. The 1024 x 768 pixel display achieves 200 Cd/m2 brightness at low power (<50 mW) with fast 1 usec response times. In addition, we summarize future directions to achieve color and the need to incorporate a production-worthy seal layer on microdisplays manufactured on silicon wafers.

Keywords: OLED, LEP, XGA, Microdisplay, Light Emitting Polymer, Organic Light Emitting Diode

1. INTRODUCTION

Information is being communicated throughout the world at a rapidly growing rate. A significant amount of information is presented to the end user in the form of a visual display. Cathode ray tubes (CRTs) and liquid crystal displays (LCDs) on glass currently implement a vast majority of displays in use today. CRT and LCD displays however are generally large, relatively heavy, and power-hungry. Figure 1A represents a typical LCD microdisplay with required multiple illumination sources, beam splitter, and complex optics.

1.1 Display trends

Computing and communication devices are rapidly becoming smaller, more portable, and therefore more convenient to use. In order to present graphical and pictorial information on the go, it is important for displays to continue to shrink in size, power, and complexity, while at the same time increasing in resolution.

Figure 1B shows a display concept that utilizes a self-emissive polymer-based display driven by a CMOS (silicon) active matrix circuit. Such a display represents an improvement in the state of the art of displays in general and microdisplays in particular, with significant simplification resulting in reductions in power, size, and ultimately, cost.

This paper describes a breakthrough in small displays: an XGA resolution (1024 x 768) full video monochrome display implemented using light emitting polymers (LEP) on a silicon integrated circuit. The display presented here as a technological demonstration is undoubtedly a forerunner of the technology that will become practical for use in devices such as personal wearable eyeglass displays, personal digital assistants (PDAs), pocket computers, videophones, portable DVD players, and digital cameras. The new display could be used in any application that requires high resolution, video display rates, low power consumption, and small size.

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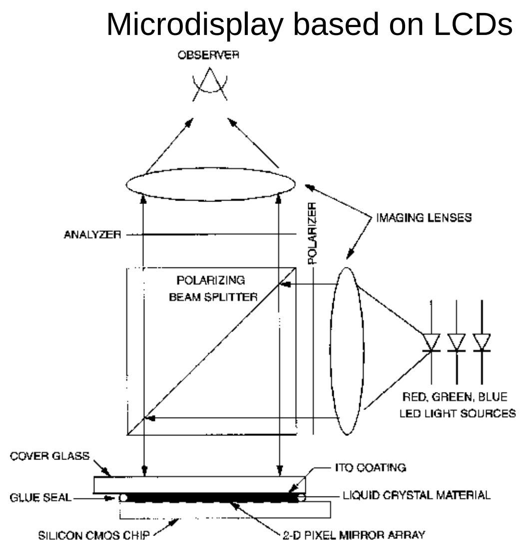
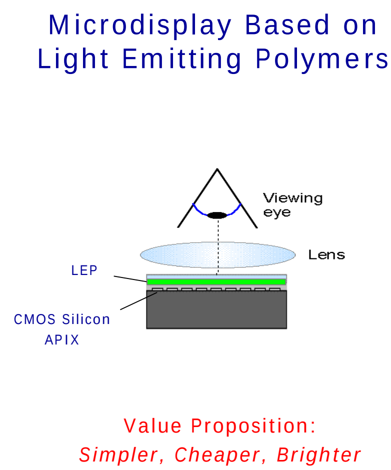


1A: LCD Microdisplay



1B: Light Emitting Polymer Microdisplay

Figure 1. Comparison of LCD and self emissive light emitting polymer microdisplays

2. BACKGROUND

The work culminating in this display began in 1992 at Agilent Laboratories (then Hewlett-Packard Labs) in Palo Alto, CA. It advanced through collaboration with Cambridge Display Technologies, LTD (CDT) in Cambridge, England to the application of light emitting polymer (LEP) material on various substrates, currently focusing on silicon. This paper reports the construction of a complete monochrome XGA video display on an active matrix silicon circuit integrated by Agilent's Imaging Electronics Division (IED) in Ft. Collins, CO. Table 1 shows the history of the development effort within Agilent.

1994	First encapsulated polymer LED-single pixel
1995	Complex single pixel with small molecules
1996	Alphanumeric small molecules
1997	32 x 64 Passive monochrome display-small molecules, then polymers
1998	CDT-HP/Agilent relationship to develop polymers on active matrix silicon
1999	Anode and cathode process investigation (VLSI lab and Ft. Collins fab)
1999	Polymer displays on APIX circuit. **First silicon XGA video display.** Ft. Collins, CO (Agilent Fab2) and Palo Alto, CA (Agilent Laboratories)

Table 1. History of LEP Investigation in Agilent

Early work at Agilent Labs investigated fundamental material properties of organic light emitting diodes (OLEDs) such as hole injection and transport [1]. Subsequent work investigated the material chemistry [2] and performance of OLEDs and conjugated light emitting polymers (LEPs) [2] [3]. An overview of that early work and a comparison of the chemistry of small molecule OLED materials and light emitting polymers, using conventional glass/ITO substrates and totally reflecting cathode electrodes, is shown in Figure 2.

Within recent years the focus of much of this work in the industry has turned to material selection, practical device construction, and cathode characterization [3]. There remains to this day a dichotomy of effort in the industry between the two approaches based on relationships with patent holders, fundamental material characteristics [2], and construction techniques, some of which are shown in Table 2.

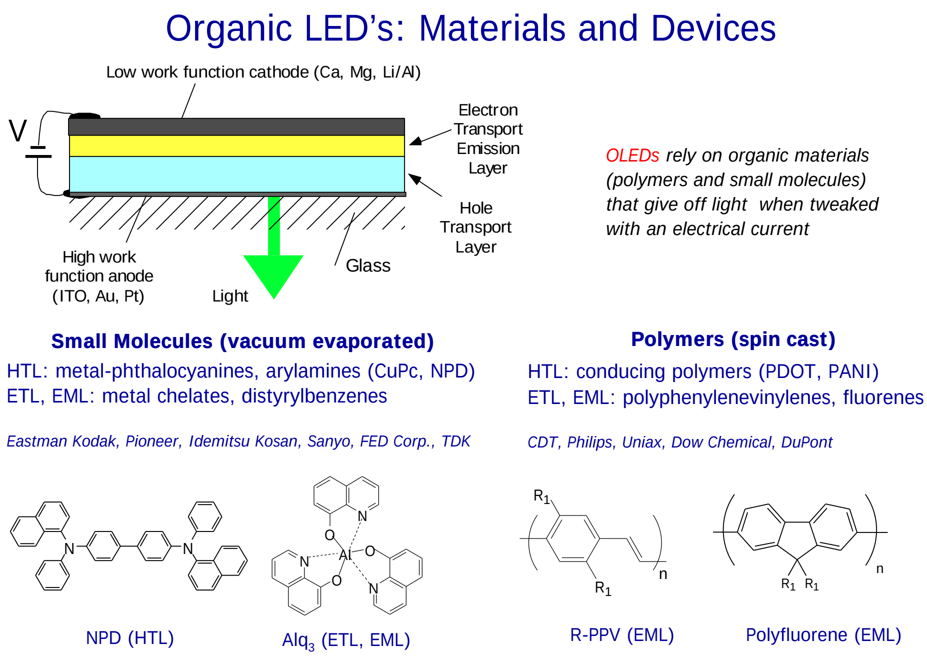


Figure 2. Organic LED's: Materials and Devices

Polymer materials have distinct advantages for highly integrated, silicon-based displays, which are summarized in Table 2. They lag in the development of long lifetime blue however. For our work the advantages of polymers outweigh the disadvantages and several of CDT's new light emitting polymers were used.

Light Emitting Polymers (LEP)	Organic Light Emitting Displays (OLED)
Polymers (PPV)	Small Molecules
Spin/Bake	Vacuum sublimation
Photolith metal layer pixels	Shadow masked color pixels
Low voltage (~2-5 volts)	High voltage (~6-8 volts)
Emerging blue/white effort	"Mature" blue material

Table 2. Light Emitting Polymer and Organic Light Emitting Diode characteristic

Figure 3 summarizes the light producing characteristics and theory of operation of polymer materials when used in a display [4]. Data reported in the industry and in Figure 3 are typical for glass/ITO/polymer/cathode structures where the components have been optimized for extraction of light through a glass substrate [4]. There are several efforts world wide to commercialize such a structure, but it is proving to be very challenging to provide switches for pixels on glass or plastic using low temperature processes which these display materials require.

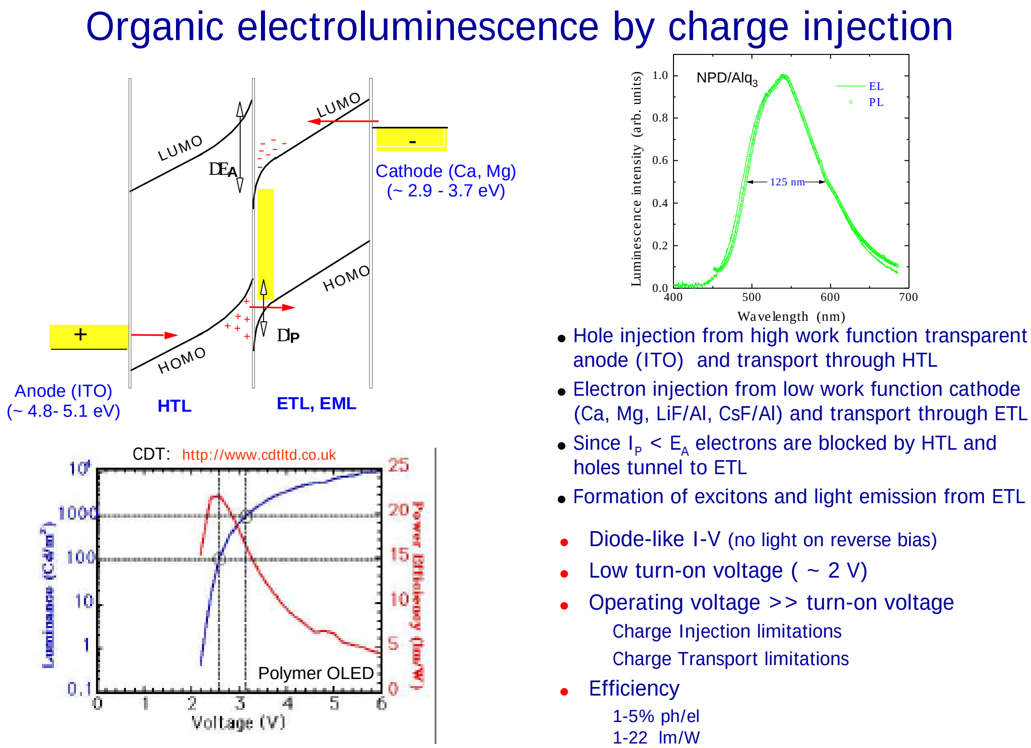


Figure 3. Organic LEP electroluminescence by charge injection

3. COMPLEX PIXEL EXPERIMENTS ON SILICON

Initial experiments were conducted with various small molecule materials, and with conjugated polymers from CDT [5]. More recently, characterization experiments with LEPs were conducted on silicon substrates. The structure characteristics are significantly different from ITO on glass. With silicon, the substrate is opaque, the anode is reflecting, and the cathode is transparent. Thus the light emitted by the polymer escapes through the top of the display where it is viewed. Pixels are formed by patterning the anodes. The cathode is a continuous film on top of the display with a stripe-conductor extending down to the region of the anode pads for wire bond convenience.

Initial experiments used complex pixel technology and consisted of four active regions in a mask pattern shown in Figure 4A. The first three regions were (from left to right) arrays of 6 um, 12 um, and 24 um square pixels connected by 1um metalization stripes and separated by 1um spaces. The final region was a continuous large area anode. These four regions were used for light, current, and voltage (LIV) measurements using a calibrated photodiode and an Agilent (HP) 4155A Semiconductor Parameter Analyzer.

A second mask pattern, shown in Figure 4B, provided a means of blocking light from the large anode in order to make static logo patterns of various sizes. In addition, this second layer provided a "blocking rectangle" over the metalization interconnects to the contact pads, to avoid shorting the anode regions during the cathode deposition.

3.1 Initial passive matrix experiment results

Properties investigated were device performance at 5V such as luminance (cd/m^2), normalized current (mA/cm^2), and device efficiency (cd/A), as well as the maximum efficiency and the corresponding voltage at which it occurs. The tests were performed using an HP4155A Semiconductor Parameter Analyzer. The luminance properties were measured in a light-sealed box using a UDT Sensor, Inc. PIN-10DP silicon photodiode. The response was previously calibrated for this photodiode system using green emission. The devices were tested in "sweep mode" of the HP4155A, with the voltage swept from 0 to 9 V while the current and luminance were recorded.

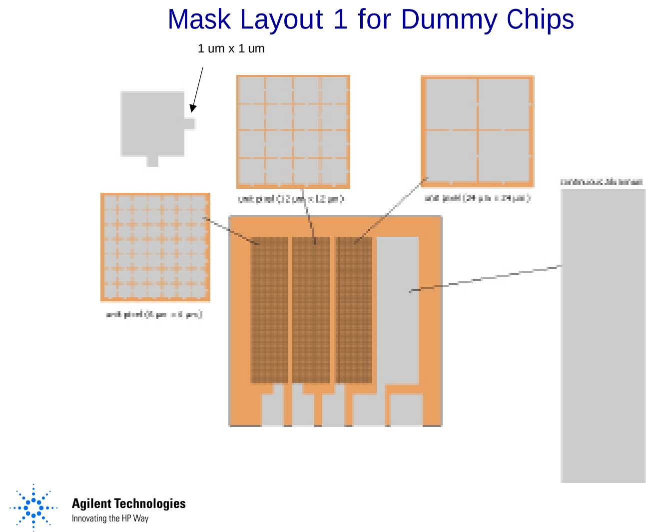


Figure 4A. Mask Layout 1 for Experimental Passive Matrix Displays

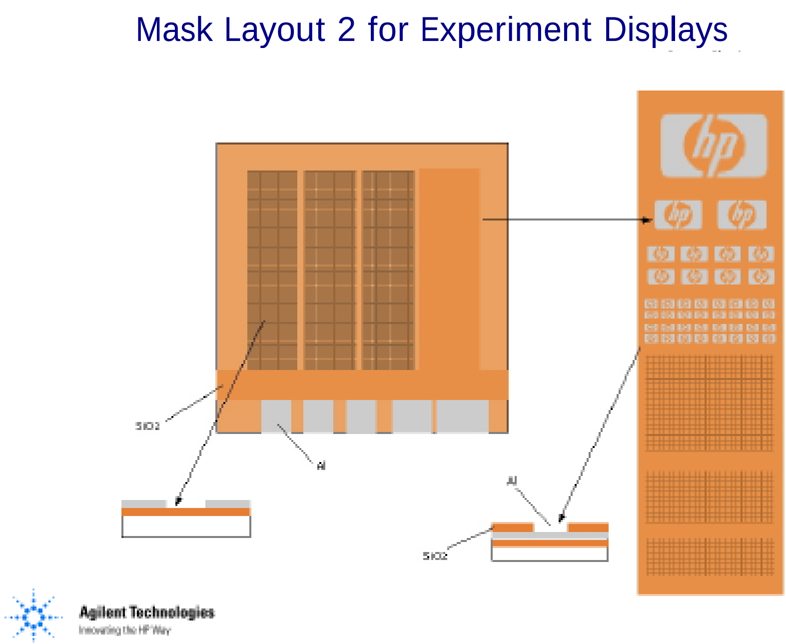


Figure 4B. Mask Layout 2 for Experimental Passive Matrix Displays

3.2 Anode optimization

A current-voltage curve measures the characteristic properties of a light emitting diode, showing the distinct turn-on voltage, a steep current rise with voltage, and a smooth roll-over at higher voltages. The current that results from the application of a given voltage varies with anode material due to hole injection efficiency and display series resistance. Similarly the luminance-voltage curve generally follows the shape of the current-voltage plot.

Several materials were investigated to determine their properties when used as anodes in making displays. Table 3 shows a summary of early anode test results using CDT 423 polymer (green). The 5V luminance properties for anode B devices are about 3x greater than that of our baseline anode A, and that of anode C is 6x greater than A. The 3x increase in luminance from anode A to anode B has a corresponding 5x increase in the current due to lower anode B efficiency. Similarly, the 6x increase in luminance from anode A to anode C gives a corresponding 8x increase in current due to lower anode C efficiency. Overall, this data indicates that anodes B and C are better choices for light emitting polymer device structures than the baseline anode A.

Property	Units	Anode Properties		
		Anode A	Anode B	Anode C
Luminance @ 5V	(cd/m2)	15	42	91
Current @ 5V	(mA/cm2)	3	15	23
Efficiency @ 5V	(cd/A)	0.5	0.3	0.4
Maximum Efficiency	(cd/A) @ V	0.6 5	0.3 4	0.4 4
Reflectivity		0.9	0.5	0.6

Table 3. Anode material characterization using CDT 423 polymer (green)

4. SILICON DRIVER

4.1 Circuit design overview

The active matrix CMOS (silicon) driver circuit for the polymer XGA video display reported here was developed in Agilent Laboratories in Palo Alto [6]. The circuit is a 1024 x 768 2D pixel array, which was fabricated in a digital 0.35 um CMOS process in the Agilent Integrated Circuits Business Division (ICBD). The color depth for this circuit is 8 bits with a pixel pitch of 12um x 12um (~85% fill factor). The active pixel array is 133 square mm with a total chip area of 214 square mm.

Pixel brightness is controlled by pulse width modulation (PWM) of the pixel voltage drive signal. The analog PWM circuitry is contained within each pixel, minimizing chip area. The 16 million transistor chip displays images at a maximum rate of 85 Hz and currently has a power dissipation of 200 mW from a single 3.3 V supply. The circuit was designed to drive a LCD and therefore uses time frame color sequencing of 255 Hz maximum frame rate.

4.2 Theory of operation

Many conventional display drivers vary the drive voltage in direct proportion to desired brightness. This class of display suffers from an interaction with the inherently non-linear LCD or light emitting polymer characteristic and perhaps a brightness coefficient that varies significantly with temperature.

The driver circuit used by Agilent for this demo display assumes that a binary voltage drive is desirable. If the cathode voltage is held at a fixed value, the circuit will make the assumption that a voltage of 0 V on the anode is minimum brightness (off) and a voltage of Vdd on the anode is maximum brightness (on). The perceived intensity of each pixel is controlled by the duration of on –vs- off during one complete display cycle. An analog voltage signal is used to generate a single pulse of correct width for the desired pixel intensity. The following sections describe the circuits used to store analog data into each pixel of the display, as well as the in-pixel PWM circuit used to generate the precise pulse widths for driving microdisplay pixels [6].

4.2.1 Video input and column amplifiers

The circuit processes an analog video waveform at approximately 200 MHz (75 Hz display rate, times 3 frames per display cycle, times 1024 columns, times 768 rows) through a sample and hold circuit driven sequentially by a pixel rate shift register.

The data for each row is loaded ½ row at a time. Buffering and settling for the first half row occurs while data for the other half of the row is loaded. This avoids line-to-line delays due to amplifier settling time. Therefore the pixels have two storage nodes so data is displayed from one set of in-pixel storage nodes while new data is written into the other set of storage nodes. This in-pixel double buffering of the analog data in conjunction with the comparator SWITCH input provides an additional benefit of comparator offset cancellation. Errors present in the comparator which render a given pixel too bright on one frame will cause the same pixel to be too dim on the subsequent frame. Because the frame rate is above the flicker fusion frequency of the human eye, the errors will average out and thereby mitigate the effects of errors in the in-pixel comparator.

The column amplifier is a single stage folded cascode amplifier with an adjustable offset [7]. This circuit provides compact implementation and a very high, stable, open loop gain.

4.2.2 In-pixel PWM circuit

The operation of the in-pixel PWM circuit is shown in Figure 5 where time-multiplexed RGB analog data are input at DATA_IN. The data is sampled and held through the SET1/SET2 switches. VRAMP is a ramp voltage that is reset every ½ display period and spans the analog voltage range. Inputs PATH1/PATH2 and SWITCH are used along with VRAMP and the voltage on DATA1/DATA2 to set the pixel output voltage, OUT, at Vdd for a time-width proportional to the input level, DATA_IN.

Figure 6 shows simplified waveforms for the in-pixel PWM circuit operation. Note the symmetrical drive within each display cycle defined by SWITCH. This provides a means of maintaining a time-averaged electric field of zero across a LCD. Since time average of zero is not needed for a LEP display, a unique VRAMP shape (not shown here) can be used to provide a 100% display duty cycle for our light emitting polymer display. In addition gamma correction (if required) can easily be provided by modifying the shape of VRAMP.

Figure 7 shows the FET-level design of the simplified circuit of Figure 5. PMOS transistors replace the data-value storage capacitors. The comparison block in Figure 5 has been replaced with a simple two-stage, PMOS input comparator. The total bias current is 8 nA. The complete circuit occupies the area under a 12um x 12um pixel in the Agilent Technologies 0.35um CMOS process.

Finally, a graphics card that can support the necessary frame rates for this display has been provided in order to drive the circuit with time-sequential color frames. While it is not necessary to provide time sequential color frames for this display, the circuit was designed for a LCD application (Figure 1A) and currently requires the additional circuitry in order to function properly. The card is configured at 1024 x 768 with minimal horizontal and vertical porch settings to provide the necessary 200 MHz pixel clock rate. The microdisplay input is multiplexed between the graphics card RGB outputs by a custom, high bandwidth, analog mux board. This board also provides signal offset and amplification and generates the display sampling clock and the chip frame timing from graphics card inputs.

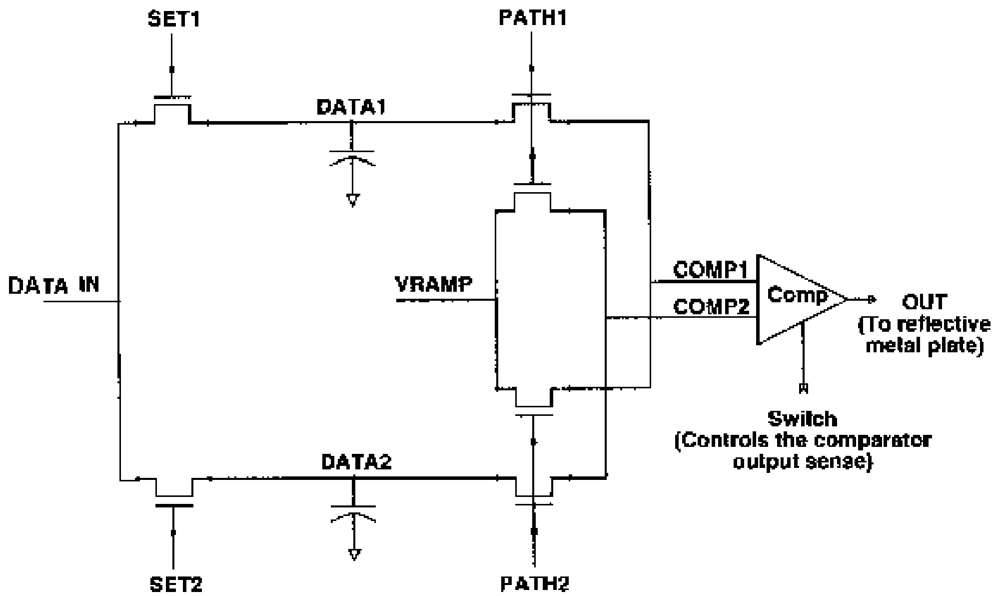


Figure 5. Simplified schematic of Analog in-pixel PWM

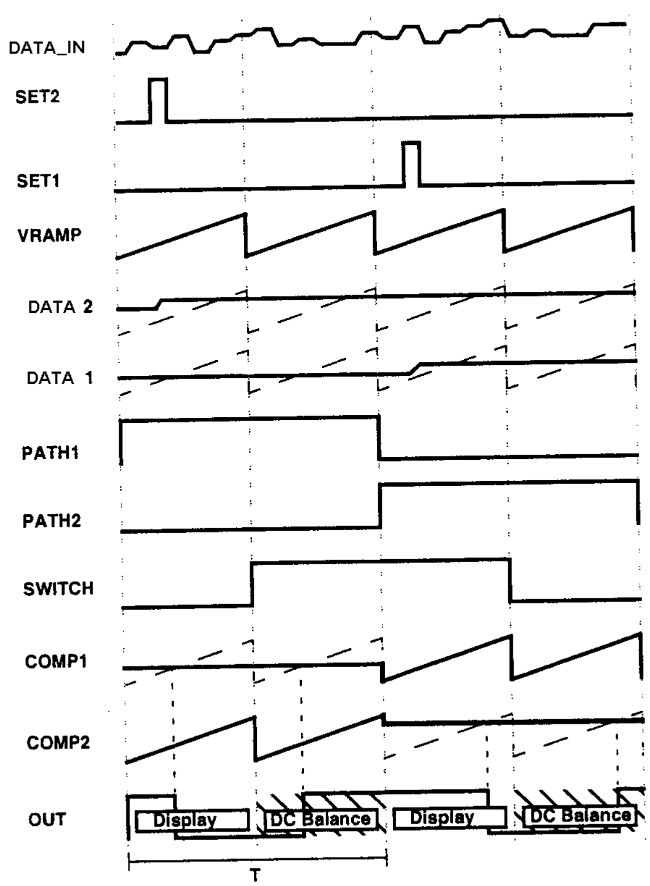


Figure 6. In-Pixel analog PWM waveforms

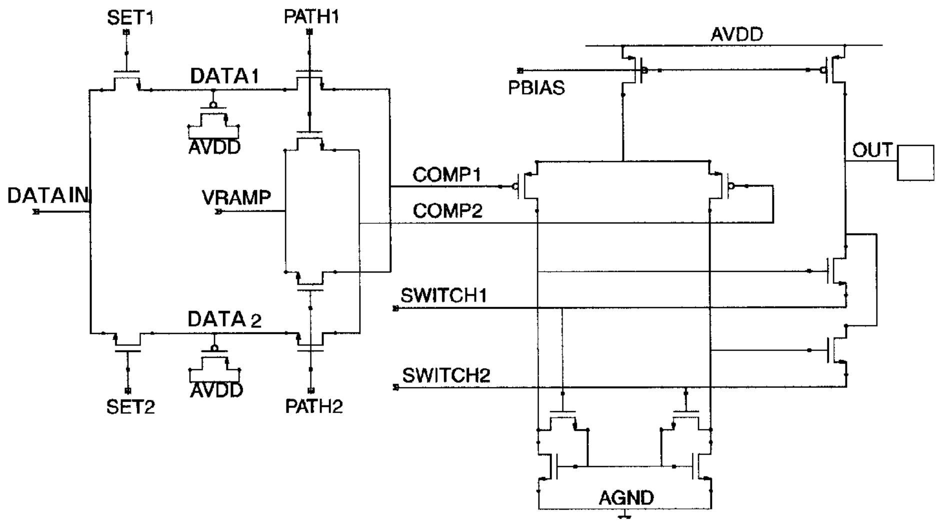


Figure 7. In-pixel analog PMW FET-level schematic

5. LEP DISPLAY INTEGRATION AND RESULTS

The necessary technology was available in Agilent in late 1999 to build an XGA LEP video display. It was however a major program challenge to combine the pieces needed to make and demonstrate a complete silicon-based display. It was especially important to develop and optimize anode and cathode technologies to accommodate the concept of an opaque (silicon) substrate with light emitted through the cathode.

Cooperation between the Ft. Collins IC Fab and Agilent Labs in Palo Alto allowed the pieces to come together successfully in a very short period of time. Table 4 shows the major program contributions required to successfully complete the goal of a working demo by November 1999.

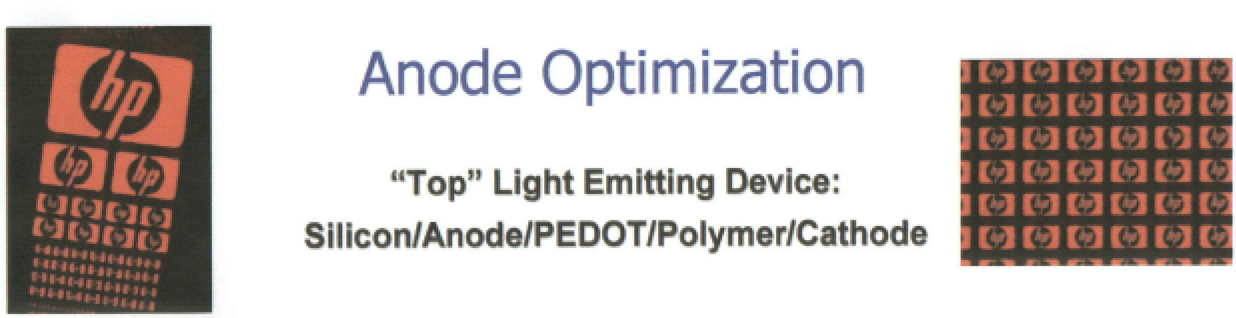
Anode and cathode optimization
Integrated circuit fabrication of the existing circuit design
Functional test
Light emitting polymer chemistry
Daughter board construction
Assembly and wire bonding
Computer support and debugging
Results

Table 4. Program Issues List for XGA Demo Display Construction

5.1 Anode and cathode optimization

While many metalization techniques are available within the integrated circuit (IC) processing community, they are generally designed for core CMOS interconnect applications. This light emitting polymer display required unique electrode properties to optimize its operation. Agilent Labs in Palo Alto developed a semi-transparent cathode conductor process using a proprietary composition. The cathode layers are required to be compatible with package processing and are patterned using a die-size shadow mask during deposition.

The anode requires high work function, high reflectivity, and a surface topography suitable for spin-casting the thin polymer layers without introducing objectionable step heights that could provide polymer thinning at the anode edges with resulting bright spots and reliability issues. Several materials and unique process operations were investigated that provided the results shown in Table 5 below and in the demo devices.



Device	Glass	(#548) CDT426 Red					
Anode	ITO CDT 419 R	A	D	B	E1	E2	C
Efficiency (cd/A) @ 5V	6.5	2.0	1.1	1.0	1.3	1.4	1.6
Max eff. (cd/A)	7	2.4	1.3	1.5	1.5	1.5	2.0
Luminance @ 5V (cd/m^2)	360	100	224	323	255	210	620
J_{led} @ 5V (mA/cm^2)	6.5	5	20	32	19	14	39

Table 5. Anode on silicon characterization for CDT 426 (Red)

5.2 Integration of silicon driver with the display

Figure 8 shows schematically the integration of the silicon driver circuit, anode processing, spin-cast light emitting polymer layers, cathode deposition, and final cover-glass seal. The resulting demo is a step toward the goal of applying integrated circuit processing technology and its disciplines to the practical construction of microdisplays.

Each of the process steps shown schematically in Figure 8 are actually combinations of steps, which when completed, produce the final display. Figure 9 shows an overview of the fabrication sequence used to build the display. This sequence can be considered a method for constructing prototype displays and therefore may form the basis for further development to refine a more suitable (future) manufacturing sequence.

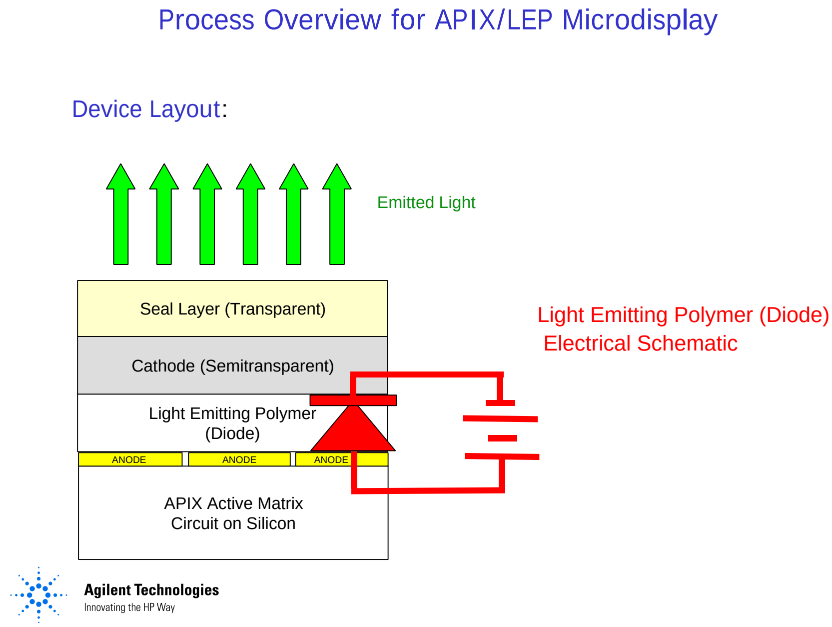


Figure 8. Process integration overview for LEP/APIX microdisplay

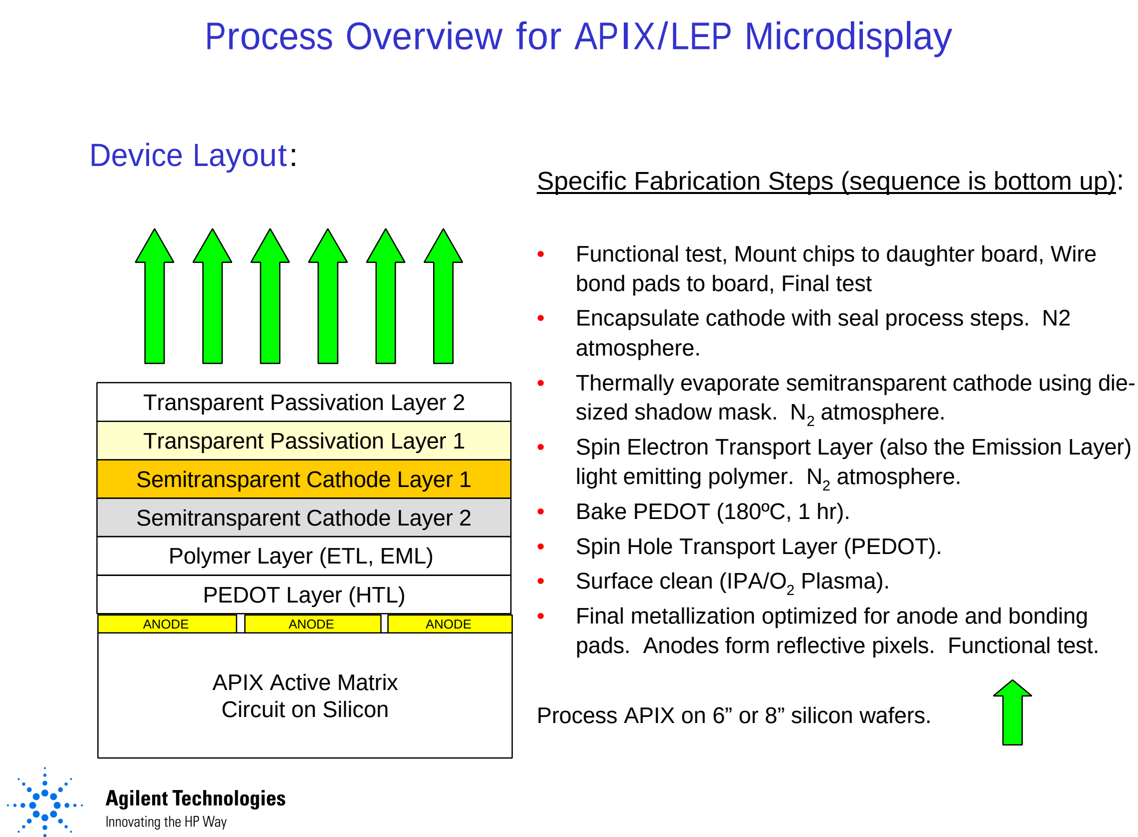


Figure 9. Process Overview for APIX/LEP microdisplay

5.3 XGA Demo results

Upon completion of the initial fabrication cycle using anode A the first demo unit worked as planned. After connection to the computer containing the custom analog board for driving the circuit, a DVD source was displayed in real-time video. The final result is reproduced in Figures 10-13 showing the display mounted on a daughter board near a USA one cent coin to indicate its size. A magnified display image is shown in Figure 13 showing the 256 gray scale and detail available with an XGA display driven by a DVD source.

Displays have also been fabricated with anode B both with green polymer and with white polymer. We find that in addition to the efficiency of the polymer, the transmission of the cathode plays a large part in the overall brightness of the resulting display. Addition fabrication cycles with both polymers are underway in order to provide additional demo capability and continue the learning process.

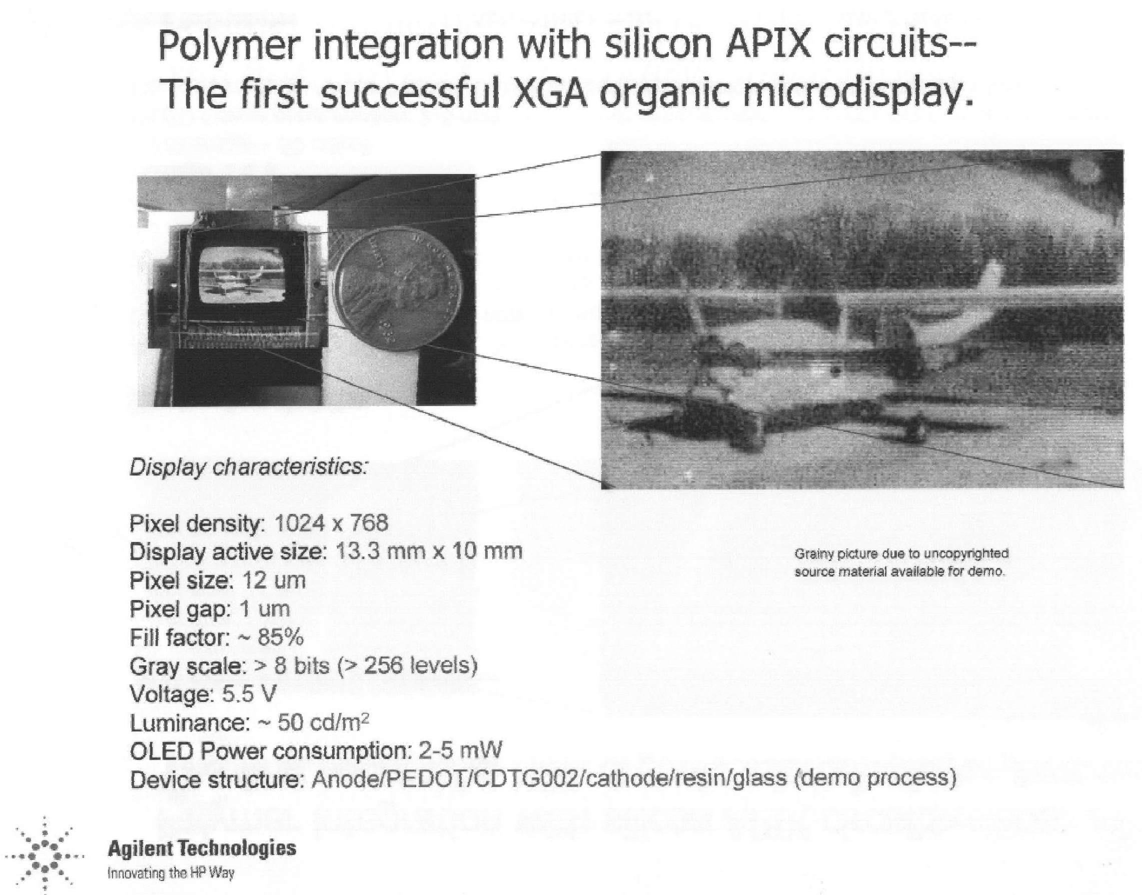
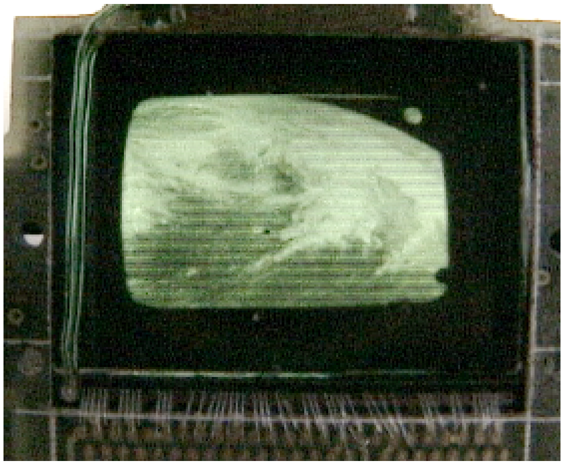


Figure 10. First successful XGA video LEP microdisplay

Two additional images taken from the demo display are shown in Figures 11 and 12. The non-copyrighted source material for these images was taken from scanned photos and an animated chess game. The new display was driven from a standard PC through the host module described above. These figures do not adequately present the capabilities of the new display, but rather stimulate the imagination as to possible applications.



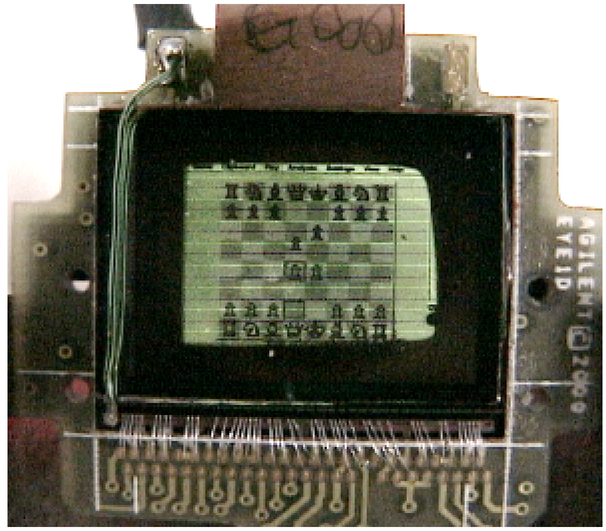


Figure 11: Weather satellite image showing a rising full moon over western USA.

Figure 12: Animated chess game

Figure 13 shows a DVD frame (shown with copyright permission from MGM/United Artists) under high magnification. Note the smooth line edges and complete absence of pixelization even at magnifications approaching 20x.

Figure 13. DVD image showing no pixelation at high magnification (used by permission)

6. FUTURE DIRECTIONS

There remain several areas to be developed before this display technology can be considered a practical reality. Foremost among them is the need for a reliable seal technology that is compatible with an overall manufacturing sequence suitable for silicon wafers. In addition, there are several reliability issues being addressed by the industry in general [4] [5]. The cathode materials need to be protected from oxygen and moisture. The polymers degrade with time, although significant advances in polymer life have been reported recently [5].

6.1 System optimization and color schemes

Additional work is needed to optimize the anode and cathode layers as well as the polymer layer itself for best efficiency. There are several approaches to optimize the display system considering such parameters as overall resistance, reflectivity of the anode, transmission and conductivity of the cathode, hole and electron injection efficiency, and finally, polymer quantum efficiency.

In addition there are several ways to build a color display [6] with comparable resolutions. While there are several important product applications for monochrome displays, most applications will benefit from true color displays, especially for video applications. The diagrams in Figure 14 show several options.

The final question raised by a discussion of this emerging display technology is one of market acceptance for a variety of applications being developed within the industry. This question, while perhaps the most fascinating one of all, is unfortunately beyond the scope of this discussion and will be left for a future forum.

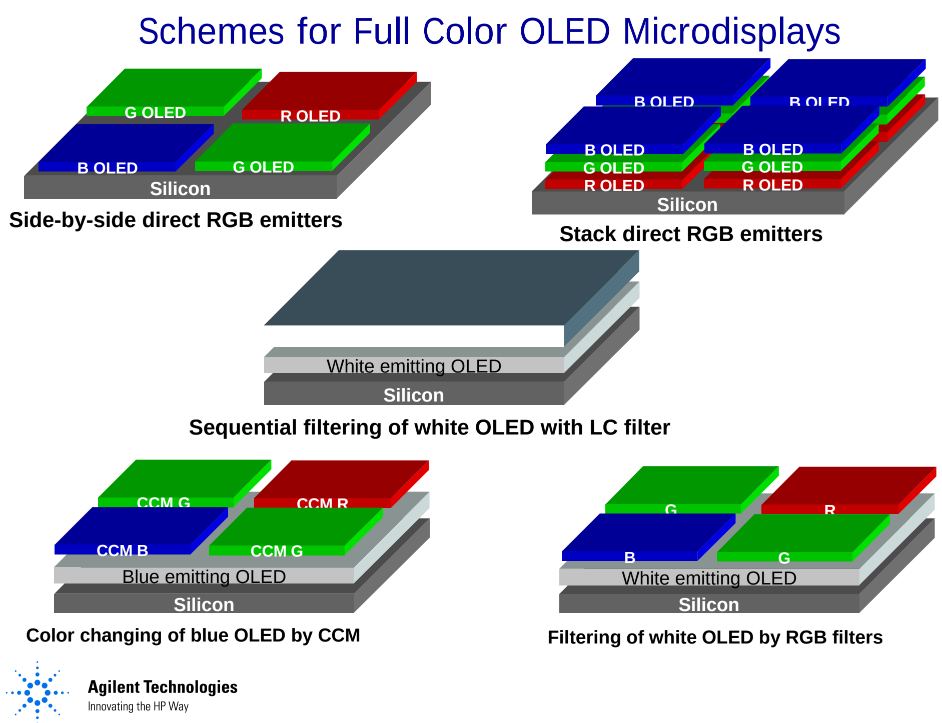


Figure 14. Possible Color schemes

7. CONCLUSION

Agilent Technologies' construction of an XGA real-time video display using light emitting polymers and an active matrix silicon driver leads to the conclusion that polymer displays may have a promising future when compared to the complexity of comparable LCD and other display technologies. While there is a significant amount of work yet to be done, it is becoming clear that light emitting polymer displays may provide an advantage over competing technologies as shown in Figure 15.

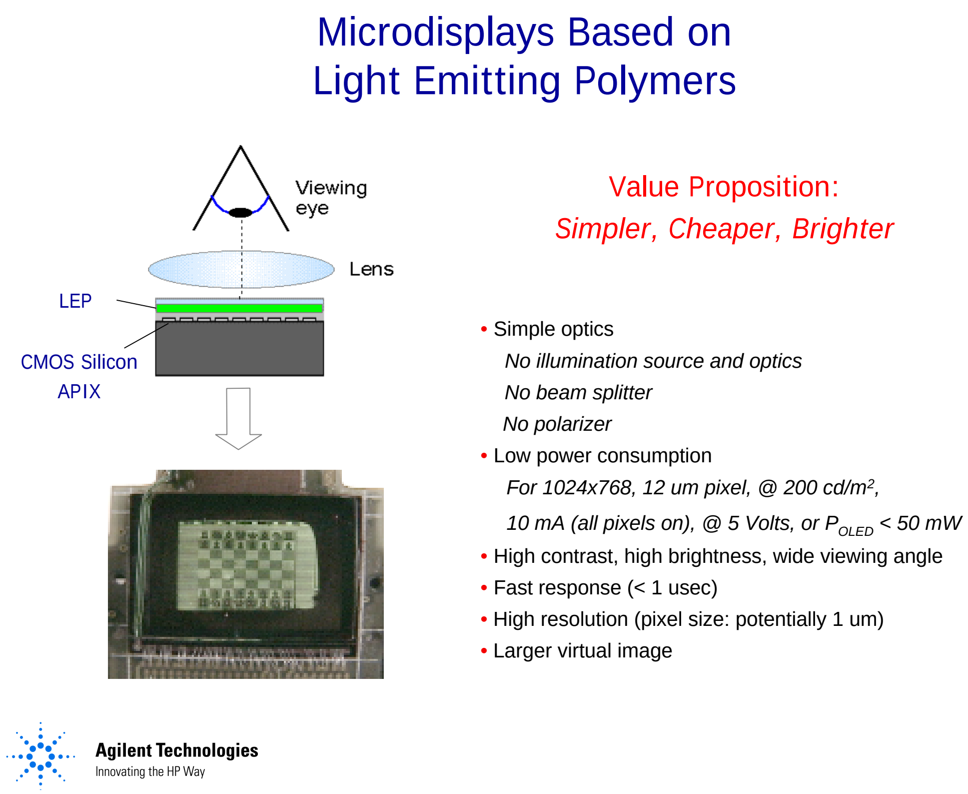


Figure 15. Conclusion: Potential advantages of Light emitting polymer displays

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