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FULL COLOR OLED ON SILICON MICRODISPLAY

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Abstract

eMagin has developed numerous enhancements to organic light emitting diode (OLED) technology, including a unique, up-emitting structure for OLED-on-silicon microdisplay devices. Recently, eMagin has fabricated full color SVGA+ resolution OLED microdisplays on silicon, with over 1.5 million color elements. The display is based on white light emission from OLED followed by LCD-type red, green and blue color filers. The color filters are patterned directly on OLED devices following suitable thin film encapsulation and the drive circuits are built directly on single crystal silicon. The resultant color OLED technology, with its high efficiency, high brightness, and low power consumption, is ideally suited for near to the eye applications such as wearable PCs, wireless Internet applications and mobile phone, portable DVD viewers, digital cameras and other emerging applications.

1. Introduction

The last few years have seen a tremendous increase in the level of activity in the OLED area since the demonstration of the first efficient OLED device.[1] This is due to the fact that the OLED technology is making leaps and bounds progress towards being product worthy. Many important issues such as the device lifetimes and good color gamut are being solved at many industries as well as universities. Product shipments are ongoing at Pioneer Corporation and eMagin Corporation.

OLEDs are attractive for flat panel display applications for various reasons such as low power consumption, wider viewing angle, and very high resolution capability. Since they incorporate OLEDs directly on single crystal silicon wafers eMagin's microdisplays are very cost competitive and lightweight. This is because the drive circuits are fully integrated in the silicon substrate, and the well matured CMOS technology of the silicon foundries make it economically feasible.

Apart from the OLED itself microdisplays also require very lightweight, compact and high quality optics in order to magnify the image to provide the experience of viewing a large screen display. eMagin Corporation's fully owned subsidiary, Virtual Vision, has a patented lens system which is capable of magnifying approximately 20X without any significant lens aberrations. Finally, the design and performance of the actual headset plays an important role in the microdisplay industry.

Organic Light-Emitting Materials and Devices V, Zakya H. Kafafi, Editor,
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SDC EX. 1020 - 1/10

2. Design Considerations

OLED on silicon microdisplays require a number of special design considerations compared to large area displays. For example, very high resolution electrode patterning capability is required for features having 2 to 3 μm critical dimensions. Because microdisplays are typically magnified by a factor of 15 to 20, they have high sensitivity to defects and black spots which are magnified along with the desired image. No shadow mask for color pixel patterning can be used because the color sub-pixel dimensions are so small that the shadow mask will be mechanically unstable.

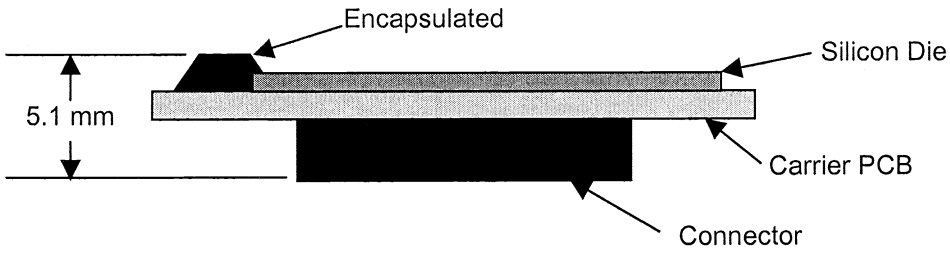
The driving circuit is integrated within the silicon using state-of-the-art CMOS technology. The feature size of the transistors in single crystal silicon can be extremely small (compared to low temperature polysilicon or amorphous silicon), thereby making very high resolution microdisplay fabrication feasible. With today's mature foundries for CMOS technology the cost per wafer is reasonable. In addition, making in excess of hundred microdisplays per wafer gives a competitive price per display. A fully integrated driver circuit together with a compact and lightweight optics system is desirable in a wearable headset.

eMagin's microdisplay is based on small molecule OLED technology originally developed by Eastman Kodak[1] for use with transparent substrates such as glass. However, since the OLED on silicon display is fabricated on a silicon wafer, the emitted light has to exit through the top surface of the device and such a structure is usually termed as a "top-emitting" structure. The anode is opaque (metal) and forms the bottom electrode while the cathode is the transparent top electrode. The display is based on a white OLED emitter, and the individual red, green and blue primary colors are generated by LCD type color filters. These color filters are fabricated directly over the OLED device using photolithograhic techniques after the OLED is hermetically sealed using a proprietary thin film seal technique which decreases the cost per display.

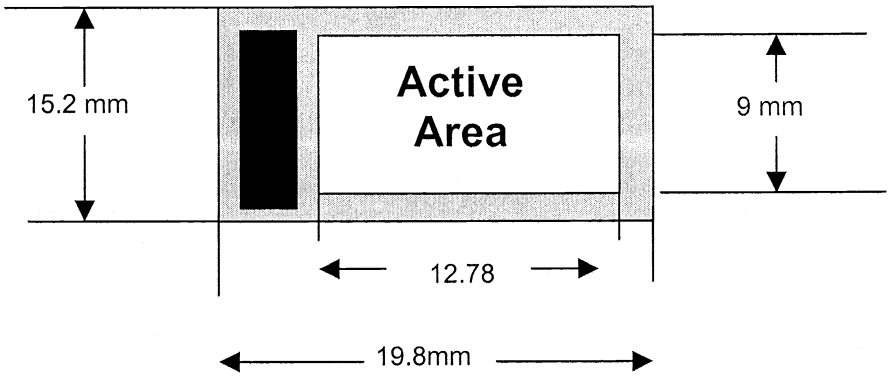
3. Physical Layout

A schematic of the physical dimensions of the SVGA+ (852 x 3 x 600 pixels) color display is shown in Figure 1. Figure 1 (a) shows the side view of the display substrate together with the carrier PCB and the connector. The overall height of the entire structure is only about 5 mm. The encapsulant shown on the left side of the display is a protective epoxy coating for the wire bonds that are made between the silicon die and the PCB board. Figure 1 (b) shows the dimensions of the active area and the total silicon real estate including the area for the wire bond pads (black region on the left). As shown in the figure the overall dimensions of the display are 19.8 mm x 15.2 mm with the active area being 9.0 mm high.

SDC EX. 1020 - 2/10



(a) Side view



(b) Top view

Figure 1. Schematic view of the display substrate, carrier PCB, and connector

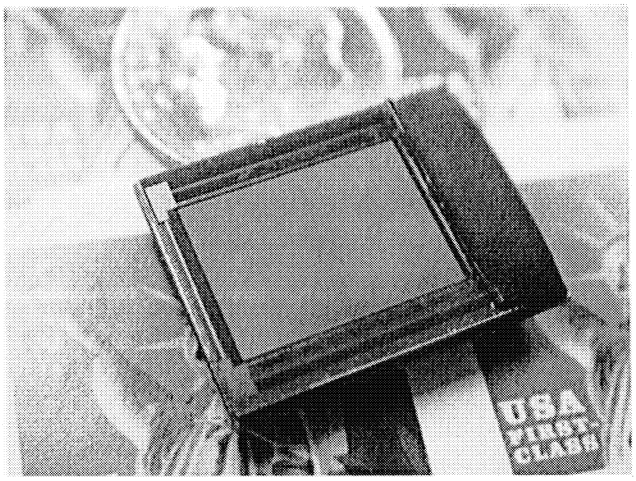


Figure 2. SVGA+ (852 x 3 x 600 pixels) microdisplay

SDC EX. 1020 - 3/10

4.0 Pixel Pattern

Figure 3 shows the pixel pattern as defined by the anode metal in the SVGA+ microdisplay. Each sub-pixel is 3.5 μm wide and 13.5 μm long with a gap of 1.5 μm. There are 852 x 3 columns and 600 rows.

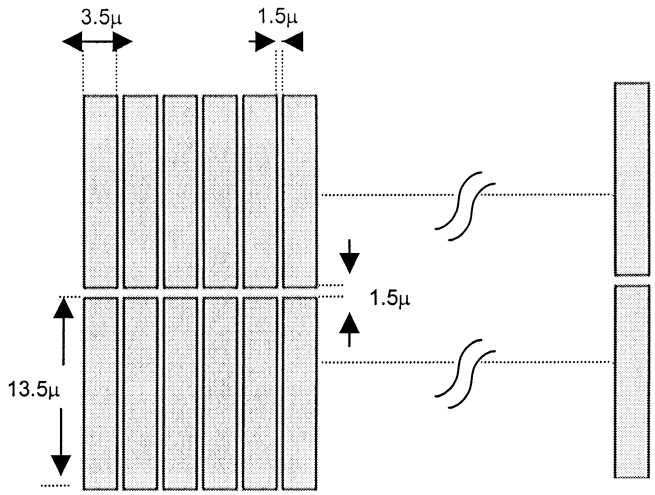


Figure 3. SVGA+ anode metal sub-pixel pattern

The color filter patterns are shown in Figure 4. Each color is in the form of stripes and is separated by black matrix. The color filter stripes are slightly larger than the anode metal sub-pixel patterns in order to ensure suitable overlap of the two. The color stripes are 4.0 μm wide and the black matrix is 1.0 μm wide.

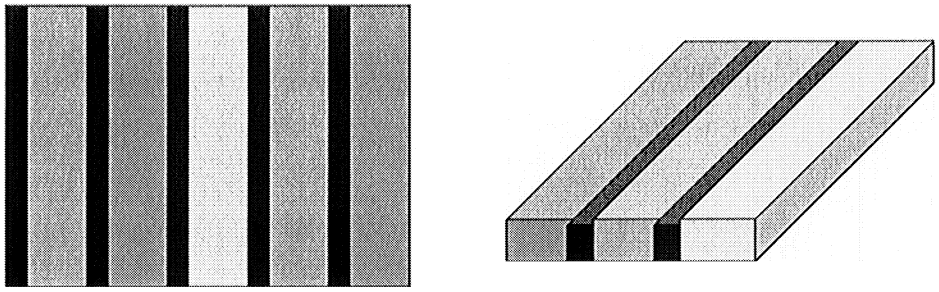


Figure 4. Color sub-pixel structure including black matrix

5.0 Fabrication

The fabrication process steps are shown in block diagram in Figure 5. Pre-processed 8-inch wafers from a commercial CMOS foundry are acquired. These wafers contain all the drive circuits in the silicon substrate. There are via studs that make contact to the underlying circuitry to the anode metal on top. The incoming wafers are then cleaned and photo-lithographically patterned for the anode metal (bottom electrode). OLED deposition is then carried out using

SDC EX. 1020 - 4/10

thermal evaporation methods. The OLED stack consists of the bottom electrode, hole transport layer, emission layer, electron transport layer and electron injector layer (cathode). Thin film seal deposition is then carried out on these wafers. Following the thin film seal deposition, LCD type color filters are photolithographically patterned on the wafer. The process involves processing each color (red, green and blue) sequentially. The black matrix is formed in a separate photolithography process similar to the individual colors. The wafers receive a top protective coating that also includes an antireflection layer. Since all the thin film seals as well as the protective coatings on top are blanket layers across the wafer the wire bond pads are opened at this stage. The wafers are then diced and individual chips are separated out. The chips are then attached to a carrier PCB board and wire bonded. The microdisplay is then tested for performance both electrically and optically. A schematic of the cross-section of the entire display structure is shown in Figure 6.

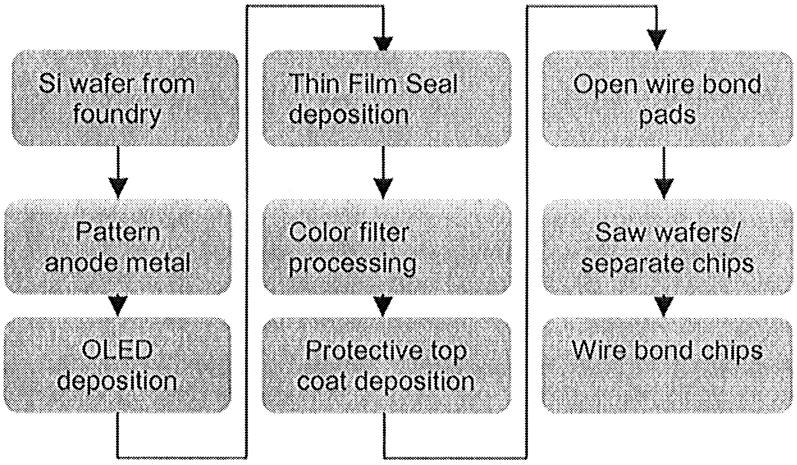


Figure 5. Fabrication process steps

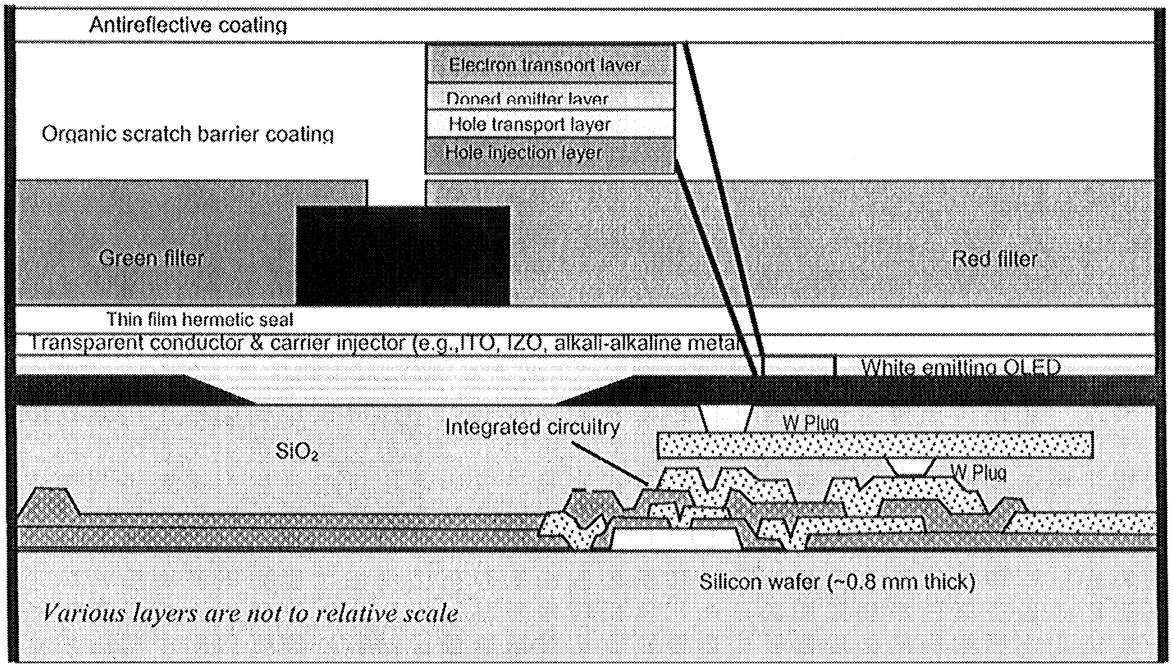


Figure 6. Schematic of top-emitting OLED on Silicon cross-section structure

SDC EX. 1020 - 5/10

6.0 Performance

Various measurements were carried out to determine the performance of the displays. Figure 7 shows a typical current-voltage plot. The OLED device exhibits a diode like characteristic with a threshold of less than 5 volts. For a voltage of about 8 volts the OLED current is about 20 mA/cm^2.

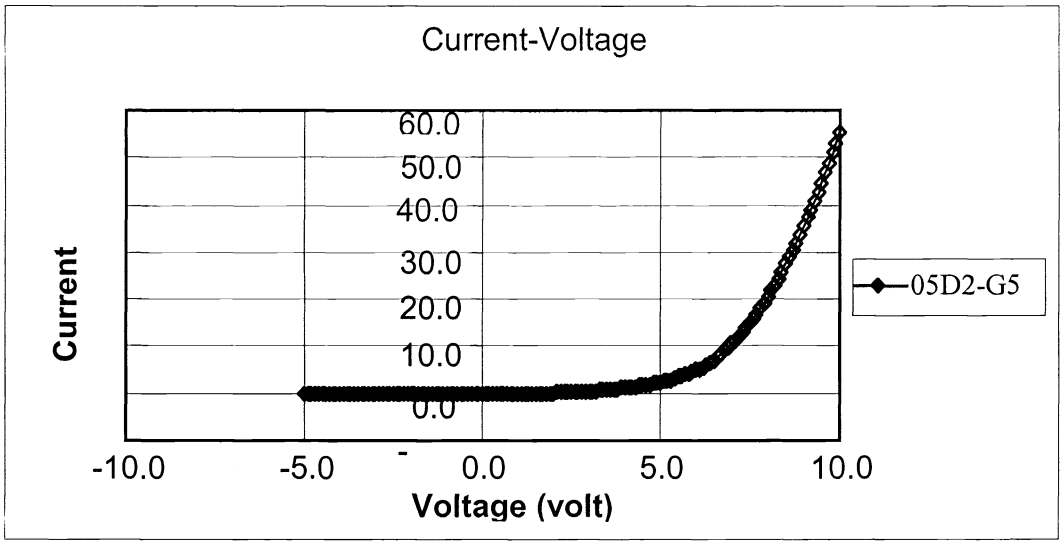


Figure 7. Typical I-V Curve for SVGA+ microdisplay

Figure 8 shows a typical luminance versus voltage plot for a double-doped white OLED display. For a voltage of about 8 volts the brightness is about 1000 cd/m^2, which is sufficient for a white display to pass through color filters and still have enough luminance in a full color display. The color filters on the average have about 20-25% transmission.

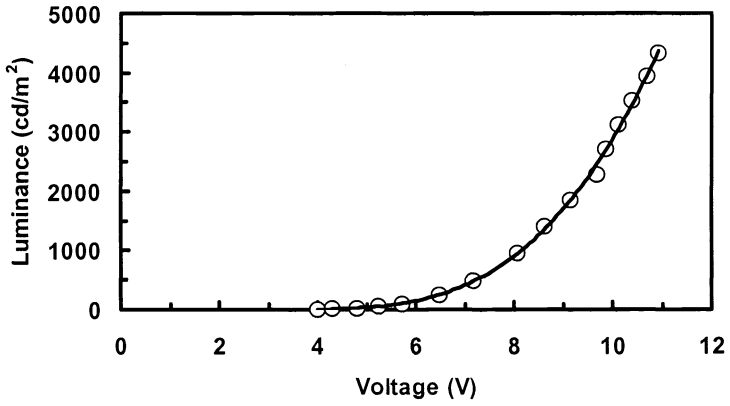


Figure 8. Luminance – Voltage curve for white OLED

SDC EX. 1020 - 6/10

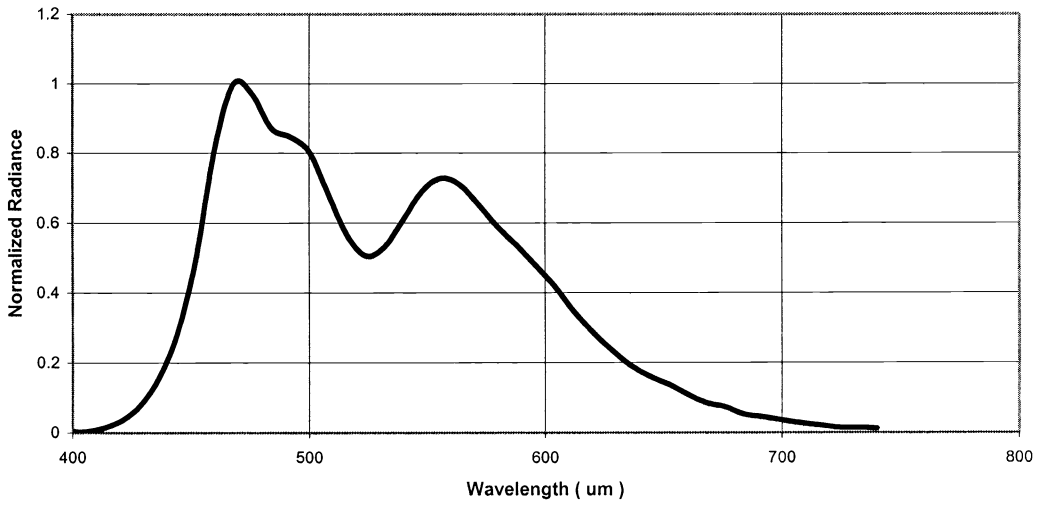


Figure 9. Spectrum of eMagin's dual dopant[2] white OLED emitter.

Figure 9 shows a typical spectrum of eMagin's dual dopant[2] white OLED emitter. It is clear from this plot that the spectrum is broad enough to generate sufficient amount of R, G, B primary colors when used with color filters.

Figure 10 shows a measured spectrum of the SVGA+ microdisplay including the color filters. The dotted line is the resultant white light emitted through the color filters and the other three curves are the red, green and blue color filter spectra.

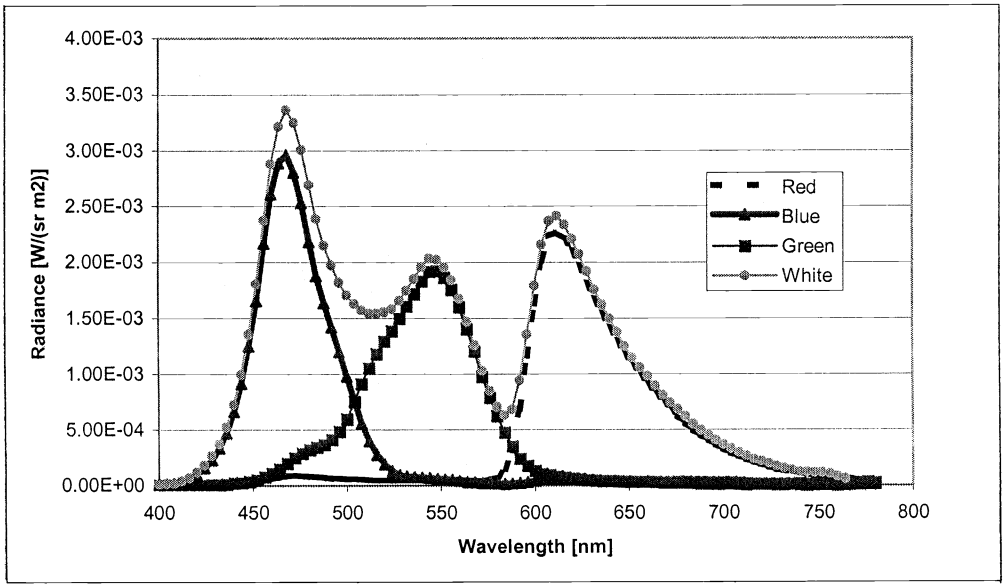


Figure 10. Measured SVGA+ microdisplay spectra including color filters

SDC EX. 1020 - 7/10

Figure 11 shows a CIE 1931 2° chromaticity plot for eMagin Corp.'s OLED display and a typical CRT display, which shows that the color gamut obtained in eMagin's OLED microdisplay is comparable to CRT color gamut. In fact, the color gamut of eMagin's OLED microdisplay exceeds the color gamut of LCD based notebook computer screens. In addition to the color gamut, typically, 16 levels of gray are obtained.[3]

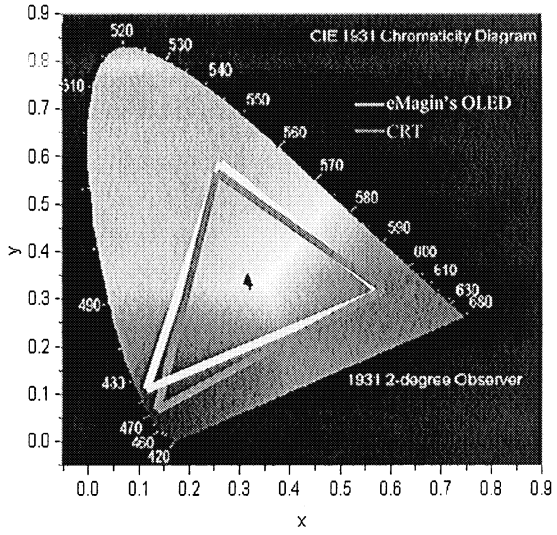


Figure 11. Measured CIE co-ordinates of eMagin's microdisplay and typical CRT

Figure 12 provides photographs of eMagin's microdisplay screen as captured by a consumer digital camera. It is obvious from these pictures that there are no discernable black spots in these displays despite the fact that multiple photolithography process steps (involving developer and water sprays) were carried out over the OLED layers and the thin film seal. This demonstrates the thin film seal's robustness. However, the true test of a long term reliable thin film seal is to subject the display to a harsh environmental test such as 85°C temperature and 85% relative humidity for an extended period of time. This is an accelerated reliability test and is widely accepted as a benchmark for product reliability.

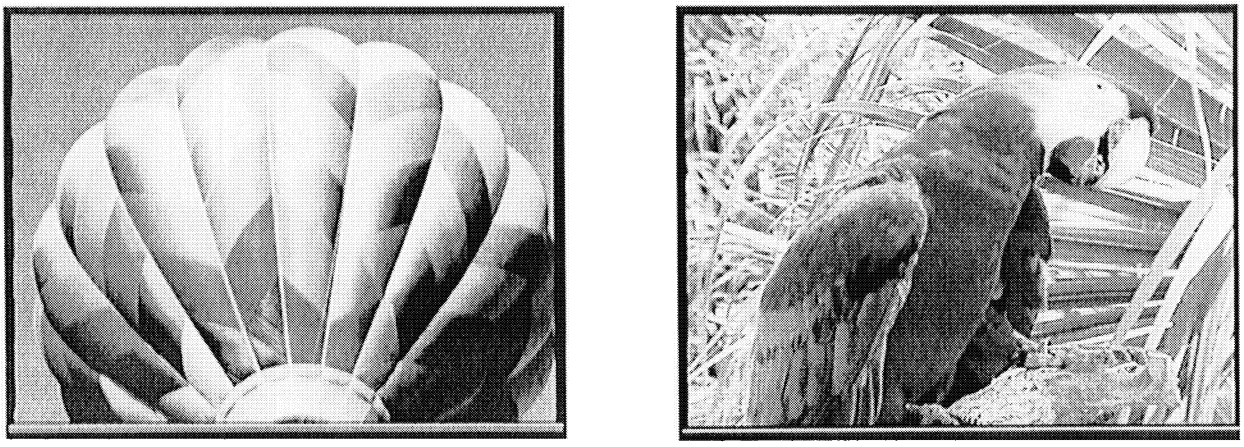


Figure 12. eMagin Corporation's microdisplay as captured by a digital camera

SDC EX. 1020 - 8/10

Figure 13 shows pictures of one quarter of the display captured with a CCD camera before and after 200 hours of 85°C/85% RH test. It is obvious from these pictures that there was no growth of black spots after 200 hours. In fact, more recent tests indicate that there are no black spots for more than 500 hours of 85°C /85% RH tests.

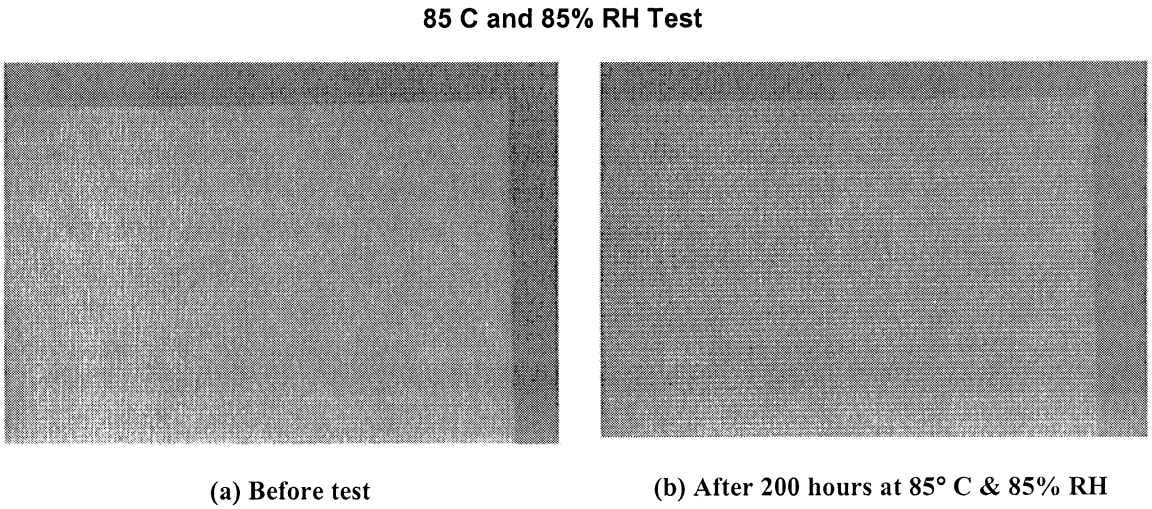


Figure 13. Temperature and Humidity Tests

The table below summarizes the performance of eMagin's SVGA+ microdisplay.

PARAMETER	MEASURED VALUE
White Brightness	>100 cd/m^2 @ 20 mA/cm^2
Power Consumption	300 mW
Operating Lifetime	>10,000 hours
Environmental	>500 hours @ 85°C /85% RH
Contrast Ratio	>130:1
White CIE	x=0.33, y=0.33
Red CIE	x=0.62, y=0.33
Green CIE	x=0.29, y=0.61
Blue CIE	x=0.14, y=0.11

7.0 Summary

eMagin Corporation has demonstrated the world's first full color OLED-on-silicon SVGA+ microdisplay with fully functional and product worthy thin film encapsulation. This is also the first demonstration of a complete low temperature color filter process used to build high resolution filters directly over the thin film encapsulated OLED device. The color gamut obtained with this technology surpasses the commercially available LCD notebook displays and is close to CRT gamut.

SDC EX. 1020 - 9/10

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SDC EX. 1020 - 10/10