0.9 -in. 6,020ppi 4Kx4K Silicon-Based Micro-OLED Display Technology

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Abstract

VR technology is an immersive, three-dimensional display technology that can bring fantastic display effects to the wearer. Micro-OLED perfectly fits VR display in terms of miniaturization, high pixel density, and high brightness, and has gradually become the first choice for high-end VR products. However, due to excessive cost constraints, micro-OLED has not yet entered the more popular products. Therefore, improving product pixel density and reducing single chip cost have become the core research topics of micro-OLED. A micro OLED display screen with up to 6020PPI, 4K*4K resolution and a size of 0.9 inch has been designed, maximizing cutting efficiency and reducing single chip product cost. And in order to enable the white OLED device to possess a high luminous efficiency, we have fully optimized the OLED microcavity, the brightness reaches 5000nit. In the end, a compact free-form surface AR glasses optical system was designed using the equal optical path theory.

Author Keywords

Silicon Based Micro-OLED, Ultra-high PPI, AR, Free-form Surface

1. Introduction

With the development of VR/AR near-eye display, the demand for high brightness, high pixel density and small size micro display screen is becoming more and more urgent. AR is increasingly widely used and recognized by more and more people [1-2].

When the resolution is high enough, with a screen of 300 PPI, the retina can no longer distinguish pixels. In order to meet the needs of human eyes, the spatial display is converted to 60-PPD (pixel per degree). When the FOV of binocular overlap is 120°, the ideal resolution of monocular is 7200*7200. Limited by the silicone-based exposure shot, the backplane size is generally less than 1.5 inch. Therefore, ultra-high PPI has become the inevitable development direction. Meanwhile, due to the loss of brightness in the optical system, the module needs to have ultra-high brightness.

In this paper, we developed ultra high PPI, ultra high brightness micro display for AR glasses, and a compact free-form surface optical system was designed using the equal optical path theory for 0.9 inch micro-OLED display.

2. OLED EL Cavity Design

It remains a great challenge to achieve color OLED displays with high luminous efficiency under ultra-high PPI at present. Currently, the technology for separately fabricating red, green, and blue pixels with high precision patterning process is still not mature enough, and using white OLEDs in combination with color filters is still the mainstream design solution.

As shown in Figure 1, in order to enable our white OLED device to possess a high luminous efficiency, we have fully optimized our OLED microcavity. This optimization makes the peaks of the emission spectra of the red, green, and blue EL materials simultaneously fall on different resonant modes of the microcavity, ensuring that all three colors can achieve high luminous efficiency simultaneously.

Among them, considering that the blue light material still has shortcomings in terms of luminous efficiency and lifetime compared to the other two colors, we have placed the main resonant peak of the microcavity within the range of the blue EL emission spectrum. Meanwhile, we have positioned the blue light-emitting EL material at the main resonant node of the microcavity. To simplify the device design, we have combined the green and red EL materials together and placed them at the secondary resonant node of the microcavity. The final formed device is shown in Figure 2.

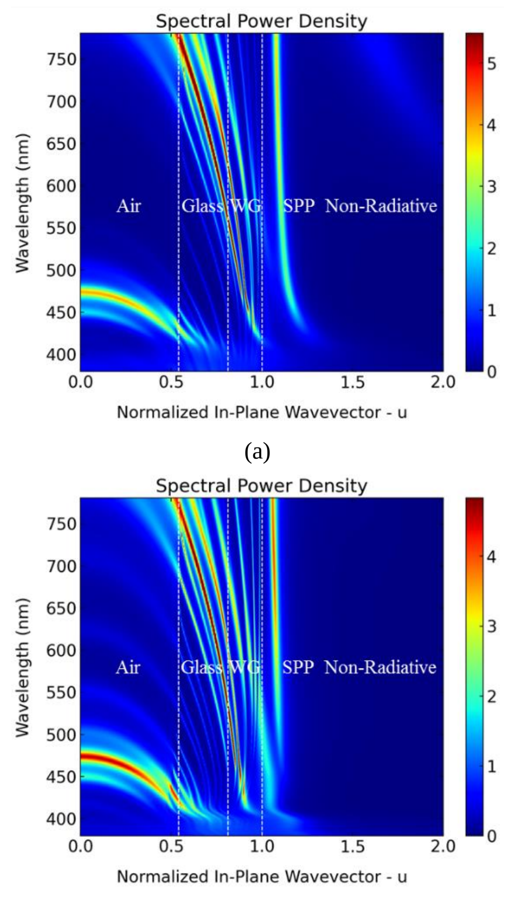

Figure 1. Mode Analysis of the OLED Cavity with the EL Emitter Positioned at Different Locations. (a) Location of the Blue Emitter; (b) Location of the Red and Green Emitters

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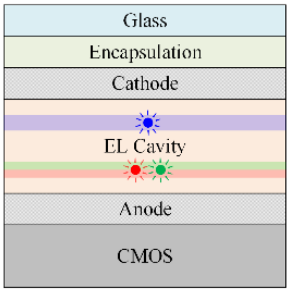

Figure 2. Schematic of the OLED EL Cavity Design

3. 0.9-inch Micro OLED Display

Due to the high cost of OLED microdisplay, its application scope is limited. Therefore, we have developed a OLED microdisplay with 4.22-um pixel pitch, 6020 PPI, and 4K resolution with the size of only 0.9-inch, which can significantly increase the number of chip cuts and reduce the cost of a single chip price.

The function modules of 0.9 inch microdisplay is shown in Figure 3, It mainly includes AA, MIPI, Power Supply, OSC, Timing Controller, Source Driver, Gate Driver, Image Processor and other functional modules.

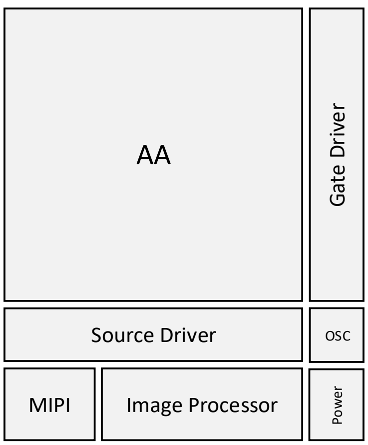

Figure 3. The function modules of 0.9 inch microdisplay.

Table 1 shows the specification of the panel.

Table 1. Specification of a 0.9 inch 4K4K Panel

Parameter	Value
Screen diagonal	0.9 inch
Fabrication process	55nm 1.2V/8V CMOS
Resolution	3840 x 3840
Pixel size	4.22um x 4.22um
Frame rate	90 Hz
Contrast	100000:1
Maximum luminance	5000 nits

3.1 Pixel Circuit design

For ultra-high PPI，The source-follower 3T1C pixel circuit is used, as shown in Figure 4. The switch adopts CMOS transmission gate, which can input data signal without loss. The source voltage of driving-MOS varies with the grid voltage, resulting in different gray levels. The source-follower relationship is derived as follows: the driver-MOS operates in the weak inversion saturation region, and the current formula in this region is shown in Formula 1, where Vt is the threshold voltage of the driving-MOS, n is the subthreshold slope, Vt is the temperature and voltage equivalent, X is the thickness of the weak inversion layer, Dn is the electron diffusion constant, and np0 is the electron equilibrium concentration of the substrate. The formula for OLED can be simplified to formula 2. When OLED emits light, the current of driving-MOS and OLED is equal, so formula 3 can be derived to obtain the relationship between the source voltage and the gate voltage of driving MOS, which is approximately linear.

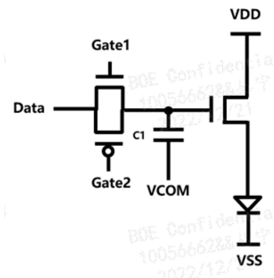

Figure 4. The Voltage-type pixel circuit.

$$I_D = \frac{W}{L} qXD_n n_{p0} \cdot e^{\left(\frac{k_2}{V_T}\right)} \cdot e^{\left(\frac{V_{GS}-V_t}{nV_T}\right)} \cdot \left[1 - e^{\left(\frac{-V_{DS}}{V_T}\right)}\right] \quad (1)$$

$$I_{OLED} = I_S \cdot e^{\left(\frac{V_S - VSS}{V_T}\right)} \quad (2)$$

$$V_S = \frac{V_G - V_t + n \cdot VSS + n \cdot V_T \cdot \ln\left(\frac{W}{L} \cdot \frac{qXD_n n_{p0}}{I_S}\right)}{n+1} \quad (3)$$

3.2 Pixel Layout Design in AA

In order to meet the demand for ultra-high PPI, layout design is particularly important. In traditional scenarios, the layout of each sub-pixel is the same. In this article, we use a center symmetric layout to place 2 * 2 pixels in repeating units. Placing NMOS and PMOS switches side by side every 3 sub pixels and connecting 6 similar switch transistor grids together through Y-axis symmetry can effectively reduce the N/P well spacing. When connected to the grid of the same type of switch MOS, the number of via between the gate lines and the gate can be reduced, further saving area.

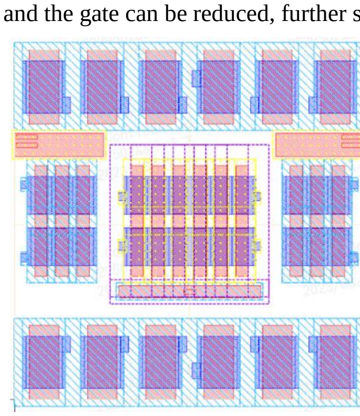

Figure 5. Layout of a repeating unit

Next, the horizontal gate line and power line is completed in the M1 and M2 layers, the data Line and vertical power routing in the M3 layer, the capacitor in the M4 and M5 layer, and the OLED anode pad in the M6 layer. Considering that the layout is densely connected and the parasitic and crosstalk between each unit is large, we use the free area of the metal layer to make multi-layer GND for shielding electromagnetic crosstalk, as shown in Figure. 6 and Figure. 7.

When the pixel area shrinks dramatically, so does the capacitance. When the capacitor is too small, flicker and crosstalk may occur. In this paper, the capacitor is superimposed with multiple layers of capacitors to maximize the capacitance value in a limited area and avoid the above problems.

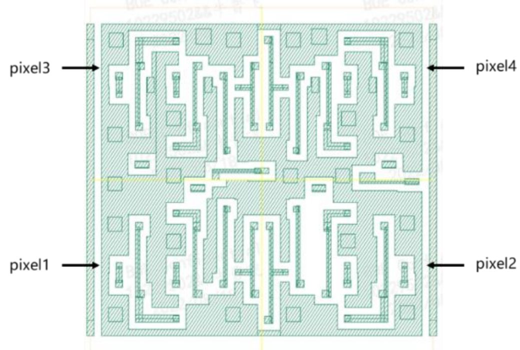

Figure 6. A repeating unit in M2

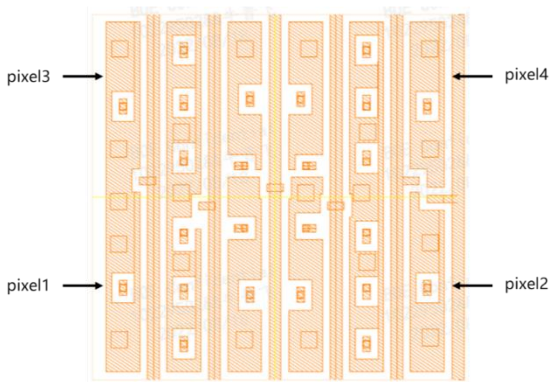

Figure 7. A repeating unit in M3

3.3 Results and Discussion

We tested all the relevant optical and electrical parameters of the panel. Due to the ultra-high PPI and 2 × 2 pixels hybrid design, there are three metrics to focus on: flicker, Crosstalk, and pixel level uniformity.

(a) Flicker

After the Data signal is written, it is stored in capacitor, and when the CMOS switch is turned off, there is leakage current Ioff , which is the cause of flicker in a frame. The Flicker test results are shown in Table 2. When the operating frequency is greater than or equal to 60Hz, flicker<-70.1dB, which is consistent with the post-simulation value.

Table 2. Flicker Test Results

Data(V)	60Hz
5.5	-70.8dB
3.5	-70.1dB

(b) Crosstalk

Electrical crosstalk is due to the influence of voltage changes of various signals on the gate voltage and source voltage of driving-MOS, including power signal , data signal, gate control signal of switch MOS, and so on. In this paper, superimposing capacitor and shielding layer are used to reduce crosstalk, the results are shown in Table 3. It can be seen from the results the horizontal crosstalk is larger than the regular spec (3%). The analysis was due to the effect of IR drop of cathode, we will make improvements in the follow-up work.

Table 3. Crosstalk test results

Crosstalk	
Vertical black crosstalk	1.9%
Vertical white crosstalk	0.8%
Horizontal black crosstalk	6.4%
Horizontal white crosstalk	5.1%

(c) Pixel Uniformity

There are four factors that affect the uniformity of pixel brightness: (1) CMOS process, (2) layout design, (3) EL anode process, and (4) EL evaporation process.

The CMOS process is reflected in aspects such as threshold voltage Vth, W value, L value, and storage capacitor size. In layout design, the asymmetry caused by uneven pixels needs to be optimized through post simulation. EL anode process and EL evaporation are related to the OLED manufacturing process. The uniformity in the article is greater than 97%, as shown in Table 4.

Table4. Pixel uniformity results

Brightness	Uniformity
2nit	97.28%
35nit	99.68%
120nit	99.60%
1000nit	99.54%

4. Panel Demonstration

Figure 8 shows the picture of the panel.

Figure 8. Picture of the 0.9 inch panel.

5. Design of Free-form Surface Optical System

A compact free-form surface AR glasses optical system was designed using the equal optical path theory [3], and the optical system structure is shown in Figure 9. This optical system uses a free-form surface reflector, with a distance of 38mm from the outermost side of the reflector to the lower vertex of the Panel, and a distance of 45mm from the lower vertex of the reflector to the upper vertex of the Panel. The FOV of this optical system is 20 °× 20 °, Eye-Relife is 20mm, Eye Box is 6mm × 6mm, MTF> 0.2@20lp /mm, detailed optical parameters are shown in Table 5.

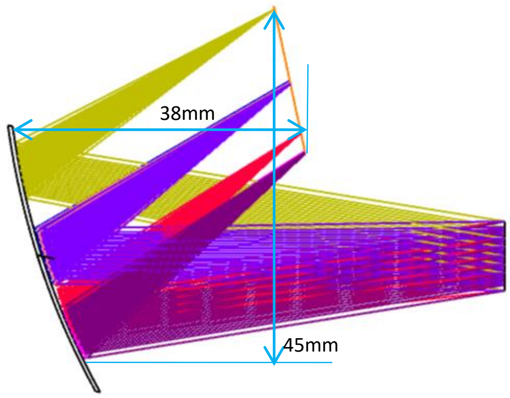

Figure.9 Optical System of Free-form AR Glasses

Table 5. Optical System Parameters of Free-form AR Glasses

Parameter	Value
FOV	20 °×20 °
Eye-Relife	20mm
Eye-Box	6mm*6mm
MTF	＞0.2@20lp/mm
Distortion	2.42%
PPD	192
Panel size	0.9inch
Panel resolution	3840×380

6. Conclusions

The above is the design of a micro OLED display with ultra-high PPI, with a pixel density of 6020 PPI, far higher than the current mainstream 3000-4000 PPI micro OLED products. By reducing the screen size, increasing the number of cuts, and lowering the cost per piece. Through the design and layout optimization of the source follower circuit, the brightness of OLED is precisely controlled by voltage. When the brightness is 2nit, the pixel level brightness uniformity can reach up to 97%. In summary, this product has excellent image quality performance, ultra-high pixel density, and low product price

References

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