A Novel Full-Color 3LED Projection System using R-G-B Light Emitting Diodes on Silicon (LEDoS) Micro-displays

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Abstract

R-G-B light emitting diode on silicon (LEDoS) micro-displays were fabricated and the world's first full color 3LED projection prototype is presented. LEDoS micro-displays were realized by flip-chip bonding of LED micro-arrays on silicon CMOS active-matrix drivers. Using trichroic prism, images generated from three self-emissive R-G-B LEDoS micro-displays were combined to form a color image, demonstrating great potential for high efficiency and high brightness projection applications.

Author Keywords

3LED; Light Emitting Diode; Micro-displays; Full-color; Active matrix; Flip-chip; projection.

1. Introduction

Driven by the rapid technology development of III-V compound semiconductor in recent years, inorganic R-G-B light emitting diodes (LEDs) with high brightness, high efficiency, and high durability are now widely available in the commercial market. Due to their superior performance and advantages, LEDs have been adopted for general lighting. It has also captured the market of backlight units (BLUs) for liquid crystal display (LCD) monitors. Furthermore, LEDs have replaced cold-cathode fluorescent lamps (CCFLs) in LCD TV and high intensity discharge (HID) lamps inside projection displays to make slimness, low weight, durable, and energy efficient display products.

The architecture of traditional projection systems generally consists of three parts: light source, display unit, and projection optics. Commercial projection technologies include: Epson's 3LCD, Texas Instruments' digital micro-mirror devices (DMD), Himax's liquid crystal on silicon (LCoS), and Microvision's micro-electro mechanical system (MEMS) scanner. For the liquid crystal related technologies such as 3LCD and LCoS, the light loss in the display unit is especially high because most of the light is absorbed by components inside the LCD or LCoS panels. Only 2.8% of the light from BLU is retained after passing through the LCD panel [1], suggesting the optical efficiency of the liquid crystal based projection systems is in need of huge improvement.

Since these common display units in current projection technologies are not emissive, a separated light source is required in the projection system. To maintain the optical efficiency of the whole light engine at an acceptable level, the light from the light source must be highly regulated and guided to pass through or be reflected by the display unit inside the light engine. Many optical components are involved in between the light source and display unit so the whole projection systems become very bulky and inefficient. Furthermore, the power consumption of the always fully on light source inside the system is wasteful because there is no difference between projecting a bright image and dark image on the screen.

Recently, self-emissive LED and OLED are emerging as alternate display technologies. Full-color OLED micro-displays are commonly used for electronic viewfinder, but cannot be driven to a high enough brightness for projection. Current LED technologies have significant advantages of high brightness, high efficiency, low voltage, good reliability, extremely long lifetime, and quick response time. Passive matrix LED arrays using individually packaged LEDs are widely used in outdoor/indoor large area displays and traffic communication systems. Monolithic LED arrays fabricated with IC technologies are being explored. Our group has demonstrated blue and UV active matrix (AM) light emitting diode on silicon (LEDoS) micro-displays by monolithic integration of thousands of LED pixels on a single chip and flip-chip bonded to a CMOS driver [2,3]. In other groups, other colors such as green, amber and red LED micro-arrays have also been developed using wavelength matched epi-wafers or by color conversion method [4,5,6]. However, there is no reported result on simultaneously projecting color images on screen by combining three R-G-B LED micro-display light streams together.

In this paper, aluminum gallium indium phosphide (AlGaInP)-based and gallium nitride (GaN)-based LEDoS micro-displays were fabricated by flip-chip process for the generation of single color red, green, and blue images. By integration of R-G-B LEDoS micro-displays using a trichroic prism and a projection lens, the world's first 3LED projector prototype is successfully demonstrated. The color of the images projected on the screen can be adjusted by changing the intensity of the three individually controlled LEDoS micro-displays

2. Experiments

Three 30×30 R-G-B matrix-addressable LEDoS micro-displays were fabricated by flip-chip bonding of LED micro-arrays on silicon CMOS active matrix drivers. Each micro-pixel has a 100μm emission aperture on a 140μm pitch. The fabrication processes of LEDoS micro-displays including LED micro-arrays, active matrix driver and flip-chip bonding, and the design and assembly procedure of 3LED projector prototype are described in this section.

R-G-B LED Micro-Arrays: The detailed fabrication process of blue LED micro-arrays has been discussed [3]. With similar process, the only change of the green LED micro-arrays is the indium composition during the growth of GaN-based epi-wafers.

However, the fabrication of red LED micro-arrays is quite different. Emission of red light using III-nitride based materials is very inefficient. Thus AlGaInP-based epi-wafers were chosen for the fabrication of red LED micro-arrays. AlGaInP epi is commonly grown on GaAs substrate (Fig.1 (A)) because of the lattice-matching property of AlGaInP on GaAs. To remove the light absorbing GaAs substrate, the epi-side was first directly bonded on a transparent sapphire supporting substrate, and then the GaAs substrate was completely removed by wet chemical etching (Fig.1 (B)). The pixels were defined by photolithography and portion of p-AlGaInP layer was exposed for p-electrode by inductively-coupled plasma (ICP) etching (Fig.1 (C)). Afterward, electronic beam evaporation and lift-off process were done to define 200nm gold electrodes on top of n-AlGaInP and p-AlGaInP (Fig.1 (D)). Finally, rapid thermal annealing (RTA) was performed in oxygen at 500ºC for 1 minute to decrease the contact resistance of gold electrodes.

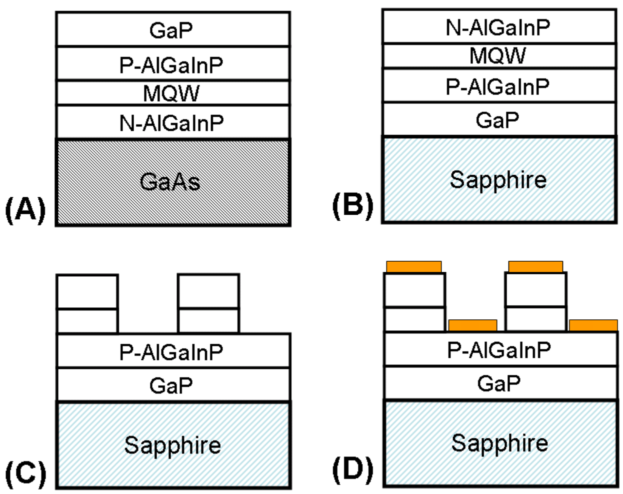

Figure 1. Cross sectional views of LED pixels after each processing step. (A) Starting substrate. (B) Sample after transferred to sapphire and removed the GaAs substrate. (C) After ICP etching. (D) After gold electrode deposition.

High Density Active Matrix Driver: Higher resolution micro-displays can be achieved when driven with higher density active matrix drivers. Here, a 30×30 CMOS active matrix driver was designed and fabricated. The detailed fabrication procedure follows the 8 × 8 CMOS active matrix driver [3]. The function of the active matrix driver is to address pixels independently so that specific images can be displayed on LED micro-array.

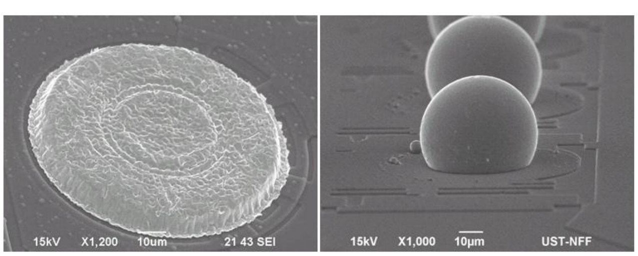

Figure 2. SEM images of circle-shaped indium plate on silicon CMOS driver after lift-off process (Left) and indium balls after reflow process (Right).

Indium Bumping and Flip-Chip Process: Before the flip-chip bonding process, a layer of PECVD silicon dioxide for surface passivation was deposited on the active matrix driver and patterned by dry etching. Ti/Ni/Au (20/50/50 nm) under bump metallization (UBM) layer was deposited by e-beam evaporation and then circular patterned UBMs on each pixel were formed by lift-off process. Afterwards, Indium was thermally evaporated and defined only on top of the UBMs as shown in Fig.2 (Left). To form ball-shaped indium as shown in Fig.2 (right), the device with indium plates was put into a reflow furnace at 220ºC for 4 minutes in the formic acid ambient. After the indium bumping process, the red, green, and blue LED micro-arrays were flip-chip bonded onto the corresponding active matrix driver circuits separately to form R-G-B LEDoS micro-displays. The alignment accuracy of the flip-chip bonder is less than 1µm.

Assembly of 3LED Projection System: Red, green, and blue LEDoS micro-displays were die-bonded and wire-bonded on their individual signal boards, which are connected to a central control board by flexible cables, and then the signal boards were precisely mounted on a trichroic prism as shown in Fig.3. The control board with a Microchip® MCU transmits image signals to three micro-displays through the three signal boards, for power supply and tuning the brightness level of micro-displays. By fine adjustment of the position of the three micro-displays, misalignment of the R-G-B images can be minimized. To demonstrate the capability of projecting full-color images, the whole system was plugged into an existing 3LCD projector with all the LCD panels, light source and other optical components removed except the projection lens. Eventually, a 3LED projector prototype was realized.

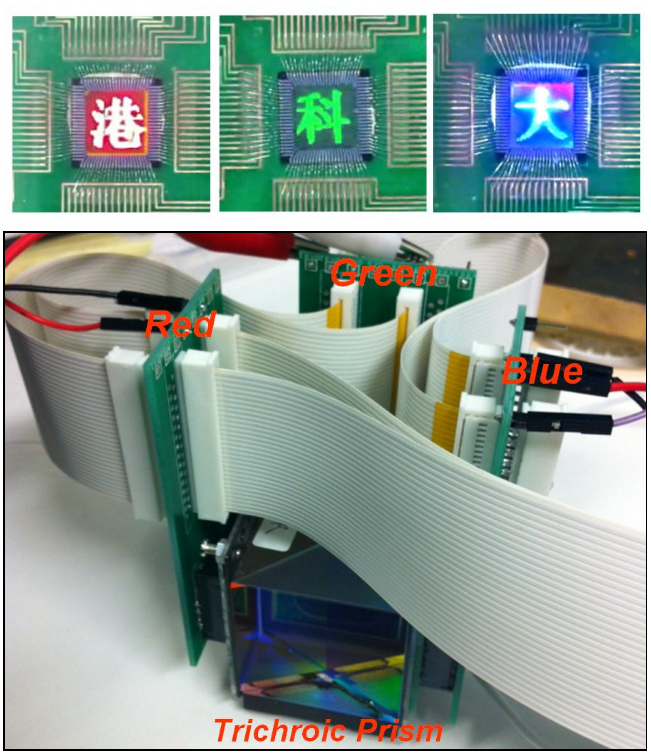

Figure 3. (Upper) Chinese characters on R-G-B LEDoS micro-displays. (Lower) 3LED system including a trichroic prism and signal boards with R-G-B LEDoS micro-displays.

3. Results and Discussion

The 30x30 R-G-B LEDoS micro-displays are programmable and can display different characters, logos or moving signs (Fig 3 (upper)). The color emitted from the 3LED projection prototype was evaluated by an Ocean Optics USB2000 spectrometer. As shown in Fig.4, red green, and blue emission peaks are located at 630nm, 535nm, 445nm, originated from the emission wavelength of AlGaInP-based red and GaN-based green/blue epi-wafers. Fig.5 shows the color coordinates of red (Fig.6 (A)), green (Fig.6 (B)), blue (Fig.6 (C)) in the CIE 1931 color space chromaticity diagram measured by the spectrometer. The point located in the middle of the chromaticity diagram is the color coordinates of the spectrum in Fig.4, which is white (Fig.6 (D)) with a color temperature around 7000K. The area inside the solid triangle shows the maximum color gamut that can be projected by the 3LED system, which is larger than the NTSC color gamut (dash line). The direct view images of red, green, blue, and white inside the trichroic prism are shown in Fig.6.

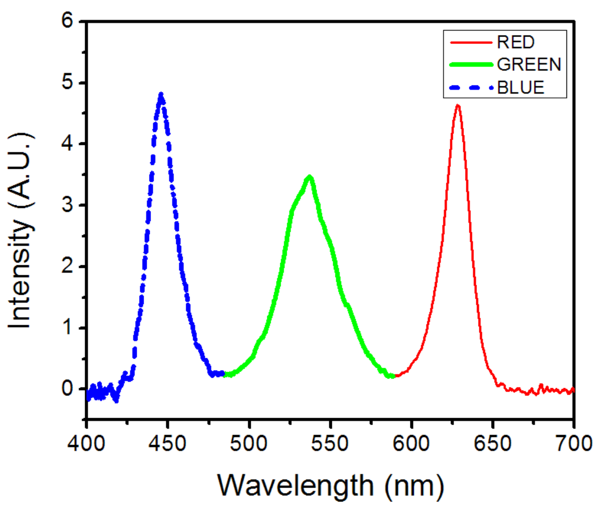

Figure 4. Output Spectrum of the 3LED system.

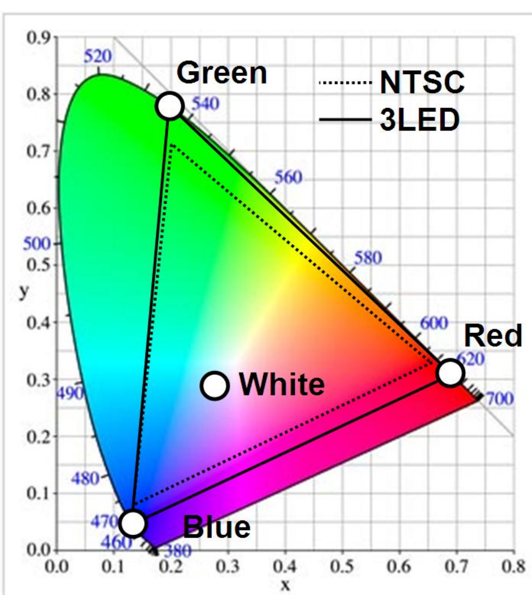

Figure 5. CIE 1931 color space chromaticity diagram.

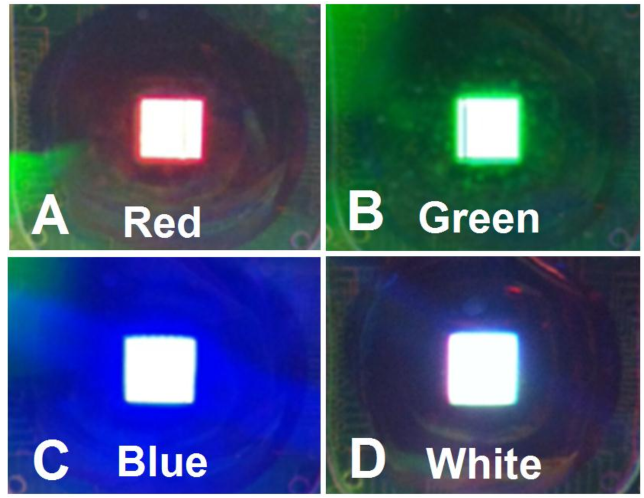

Figure 6. Direct view images of red, green, blue and white inside the trichroic prism.

The world's first 3LED projector prototype was demonstrated in this experiment (Fig.7 (A)). A projection lens can magnify images inside the trichroic prism (Fig.7 (B)) and project it on the wall (Fig. 7(C)). The color and brightness of the images can be adjusted by tuning the supply voltage of each LEDoS micro-display or changing the duty cycle of the control signals to each pixel. Sharpness of the HKUST logo in Fig.7(C) can be further improved with better alignment of the three panels.

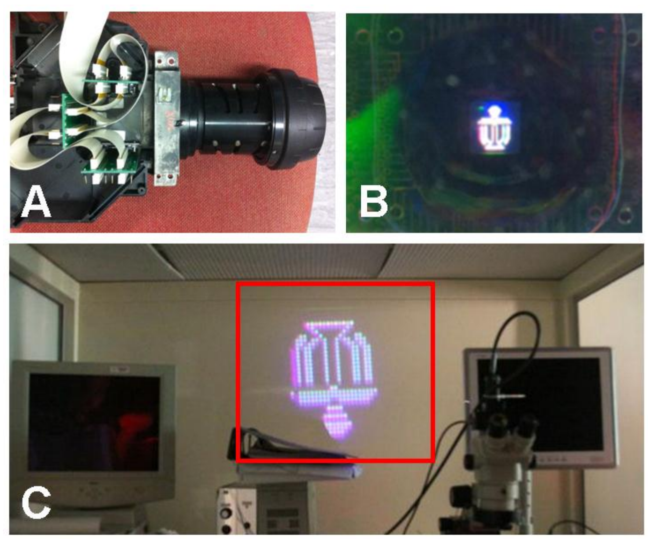

Figure 7. (A) 3LED projector prototype with 3LED system and projection lens. (B) White HKUST logo formed inside the trichroic prism. (C) A HKUST logo (upside down) projected on the wall.

Fig.8 shows the architecture of a commercial 3LCD projector and the 3LED projector prototype. R-G-B LEDoS micro-displays are all self-emissive thus separated light source; complicated and lossy optical components are not required in the 3LED system. Therefore, the total power consumption can be reduced and the optical efficiency can be greatly improved. Meanwhile, the 3LED system is much simpler and smaller than 3LCD.

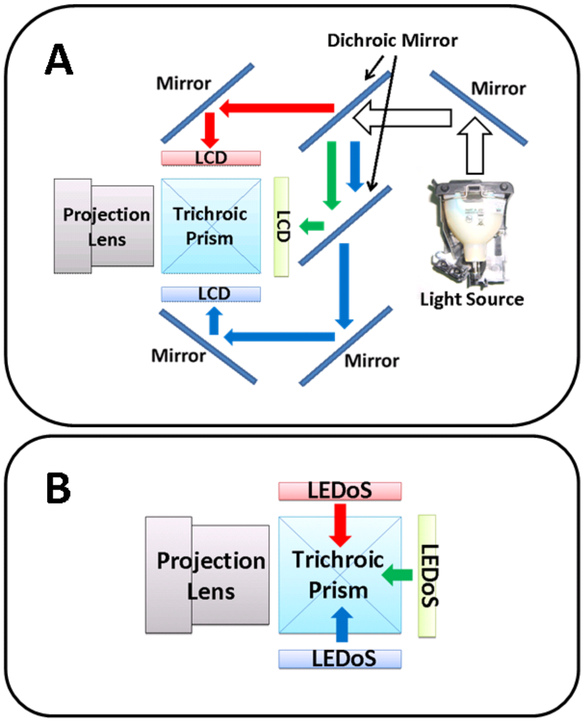

Figure 8. Architectures of (A) 3LCD and (B) 3LED projection system.

Integration of the high-brightness and high-efficiency R-G-B LEDoS micro-displays would be able to provide sufficient light output for projection. By further miniaturizing the size of LEDoS micro-displays, trichroic prism, and other external drivers, the 3LED projection system's size can be comparable or even smaller than existing pico-projectors, which makes it possible to do ultimate miniaturization of projector with better performance in commercial applications.

4. Conclusion

R-G-B light emitting diode on silicon (LEDoS) micro-displays were fabricated and used for the world's first full color 3LED projection prototype. Using a trichroic prism, images generated from the three individually controlled self-emissive red, green, and blue LEDoS micro-displays are optically combined to form color images. The color of the images can be adjusted and images were projected on the screen by adding a projection lens in front of the trichroic prism. The concept of 3LED has high potential to replace existing projection technologies because of its high efficiency, high brightness, and compact size.

5. Acknowledgments

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