A Novel BLU-Free Full-Color LED Projector using LED on Silicon Micro-Displays

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***Abstract*—In this letter, we have described the design and fabrication of a novel backlight-unit (BLU)-free full-color LED based projector. The prototype used three active matrix (AM) addressable light emitting diode on silicon (LEDoS) micro-displays with peak emission wavelengths of 630nm, 535nm, and 445nm. The LEDoS micro-displays were realized by integrating monolithic micro-LED arrays and silicon-based integrated circuits using a flip-chip bonding technique. Since the LEDoS micro-displays are self-emitting, conventional BLUs used in liquid crystal displays (LCDs) were not needed. Using a trichroic prism to combine the light from the three LEDoS chips, we have produced the world's first 3-LEDoS projector. This BLU-free 3-LEDoS projector consists of much fewer optical components and has significantly higher light utilization efficiency (LUE) compared to conventional projectors.**

***Index Terms*—Light Emitting Diode, Projection Display, Self-emitting Display, Active Circuits**

I. Introduction

Projection displays have been developed for many decades and are now widely used commercial products. Projection systems in the market can be classified into three main categories: liquid crystal display (LCD) based projection [1] [2], micro-electro-mechanical systems (MEMS) based projection [3]-[5], and organic light emitting diode (OLED) based projection [6]-[8]. The architectures of these conventional projection systems generally consist of three parts: a backlight unit (BLU), a projection chip (chipset), and an optical system [9]. Their light utilization efficiencies (LUE) vary but are generally very low. LCD based projection displays, with the lowest manufacturing cost and largest market share nowadays, can be further divided into three sub-types: single chip high temperature thin film transistor (HT-TFT) LCD, 3-LCDs, and liquid crystal on silicon (LCoS). However, power consumption is an immense challenge for LCD based projection technologies and its future improvement. Although many technologies have been developed to reduce their power consumption, the inherently low LUE in LCD panels renders further power reduction difficult [10] [11]. MEMS based projection displays include digital light processor (DLP) and scanning laser technologies. Their LUEs are higher than that of LCD based projection displays because polarizers are not necessary. However, the manufacturing costs of MEMS based projectors are higher than LCD based projectors. Recently, OLEDs are being developed as a projection source for their self-emitting and good color saturation properties, as well as potential low cost. Yet, the brightness of OLEDs is relatively low for the requirements of most projector applications. In addition, the lifetime of OLEDs is another bottleneck that limits the success of OLED projectors in outdoor applications [8]. Table 1 summarizes the architecture, LUE, manufacturing cost, and maturity of existing mainstream projection technologies and the novel LEDoS projection technology demonstrated in this work.

TABLE I
Comparison among projection technologies

Technology	LCoS LCD+IC	DLP MEMS+IC	OLED OLED+IC	LEDoS LED+IC
BLU	Arc lamp /LED	Arc lamp/ LED	None	None
Color filter/color wheel	Color filter*	Color wheel**	None	None
Polarizers	Yes	None	None	None
Outdoor visibility	Low	High	Low	High
LUE	Low	Middle	Middle	High
Manufacture cost	Low	High	Low	Low
Lifetime	Long	Long	Short	Long
Maturity (1-10)	9	9	4	2

* Field sequential (FC) LCOS doesn't require color filters
** Color wheel is not necessary in DLP with 3-LED light source

LEDs, as self-emitting devices without the need of BLU, have been developed for many applications such as solid-state lighting, large area outdoor displays, and micro-displays. With LED micro-displays' excellent properties and performance, particularly in high LUE, design simplicity (BLU-free), long lifetime, and excellent visibility under bright day-light [12], monolithic LED micro-displays could out-perform all present virtues of LCDs and OLED displays. Several LED based displays have been developed in recent years with both passive matrix (PM) and active matrix (AM) programming methods [13]-[18]. Others have also attempted to utilize LED based display as a novel source for projection display: a passive matrix

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inorganic LED array as a projection source was reported in the Display Week 2010 [19]; a micro-pixellated GaN LED micro-display system in the year 2011 [20]; and a green LED micro-display with gray scale control [21]. With ever increasing light output power and efficiency, LED based projection displays are attracting more and more attention. However, no full-color projection has been reported to date.

In this work, we report a BLU-free full-color LED based projection display by combining AM LEDoS micro-displays with individual emission wavelengths of 630 nm, 535 nm, and 445 nm. Aluminum gallium indium phosphide (AlGaInP)-based (for red) and gallium nitride (GaN)-based (for green and blue) LEDoS chips were designed and produced by integrating micro-LED arrays fabricated on sapphire substrates and AM panels fabricated on single crystal silicon substrates using flip-chip technology. The world's first 3-LEDoS projector prototype was demonstrated by combining of the red, green and blue LEDoS chips using a trichroic prism and a projection lens.

II. Experiment

The design and fabrication process of the LEDoS micro-displays can be found in reference [17] and will not be described in details. Here, we will only discuss several specific considerations of the LEDoS micro-displays.

To ensure successful contacts in all the pixels on each LEDoS chip after flip-chip bonding, it is critical to accommodate for the height differences in the bonding pads. Fig. 1 shows the schematics of (a) a finished green/blue micro-LED pixel and (b) red micro-LED pixel. The height difference between the flip chip (FC) pads on the p-GaN (above multiple quantum wells (MQWs) region) and n-GaN (n-electrode) contacts (Fig.1 (a)) was about 1 μm. The indium solder bumps were fabricated on the silicon substrate with the same height as shown in scanned electron microscope (SEM) observations [17]. During the flip-chip bonding process, the compressive force between the LED micro-array and the AM panel must be carefully adjusted. The indium solder bumps conformed from spherical to ellipsoidal shape, making good contact and compensating for the height difference between the FC pads on p-GaN and n-GaN electrodes. However, in the red chip, the epi-layers were transferred to a sapphire substrate with the electrodes reversed (shown in Fig. 1 (b)).

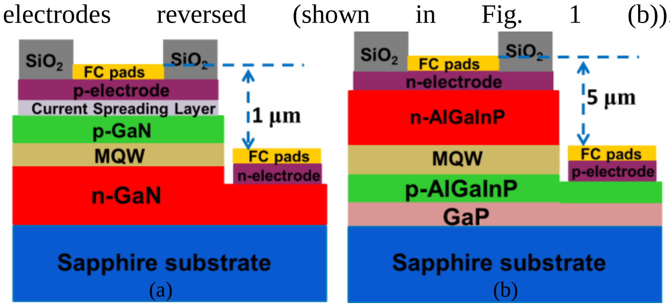


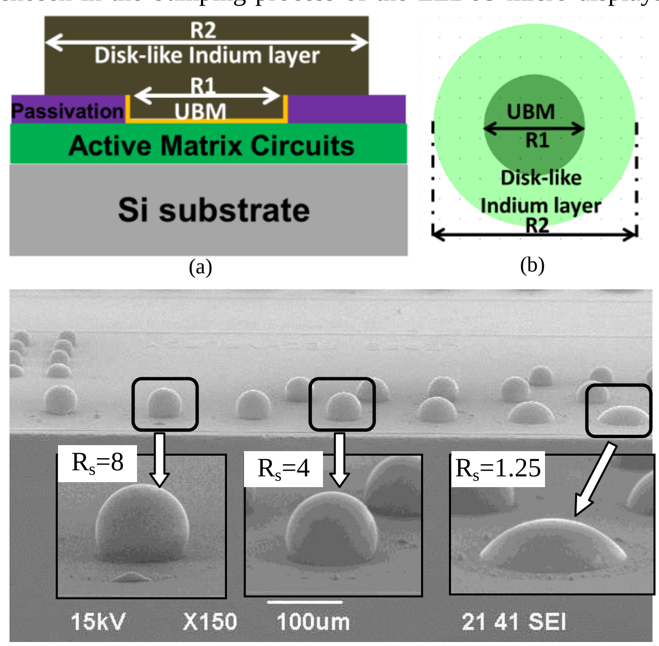
Fig. 1 Cross-sectional diagram of (a) a finished green/blue micro-LED pixel and (b) a finished red micro-LED pixel.

In the fabrication process, about 5 μm of n-AlGaInP and MQWs were etched away to expose the p-AlGaInP region of the micro-LED pixels for contacting. The resulting 5 μm height difference might lead to poor contact between the p-electrode of micro-LED pixel and the indium solder bumps, so care must be taken to avoid these problems by optimizing the solder bump size.

As described in reference [17], the smallest solder bump has a diameter of 5 μm, which will allow ultrahigh pixel density in next generation LEDoS micro-displays with a pixel pitch smaller than 10 μm. The relationship between the profile of the solder bumps and the ratio of indium deposition area versus under bump metal (UBM) area was investigated in this study. Fig. 2 (a) shows a cross-sectional diagram and (b) shows a top view diagram of the solder bump structure before the reflow process. The thickness of the disk-like indium layer deposited by thermal evaporator was about 4 μm. During the reflow process, the indium melted and balled up to the center of the structure defined by the Ni/Au UBM layer. With fixed indium thickness, the profile of the solder bumps was highly dependent on the area ratio (R_s) between the disk-like indium layer and the UBM layer. Shown in formula (1), R_s was designed with different values and resulted in different solder bump profiles as shown in Fig. 2 (c). Smaller R_s (< 4) led to non-spherical solder bumps and smaller bump height for the flip-chip bonding.

$$R_s = \frac{\text{Area of disk-like Indium layer}}{\text{Area of UBM layer}} = \left(\frac{R_2}{R_1}\right)^2 \quad (1)$$

Larger R_s led to more spherical solder bumps until reaching a certain limit. It was observed that solder bumps shifted from the center of the structure when R_s was larger than 4. We believe this was due to the insufficient cohesive force provided by the decreasing UBM area during the reflow process. So $R_s = 4$ was chosen in the bumping process of the LEDoS micro-displays.



(c)

Fig. 2 (a) Cross-sectional diagram and (b) top view of the solder bump structure before reflow process. (c) Profiles of the solder bumps varied with different R_s.

After flip-chip bonding of the micro-LED arrays onto the AM panels, the red, green, and blue LEDoS chips were die-attached and wire-bonded onto individual packaging boards and connected to a control board. Then the packaging boards were mounted to a trichroic prism to form a full-color projection source as shown in Fig. 3 (a). A computer based interface was developed with a Microchip® MCU to transmit image signals to the three signal boards. The signal boards supply power and control to tune the brightness level of the respective micro-displays. Fine adjustment of the three micro-display positions can be performed using mounting screws for alignment of the R-G-B images. To demonstrate the capability of projecting full-color images, the whole system was plugged into an existing 3-LCDs projector. All the LCD panels, BLU and other optical components were completely removed except the projection lens. A BLU-free full-color 3-LEDoS projector prototype and the optical architecture were successfully assembled as shown in Fig. 3 (b). The optical schematic of the 3-LEDoS projector is shown in Fig. 3 (c).

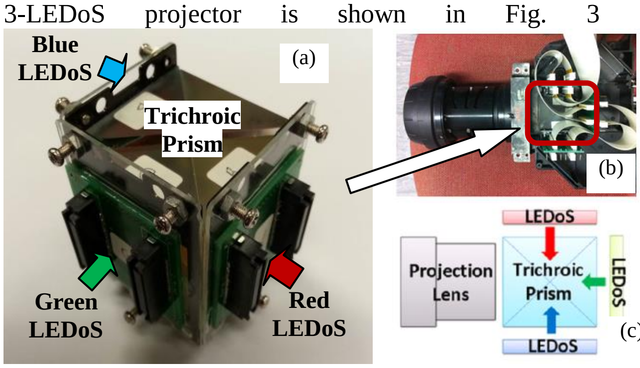


Fig. 3 (a) The assembled LEDoS projection source with red, green and blue LEDoS packaging boards and a trichroic prism. (b) The 3-LEDoS projector prototype and (c) the schematic of the optical architecture.

III. Results and Discussion

The red, green and blue LEDoS micro-displays have a resolution of 30×30 and a pixel pitch of 140µm, equivalent to 180 pixels per inch (PPI). The electrical characteristics and spectral luminosity profile of the three LEDoS chips were measured and discussed in reference [17]. In our red LEDoS chip, the driving transistors and LED pixels were in current sink connection because the p- and n-electrodes of red LED were reversed. The emission peaks of the AlGaInP-based red epi-wafer and GaN-based green/blue epi-wafers are located at 630nm, 535nm and 445nm respectively.

With peripheral driving boards, the LEDoS micro-displays were programmed to display representative images such as Chinese characters, traffic signals and "LEDoS DEMO" as shown in Fig. 4.

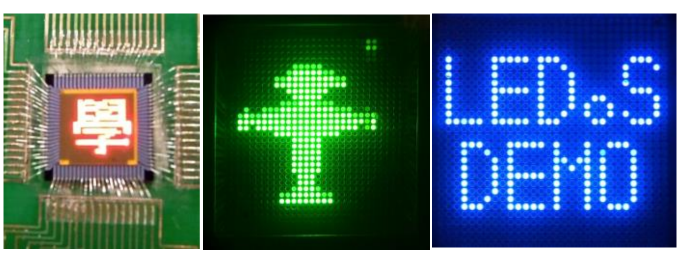


Fig. 4. Reprentative images were displayed by the red, green and blue LEDoS chips, respectively. The color saturated due to the high brightness of the LED pixels.

The color coordinates of three chips were measured by a spectrometer and plotted on the CIE 1931 color space chromaticity diagram measured as shown in Fig. 5. The point located in the center of the diagram is the color coordinate of the combined white with a color temperature of around 7000 K. The area inside the solid triangle shows the maximum color gamut that can be projected by the 3-LEDoS projector, which is somewhat larger than the NTSC color gamut (dash line).

Fig. 6 shows the projection results of the 3-LEDoS projector prototype. A 15-inch diagonal HKUST logo was projected on a wall with the existing projector lens and a projection distance of about 2 meters. Two colorful images such as the logo of the Photonic Technology Center (PTC) and a cartoon character were also projected. A custom-designed projection lens and supporting frame will be designed to optimize the power of magnification, brightness, and projection distance. The power consumption of the 3-LEDoS projector was measured to be approximately 1 Watt. Because of the polarization sensetive coatings on the prism, the LUE of the 3-LEDoS projector was measured to be 2.5%. Removing the filters has quadrupled the LUE to 10%. With a customed designed prism, the LUE was further increased to 26%.

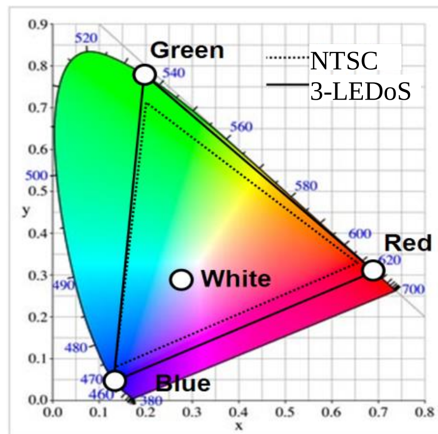


Fig. 5. CIE 1931 color space chromaticity diagram of the 3-LEDoS projection display and NTSC.

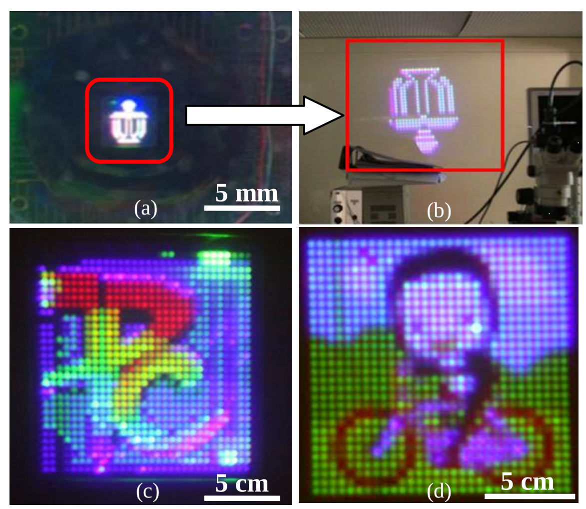


Fig. 6. (a) A white color HKUST logo formed inside the trichroic prism, (b) a HKUST logo (upside down) projected on the wall with 15-inch diagonal, (c) a projected colorful PTC logo and (d) a projected cartoon character.

After the LED arrays were magnified on the screen, pixels could be easily observed due to the 140 µm LEDoS pixel pitch and 30×30 resolution. Higher quality LEDoS chips have been fabricated recently with a higher resolution of 100×100 and a pixel pitch of 50 µm.

In reference [16], we demonstrated a method of full-color LEDoS display by depostion of red, green and blue phosphors on a ultravolient (UV) 8×8 LEDoS chip. This is an alternative method to achieve a full-color projection with a monolithic LEDoS chip. Fig. 7 shows an architecture comparison between the LEDoS projector and conventional projectors. It can be clearly seen that the LEDoS projector has the simplest optical system with the highest LUE, allowing a small form factor, less materials and weight. With mature silicon complementary metal-oxide-semiconductor (CMOS) and LED technologies, manufacturing cost of mass production can be reduced to the same level as LCD based projectors.

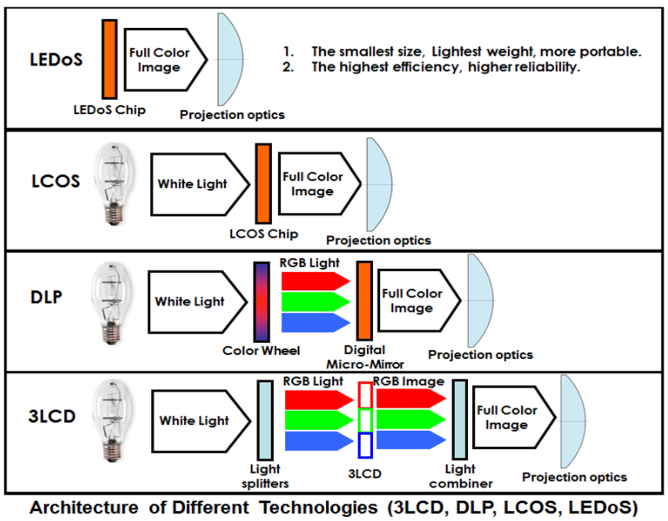


Fig. 7. Architecture comparison of different projection technologies (3-LCD, DLP, LCoS, and LEDoS).

IV. Conclusion

In this work, we have demostrated the world's first full-color 3-LEDoS projector prototype by combining the primary color images of three individual active matrix LEDoS micro-displays. Using a trichroic prism, trichromatic images were optically combined and projected as a full-color image. In the absence of BLU and other optical components, the 3-LEDoS projector has the simplest optical structure and the highest light utilization efficiency compared to conventional projectors. Further optimization is underway to improve the resolution, LUE and light output power of the 3-LEDoS projector.

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