

Solid-State Reflective Displays (SRD®) for Video-Rate, Full Colour, Outdoor Readable Displays

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ABSTRACT

Solid State Reflective displays (SRD®) have been proposed as a new route for next generation reflective displays. We present the first optical measurements of a combined RGBW states, together with a simulated black state. These results demonstrate the feasibility of a future high performance, video capable, full colour, SRD display.

1. BACKGROUND AND OBJECTIVES

Phase change materials (PCMs) are chalcogenide based functional glasses commonly used as active elements in rewrite-able optical disc storage and electronic memory technologies[1]. Common examples of phase change materials are tellurium and antimony based alloys compounds such as $\text{Ge}_2\text{Sb}_2\text{Te}_5$ and AgInSbTe . PCMs have the ability to dramatically and reversibly change their complex refractive index between two stable phases, amorphous and crystalline, based on the application of an optical or electrical energy pulse. Importantly, the difference in the real part of the refractive index between the two states (Δn) is as high as 1.5/2 while the absorption coefficient (Δk) can change by more than 3 upon switching[2].

We recently demonstrated the feasibility of a low-power, high colour reflective display based on a new optical modulation mechanism – reversible phase-change material crystallisation in an ultra-thin film stack – which is entirely new to the field of displays[3-5]. Our simulated performance indicates that a display utilising this effect can be designed to provide white-state luminance reflectivity of over 50% and a colour gamut between 40% to 80% of sRGB depending on fabrication complexity[6]. This compares very favourably with current monochrome e-reader displays which offer similar luminance reflectivity but no colour capability, and reflective LCD displays which have much reduced reflectivity and typically ~20-30% sRGB gamut capability. A solid-state reflective display (SRD) is intended to be suitable for a range of potential applications where zero power image maintenance, vivid colour freedom of design and video capability are desirable simultaneously. Examples ranging from simple 2-colour displays for wearable devices, internet-of-

things objects, and secondary notification displays for mobile phones, to full-colour reflective displays for colour e-readers, automotive and outdoor signage applications have been discussed. The basic characteristics of the technology, and the first demonstration of reversible electrical switching of display pixel sized phase-change material based devices, have been described elsewhere and summarized in Figure 1 for convenience to the reader. In brief, an ultra-thin optical cavity is designed to reflect a targeted colour using a strong interference effect. The interference properties of the cavity are actively modulated by electrically switching the physical state of an ultra-thin solid-state phase change material embedded within the cavity. The modulation produces a large optical change that can be designed to create a unique type of reflective display system. Recently, we have shown how a full colour SRD displays requires at least three separate subpixels designed to switch between a primary, highly saturated colour and a pale, more luminous, version of the same colour. The combination of the three subpixels, together with a top optical shutter, enable the implementation of a high performance, video capable, full colour, reflective display.

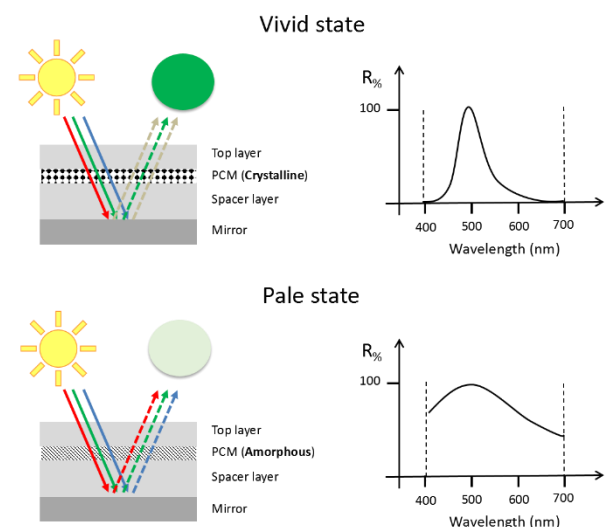


Figure 1 – Basic description of a RGB type SRD display.

Here, we present the spectral measurements of three primary RGB to pale, prototype films together with their combined high brightness white state and simulated black state.

2. RESULTS

Large area, uniform colour, RGB static films were deposited on a rigid glass substrate using a standard vacuum sputtering technique. The films were deposited at room temperature and designed to appear in their pale state as deposited, with the phase change material in the fully amorphous phase. Each sample was subsequently diced in half using an automated dicing saw machine and one half heated up to 200 C for 1 minute in order to fully crystallize the ultra-thin, active PCM layer.

Figure 2 shows a picture of a total of 6 samples; R,G and B combinations in both the pale (right) and the vivid (left) states, viewed from both normal (top) and oblique (bottom) viewing angles. The films show good colour saturation, measured at 47% of that of sRGB and good luminosity.



Figure 2 – RGB static samples in the vivid (left) and pale (right) states at two different angles on a cloudy afternoon. No contrast enhancement of any kind has been applied to these pictures.

The RGB reflectivity spectra for both pale and saturated states and the resulting bright white state are shown in

Figure 3 a,b,c and d respectively. It is important to note that the resulting white state has not been optimized for pixel size nor white point fidelity; each colour (sub pixel) was divided into 1/3 of a total pixel. The measured luminosity of the white state is 30% which is small compared to the 50% expected from the optical thin film simulations but still remarkable considering the large (47% s-RGB) measured area of colour gamut. Continuous optimization of the deposition process, together with a deeper understanding of the thin film optical properties are expected to push the performance of the films close to the simulated ones.

Pictures of a lithography defined SRD white state from both normal and tilted angles can be found in Figure 4c. The exact design and composition of the white SRD sample will be explained later in this paper.

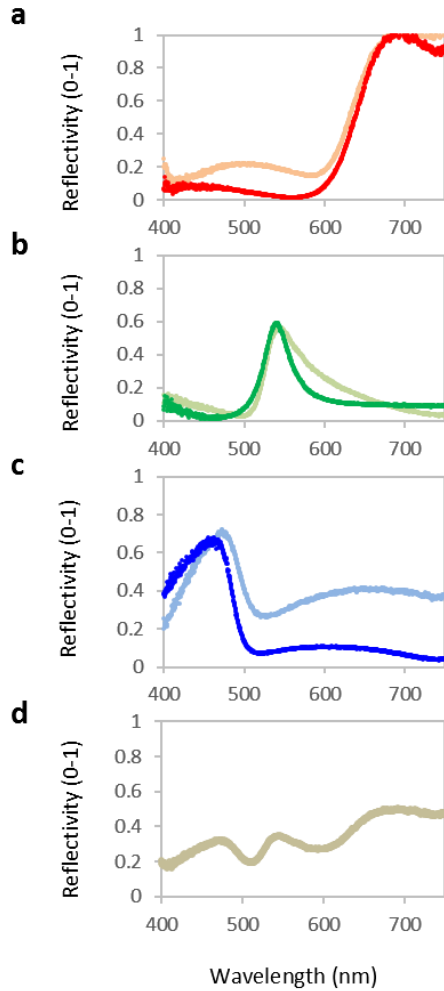


Figure 3 – a,b,c. Spectrum measurements of RGB static film prototypes in both their pale and saturated phase. d. Resulting white state with an identical 1/3 subpixels architecture.

As previously discussed, an SRD display requires an optical shutter in order to achieve full RGBWK colour performance using an adjacent sub-pixel primaries type architecture, as shown in Figure 4a. It is known that such an architecture could limit the amount of brightness of a reflective display as well as delivering an optically unappealing white state. We fabricated a series of 9 static RGB subpixel like structures in order to quantify the performance of a future SRD display with an adjacent subpixels architecture, as shown in Figure 4b. Each R, G and B subpixel structure has 100 μm width and 1 cm length, fabricated using a standard three steps optical lithography process. A microscope picture of the final sample comprising the three lithographically defined R, G and B subpixels can be found in the center of Figure 4b. A total of 9 structures were fabricated on a single substrate named “colour tiles”.

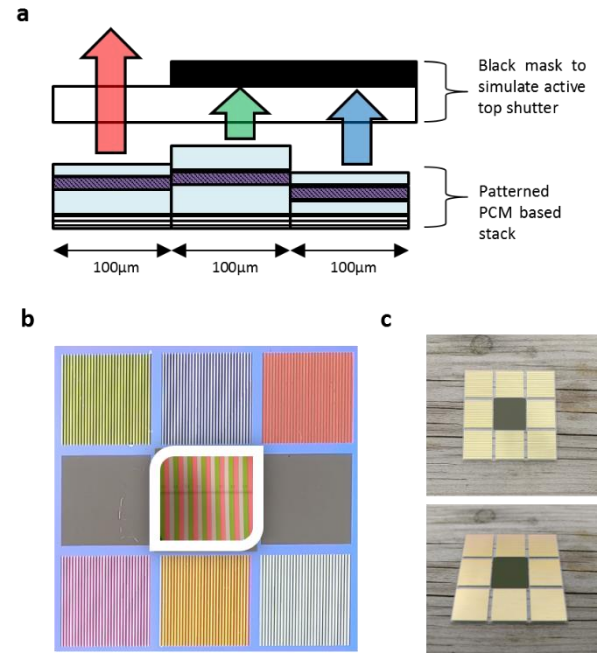


Figure 4 – a. Proposed architecture for a full RGBWK SRD reflective display. 3 RGB subpixels define the gamut and bright white state while an integrated top optical shutter is used for the black and grey scales.

Each part of the colour tiles sample was then selectively covered with a black resist mask to show:

1. A white state when no resist was used. Such state would resemble a pixel with all subpixels in the pale state and all 3 optical shutters left in their clear state. Pictures of a white state sample, from both normal and tilted angles can be found in Figure 4c.
2. A black state when resist was deposited on all subpixels. This state would resemble a pixel with all shutters set in their dark state. Figure 4b shows the black subpixels in the center line of the colour tiles sample.
3. A red, green and blue state when resist was deposited on 2 out of 3 subpixels leaving the remaining visible pixel the defining colour pixel. Figure 4b shows the G, B and R states in the top row of the colour tiles sample.
4. A cyan, yellow and magenta state when resist was deposited on only 1 out of 3 subpixels. Figure 4b shows the M, Y and C states in the bottom row of the colour tiles sample.

Finally, a complete RGBWK static SRD demo was created using a similar sub-pixelated approach and a black matrix resist to simulate the optical appearance of a top shutter. The demo does not have the ability to switch image (no backplane is

placed underneath the pixel), but it demonstrates the genuine optical quality and the full potential of a future full-colour SRD display. As previously explained, SRD pixels are deposited in their amorphous phase and can be switched (crystallised) by increasing the temperature of the active layer above its crystallization temperature. Once switched, they will remain in their crystalline phase for many years. We created a static demo by choosing a colourful picture of a parrot (shown printed on paper in Figure 5a) and converting it into a 7 steps lithography process. Firstly, the input image data was analysed to identify which of the RGB subpixels should be converted into the crystalline (pale) state where deposited, and which should remain amorphous (vivid) in order to allow the demo to most closely reproduce the intended colour and luminance of each pixel. Those RGB sub-pixels requiring crystallisation were first deposited, and once completed, the wafer was put on a hot plate a 200 C for a few seconds to ensure full crystallization of the pixels.

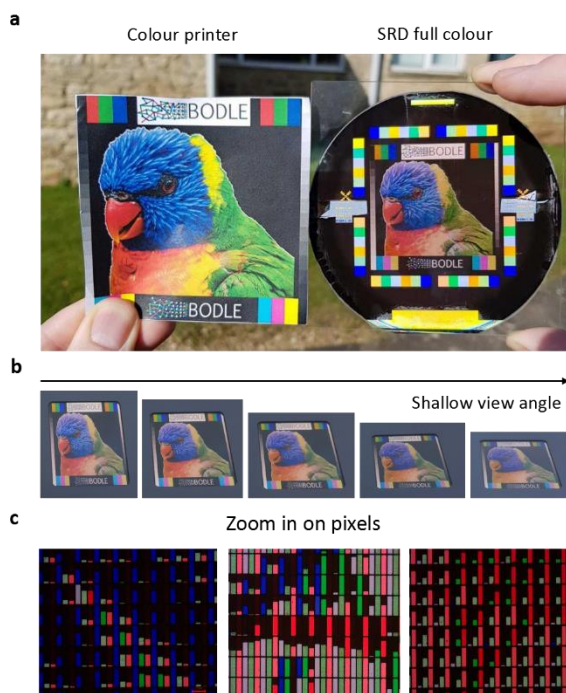


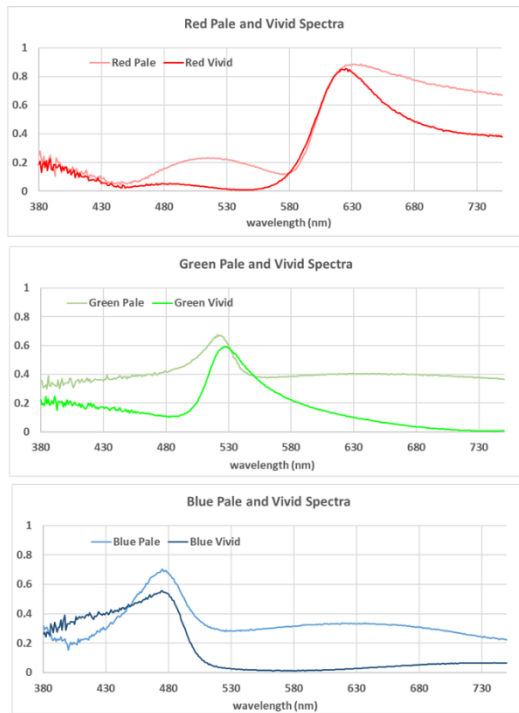
Figure 5 – a. A static full colour SRD demo created via a lithographically defined sub-pixelated process (right) is placed next to a colour printed version of the same picture (left). No enhancement in contrast or brightness was applied to this picture. **b.** Overall view angle performance of the SRD static demo showing small variation in colour even for shallow viewing angle. **c.** Three microscope pictures taken at high magnification of different regions in the parrot image. Pale and vivid versions of the RGB sub-pixels, together with the corresponding black matrix shutter, can be seen in each

picture.

Subsequently, the remaining RGB subpixels, expected to remain in the amorphous state, were deposited. Sputtered pixels are naturally deposited in their amorphous form therefore no annealing was necessary after these steps. Finally, a black mask simulating an optical shutter with graduated area coverage of each pixel as would be produced by an electrowetting type shutter, was lithographically defined on top of the pixels. The result: an optically genuine full colour SRD static demo is shown in Figure 5a next to a printed version of the same image. In sunlight, the subjective image quality of the demo can be seen to be comparable to high quality colour printing, and in indoor lighting the image quality clearly exceeds that produced by any existing colour reflective display. A laminatable diffuser film may be applied to the demo to provide a more matte appearance while also improving the average reflectivity over all viewing angles, regardless of illumination. Additionally, the viewing angle dependence of the image can be seen to be minimal, as shown in Fig 5b, a further consequence of the ultra-thin film interference effect utilized rather than conventional bragg type interference. The microscopic appearance of the image demonstrator is shown in Fig 5c. These pictures show the conventional RGB stripe sub-pixel arrangement used, but also the significant change in appearance of each sub-pixel type in the pale and vivid states. It is this large change which allows the simultaneous large colour gamut and high brightness white state, despite the shared reflective area RGB sub-pixel scheme which limits the brightness and gamut of conventional colour reflective displays with fixed colour filter reflection spectra.

Pixel level reflectance measurements of the various RGB sub-pixels, in both their vivid and pale states, are shown in Figure 6a. It is important to note that the use of improved designs with respect to the ones shown in Figure 3 translated into a higher pale to vivid contrast and high optical quality as already shown. Figure 6b shows a total measured gamut of 61% sRGB while having a luminance of $L^*=68.975$ ($Y = 0.394$) at the same time. The resulting white points are slightly off-centered in both states, this is due to all the pixels having the same dimensions. In practice, a correction factor is always needed given the varying sensitivity of the human eye to different primary colors.

a



b

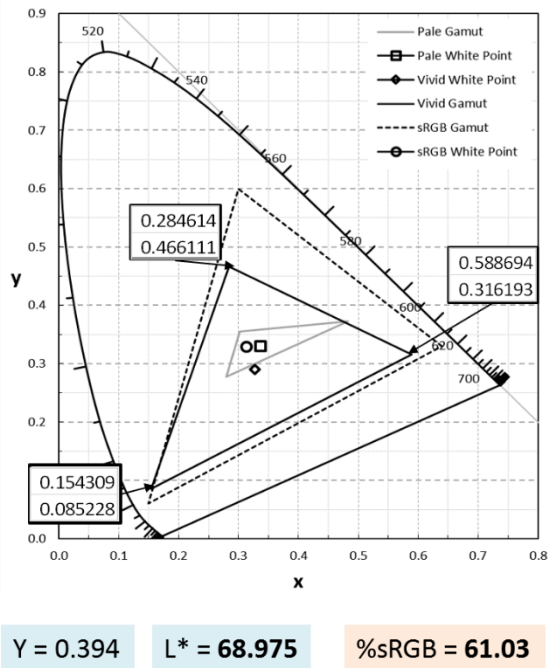


Figure 6 – a. Pixel level reflectance measurements for both vivid and pale RGB sub-pixels. **b.** Measured total colour gamut and luminance for the full colour SRD demo.

3. CONCLUSION

The current state of the art reflective display technologies, primarily electrophoretic and reflective liquid crystal mode displays, are inherently unable to deliver high colour gamut (>40%), high brightness white state and video on the same platform concurrently. The results shown in this paper are the first experimental evidence of the potential for SRD to achieve those combined characteristics at the same time without compromising in optical performance. Improved colour characteristics, especially in terms of brightness contrast, are expected to become available as the technology matures and a deeper understanding of the manufacturing processes is achieved. Finally, integrating SRD pixels with standard TFT driven backplanes, over large areas, is another important innovation that remains to be demonstrated. As previously discusses, SRD pixels can be switched using a precise heat cycle. A future TFT backplane will be designed to selectively heat a micrometer sized area of the PCM film via common joule heating. Careful tailoring of the voltage pulses, and hence heat pulses, will switch the material between its two states reliably and repeatably.

REFERENCES

1. Wuttig, M. and N. Yamada, *Phase-change materials for rewriteable data storage*. Nature Materials, 2007. **6**: p. 824.
2. Kim, S.-Y., et al. *Variation of the complex refractive indices with Sb-addition in Ge-Sb-Te alloy and their wavelength dependence*. in *Optical Data Storage '98*. 1998. SPIE.
3. Hosseini, P., C.D. Wright, and H. Bhaskaran, *An optoelectronic framework enabled by low-dimensional phase-change films*. Nature, 2014. **511**(7508): p. 206.
4. Hosseini, P. and H. Bhaskaran. *Colour performance and stack optimisation in phase change material based nano-displays*. in *SPIE Microtechnologies*. 2015. SPIE.
5. Carlos, R., et al., *Color Depth Modulation and Resolution in Phase - Change Material Nanodisplays*. Advanced Materials, 2016. **28**(23): p. 4720-4726.
6. Broughton, B., et al., *38 - 4: Solid - State*

Reflective Displays (SRD ®) Utilizing Ultrathin Phase - Change Materials. SID Symposium Digest of Technical Papers, 2017. **48**(1): p. 546-549.