Electrically Tunable Non-volatile Reflective Display Pixel Structure Based on Phase Change Material

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Abstract. A multi-layered non-volatile solid-state reflective display pixel structure composed of a Fabry-Perot type resonance cavity and an ultrathin phase change material film has been fabricated and analysed. By electrically switching the phase states of a phase-changing Ge$_2$Sb$_2$Te$_5$ (GST) film using an electric micro-heater under the stack, a pronounced colour change in pixel structures is observed, which is attributed to the change in the resonance condition of the multi-layered stack. Furthermore, the range of attainable colour can be widened by exploiting a spatial colour mixing structure.

1. Introduction
Chalcogenide-based phase change materials (PCMs) are typically used as active elements for photonic applications [1-4]. They have capability of reversibly switching at ultrahigh speed between amorphous and crystalline states under optical, electrical or thermal stimulation [5-6]. These states exhibit distinguishable optical and electrical properties and exhibit non-volatile behaviour for many years at room temperature [7-9]. These attributes mean that two highly differentiated optical states can be achieved with the same thin-film and remain stable at zero static power, which makes them important candidates for low power, ultrafast and non-volatile displays. Recently, Hossinei et.al proposed a sandwiched structure composed of transparent spacers (ITO) and an intermediate Ge$_2$Sb$_2$Te$_5$ (GST) layer to achieve a reflective nanodisplay with ultrafast colour modulation [10]. This pixel structure relies on the Fabry-Perot interference effect, hence the resonance condition of the optical cavity can be tailored by changing the optical property or thickness of one layer, thereby tuning the colour of the pixel structure.

The sandwiched structure is similar to a conventional cross-bar phase-change memory cell and has been proven to be electrically switchable by applying electrical pulses. However, previous works have shown that GST is a nucleation-dominated PCM, in which a highly conductive filament will be formed in the process of crystallization, preventing crystallization of the entire GST film [11-12]. This can be issue for display applications which requires colour change over the entire GST area. As GST is a thermal-induced PCM, thermal stimulation can effectively modulate the crystallization-amorphization process. The crystalline state can be obtained when the region is at a temperature between the crystallization temperature (450K~500K) and the melting temperature for sufficient time. The amorphous state can be obtained when the region is locally heated above the melting temperature and then rapidly quenching with extremely high cooling rate to freeze the liquid-like GST [13]. Therefore, the phase transition of GST can also be achieved by a buried micro-heater [14], which is expected to achieve more uniform switching over the entire GST area within a pixel structure.
In this work, we investigated the optoelectronic and color modulation of two GST-based pixel structures, one in conventional vertical electrical configuration and the other in lateral electrical configuration. In vertical pixel structure, the GST film itself is functioned as a heating element, while the lateral pixel structure uses a buried micro-heater as heating element to achieve similar modulation. Experimental results demonstrated that the lateral pixel structure is capable of achieving a more uniform phase transition of GST and allows large-area displays. In addition, we proposed a spatial color mixing structure to investigate the color modulation of GST-based pixel structure. Intermediate color can be obtained by alternatively arranging the subpixels of different colors.

2. Simulations and Experiments

2.1 Optical and electrical simulations

Figure 1 shows two different pixel structures of ITO/GST/ITO/W stack studied in the work: a conventional vertical electrical configuration and a lateral electrical configuration. The optical properties of these pixel structures are greatly influenced by the thickness of stack and the phase state of GST. In order to optimize the thickness of each layer for any specific color, we firstly use Transfer Matrix Method to obtain the reflectance spectra, and use CIE-XYZ standard system to simulate its colors which can be perceived by human eyes. Beside, by performing this simulation in different GST phases, we can quantify the reflection spectra and corresponding color changes. The complex refractive index of materials used in this optical simulation is measured via ellipsometry.

Figure 1. Schematic diagrams of pixel structures of ITO/GST/ITO/W stack studied in the work, (a) with a vertical electrical configuration, (b) a lateral electrical configuration (micro-heater).

Table 1. Physical parameters of materials used in the pixel structures in Figure 1.

|                | $\sigma$ (1/Ω·m) | $\rho$ (kg/m³) | $K$ (W·kg⁻¹·K⁻¹) | $C_p$ ($J$·kg⁻¹·K⁻¹) |
|----------------|------------------|----------------|------------------|---------------------|
| GST (crystalline) | 2770             | 6200           | 0.5              | 202                 |
| GST (amorphous)  | 3                | 6200           | 0.2              | 202                 |
| W               | $1.7 \times 10^7$ | 19300          | 178              | 132                 |
| ITO             | $2.6 \times 10^5$ | 6800           | 5.86             | 379                 |

2.2 Fabrication Method
Figure 2 shows the schematic diagram and optical microscope image of a fabricated device. We choose W among other metals for micro-heater due to its high resistivity and good stability under high temperature. The electrical contacts are designed much thicker than the bottom metal layer to ensure most of the voltage is applied across the micro-heater. The structure is patterned using lithography system (Karl Suss MA6 Mask Aligner) and the materials are deposited by sputtering system (DENTON Sputter System, DISCOVERY635).

![Figure 2](image)

Figure 2. (a) Schematic diagram and (b) micro-photograph of the fabricated device with the pixel structure (ITO/GST/ITO/W multi-layer stack) shown in Figure 1(b).

3. Results and Discussions

We fabricated a 50μm ×50μm pixel structure with vertical electrical configuration, as illustrated in Figure 1(a), and tested its electrical and optical characteristics. The GST film was switched by voltage pulses applied between the top ITO layer and the metal layer. Firstly, we measured its IV-characteristic to investigate whether the phase state of GST is transited. As shown in Figure 3, when the voltage was changing across a threshold switching voltage, about 2.4V, the resistance of the device, i.e. the slope of the IV curve, increased suddenly and dramatically. This large resistance contrast indicates that the region had transformed from amorphous state to crystalline state. However, no obvious colour change in this pixel structure was observed. The reason for the missing colour variation of the pixel structure is because only a very small area of GST had been switched to crystalline state. Since GST is a nucleation-dominated PCM, some local points in the GST film will turn into crystalline phase before other regions [6, 12]. When these local areas are connected to form a filament, most current will flow through the filament path because the resistance of crystalline phase is much lower than that of the amorphous state. This prevents crystallization of the rest GST film area and causes a non-uniform phase transition within a pixel. In fact, because the crystallized filament area is usually very small compared the entire GST film, the most area of the GST film are not crystallized. This explains why we did not see colour change in this structure although its electrical IV curve has indicated the phase change.

![Figure 3](image)

Figure 3. I-V curves of vertical pixel structure, showing a characteristic switching behaviour between amorphous and crystalline states of GST film.
To achieve a more uniform colour transition on large area of GST film, which is required for display applications, we constructed the pixel structure with a lateral micro-heater as shown in Figure 1(b). The temperature distribution of the lateral pixel structure is controlled by the joule heating of the micro-heater and is independent on the phase state of GST film, so a more uniform phase state transition of GST film can be achieved. In this simulation, we first explored the heating and cooling behaviour of the lateral pixel structure to verify its feasibility as a tunable pixel structure. As shown in Figure 4(a), firstly we applied an electrical pulse with an amplitude of 1V and a width of 2.5\(\mu\)s to crystallize the lateral pixel structure. The variation of the peak temperature in the GST film during the application of voltage pulses is shown in Figure 4(c), and the temperature distribution across the device stack at the end of the electrical pulse application is shown in Figure 4(e). The simulated results demonstrated that the GST film could be crystallized by heating above the crystallization temperature but below the melting point for sufficient time. Secondly, as shown in Figure 4(b), we applied an electrical pulse with an amplitude of 2.2V and a width of 50ns to amorphize the GST film. As shown in Figure 4(d) and Figure 4(f), the simulated results showed that the temperature of the GST layer first increases to 1000K above the melting temperature, and then rapidly drops below 400K at a rapid quenching rate, which is a necessary condition for amorphization. These results demonstrated the feasibility of the pixel structure with a lateral micro-heater to switch the GST film between crystalline and amorphous states.

**Figure 4.** Thermal-electrical simulations of the pixel structure with a lateral micro-heater illustrated in Figure 1(b). Voltage pulses applied to crystallize (a) and amorphize (b) the GST film. Variation of the peak temperature in the GST film during the application of voltage pulses over the micro-heater, corresponding to the crystallization (c) and the amorphization process (d). Temperature distributions of the multi-layer stack at the end of voltage pulses applied for crystallization (e) and amorphization (f).
Based on those results, we have then fabricated a lateral pixel structure described in Figure 2. The structure has a display area of 30μm × 30μm and has the following layer thicknesses: a layer of ITO of 90nm, a layer of GST of 10nm, a layer of ITO of 45nm, a layer of metal W of 20nm, from the top to bottom, over Si substrate. To test the colour change by switching the phase state of the GST film, we applied a 1A current pulse with 10ms duration. As shown in Figure 5, the images of optical microscope showed a distinguishable and uniform colour change over the entire device area before and after the pulse application. This indicates that the colour change is consistent with the phase change of the GST film between the amorphous state before the pulse application and the crystalline state after pulse application. Compared with the vertical structure, the results demonstrated that the pixel structure with a lateral micro-heater is capable of achieving uniform phase transition of GST film.

![Figure 5. Micro-photographs of the fabricated pixel structures shown in Figure 2, with the GST film in as-deposited amorphous state (left), and after switched to crystalline state with the application of electrical pulse over its micro-heater (right), which shown dramatic colour change.](image)

Lastly, we have designed a spatial colour mixing structure, as shown in Figure 6(a), which consists of two different colours of subpixels: subpixel structure A is made of a stack of 45nm ITO/10nm GST/180nm ITO/100nm W and subpixel structure B is made of a stack of 90nm ITO/10nm GST/45nm ITO/100nm W. The simulated results of both structures were illustrated in Figure 6(b), showing the reflectance spectrum and the reflected colour appearance. Because of the Fabry-Perot interference effect, the reflected colour relied on the thickness of ITO. Because of the difference in ITO film, structure A and structure B exhibit two different colours. Using these subpixel structure A and B, we design a spatial colour mixing logo as shown in Figure 6(c), where the middle region is arranged with subpixel structure A and structure B alternatively. The size of the subpixels is 100μm × 100μm and the gap between the subpixels is 10μm. As shown in Figure 6(d), the fabricated logo sample presented three uniform colours: the top and bottom regions were composed of structure A only and structure B only, respectively, and they show similar colours to the simulation results of Figure 6(b). However, the middle region showed a uniform olive colour, which is different from the colour of Structure A and Structure B. This experiment demonstrates the feasibility and effectiveness of spatial colour mixing. Furthermore, using this spatial colour mixing structure, any combination between structure A and structure B can be easily designed, therefore more colours and more accurate “grayscale” modulation can be easily achieved.
Figure 6. (a) Schematics of two different stack structures used in a spatial colour mixing configuration fabricated in this work: Structure A has a stack of ITO (45nm) / GST (10 nm) / ITO (180 nm) / W (100 nm), and Structure B has a stack of ITO (90 nm) / GST (10 nm) / ITO (45 nm) / W (100 nm), from the top to bottom. (b) Reflectance spectrum and simulated colour of Structure A and B illustrated in (a). (c) Design layout of a logo, which is divided into 3 regions: the top region is designed using only Structure A, the middle region using a spatial mixing of Structure A and B, and the bottom region using only Structure B. The inset shows its spatial mixing configuration. (d) Microphotograph of the fabricated logo sample, which shows that the colour of the top region and bottom region are close to that simulated in (b), but the colour of the middle region is neither the colour of Structure A nor the colour of Structure B, instead it exhibits a new uniform colour.

4. Conclusion
In summary, we have fabricated a non-volatile reflective display pixel structure based on GST film and demonstrated the feasibility of colour switching operations using a lateral electrical micro-heater. The lateral pixel structure exhibits a distinguishable change in reflected colours before and after the applied electrical pulses, which can be attributed to an electrically induced phase change of GST film. Compared to the conventional structure with vertical electrical configuration, the colour change of this pixel structure with a lateral micro-heater is much more uniform over the entire area of the pixel structure, which is a critical requirement for display applications. In addition, we used a spatial colour mixing configuration to achieve more colours using combination of subpixels of with different thickness of ITO.

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