Multi structural tunable filters using optical phase change materials for visible and IR regions

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Outline

- Introduction to phase change materials
- Motivation for this research
- Objectives of the project
- Ge2Sb2Se4Te1(GSST) characterization
- Different design approaches and results
- Future work

Optical phase change materials

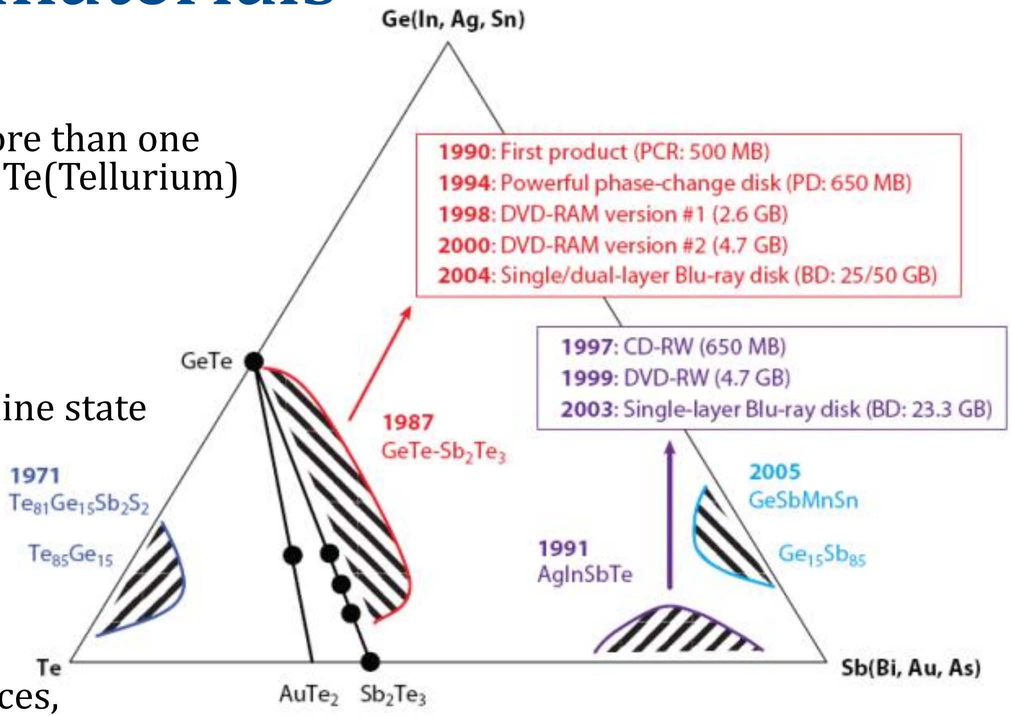
- Categorized as chalcogenide glass – include more than one chalcogenides such as S(sulfur), Se(Selenium), Te(Tellurium) etc.

- They can undergo solid state phase transition;

Amorphous —(Temperature, Current, or Optical excitation)→ Crystalline state

- Optical and electrical properties change with the phase transition

- Popular applications- optical switching, photonic memories, reconfigurable meta-surfaces, and non-volatile displays.



Ternary phase diagram depicting different phase-change alloys and their year of discovery (Wuttig and Yamada, Nat. Mater. 6 (2007) 824)

Motivation

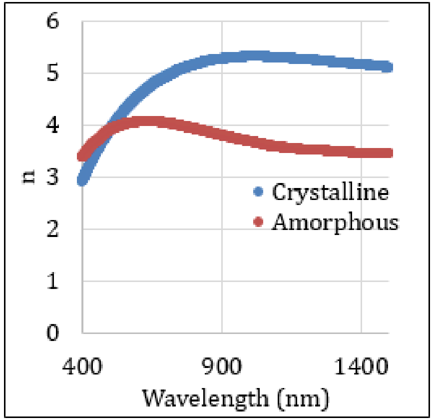
- For filters in the visible and IR regions, there are many popular applications
  - Visible range - Image sensors, liquid crystal display (LCD) devices, 3D projection systems, biosensors and photovoltaic cells etc.
  - IR range - IR imaging, spectroscopy applications, IR sensing
- Natural objects have more colors than current LCDs can display
- There is an urgent need for a wider color gamut in order to reproduce original colors and tunable filter can be a potential solution
- Existing IR filters have many drawbacks that can be addressed by a tunable filter working in transmission mode
- Tunable optical filters can provide very high resolution while consuming minimal power.

Objectives of the project

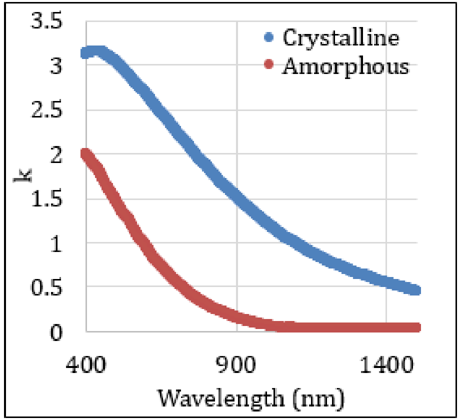
- Design and fabricate a tunable filter in the visible and IR region
- Expected properties of the filter;
  - Maximum transmission and zero reflection at the reference wavelength
  - A switchable design between amorphous and crystalline state of the Phase change material (PCM) with a low power input
  - A larger shift in the transmission peak after phase transition
- Ge2Sb2Se4Te1 (GSST) was chosen as the optical PCM for this project
- Ideal filter design will have a maximum transmission at the reference wavelength in both states as well as a considerable shift in the peak transmission

GSST characterization

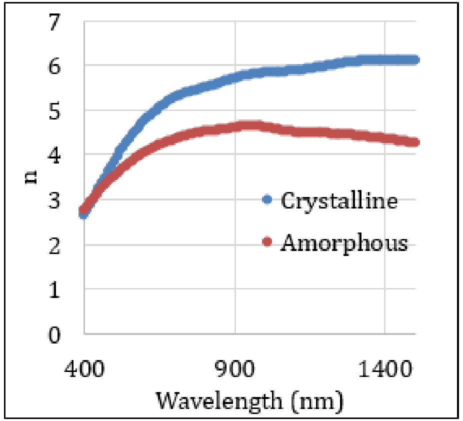
- Ge2Sb2Se4Te1 (GSST) has comparatively low refractive index(n) and extinction coefficient(k) compared to the most common PCM ,Ge2Sb2Te5(GST) in both amorphous and crystalline states



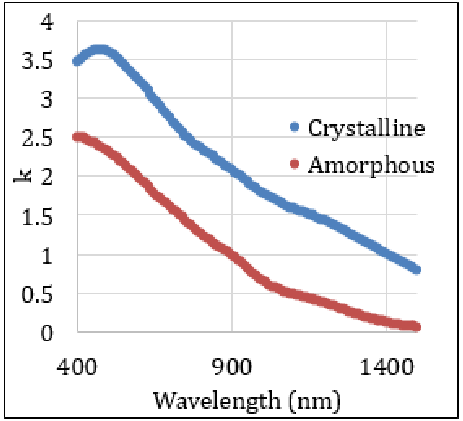
(a)



(b)



(c)



(d)

(a) Refractive index (n) and (b) Extinction coefficient (k) of GSST at amorphous and crystalline state

(c) Refractive index (n) and (d) Extinction coefficient (k) of GST at amorphous and crystalline state

GSST characterization contd..

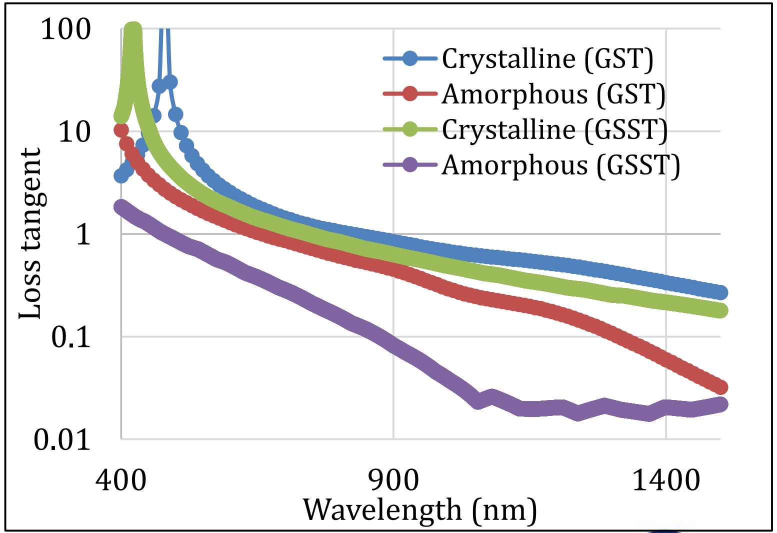
Optical properties

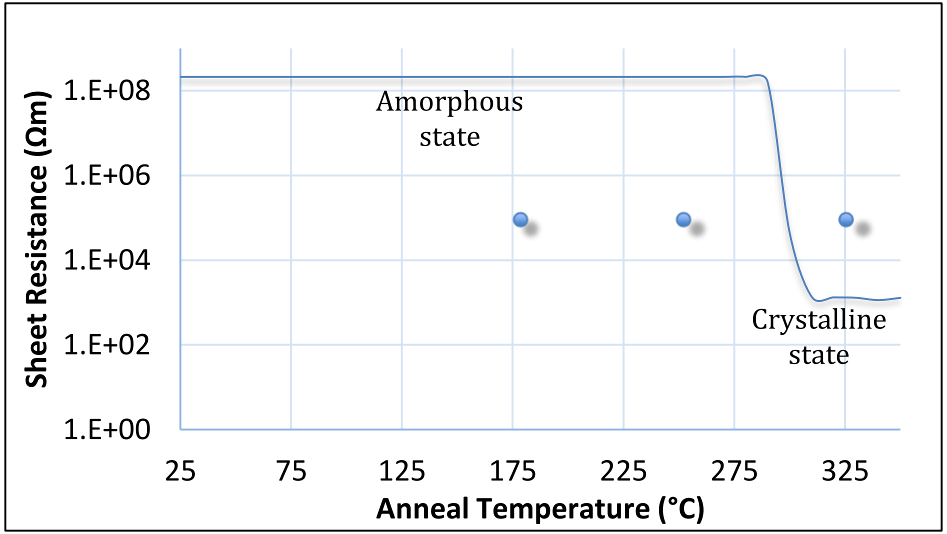
- GSST has lower absorption loss compared to GST, especially in amorphous state
- Absorption loss can be quantified by loss tangent;

$$\tan\delta = \frac{2\, n_r \kappa}{{n_r}^2 - \kappa^2}$$ where n_r - refractive index and κ – extinction coefficient

Electrical properties

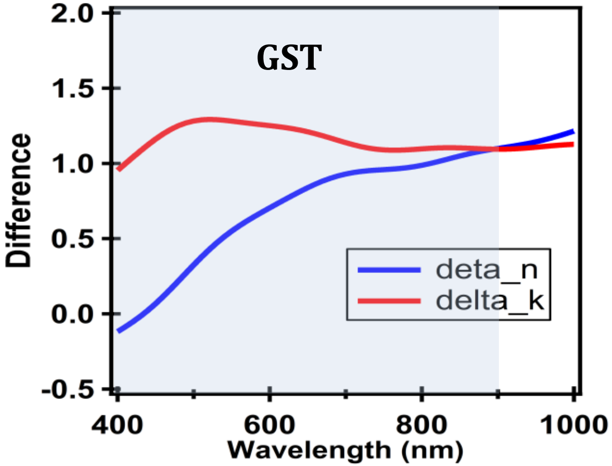
- Phase transition takes place around 300^0C
- Conductivity increases significantly with the phase transition
- Following graph of sheet resistance measurements indicates the variation of sheet resistance with phase transition

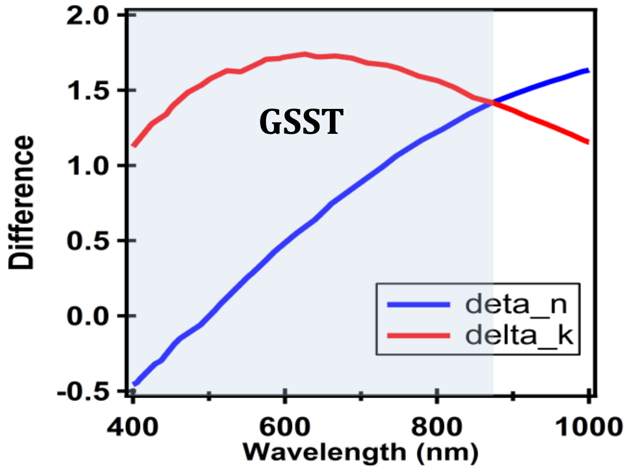




GSST characterization contd..

- The behavior of n and k is useful in designing these tunable filters.
- GSST has higher Δk(difference in extinction coefficient) than GST and has a maximum value in the visible spectrum.
- Δn (difference in refractive index) reaches a maximum in the SWIR and becomes zero around 500nm.
- Therefore it is difficult to utilize GSST to create a tunable filter in the visible spectrum based on optical phase change alone.

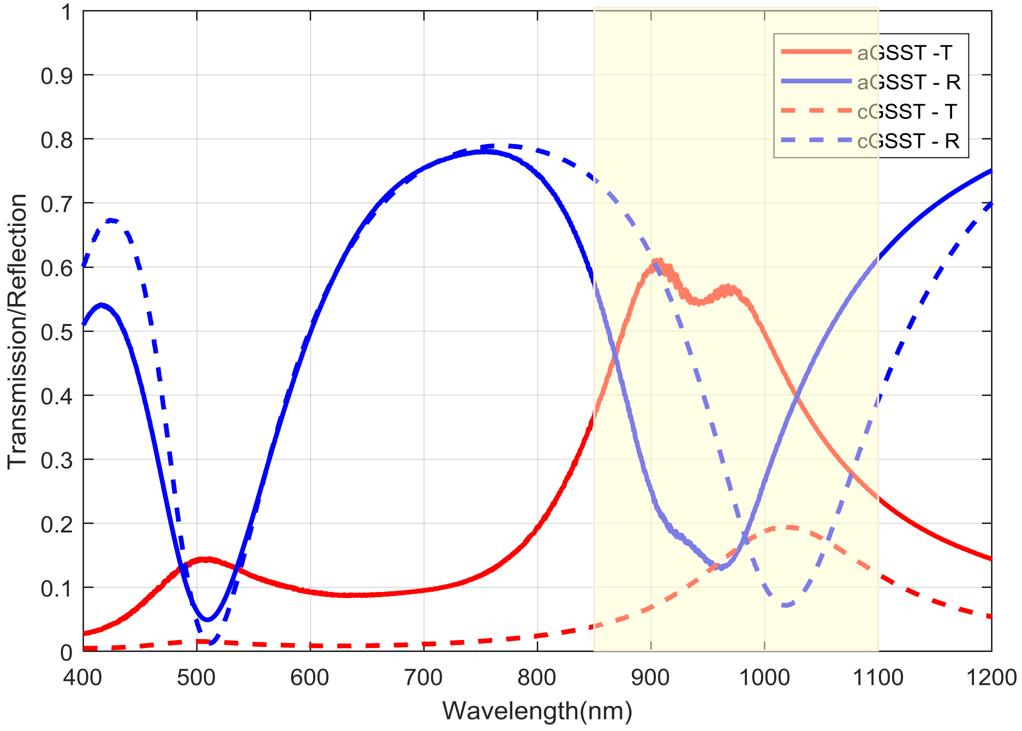




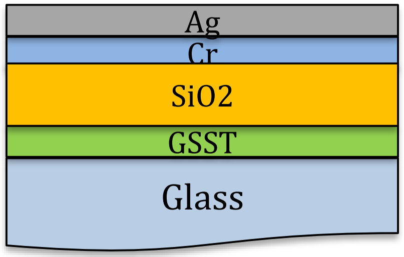
Different design approaches

- MIM cavity (Metal-Insulator-Metal structure) – IR region
- DFB cavity (Distributed feedback cavity) – IR region
  - Resonator consists of a periodic structure
- Variable reflective design – Visible range
  - This is recreated from a previous publication (***C. Ríos, P. Hosseini, R. A. Taylor, and H. Bhaskaran, "Color Depth Modulation and Resolution in Phase-Change Material Nanodisplays," pp. 4720–4726, 2016***) to compare the color contrast from different phase change materials available in the laboratory

MIM cavity design 1



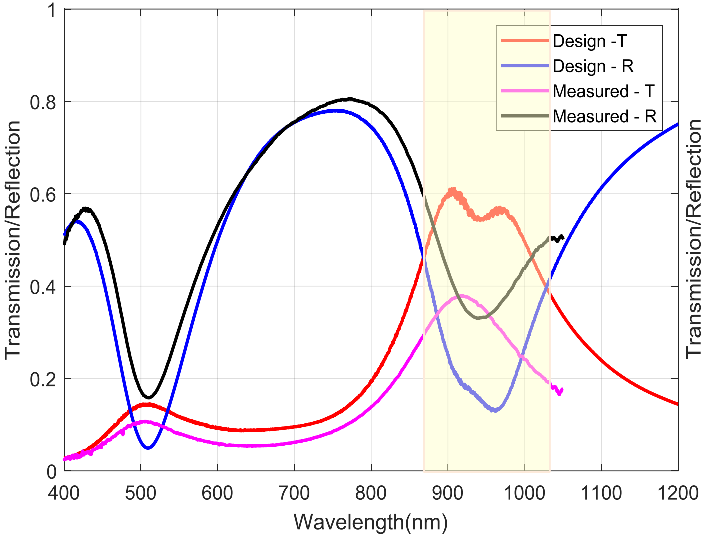
Simulated results for the design



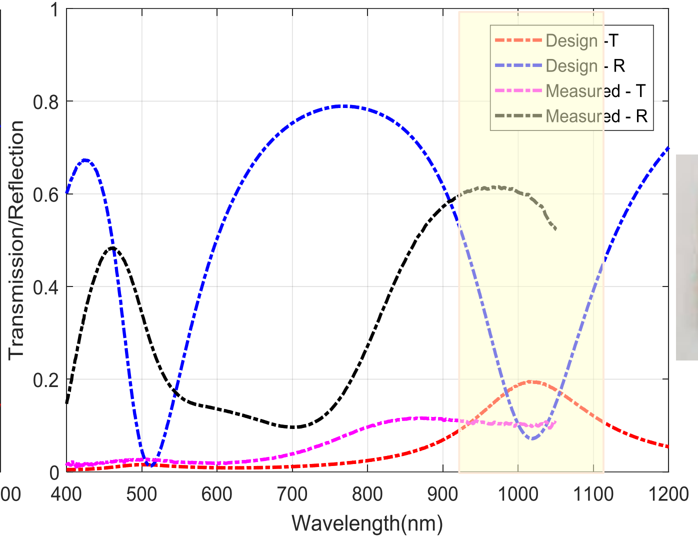
Design schematics

- Reference wavelength – 950nm and expected peak shift ~70nm
- If the Glass substrate is AR coated, reflection at reference wavelength will be zero
- Additional layer of Cr needs to be added as an adhesion layer for Ag
- It reduces the transmission peak by ~20%
- Transmission peak drops by 40% with the phase transition - due to higher refractive index in the crystalline state and it is difficult to avoid

MIM cavity design 1 – Experimental results



Comparison between measured and simulated spectra of the final design at **amorphous state of GSST**



Comparison between measured and simulated spectra of the final design at **crystalline state of GSST**

As deposited (aGSST)

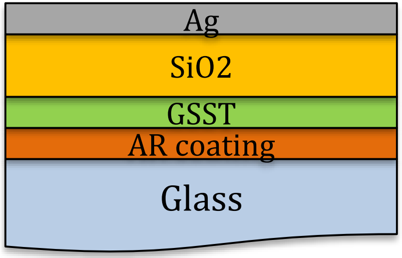
Annealed at 350^0C (cGSST)

Fabricated sample

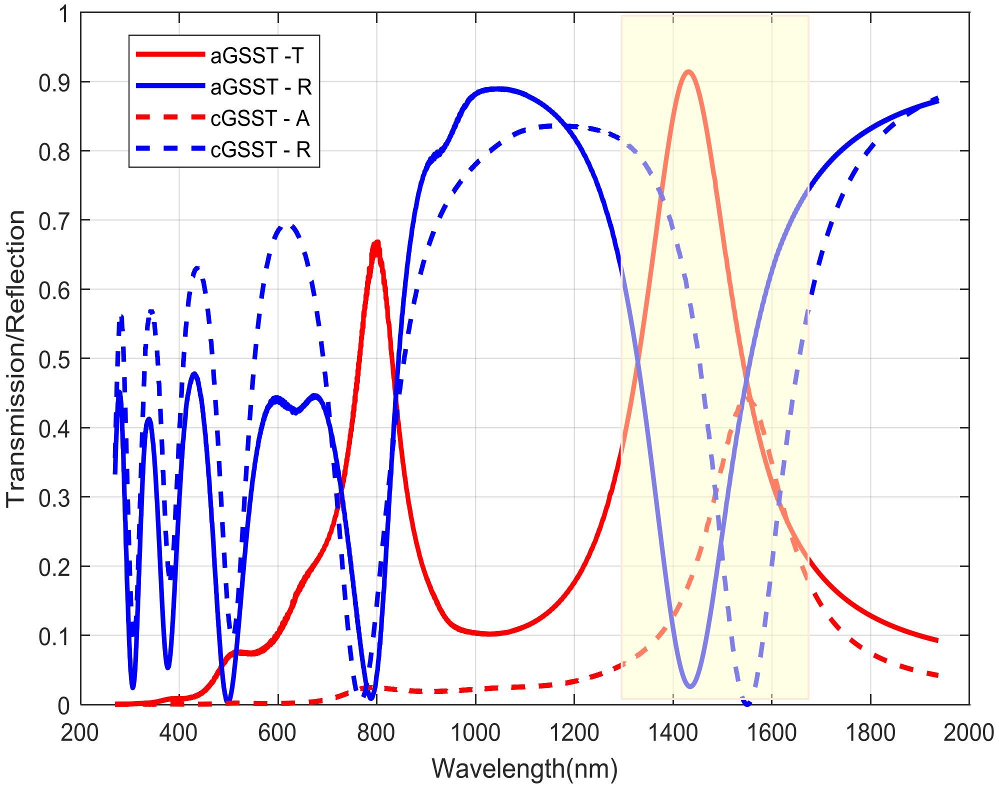
- Experimental results do not fully agree with simulations
- We can only measure reflection/transmission spectrum up to 1000nm in the laboratory
- Greater contrast in visible range was observed between amorphous and crystalline states which was unexpected.
- Need to repeat the experiment with AR coating for the glass substrate and measure reflection and transmission spectra after each layer, to understand the discrepancy

MIM cavity design 2

- Further towards the IR region, the peak shift between two states increases
- Reference wavelength – 1550nm
- Phase change still cause reduction in transmission peak
- Peak shift is ~120nm
- Design needs to be optimized to suppress the short wavelength transmission in amorphous state



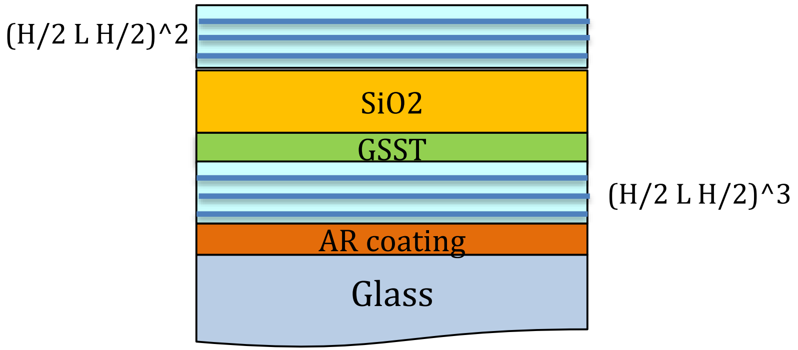
Design schematics



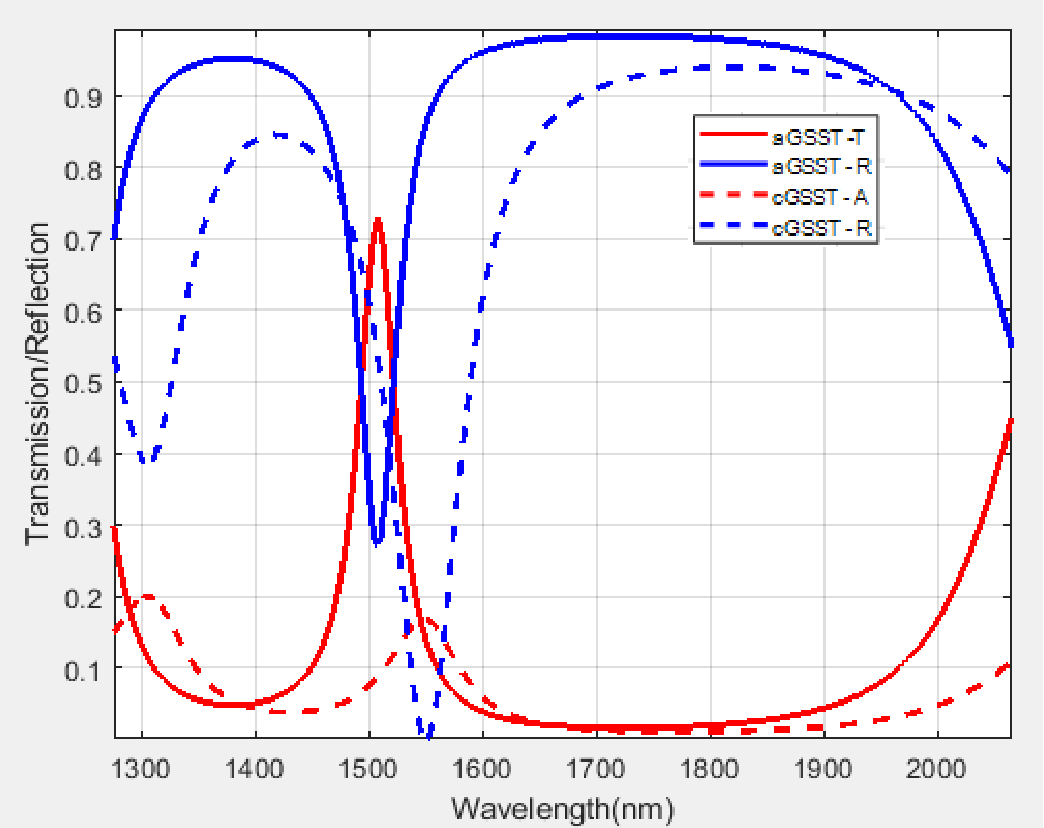
Simulated results for the design

DFB cavity design

- Reference wavelength – 1550nm
- Transmission peak reduces in this design as well
- Peak shift is ~50nm
- H – quarter wave thick TiO_2 layers
- L – quarter wave thick SiO_2 layers
- This design needs to be optimized to increase the transmission peak in crystalline state



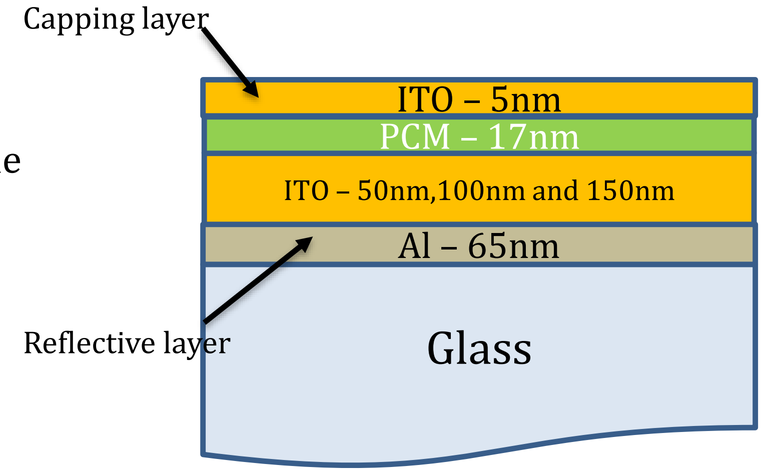
Design schematics



Simulated results for the design

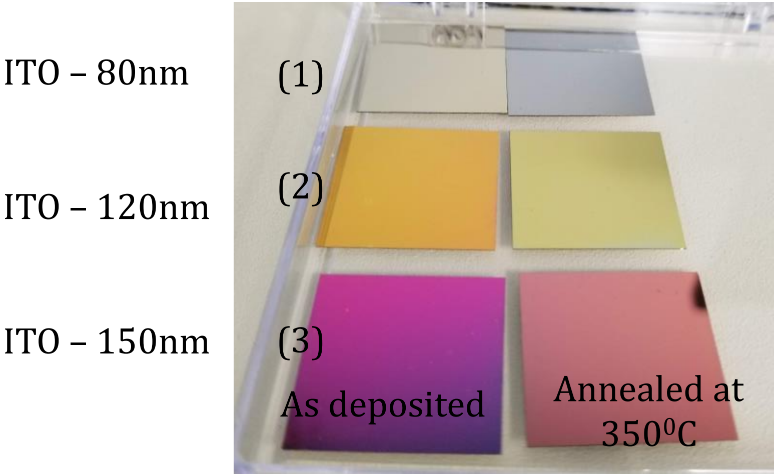
Variable reflector design

- By changing the ITO layer thickness, reflective color can be varied
- This design was fabricated using all PCMs available in the laboratory
  - $Ge_2Sb_2Se_4Te_1$ (GSST)
  - Ge_7Te_3
  - GeSe
  - Sb_2Te_3
- Reflection/transmission spectra of each sample was measured at amorphous(as deposited) and crystalline(annealed to 350^{0}C) states
- This information is useful in understanding characteristics of these PCMs and can be used in achieving the goal of this project

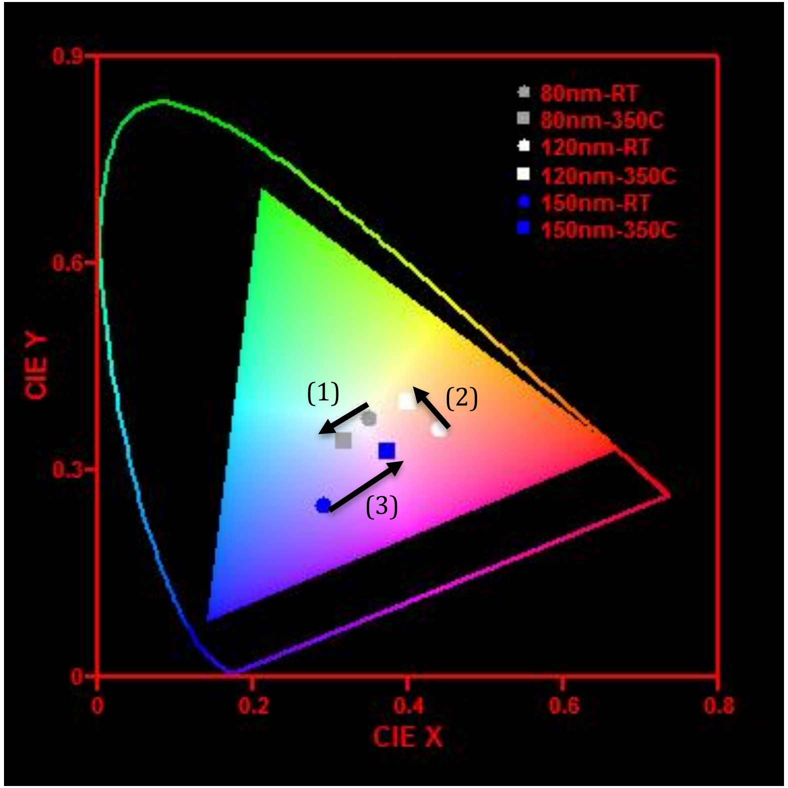


Design schematics

Variable reflector with GSST



Fabricated samples



chromaticity diagram that indicate colors of each sample at two different states

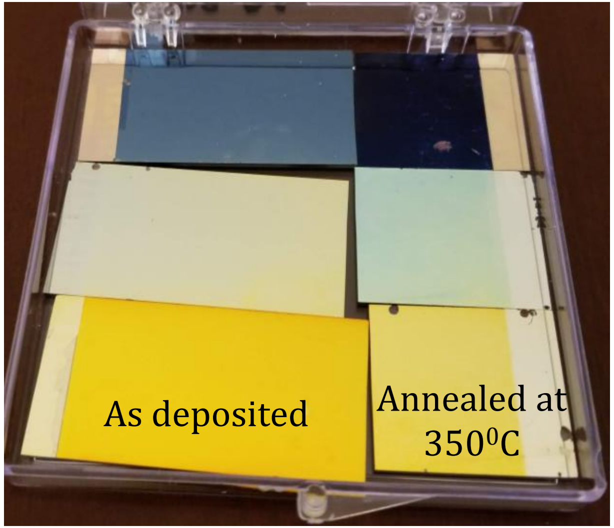
- These samples show some bright colors and there is a considerable contrast between two phases

Variable reflector with Ge7Te3

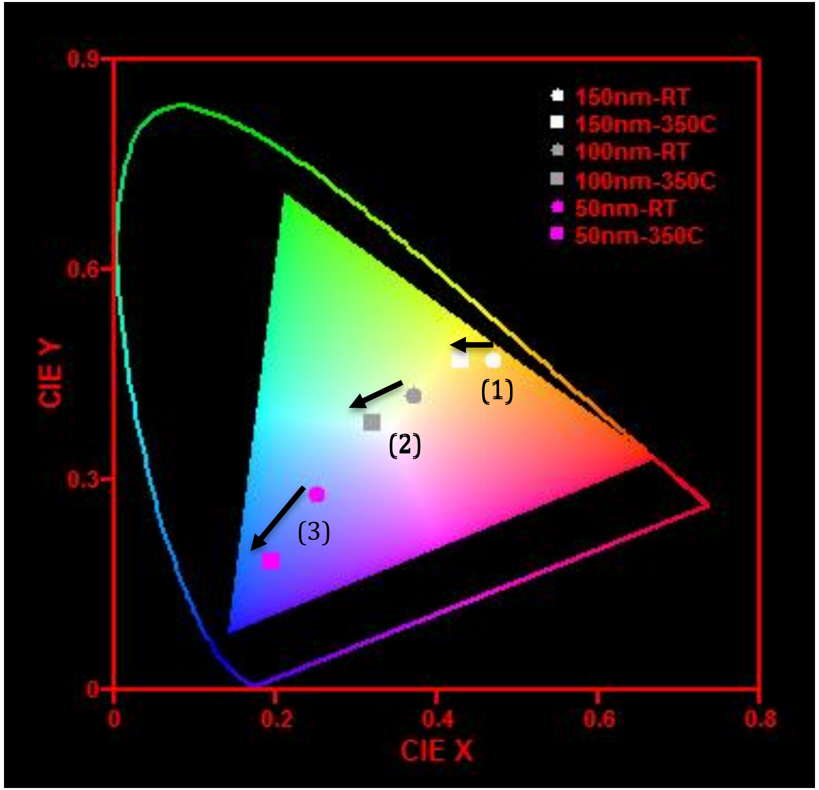
ITO – 50nm

ITO – 100nm

ITO – 150nm



Fabricated samples



chromaticity diagram that indicate colors of each sample at two different states

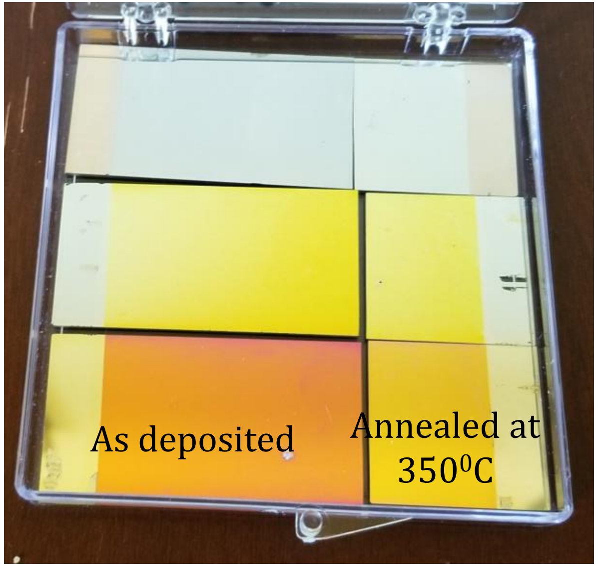
- These samples show grater contrast between two phases and the colors are well distributed in the gamut

Variable reflector with GeSe

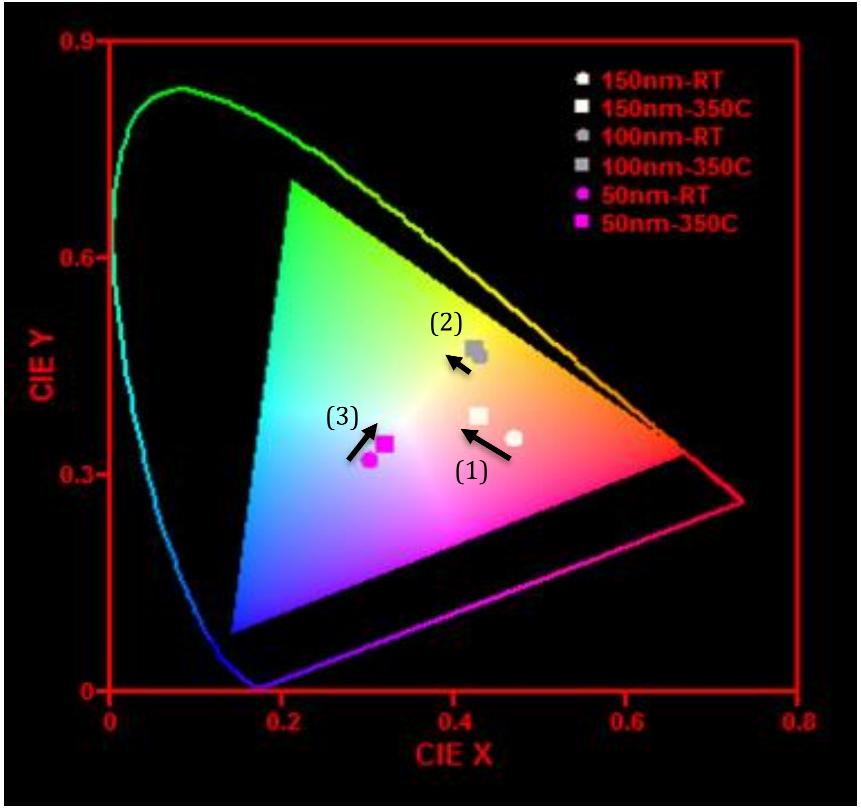
ITO – 50nm

ITO – 100nm

ITO – 150nm



Fabricated samples



chromaticity diagram that indicate colors of each sample at two different states

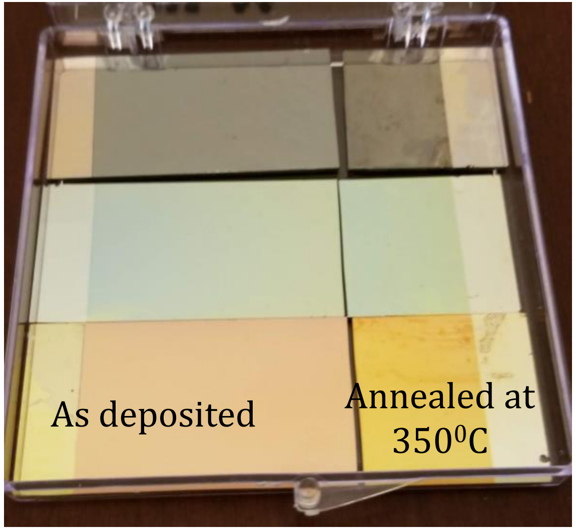
- Observed colors from these samples are somewhat bright and the contrast between two phases is small

Variable reflector with Sb2Te3

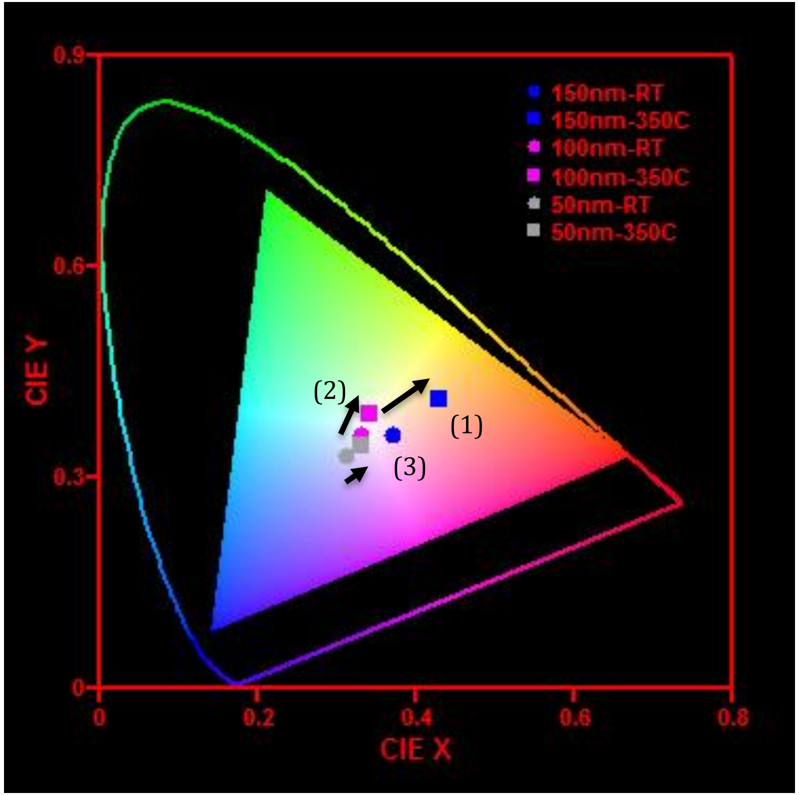
ITO – 50nm

ITO – 100nm

ITO – 150nm



Fabricated samples



chromaticity diagram that indicate colors of each sample at two different states

- Observed colors from these samples are not as sharp as the others and contrast between two phases is small

Future work

- Previously discussed designs need to be analyzed further to optimize the results
- Need to characterize other PCMs in expanding the knowledge on this topic
- More samples need to be fabricated and tested
- Other possible design approaches such as meta-surfaces need to be evaluated for improved results
- An electrical circuit will be designed to generate fast pulses that is capable of switching PCM pixels between amorphous and crystalline states

Reference

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