Overcoming diffusion issues in hybrid phase-change metasurfaces

Joe Shields*, Carlota Ruiz de Galarreta, Jacopo Bertolotti and C. David Wright
College of Engineering Mathematics and Physical Sciences, University of Exeter, Exeter EX44QF, UK, *js1116@exeter.ac.uk

ABSTRACT

The optical performance of phase-change metasurfaces can be irreversibly degraded by the effect of thermally activated diffusion during device switching. Here we present a systematic case-study of this effect in metasurfaces designed for modulation in the O and C telecommunication bands and a method for addressing such issues using ultra-thin Si_3N_4 barrier layers.

Key words: phase-change material, metasurface, diffusion.

1. INTRODUCTION

Thermally tunable optical metasurfaces using chalcogenide phase-change materials (PCMs) offer a promising approach to the design of devices for the active control of the amplitude, polarisation and phase of light. Moreover, they can do this in a flat, compact and relatively low-cost format and can be switched on short (nanosecond) timescales. However, there are important considerations that must be taken into account in the design of devices that can operate usefully in real-world scenarios [1]. In particular, the use of common plasmonic metals such as gold (Au) and silver (Ag) in the device structure can lead to diffusion of these metals in semiconductors and/or PCMs such as silicon or $Ge_2Sb_2Te_5$ (GST). Parasitic interfacial gold/silver tellurides and gold/silver silicides can also be formed, and the combination of diffusion and telluride/silicide alloy formation can dramatically and irrevocably degraded the optical performance of devices [2].

In this work we present a set of hybrid dielectric/plasmonic phase-change metasurfaces with different materials to investigate the effect of thermally activated diffusion on the optical properties of such devices. Hybrid metasuface devices offer the high optical efficiency typical of all-dielectric optical metasurfaces, while at the same including a metal ground plane that would allow for the use of in-situ heating via the embedded micro-heater approach, as recently discussed for example in [3].

2. EXPERIMENTAL

A set of resonant hybrid dielectric/plamonic PCM-based metasurfaces for O and C telecoms band modulation were designed and fabricated. Schematics of the devices can be seen in figure 1 (top). All devices designed had the same basic architecture: reflecting metal back plane below a periodic arrangement of silicon cubic nanoresonators with GST layers embedded within. These were fabricated and tested systematically with different back planes; aluminum as a low melting point non-diffusive material and gold as a high melting point diffusive material, as well as with and without diffusion barrier layers (Al_2O_3 and Si_3N_4). The devices were designed with re-amorphisation in mind, the back metal plane being able to act as a heat sink to allow for the rapid cooling required for successful re-amorphisation, as well as the possibility of using this plane as an in-situ resistive heater.

3. RESULTS & DISCUSSION

The results from the study can be seen in figure 1 (bottom), showing the reflectance spectra across the O and C telecommunication bands for the different devices. Figure 1 (a) shows the reflectance spectra of the non-diffusive Al structure, showing the expected characteristic absorption at 1310 nm in the amorphous phase and 1550 nm in the crystalline phase. Figure 1 (b), however, shows that with diffusive Au as the bottom reflecting plane the resonance in the crystalline phase is dramatically degraded on device annealing (at 200 ^{0}C in air for 10 minutes). By introducing an ultra-thin diffusion barrier layer Si_3N_4 into the design, the results of which can be seen in figure 1 (c), we can see that the devices again perform consistently with simulations and the characteristic resonance at 1550 nm remains intact, even after annealing to form the crystalline phase.

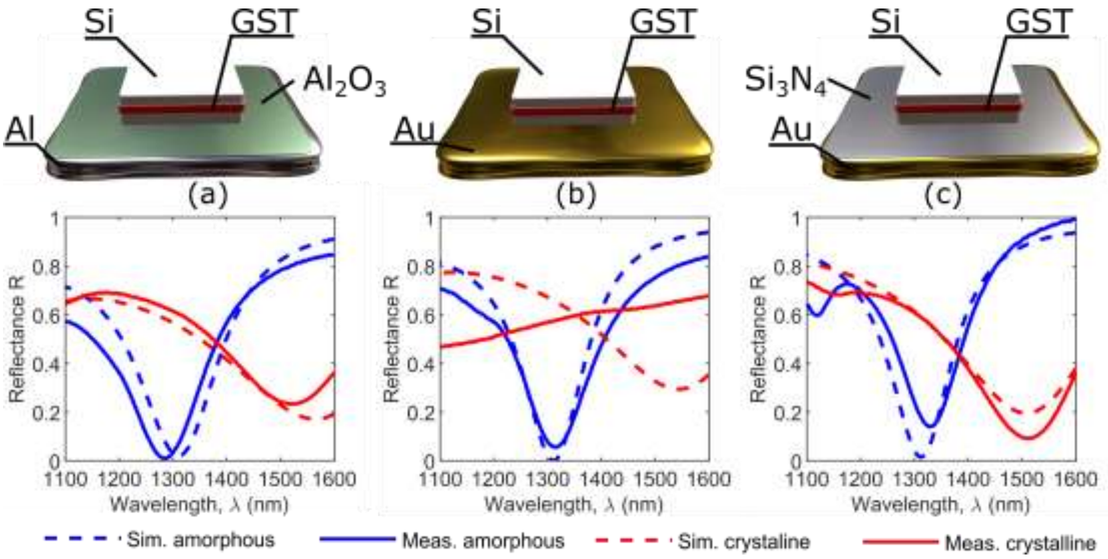

Figure 1: *Schematics of the PCM metasurface unit cells (top) and associated reflectance spectra (simulated and measured), for amorphous and crystalline phases of the GST layer (bottom), (a) Al-based design, (b) Au-based design, the spectra of which can be seen to be severely degraded after thermal annealing and (c) designe based on Au with a Si_3N_4 barrier layer, which show expected crystalline response after annealing. Figure adapted from [4].*

4. CONCLUSIONS

In this work we have shown the effect of thermally-activated diffusion on phase-change based metasurfaces through a systematic study of different device configurations. The results highlight the importance of proper device design to eliminate the adverse effects of diffusion of good plasmonic metals in phase-change based tunable metasurfaces and other similar photonic devices.

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