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All-Optical Switching of Photonic Metamaterials Enabled by Surface-Mediated Phase Transitions in Gallium

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Abstract **– Reversible, optically-induced surface metallization in a nanoscale layer of elemental gallium forming the backplane of a photonic metamaterial absorber provides a mechanism for a strong, resonantly enhanced reflective optical nonlinearity at μW/μm^2 intensities.**

I. INTRODUCTION

We report on the first experimental demonstration of a nonlinear optical photonic metamaterial based on a light-induced surface transition between solid and liquid phases occurring in a confined nanoscale layer of the plasmonic structure, enabling all-optical switching at near-infrared wavelengths with high contrast at low, μW/μm^2, laser excitation intensities.

Resonant metamaterial absorbers typically comprise a planar array of sub-wavelength plasmonic metal resonators and a continuous metallic (mirror) backplane, separated by a thin dielectric spacer – the resonant frequency being a function of the pattern in the nanostructured metal layer and thickness of the spacer. Dynamic tuning and switching of the response in such structures, or indeed in any photonic metamaterial, conventionally relies on functional media (e.g. silicon [1], chalcogenide phase-change glasses [2], liquid crystals [3]) hybridized with the plasmonic metal framework. Here instead we harness a light-induced interfacial structural phase change in the metallic framework itself (specifically the mirror backplane of a resonant absorber) to drive reversible changes in spectral response (Fig. 1).

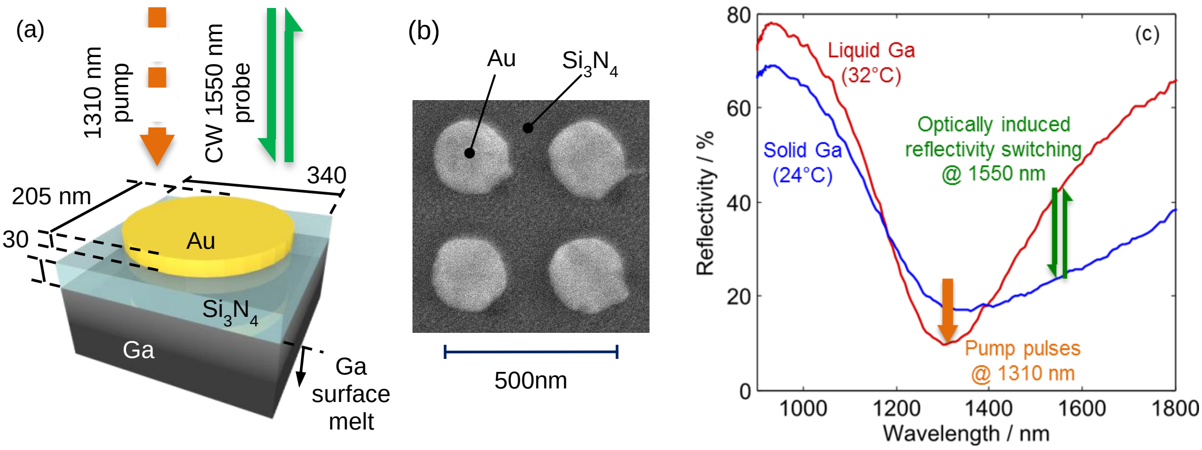

Fig. 1. (a) Artistic impression and unit cell design dimensions for a gallium-backplane metasurface with an absorption resonance at a wavelength of ~1310 nm. (b) Plan view scanning electron microscope image of a section of the fabricated gold disc metasurface array on silicon nitride. (c) Experimental reflectivity spectra for the limiting liquid and solid phase Ga backplane states of the metasurface absorber. Optical pumping at the 1310 absorption resonance drives reversible reflectivity changes at the 1550 nm probe wavelength.

The optical and electronic properties of elemental gallium display considerable differences between its solid 'semi-metallic' α-phase (the stable bulk form) and its liquid phase, which is essentially a free-electron metal [4-5]. As a result, at the solid-liquid transition occurring at T_m = 29.8°C a significant change is observed in the optical characteristics of a gallium/dielectric interface. Gallium is also subject to a strong 'surface melting' effect whereby, even at temperatures several degrees below T_m, a thin metallic liquid phase layer (a few-nanometres thick) exists at interfaces between the solid α-phase and a dielectric. The thickness of this interfacial liquid layer (and therefore the reflective properties of the metal/dielectric interface) is highly sensitive to both temperature and incident light intensity. This sensitivity provides a mechanism for dynamically controlling, with light, the resonant response of a photonic metasurface comprising a solid gallium backplane and a gold metamaterial disc array separated by a nanoscale silicon nitride spacer (Fig. 1).

II. Methods, Results & Discussion

The gold disc array is fabricated by focused ion beam milling in a thin film of gold evaporated onto one side of a silicon nitride membrane. This is pressed onto a bulk liquid gallium droplet which is then solidified to create the solid α-gallium/membrane interface that serves as the metasurface backplane. The structure provides strong resonant absorption at a frequency initially set by the design of the gold layer and thickness of the nitride membrane and subsequently dependent on the phase state of the gallium.

The reflective nonlinear response of the gallium metasurface is interrogated at near-IR telecoms wavelengths in a modulated pump / CW probe configuration: it is found that 1310 nm excitation (the structure's absorption resonance wavelength for the solid phase of the gallium backplane) can change the metasurface reflectivity at 1550 nm by as much as 50% at intensities <17 μW/μm^2 – an order of magnitude lower than those required to induce a comparable response at the same temperature in a planar gallium/silicon nitride interface. Induced changes occur with sub-millisecond response and relaxation times, and achieve maximum magnitude at temperatures just below T_m.

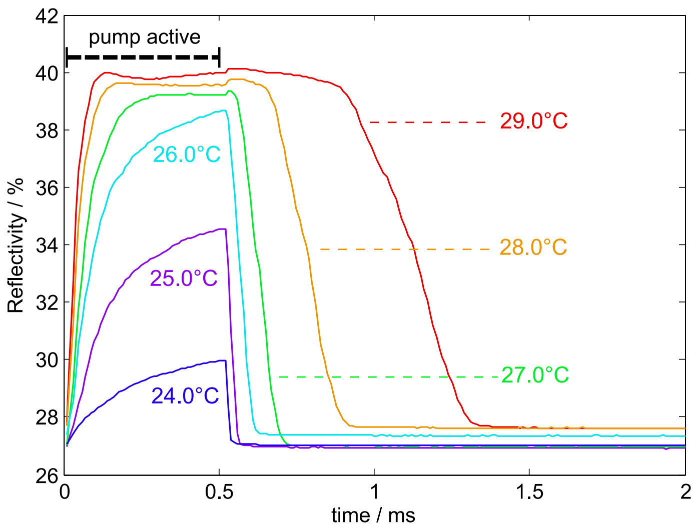

Fig. 2. Absolute reflectivity of the gallium metasurface of Fig. 1 probed at 1550 nm as a function of time during and after excitation with a 0.5 ms, 16.8 μW/μm^2 pump pulse at 1310 nm, for a selection of sample temperatures (as labelled) approaching the metal's bulk melting point.

III. Conclusion

The realisation of actively controllable, nonlinear and self-adaptive spectral response functions in ultrathin photonic metasurfaces offers potential for applications in fields ranging from radiation emitters and sensors to spatial light modulators. We have shown that gallium, as a functional medium undergoing optically-induced surface metallization at low light intensities, provides unique functionality for continuously tuning and switching the spectral response of such structures with a nonlinear figure of merit an order of magnitude larger than unstructured gallium/dielectric interfaces.

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