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# Tunable Mie-resonant dielectric metasurfaces based on VO<sub>2</sub> phase-change materials

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**Abstract:** We demonstrate Mie-resonant silicon metasurfaces tunable via the insulator-to-metal transition of a deposited VO<sub>2</sub> layer. We observe two orders of magnitude modulation depth of the metasurface reflection with reversible properties and a hysteresis-like behavior.

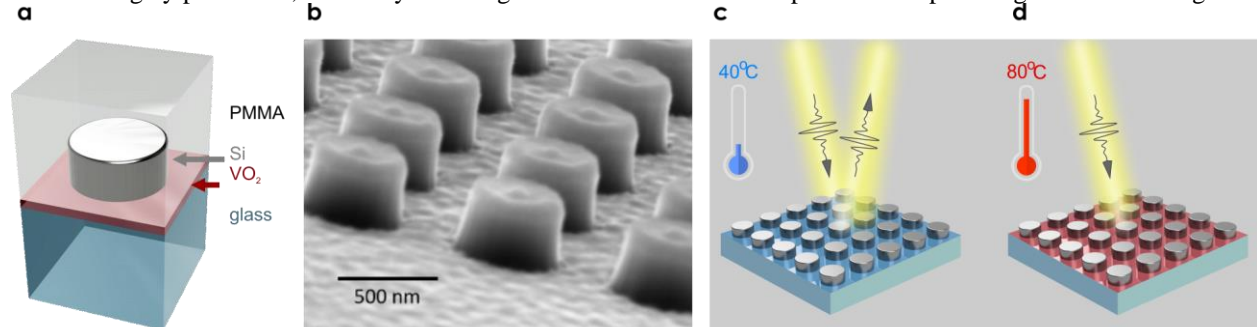
**OCIS codes:** (160.4236) Nanomaterials; (310.6628) Subwavelength structures, nanostructures; (220.4241) Nanostructure fabrication

## 1. Introduction

Metasurfaces have emerged as a flexible and efficient platform for manipulating electromagnetic waves. Although there has been a considerable progress in the development of plasmonic metasurfaces, some of their functionalities remain compromised by Ohmic losses and heating. More recent developments suggest an alternative way towards highly efficient metasurfaces based on Mie-resonant nanostructures made of high-index dielectric materials [1].

While static all-dielectric resonant metaphotonics is reaching maturity, big challenges remain in the design and fabrication of efficient reconfigurable and tunable structures [2] that are highly desirable for a number of applications in optical communications, information storage, imaging, detectors, and sensors. A promising pathway towards tunable metasurfaces is an incorporation of phase-change materials into the design. While substantial efforts have been made towards tunable nanophotonic devices made of metallic nanostructures coupled to various phase-change materials such as GeSbTe, VO<sub>2</sub>, etc. [2-4], all-dielectric tunable nanostructures remain largely unexplored.

In particular, VO<sub>2</sub> is an attractive phase-change material [5] and its tunability occurs at temperatures close to ambient (~68°C). The transition can be triggered thermally, optically, or electrically. Furthermore, the dynamical change of phase corresponds to a crystalline-to-crystalline transition and therefore not accompanied by catastrophic volume change, void creation, etc, enabling a hybrid integration of this material into complex nanostructures. Therefore, VO<sub>2</sub> is compatible with materials and/or technologies that cannot support high temperatures and high energy pulses needed to switch back and forth other phase-change materials such as GST. Nanofabrication of VO<sub>2</sub> remains largely premature, and its hybrid integration with dielectric nanophotonics imposes significant challenges.



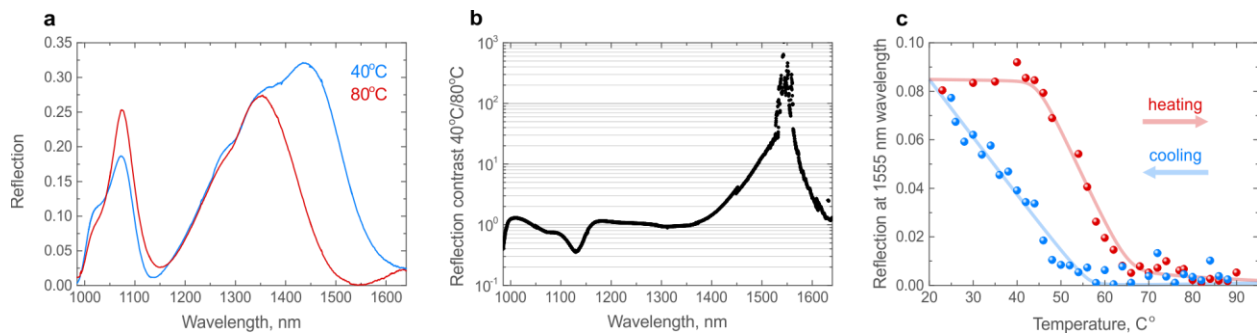
**Fig. 1.** (a) Design concept: a silicon meta-atom is embedded into glass/PMMA surrounding with a buried thin VO<sub>2</sub> layer. VO<sub>2</sub> thickness: 25 nm, Si disk height: 240 nm, disk radius: 270 nm, square lattice period: 800 nm, PMMA layer thickness: 400 nm. (b) Electron microscope image of the fabricated Si-VO<sub>2</sub> metasurface prior to the PMMA coating. (c-d) Functionality concept: (c) at low temperatures, the metasurface reflects light at a designed wavelength, and (d) at high temperature the light is absorbed by the metasurface.

Here we design, fabricate, and characterize a dielectric metasurface made of Si resonators coupled to a layer of VO<sub>2</sub> phase-change material, as presented in Figs. 1(a, b). The metasurface is designed to support both electric and magnetic Mie modes. The phase state of the VO<sub>2</sub> layer defines the interaction between an incident light and two resonant modes. Reversible tuning of VO<sub>2</sub> allows to approach a regime of coherent perfect absorption reducing metasurface reflection by more than two orders of magnitude (see a sketch in Figs. 1(c, d)). We perform numerical calculations of the metasurface in CST Microwave Studio with the parameters specified in the caption to Fig. 1.

## 2. Demonstration of reversible tuning of silicon metasurfaces via VO<sub>2</sub> phase change

To fabricate the metasurface, we start with a 25 nm thin VO<sub>2</sub> layer deposited on quartz by magnetron sputtering from a V<sub>2</sub>O<sub>5</sub> target under Ar/O<sub>2</sub> partial pressure. During the deposition, the substrate temperature is maintained at 750°C to crystallize the VO<sub>2</sub> layer during growth. We then deposit a 240 nm-thick layer of amorphous Silicon (a-Si) by plasma-enhanced chemical vapor deposition using SiH<sub>4</sub> precursor at a temperature of 300°C. Hydrogen Silsesquioxane (HSQ) resist is then spun on the sample and patterned using E-beam lithography. After development in TMAH, the HSQ resist is used as a hard mask to transfer the patterns into a-Si via ICP-RIE dry etching with Cl<sub>2</sub>/Ar. Finally, a 400-nm-thick layer of PMMA is spun on the sample. A small part of the sample is covered by a 200-nm-thick gold serving as a reference layer for the reflection measurements.

To measure optical properties and VO<sub>2</sub>-induced tunability of the metasurface, the sample is placed on a heat cell enabling  $\pm 0.1^\circ\text{C}$  temperature control. A broadband light source (halogen lamp) is focused on the devices through a 10x objective and the reflection from the metasurface is collected with the same objective. Reflected light is then dispersed in a spectrometer and detected with an InGaAs IR camera. The setup response is calibrated using a gold reference layer deposited on the sample. To measure the reversible tunability, the temperature is raised from 23°C to 90°C and back to room temperature. The heating-cooling cycle is repeated 10 times with no noticeable changes to the sample performance. A spectrum is collected every 2°C. In Fig. 2(a), we show two reflection spectra corresponding to insulator (40°C) and metal (80°C) phases of VO<sub>2</sub> layer. Fig. 2(b) emphasizes the experimentally observed reflection contrast between the two states. At a wavelength 1550 nm that corresponds to the fiber communication C-band, the modulation depth exceeds two orders of magnitude. Finally, in Fig. 2(c) we trace the reflection at 1550 nm and observe a hysteresis behavior of reflection versus temperature. In the region 30°C–70°C the metasurface reflection can be in one of the two states depending on the history of heating-cooling cycles.



**Fig. 2.** Experimental results on the tunable reflection of the Si-VO<sub>2</sub> metasurface. (a) Reflection spectra for two temperature points: 40°C (a dielectric phase of VO<sub>2</sub>) and 80°C (a metallic phase of VO<sub>2</sub>). (b) Reflection contrast between the two temperature points. (c) Reversible temperature tuning of the metasurface reflection at 1550 nm wavelength exhibiting a hysteresis-like behavior.

## 3. Conclusions and outlook

We have demonstrated, for the first time to our knowledge, the Mie-resonant silicon metasurfaces tunable by VO<sub>2</sub>. The reversible tuning of the VO<sub>2</sub> state introduces two-orders-of-magnitude modulation depth in the metasurface reflection. The metasurface optical response further features a hysteresis behavior thus possessing a non-volatile memory of its state. We believe our work uncovers a great potential of tunable dielectric metasurfaces for manipulating light in a rapid manner as the phase transition can be driven by fast light pulses. It paves the way to nanoscale optical switches, modulators, and sensors based on all-dielectric resonant metasurfaces.

## 4. Acknowledgements

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