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All-chalcogenide Phase-Change Plasmonics

B. Gholipour[1], A. Karvounis[1], J. Yin[2], C. Soci[2], K. F. MacDonald[1] and N. I. Zheludev[1, 2]

[1]Optoelectronics Research Centre and Centre for Photonic Metamaterials,
University of Southampton, Southampton, SO17 1BJ, UK
[2]Centre for Disruptive Photonic Technologies & The Photonics Institute,
Nanyang Technological University, Singapore 637371
bg305@orc.soton.ac.uk

***Abstract* – We demonstrate that chalcogenide phase-change media provide a uniquely reconfigurable platform for nanostructured photonic metamaterials, which can be reversibly switched in non-volatile fashion between plasmonic and non-plasmonic states. Amorphous germanium antimony telluride is a transparent dielectric, but in the crystalline phase it presents a negative value of ε_1 (real part of relative permittivity) and supports plasmonic resonances in the ultraviolet-visible spectral range.**

I. INTRODUCTION

Phase-change materials, including chalcogenides [1-3], vanadium dioxide [4, 5], gallium [6], and liquid crystals [7-9] have played a significant role in the evolution of active plasmonic and photonic metamaterial concepts – delivering a variety of switchable, tuneable, reconfigurable, and nonlinear optical functionalities through hybridisation (as active media) with plasmonic (noble metal) frameworks. It has further been demonstrated recently that chalcogenides can serve as a platform for both nanostructured and optically-rewritable *all-dielectric* metamaterials: Non-volatile, laser-induced phase transitions enable resonance switching in nanostructured chalcogenide meta-surfaces [10] and allow for reversible direct-writing of arbitrary meta-devices in chalcogenide thin films [11].

Here, we show that the chalcogenide alloy germanium antimony telluride (GST) – which has been widely used as the functional basis of rewritable optical disk and electronic phase-change RAM technologies over many decades – can be converted between amorphous and crystalline states that are respectively, at UV/VIS frequencies, dielectric and metallic (i.e. plasmonic). The amorphous-to-crystalline transition, which changes the sign of the real part of the material's relative permittivity (ε_1) from positive to negative (Fig. 1a), is an annealing process that may

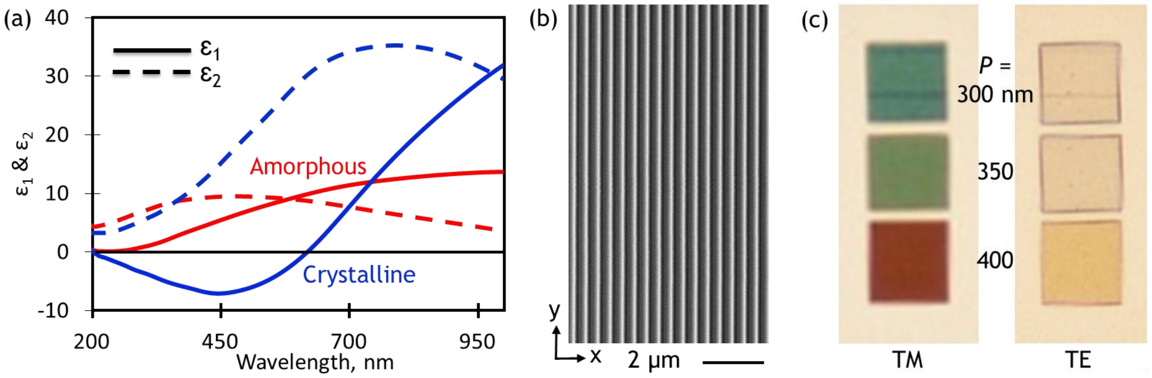

Fig. 1. (a) Spectral dispersion (from variable angle ellipsometric measurements) of the real and imaginary parts of the relative permittivity of a 500 nm thick germanium antimony telluride film in its amorphous and crystalline phases. (b). Scanning electron microscope image of a section of a GST nano-grating fabricated by focused ion beam milling. (c) Reflection optical microscopy images of crystalline phase GST nano-gratings [20 μm × 20 μm square domains surrounded by unstructured crystalline GST] of varying period [as labelled], for TM and TE polarized incident light.

be initiated by heating or by pulsed laser or electronic excitation, bringing the chalcogenide to a temperature above its glass-transition point T_g (around 160°C) but below its melting point T_m (600°C). The reverse transition – a melt-quenching process – can be driven by shorter, higher energy pulsed excitations that bring the material momentarily to a temperature above T_m.

II. METHODS, RESULTS AND DISCUSSION

Our work employs nanoscale thin films of the chalcogenide phase-change medium $Ge_2Sb_2Te_5$ (GST). 500 nm thick amorphous films deposited under high vacuum are structured by focused ion beam milling with non-diffracting, sub-wavelength grating metasurface patterns having periods in the 300-400 nm range (Fig. 1b). Unstructured, amorphous GST is a transparent absorbing dielectric at ultra-violet/visible wavelengths, with a reflectivity (of 15-30% in the present case) that is not substantially modified in this spectral range by the nano-grating structures. In stark contrast however, the crystalline phase has a negative value of ε_1 in the wavelength range from 200-615 nm and may thus support surface plasmon resonance modes that dramatically change the optical response of nanostructured surfaces.

This is illustrated by the vibrant colours produced in reflection imaging of the crystalline GST nano-gratings (Fig. 1c) under TM polarized light, which vary as a function of grating period. The spectral dispersion of normal-incidence reflectivity for a 300 nm period grating in amorphous (dielectric) and crystalline (plasmonic) phases is presented in Fig. 2. For incident light polarized perpendicular to the grating lines (along the *x* direction defined in Fig. 1b - the TM grating orientation) there is a significant change in this dispersion associated with the crystallization of the GST (Fig. 2a): The metallic crystalline phase presents a pronounced reflection resonance

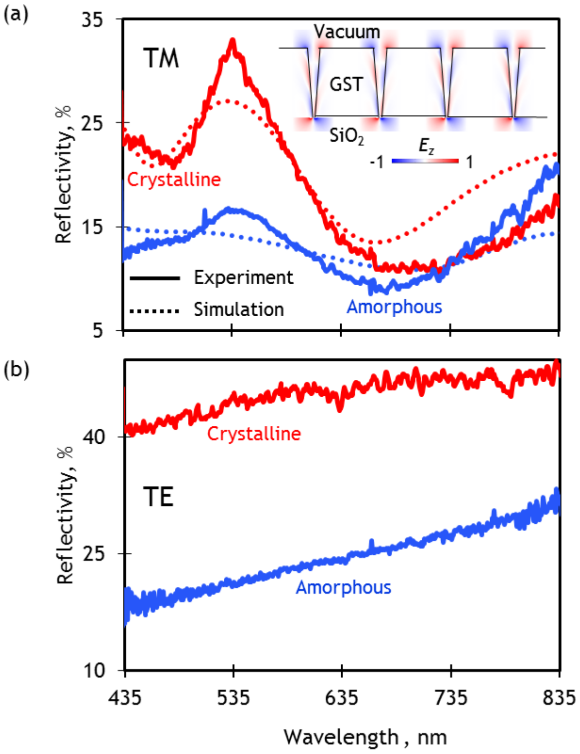

Fig. 2. Spectral dispersion of normal incidence reflectivity for a 300 nm period grating in a 500 nm thick GST film for (a) TM- and (b) TE-polarized light and for the amorphous and crystalline phases of GST [as labelled]. Dotted lines in (a) are numerically simulated TM spectra for the nanograting structure. The inset to (a) shows the numerically simulated distribution of the *z*-component of electric field in the *xz*-plane for the crystalline phase of GST at the 535 nm resonance wavelength.

centered at 535 nm, giving rise to the vivid green color shown in Fig. 1c. Finite element method simulations utilizing material parameters from Fig. 1a reproduce the experimentally observed reflection resonance at 535nm for TM-polarized light and reveal the nature of the plasmonic mode excited in the nanostructure at this wavelength (see field map inset to Fig. 2a). For TE-polarized light, no resonances are observed; the amorphous-crystalline transition produces only a broadband change in the level of reflectivity (Fig. 2b): In this orientation the nano-grating behaves as a linear medium with a non-dispersive effective refractive index related to that of the GST and its fill fraction within the grating structure.

III. CONCLUSION

We show that the chalcogenide phase-change medium, germanium antimony telluride (GST), can be switched in a non-volatile fashion between amorphous and crystalline phases of respectively dielectric ($\varepsilon_1>0$) and metallic ($\varepsilon_1<0$) character, enabling ultraviolet-visible plasmonic resonances in nanostructured GST to be switched on and off. As such it offers a uniquely flexible CMOS-compatible material platform, with compositionally tuneable as well as optically/electronically switchable properties, for active and reconfigurable metadevices.

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