COMMUNICATION

An All-Optical, Non-volatile, Bidirectional, Phase-Change Meta-Switch

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Today's telecommunications networks are still largely optically opaque – consisting of electronic nodes connected by point-to-point optical links, relying on a series of optical-electrical conversions. Moving to all-optical switching will allow increased bit rates and low latency movement of data, providing greater routing agility, reducing energy requirements and simplifying network structures. This promise, and indeed the fact that the fundamental capacity limits of existing infrastructure are being reached,[1] has sparked renewed interest in the extension of telecommunications bands to longer infrared wavelengths[2,3] (where lower intrinsic losses in fibre media are possible)[4] and intense efforts to develop techniques based on space-division multiplexing (in which many distinguishable data paths are established through the same fibre strand using either multiple cores or a multimode core) to substantially increase capacity. Future network architectures will require a new generation of highly integrated devices capable of functions such as all-optical switching and mode (de)multiplexing. We report here on the proof-of-principle demonstration of a non-volatile all-optical switch that combines the chalcogenide glass phase-change medium widely used in rewritable optical disks with nanostructured plasmonic metamaterials to yield a high-contrast, large area, reversible switching solution that may be optimised to function across a broad infrared band.

Metamaterials are artificial electromagnetic media with unusual and useful functionalities achieved by structuring on the sub-wavelength scale. Conceived originally as a paradigm for achieving extraordinary electromagnetic response parameters (e.g., negative refractive index, terahertz magnetism, giant chirality) in passive media, they have advanced rapidly in recent years to deliver active (switchable, tuneable, non-linear) photonic functionalities that may form the basis of future integrated "metadevices"[5] for such applications as optical data processing. Dynamic, controllable photonic metamaterial properties have been realized via mechanically reconfigurable nanostructures,[6–8] by harnessing the non-linear or superconducting properties of metamaterial frameworks,[9–12] and through the hybridization of metamaterials with functional materials including carbon nanotubes,[13] liquid crystals,[14,15] graphene,[16] and phase-change media.[17–19] Here, we show experimentally that bistable, optically-induced phase switching in germanium antimony telluride ($Ge_2Sb_2Te_5$ or "GST") – a member of the Te-based chalcogenide alloy family upon which all of today's rewritable optical disc and phase-change RAM technologies are based[20–22] – provides a platform for the engineering of non-volatile metamaterial transmission/reflection modulators (**Figure 1**) for near- to mid-infrared wavelengths with thicknesses down to $^1/_{27}$ of the operating wavelength and active domains as large as 2000 μm^2 switched by single nanosecond pulses.

In simple terms, the modulation of an optical signal requires that its amplitude or phase be substantially changed by a control-input-induced change in propagation loss or delay. Conventionally this is achieved by modulating the refractive index or absorption coefficient of a medium through which the signal passes. However, where device (propagation) lengths are measured in nanometers, as mandated by the integrated nanophotonics paradigm, which furthermore precludes the application of intrinsically large (>wavelength) resonator/interferometric arrangements, an exceptionally large relative change (of order unity) in the refractive index and/or absorption coefficient is required to deliver a significant single-pass change in signal amplitude or phase.[23]

Among naturally occurring media only metals such as gallium, which can undergo thermally, optically and electron-beam-induced transitions among structural states with radically differing optical properties, have been shown capable of delivering such changes.[24,25] Planar plasmonic metamaterials provide a robust and highly adaptable alternative by virtue of the fact that their resonant optical properties depend strongly on the near-field dielectric environment: small changes in the refractive index or absorption coefficient of an adjacent functional nanolayer can produce massive changes in the transmission and reflection characteristics of the hybrid structure. A variety of active photonic metamaterials responding to the application of heat, light, current, voltage, or electric/magnetic field have been demonstrated,[5–19] but the response of the metamaterial is almost invariably volatile (i.e., the "switched state" is maintained only while the control stimulus is present).

Driscoll et al. have demonstrated electrically controlled persistent frequency tuning of a gold split-ring resonator array metamaterial hybridized with a thin film of vanadium

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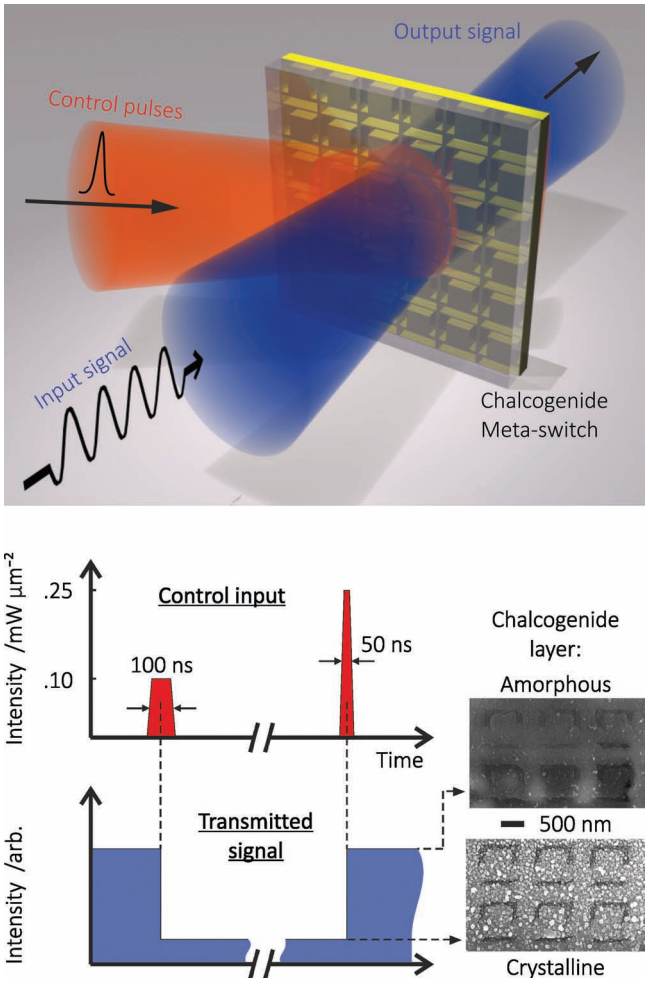

Figure 1. All-optical, non-volatile, chalcogenide glass metamaterial switch: single laser pulse control excitations homogenously convert a chalcogenide phase-change nanolayer, hybridized with a photonic metamaterial, back and forth between amorphous and crystalline states over areas encompassing up to 12 000 metamaterial unit cells (the electron microscopy images bottom right show 3 × 2 cell sections of an experimental sample with the overlying GST film in its amorphous and crystalline states). The device thus provides for high contrast transmission and reflection switching of signals at wavelengths close to the metamaterial resonance.

dioxide,[18] harnessing the well-known insulator-to-metal transition in VO_2. Frequency shifts induced by one-second current pulses were observed to persist for at least 20 min, but only while the system was held at an elevated temperature of ≈339 K (at which the VO_2 insulator-metal transition is hysteretic); the ground state being recoverable only by reducing this bias temperature to thermally reset the system. It has also been shown that the resonance shift brought about by an electrically initiated, non-volatile amorphous-to-crystalline transition in a chalcogenide (gallium lanthanum sulphide) hybrid metamaterial brings about a substantial change in near-infrared transmission – a 4:1 contrast ratio from a structure only one third of a wavelength thick.[19] However, the sample configuration in this case does not allow for concurrent input of optical probe and electrical control signals; nor does it readily provide for cyclical switching of the chalcogenide film.

In what follows, we demonstrate all-optical chalcogenide metamaterial modulators for near- to mid-infrared wavelengths, with a "controlled hysteretic" response function (akin to that of phase-change RAM) based on reversible optically induced amorphous-crystalline transitions in germanium antimony telluride. GST is a semiconducting chalcogenide alloy with a crystallization temperature T_c of ≈160 °C and a melting temperature T_m of ≈600 °C, which has been extensively proven as a platform for fast, robust, reproducible, non-volatile phase-switching.[20–22] Transitions can be optically driven in both directions:[26,27] the crystalline-to-amorphous transition being a melt-quenching process initiated by a short, high-intensity pulse sufficient to raise the local temperature momentarily above T_m; the amorphous-to-crystalline transition an annealing process requiring a longer, lower intensity pulse to hold the material above T_c for a short time.

In contrast to optical-data-storage applications, where the challenge is always to maximize the data density by minimizing the size of phase-switched domains, the limit being set by diffraction and thereby read/write wavelength (e.g., the Blu-ray minimum mark length is ≈150 nm), for planar meta-device applications one requires that transitions are initiated uniformly across large areas (tens of square micrometers and more) of chalcogenide thin film. We report here on GST hybrid metamaterial device structures (**Figure 2**) wherein domains of the chalcogenide film up to 50 μm in diameter are reversibly, homogeneously switched on by single 50–100 ns laser pulses at intensity levels ≤0.25 mW μm^{-2}, providing optical transmission/reflection contrast ratios of 4:1 at near- to mid-infrared operating wavelengths set by metamaterial design.

Our experiments employ planar metamaterials of a type that supports trapped-mode plasmonic excitations.[28–30] Weak coupling of the excitation mode to free-space radiation modes within such structures – arrays of asymmetric split ring slots in metal films, creates narrow reflection, transmission, and absorption resonances with asymmetric, Fano type dispersion (Figure 2c).

Figure 2a shows an exploded schematic of the experimental sample layer structure, which comprises (on fused quartz for near-infrared operating wavelengths; calcium fluoride for mid-IR):

- A metamaterial layer – a thermally evaporated gold film with a typical thickness of 50 nm and surface roughness of 2–3 nm, patterned by focused ion beam (FIB) milling, with 50 μm × 50 μm spare arrays of asymmetric split rings (with unit cell sizes of 400 and 900 nm for near- and mid-infrared devices respectively);
- A functional 15–40 nm film of GST sputtered under argon;
- An inert 10–30 nm buffer layer of ZnS/SiO_2 between the metamaterial and chalcogenide to prevent diffusion of gold into the chalcogenide;
- A 100 nm capping layer of ZnS/SiO_2 or pure SiO_2 on top of the GST to prevent degradation of the chalcogenide in air, especially at elevated phase transition temperatures (samples remain under vacuum throughout the process of buffer, chalcogenide and capping layer deposition.)

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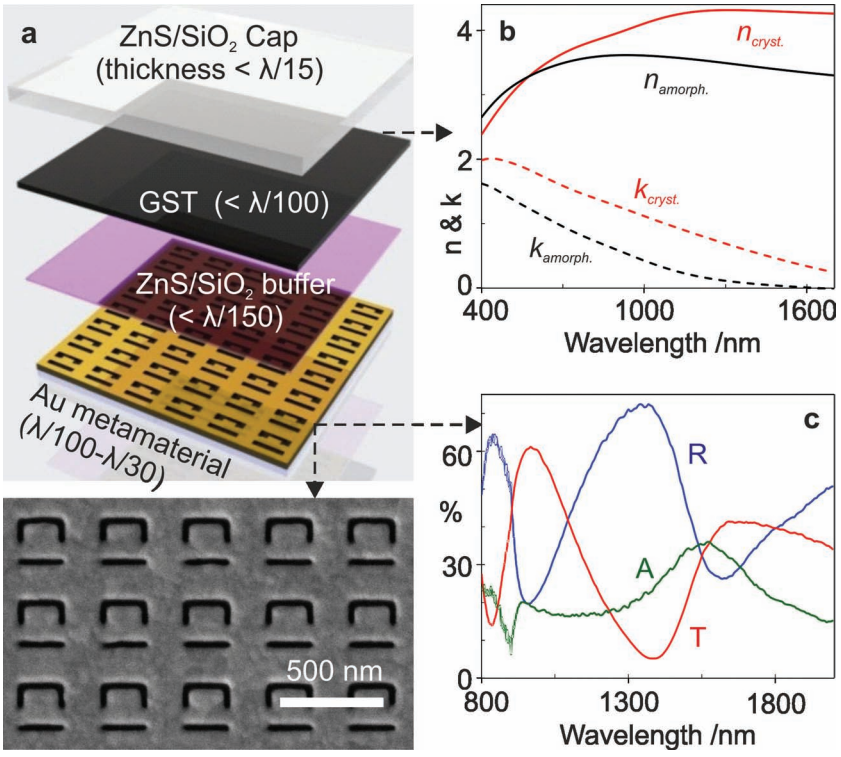

Figure 2. a) Multilayer structure of near- to mid-IR chalcogenide hybrid metamaterial switches (indicative thicknesses in brackets). The phase-change nanolayer of germanium antimony telluride (GST) and protective buffer and capping layers are sputtered onto planar photonic metamaterials manufactured by focused ion beam milling. b) Ellipsometrically measured vis–NIR index of refraction *n* and extinction coefficient *k* of the GST layer in its amorphous and crystalline states. c) Reflection, transmission and absorption spectra of a near-IR resonant metamaterial prior to application of the buffer, GST and capping layers (here, and in all subsequent metamaterial spectra, incident light is polarized perpendicular to the split in the ring resonators to ensure excitation of the trapped-mode resonance.)

The transmission, reflection and absorption characteristics of the chalcogenide modulators were quantified using a microspectrophotometer (CRAIC QDI2010) for meta-devices operating in the vis–NIR range and a Fourier transform IR spectrometer (Jasco FTIR-4000) for mid-IR devices.

Phase transitions were initiated homogenously across large (≈50 μm diameter) areas of the GST film in metamaterial hybrid devices by single-pulse laser excitation at a wavelength of 660 nm (selected for its strong absorption in GST). Control pulses were shaped using an Agilent 8110A pulse generator and optimized for peak intensity and duration separately for crystalline-to-amorphous and amorphous-to-crystalline switching directions, the former being achieved with pulses as short as 50 ns at a peak intensity of order 0.25 mW μm^{-2}; the latter with 100 ns pulses at 0.1 mW μm^{-2}.

The laser-induced phase transitions in the GST layer of the chalcogenide meta-device structures bring about dramatic changes in the spectral dispersion of their optical transmission and reflection characteristics as illustrated for a near-IR modulator in **Figure 3**: Figure 3b,c show amorphous and crystalline state reflection and transmission spectra respectively for a device with a metamaterial unit cell size of 400 nm and a total functional multilayer thickness of only 175 nm (≈$^1/_8$ of the operating wavelength). The increase in the real part of the GST refractive index associated with the amorphous-to-crystalline transition red-shifts resonant features by around 200 nm (the small increase in the imaginary part of the index being responsible for the observed broadening of features and the decrease in average reflection and transmission across the spectral range presented). As a result, the absolute reflection and transmission of the structure at certain wavelength bands changes by as much as a factor of four (Figure 3d) – a contrast ratio already more than adequate for short-reach (intra-/interchip) optical interconnect applications in data processing architectures, where ratios of only 2.5:1 (modulation depths as low as 4 dB) can be sufficient.[31] Higher contrast still may be achieved through the optimization of metamaterial design to maximize resonance quality factors and, within certain constraints (see below), by reducing buffer layer thickness.

This non-volatile, all-optical modulation functionality can be translated to any wavelength band within the transparency range chalcogenide phase-change layer by modifying the metamaterial design. **Figure 4**, for example, shows reflection and transmission contrast ratios, again approaching 4:1, in the 5–7 μm mid-IR range (900 nm metamaterial unit cell size) where the meta device thickness is only ≈$^1/_{27}$ of the operating wavelength.

The non-volatile reversibility of the optical switching functionality was verified through repeated cyclical operation of the meta-devices. In the proof-of-principle device architectures presented here, the functional GST layers typically endure ≈50 transition cycles (amorphous-to-crystalline and back) before showing signs of degradation. Device-failure mechanisms (likely to include inter-diffusion of layers during repeated melt/quench cycling as a result of material fatigue) require further investigation and it is anticipated that the optimization of all layer compositions and thicknesses will enhance device durability. The buffer layer is of particular importance as a balance must be struck between durability (improved by increasing thickness) and optical switching contrast (improved by decreasing thickness, that is to say, bringing the functional chalcogenide layer closer to the metamaterial). Here, the exploration of new material families to achieve buffer functionality that is more robust against repeated melt/quench cycling while maintaining, or even reducing thickness may lead to significant improvements in device performance and integrity.

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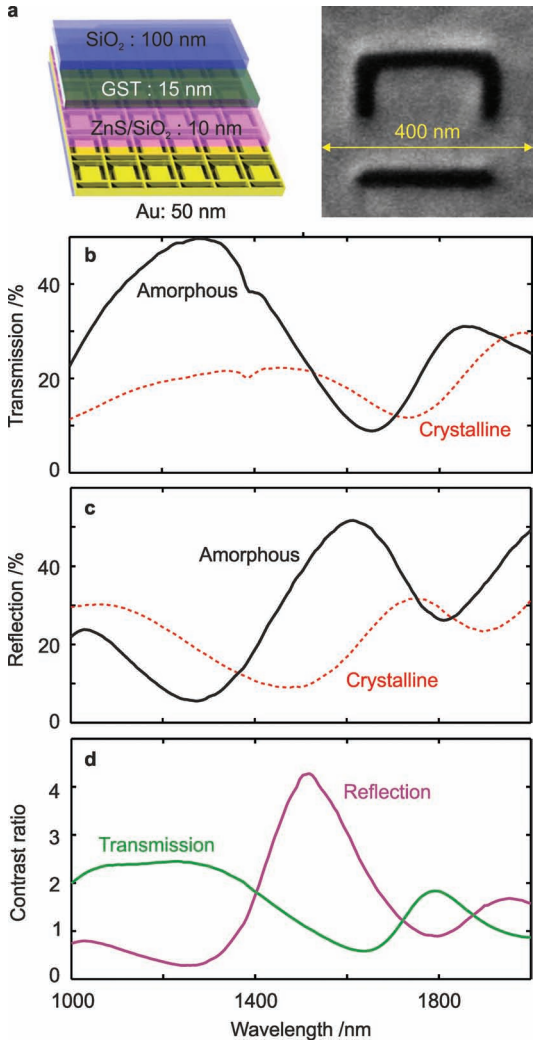

Figure 3. a) Structural details of a near-IR chalcogenide meta-switch layer thicknesses (left) and a scanning electron microscope image of a single 400 nm unit cell (right). b,c) spectral dispersion of the hybrid device structure's optical transmission and reflection for the amorphous and crystalline phases of the GST layer (as labeled). d) Spectral dispersion of transmission and reflection modulation contrast associated with chalcogenide phase switching in the meta-device.

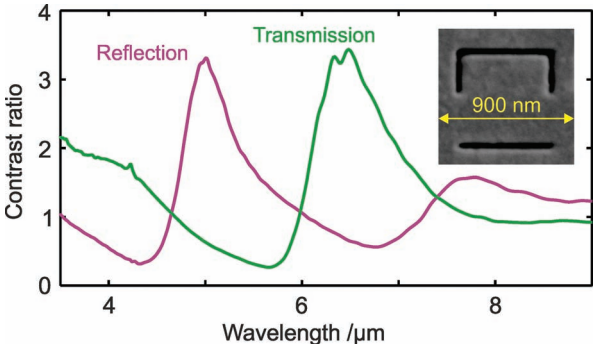

Figure 4. Transmission and reflection modulation contrast associated with GST phase-switching in a chalcogenide meta-switch engineered for mid-IR operation. A 900 nm metamaterial unit cell is shown in the scanning electron microscope image inset.

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