Electrical tuning of phase-change antennas and metasurfaces

Yifei Wang1, Patrick Landreman1, David Schoen1,2, Kye Okabe3, Ann Marshall1, Umberto Celano1,4,5, H.-S. Philip Wong3, Junghyun Park6 and Mark L. Brongersma1,6

The success of semiconductor electronics is built on the creation of compact, low-power switching elements that offer routing, logic and memory functions. The availability of nanoscale optical switches could have a similarly transformative impact on the development of dynamic and programmable metasurfaces, optical neural networks and quantum information processing. Phase-change materials are uniquely suited to enable their creation as they offer high-speed electrical switching between amorphous and crystalline states with notably different optical properties. Their high refractive index has already been harnessed to fashion them into compact optical antennas. Here, we take the next important step, by showing electrically-switchable phase-change antennas and metasurfaces that offer strong, reversible, non-volatile, multi-phase switching and spectral tuning of light scattering in the visible and near-infrared spectral ranges. Their successful implementation relies on a careful joint thermal and optical optimization of the antenna elements that comprise a silver strip that simultaneously serves as a plasmonic resonator and a miniature heating stage. Our metasurface affords electrical modulation of the reflectance by more than four-fold at 755 nm.

The development of metasurfaces for the passive manipulation of optical wavefronts has witnessed tremendous progress over the past decade1–5. The research focus is now shifting towards dynamic metasurfaces, which offer new applications and directions for explorative science as they are not bound by the same fundamental limits as static elements6–8. The creation of metasurface pixels that can dynamically alter their light-scattering behaviour not only requires the use of resonant structures to boost the light–matter interaction, but also the broad tunability of their resonant behaviour. Effective ways of manipulating resonances apply mechanical motion5–9, electrical gating to modify carrier concentrations10–14 or to induce the Stark effect5, electrochemistry15–19, liquid crystals20–22 and phase-change materials23–31. Materials exhibiting structural phase transitions between crystalline and amorphous states show particular promise as they offer non-volatile switching. Metasurfaces with non-volatile pixels could afford convenient programming of the desired functions and a reduced power consumption since pixels remain in the desired state after any external stimulus is removed. Reducing power consumption in dynamic metasurfaces with nanoscale pixel-arrays is shaping up as one of the key challenges moving forwards as it will rival those of densely-integrated electronic circuitry. This line of work complements research on metasurfaces based on materials showing volatile phase changes such as VO2 that can also find use in the dynamic modulation of optical wavefronts16,31.

In this work we employ germanium antimony telluride (GST), which is one of the most well-established phase-change materials based on its use in optical storage media (for example, in compact discs) and non-volatile electronic memories32. GST brings many desirable properties, including unity-order changes in the permittivity across a broad spectrum, retention times exceeding ten years, robust switching over 109 cycles, and short programming times of ~100 ns (refs. 24,32–34). To appreciate the challenges in creating electrically-programmable GST antennas and metasurfaces, it is of value to study previous works on the electronic and optical switching of this material. The crystallization of GST from the amorphous state can be achieved by simply heating it up to its crystallization temperature35,36. The reverse transformation back into the amorphous state is more challenging. This requires a rapid melt-quenching process with cooling rates exceeding 109 K s–1 (refs. 36,37). This was first accomplished with focused, short laser pulses as the heating source37,38. Laser-heating is widely used in optical disc technology and recently facilitated demonstrations of a variety of optically-reconfigurable photonic elements39–42, including plasmonic39–42 and Mie-resonant antennas43, waveguide-based modulators44 and metasurfaces for beamsteering45, lensing46, perfect absorption47, displays48 and holographic elements49. The reversible electrical switching of photonic structures has proven to be more challenging. Electrically controlled thermal cycling is well established for switching ultracompact, 10-nm-scale GST memory cells50. Researchers have found that this approach can produce highly conductive, crystalline filaments in amorphous GST25,49 and recently it has been successfully implemented for GST in ultrasmall plasmonic gaps to modulate waveguide transmission48. However, optical antennas are notably larger than memory cells (~100 nm) and their tuning remains challenging as it requires a controlled phase change throughout their entire volume. This is hard to achieve as the comparatively low surface-to-volume ratio of these larger photonic structures tends to result in a slow cooling process that prevents an effective quench34. Nonetheless, switching of large-area, thin layers of GST has recently been achieved through the use of micro-heater stages41–43. This has enabled a new class of mixed-mode electronic–photonic devices that are capable of seamlessly interconverting electrical and optical signals in waveguide devices43,50, as well as
in meta-absorbers by shaping micro-heaters into plasmonic structures\(^5\). In this work, we carefully co-optimize metallic heaters and adjacent GST nanobeams into electrically-switchable and strongly scattering plasmonic antennas. To achieve robust and reversible electrical tuning of such phase-change antennas requires a thoughtful co-optimization of their electrical, thermal and optical properties. In addition, we use the insights acquired in realizing dynamic phase-change antennas to produce tunable metasurfaces.

**An electrically tunable phase-change antenna**

We first demonstrate the possibility of electrically tuning the scattering properties of phase-change antennas. Figure 1a schematically illustrates one of our antenna designs with a 60-nm-wide and 25-nm-thick GST nanobeam stacked on top of a 140-nm-wide and 36-nm-thick silver nanostrip. The basic idea is that the silver strip will deliver a plasmonic antenna function and the GST beam will bring dynamic switching functions. These two elements are electrically separated from each other by a 6-nm-thick layer of Al\(_2\)O\(_3\) and are connected to two sets of electrodes at both ends. The entire device sits on a 120-nm-thick SiO\(_2\) layer on a silicon substrate, whose approximately quarter-wavelength thickness was chosen to enhance the optical excitation of and collection from the antenna in the near-infrared. It was finally covered by a 20-nm-thick Al\(_2\)O\(_3\) capping layer to protect it from oxidation. This design offers several desirable optical, electrical and thermal properties that facilitate the effective tuning of the light scattering. To perform accurate optical simulations, the optical properties of our GST material are first measured using ellipsometry (Supplementary Note 1). Our simulations show that under dark-field illumination with light polarized in the transverse magnetic (TM) direction (with the \(\mathbf{H}\) field directed along the length of the nanobeam) at 800 nm, surface plasmon polaritons (SPPs) are excited at the interface between GST and silver (Fig. 1b). The fields are largely confined to the volume of the GST beam. This is consistent with a physical picture where excited SPPs resonate by oscillating back and forth inside the GST beam, reflecting from its side walls\(^5\). For this reason, the width of the GST beam critically controls the resonance wavelength and narrower (wider) beams can be chosen to shift the resonance to the blue (red). Good modal overlap of the SPP mode with the switching medium ensures the effective tuning of the resonant scattering properties upon a phase change.

Figure 1c shows the resonant scattering behaviour for the cases where the GST is in the amorphous (a-GST) and crystalline (c-GST) phase. The long wavelength resonance corresponds to the...
fundamental dipole resonance with one antinode in the magnetic field above the silver strip; the short wavelength resonance corresponds to a resonance with three antinodes (Supplementary Fig. 3). Both resonances exhibit clear redshifts as the phase is transformed from amorphous to crystalline due to an increase of the imaginary part of GST permittivity. In this work we will mainly focus on the stronger, fundamental resonance. The scattering cross-section reduces upon switching from a-GST to c-GST due to the higher material loss in the crystalline phase at longer wavelengths.

The changes in the scattering cross-section can be directly observed in dark-field microscopy under white-light illumination. Figure 1d shows a scanning electron microscopy (SEM) image of the antenna and pads that electrically connect the GST beam and the silver strip. The optical images taken from the antenna before and after amorphization show clear differences in the scattered light intensity (Fig. 1c). Both antennas show a more or less constant scattering intensity along the length of the beams, as expected for well-fabricated antennas.

A structural analysis of the antennas before and after switching further confirms our ability to reversibly switch the GST material between the crystalline and amorphous phases. Using a focused ion beam lift-out technique, we prepared antennas for electron microscopy analysis. Transmission electron microscopy (TEM) cross-sectional imaging (see Fig. 1f) shows that the structure was successfully fabricated with the intended geometry and dimensions. High-resolution TEM images of the GST nanobeams after a reset pulse display no lattice fringes, consistent with an amorphous phase, while GST after a set pulse shows lattice fringes with a spacing that is consistent with the crystalline phase. More details on the sample preparation and measurement analysis are discussed in Supplementary Note 4.

The silver strip also performs important electrical and thermal functions. By running a current through the beam, it can serve as a miniature hot-plate that is capable of heating the GST beam that sits on top. Two kinds of current pulses with different temporal profiles are sent through the silver strips. Set pulses of a 1 μs duration and with a 20 μs trailing time are used to heat the GST above the crystallization temperature (T_c) and then maintain the high temperature long enough to facilitate complete crystallization. Reset pulses feature a higher current for a shorter duration of 500 ns to rapidly raise the local temperature above the melting temperature of GST (T_melt ≈600 °C). The pulse is then switched off quickly with a 20 ns trailing time to achieve an effective melt-quench that freezes in the amorphous phase. The key challenge towards realizing reversible switching is achieving a sufficiently fast cooling rate to prevent recrystallization as the GST cools. From the literature it has been established that for our thermal cycle, typical crystallization times are around 80 ns (ref. 15). We find that it is beneficial to have a silver strip that is wider than the GST beam to ensure excellent heat dissipation to the substrate. A thermal simulation (Methods) of the device shows that a reset pulse with a 100 ns rise time can effectively heat the GST beam to above T_melt in about 200 ns (Fig. 2a). At the end of the pulse, the current drops with a 20 ns trailing time and this allows the GST to cool to a temperature below 120 °C (below T_c ≈160 °C) in less than 50 ns (Fig. 2b). Our two-dimensional (2D) simulations assume that the antenna is infinitely long, which is justified for our 10-μm-long and 140-nm-wide antennas (Fig. 1d).

We further analyse the GST switching behaviour by monitoring the resistance of the GST nanobeam after sending every reset and set pulse (see Fig. 2c). The resistance after each reset pulse is seen to increase consistently by at least an order of magnitude and the opposite occurs after each set pulse. This confirms that we can achieve robust, reversible switching between the a-GST and c-GST phases. The slight variations in the resistance may indicate not fully completed transformations. In addition, we performed conductive atomic force microscopy to demonstrate that the phase transition happens along the entire length of the GST nanobeam (Supplementary Note 5).

Scattering spectra from the antenna are taken after each current pulse (Fig. 3a). The measured spectra show broad resonances that peak just above 700 nm. They qualitatively match the simulated spectra of the total scattering cross-section in Fig. 1c. A notable 30% modulation in intensity is observed on resonance. The spectra for the amorphous and crystalline phases show good consistency over many cycles. The simulated spectra in Fig. 3b show good agreement when we take into account that in our experiments we only collect back-scattered light through a ×50 objective with a numerical aperture (NA) of 0.6. The spectra that are simulated assuming complete amorphization and crystallization indicate a possible signal modulation exceeding 50%. An antenna with different volume fractions of amorphous material is also simulated, assuming that the top part of the antenna is in the crystalline phase. We find that the spectra continuously morph from the crystalline spectrum to the amorphous spectrum as the volume fraction is increased. The measured spectra
after the reset pulses in Fig. 3a agree best with simulations assum-
ing a high (~75%) volume fraction of a-GST. It could be that the
GST antenna does not return to the completely amorphized state
after reset pulses and part of the GST material may have recrystal-
lized during the quenching process. We confirmed that GST can
indeed be switched completely to the crystalline state by sending set
pulses with a higher current. In that case, no further decrease of the
back-scattered signal is observed after multiple set pulses.

We also use a charge-coupled device (CCD) camera to image the
antenna in real time as we are sending switching pulses (see Fig. 1e).
We integrate the intensity over the antenna area to plot the scattered
intensity against time as different set and reset pulses are delivered
to the antenna (Fig. 3c). The collected signal shows changes of 30%
for more than 100 cycles, as shown in Supplementary Fig. 11.

While the reset pulses quench the GST quickly in the above
experiments, we can increase the trailing time to induce slower
cooling and allow the GST to crystallize fully. By varying the tempo-
rnal shape of the pulses, we can control the degree of crystallization
and achieve multi-level operation (Supplementary Fig. 12).

**An electrically tunable phase-change metasurface**

After we demonstrated the repeatable switching of a single
antenna, we moved on to explore whether or not more complex
metasurfaces can be created comprised of multiple antennas.
Figure 4a shows a schematic of a metasurface designed to operate
as a perfect absorber in the crystalline phase. Here, 85-nm-wide
and 35-nm-thick GST nanobeams are placed in an array with a
period of 200 nm on top of a 60-nm-thick silver strip. The silver
strip is chosen to be thick enough to prevent any light transmis-
sion. We again use a thin (6 nm) layer of Al₂O₃ as a spacer and
a 50-nm-thick Al₂O₃ capping layer was deposited to protect the
device. In Fig. 4b (left), we show a finite-difference time-domain
(FDTD) simulation of the metasurface with c-GST beams under
TM-polarized illumination at normal incidence. We first show
the field distribution at the wavelength of 730 nm, where SPPs
are excited on the silver surface and inside the GST beams. The
high fields result in substantial dissipation inside the beams caus-
ing almost perfect absorption. This is confirmed by the overlaid
flowlines of the Poynting vector that show efficient funnelling of
an incident plane wave into the lossy GST beams. The ability to
achieve perfect absorption can be understood by comparing the
scattered fields from a sample with just the silver strip and one with
the GST beams on top of the strip in Fig. 4b (right). They are seen
to be perfectly out of phase and of equal amplitude. This indicates
that the non-resonant path (reflection from the silver strip) and
the resonant path (storing energy in the resonant antenna modes)
can destructively interfere and prevent an outgoing/reflected wave.
After switching to a-GST, the metasurface reflects 30% of the light
at 730 nm and the absolute modulation of the reflectance increases
at longer wavelengths (Fig. 4c).

To verify the simulations, we measure reflection spectra from the
metasurface at normal incidence. When the beams are in the
crystalline phase the lowest reflectance of 4.3% is achieved at the
wavelength of 700 nm, which is consistent with the simulations.
After a reset pulse, the reflected light intensity at this wavelength
increases to 14.5%, a more than threefold change. The non-zero
reflectance for c-GST is attributed to the small variations in the
nanobeam dimensions that disturb the delicate, destructive inter-
fERENCE condition. The highest modulation in the reflectance of a
factor 4.5 is achieved at a wavelength of 755 nm (Fig. 4d). We also
collect the reflected light with a CCD camera after passing through
a band-pass filter centred at 690 nm, with a full width half max-
imum of 10 nm. In Fig. 4c, the reflected signal is modulated up and
down with preset and set pulses respectively, showing a good consis-
tency with repeated cycling.

The electrically tunable optical antennas demonstrated in this
work can serve as meta-atoms to construct large-scale dynamic
metasurfaces in which each pixel can be individually accessed, akin to what recently has been demonstrated for indium tin oxide-based metasurfaces (see Supplementary Note 2 for details). Based on the times required to set and reset the antennas, we can achieve devices operating in the 10 kHz range. As phase-change memory applications employing GST use programming pulses in the range of 10–100 ns routinely, even faster operation on the 500 ps level has also been demonstrated. We expect a comparable ultimate limit for the operation speed for our proposed devices with further improved and compact antenna designs.

**Conclusion**

In conclusion, we have demonstrated a method for realizing elec-
trical, non-volatile and reversible switching of phase-change anten-
as and metasurface devices based on a chalcogenide phase-change
material. A design was created in which silver nanostraps can con-
vieniently function as a nano-heater and enable plasmonic antenna
functions. We show that an optical antenna that offers strong scat-
tering in the visible and near-infrared spectral ranges and substan-
tial (30%) electrical modulation of the scattered light intensity.
Utilizing destructive interference between two pathways, a meta-
surface is also demonstrated, with an electrical modulation of the
reflectance by more than fourfold. This work opens the opportunity
Fig. 4 | An electrically tunable phase-change metasurface. a, A schematic of the proposed metasurface is shown on the right, with a dense GST nanobeam-array placed on an optically thick silver strip. Reset and set pulses are sent through the silver strip to heat the metasurface and reversibly transform it between a-GST and c-GST phases. The top left inset is an SEM image of a device. The bottom left inset is a false-coloured SEM image of the GST array, where the red regions highlight the GST nanobeams. b, FDTD simulation (left) of the metasurface with c-GST at normal incidence and with TM-polarized light at a wavelength of 730 nm. The first figure plots the total field. The rightmost images show the scattered field for the silver strip by itself and for the case where the GST nanobeams are added, displaying a π phase difference. c, Simulated spectra of the reflectance and transmittance of the metasurface with a-GST and c-GST beams. The ratio of the reflectance for the a-GST and c-GST states is shown by the dotted black curve. d, Measured spectra of the reflectance of the metasurface taken after a reset and set pulse. The on/off ratio of the reflectance (reset/set) is also shown as the black dotted curve, with a maximum ratio of 4.5 at the wavelength of 755 nm. The full width half maximum of the band-pass filter used to obtain the spectra is shown in e.

We note that a relevant paper has been peer-reviewed at the same time as this work.1

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Methods

Device fabrication. The optical antennas and metasurface devices are fabricated following many of the same, initial fabrication steps. First, a 120-nm-thick layer of SiO₂ is grown by thermally oxidizing a silicon substrate. Alignment markers and contact pads are subsequently defined on the substrates by photolithography. We then use electron-beam evaporation to first deposit a 5-nm-thick titanium adhesion layer, followed by a 45-nm-thick gold layer and a lift-off in acetone.

The next steps to fabricate the optical antennas involve electron-beam (e-beam) lithography to define the silver strips, followed by e-beam evaporation of a 4-nm-thick titanium adhesion layer and a 36-nm-thick gold layer and ultimately a lift-off. We then deposit an Al₂O₃ layer with a thickness of 6 nm by atomic layer deposition (ALD). Another set of contact pads are defined by photolithography, designed to connect the GST beams. A 5-nm-thick titanium adhesion layer and a 45-nm-thick gold layer are then deposited by e-beam evaporation. For the next layer, we use e-beam lithography to define the pattern, then use direct current magnetron sputtering to deposit the GST from a Ce₅S₇Te₅ (GST-326) target, to achieve 24-nm-thick GST nanobeams. As the last step, a protective Al₂O₃ capping layer with a thickness of around 20 nm is deposited by ALD (thinner on top of GST at 13 nm).

The next steps to fabricate active metasurfaces involve e-beam lithography to define the silver strips and the deposition of a 6-nm-thick titanium adhesion layer and a 54-nm-thick gold layer. We then deposit a 6-nm-thick Al₂O₃ layer by ALD. Electron-beam lithography is used to define the GST patterns, followed by direct current magnetron sputtering of GST-326, producing 34-nm-thick GST nanobeam-arrays. An Al₂O₃ capping layer with a thickness of around 50 nm is deposited by ALD.

Finite-difference time-domain simulations. Optical simulations are carried out with the FDTD method (FDTD Simulations, Lumerical). Two-dimensional simulations of the single optical antennas are performed with perfectly matched layer boundary conditions. While a single-wavelength TFSF, or total-field scattered-field, source is used to study the impact of an inclined illumination at 46°, we sweep the wavelength with a fixed angle of incidence to obtain the spectrum across a broad wavelength range. Monitors are placed around the device, outside of the TFSF source region to calculate the far-field profile of the electromagnetic field at each wavelength. We then integrate the field intensity within a solid angle, corresponding to an NA of 0.6. To simulate the experimental condition further, we measure the collection efficiency of the objective used in the experiments (Nikon T×U Plan ×50/0.60) at each wavelength. This allows us to correct for the instrument response. Two-dimensional simulations of the metasurface are performed using periodic boundary conditions. The performed 2D simulations treat the antennas as infinitely long, which is expected to provide a good prediction of the measurements of our fabricated devices whose length is 10 μm and thus considerably longer than the illumination wavelengths of interest in the visible spectral range.

Finite element method simulation. We also performed 2D thermal simulations using a finite element method (COMSOL Multiphysics). They are implemented for a 10 × 10 μm region, with the boundary set at room temperature. The thermal model is discussed in more detail in Supplementary Note 2.

Electrical characterization. A semiconductor device parameter analyser is used for electrical characterization, including a pulse generator which sends electrical pulses through silver strips to induce phase transition and measurement units to monitor the resistance of both silver and GST strips. Please refer to Supplementary Note 3 for more details.

In situ optical measurements. We measure the dark-field scattering spectra of the antennas and the bright-field reflection of the metasurfaces using a Nikon C2 confocal microscope. A halogen lamp is used as the illumination source. After being collected using a ×50 objective (Nikon T×U Plan ×50/0.60), the scattered light from devices is polarized in the TM direction with respect to the devices and is subsequently sent into either of two paths. In the first path, a Nikon DS-Fil camera is used to capture images and videos. Alternatively in a second path, a confocal scanner spatially selects the scattered light from the devices and sends it to a Princeton Instruments SpectraPro 2301i spectrometer (150 lines mm⁻¹, blazed for λ = 500 nm) and a Pixis Si CCD camera (~70°C detector temperature) to analyse the spectrum. The antennas are measured under dark-field illumination at a 46° incident angle. The scattered light is collected through a 30-μm-diameter pinhole in the confocal scanner, before analysis by the spectrometer. The measured spectra are normalized to the scattered spectrum of a Lambertian reflector ( Labsphere Spectralon 99%) measured under the same conditions. The metasurface devices are measured under normal-incidence illumination, with an aperture stop closed to ensure a minimal beam divergence. The measured spectra are normalized to the reflection spectrum of a silver mirror (Thorlabs PF-10–03–P01). While under the microscope for in situ optical measurement, the devices are connected to a semiconductor analyser by probe tips to perform electrical switching.

Transmission electron microscopy and sample preparation. Transmission electron microscopy was used to analyse the structural phase and physical dimensions of the devices. Details can be found in Supplementary Note 4.

Conductive atomic force microscopy. Please see the discussion in Supplementary Note 5.

Data availability

The data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request.

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Author contributions

Y.W., P.L., J.P and M.L.B. conceived the ideas for this research project. Y.W. fabricated the devices, performed optical simulations and implemented optical microscopy measurements. D.S. and A.M. prepared the sample and carried out TEM measurements. Y.W. conducted thermal simulations and electrical measurements with the help of K.O. and H.-S.P.W. Conductive atomic force microscopy measurements were performed by Y.W. and U.C. All authors contributed to the writing of the manuscript.

Competing interests

Y.W., M.L.B. and J.P. are inventors on the US patent provisional application (63/064,687) held and submitted by Samsung Electronics that covers the use of electrically tunable phase-change antennas in metasurfaces for dynamic wavefront control.

Additional information

Supplementary information The online version contains supplementary material available at https://10.1038/s41565-021-00882-8.

Correspondence and requests for materials should be addressed to M.L.B.

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