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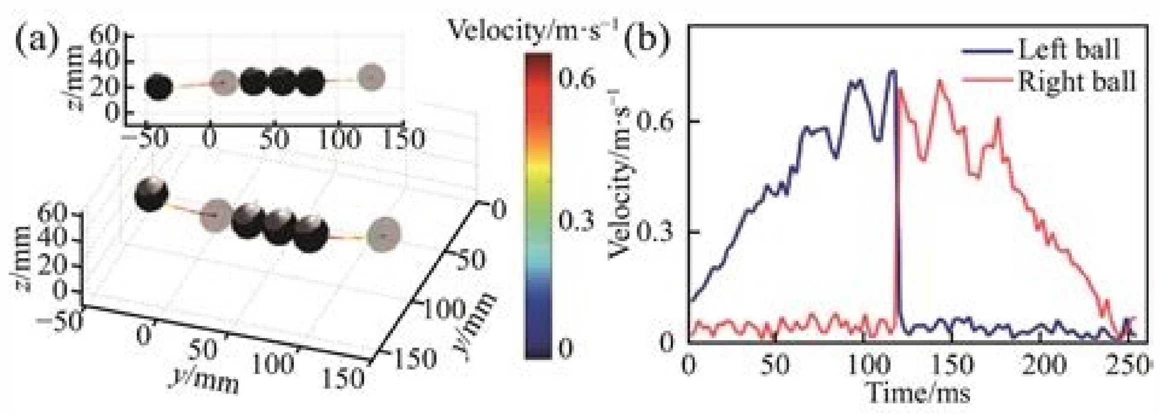

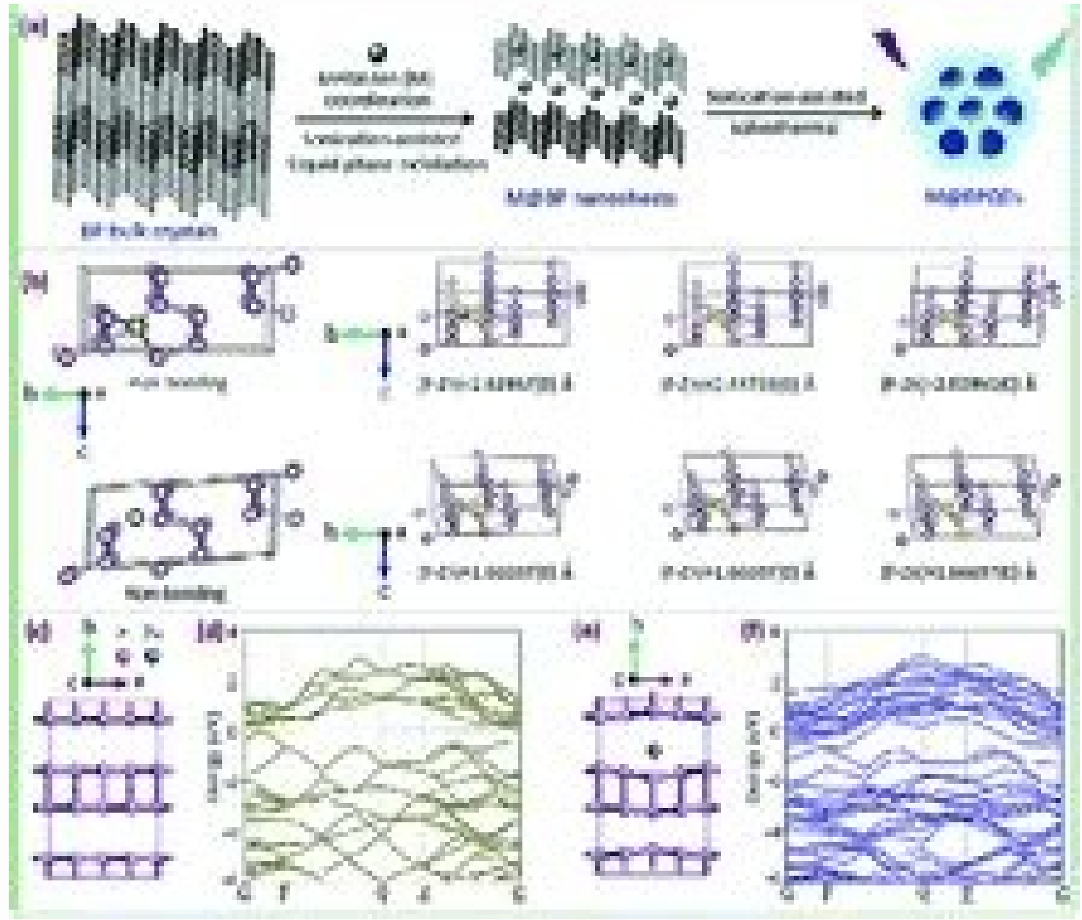

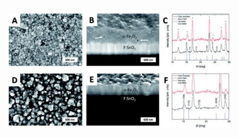

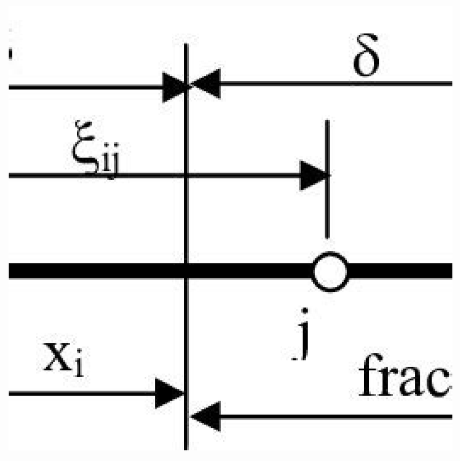


STABILITY AND ELECTRONIC PROPERTIES OF LOW-DIMENSIONAL NANOSTRUCTURES

by

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This allows us to fairly decrease the thickness of the PCM layer without compromising the optical performance. S6a represent the normally incident light coupled to (i, j) = (1, 0) LR-SPP mode of the phase-change metasurface. It then optimizes these two similarity measures based on a predefined cost function. S6b display that, for all three phases of GST, variation of dAu negligibly affects the location of the resonance dip, as predicted by Eq. 1, which ascertains the existence of the LR-SPP mode in the lower wavelengths.Along with the LR-SPP mode, when the phase-change metasurface is illuminated by an x-polarized beam, the nanodisk, and subjacent layers can be modeled as a Fabry–Pérot resonator supporting the SR-SPP mode with a resonantly enhanced field at the interface of the Au nanodisk and the top Al2O3 layer. M. To corroborate the design strategy, the statistical distribution of experimentally measured reflectance spectra over 50 consecutive cycles of crystallization-amorphization is displayed in Fig. 2c (see Supplementary Fig. The application of a thin PCM layer is necessary for the realization of a repeatable and reliable amorphization process while avoiding elemental segregation as a typical failure mechanism of PCMs during melt-quenching19,21. Another grand challenge is the realization of sufficiently fast cooling rate of PCMs in the amorphization process. Evidently, a pronounced tuning range is achieved upon multi-state conversion of GST using electrical pulses with small voltages. In addition, our architecture significantly reduces the deformation of the meta-atoms caused by inevitable heating of the alternative resistive microheaters33 that use plasmonic materials like silver with low melting temperature. 8, 1 (2017).ADS Google Scholar Kamali, S. 6, 1 (2015). A scanning electron microscope (SEM) image of the heterostructure metadevice and a bird's-eye view of the metasurface consisting of an array of 17 × 17 identical meta-atoms are depicted in Fig. 2a(ii) and a(iii), respectively. First, the heterostructure metadevice platform formed by the integration of a robust microheater underneath the metasurface enables uniform electrothermal phase conversion without adding excessive dissipative loss to the optical device. Google Scholar Maaten, L. Nanoelectronic programmable synapses based on phase change materials for brain-inspired computing. Alù acknowledges support from Air Force Office of Scientific Research and the Simons Foundation. Light: Science & Applications (2022) By submitting a comment you agree to abide by our Terms and Community Guidelines. White dashed lines in Supplementary Fig. Third, we use technologically mature GST that provides highest index contrast among all PCMs at the near-infrared (near-IR) spectral range. For the full crystallization of the GST film in the meta-deflector, we apply a a 10.5 V set pulse with 200 µs-long double exponential waveform to the Au pads connected to the microheater.In situ optical measurementsExperimental optical measurements is performed by directly measuring the intensity of the reflected light from the surface of the fabricated device installed on a xyz-translation stage (see Fig. 2b). Nonvolatile programmable silicon photonics using an ultralow-loss sb2se3 phase change material. By fully converting the state of GST using electrical Joule heating, a significant index contrast can be observed (see Supplementary Fig. 10, 396 (2019).ADS PubMed PubMed Central Google Scholar Abdollahramezani, S. To verify the material state of GST, we benefit from confocal Raman microscopy to study the Raman scattering of the A-GST/C-GST film after applying set/reset pulses. & Faraon, A. Relevant data supporting the key findings of this study are available within the article and the Supplementary Information file. Data visualization by nonlinear dimensionality reduction. Res. Reaching 80% optical efficiency, our platform outperforms the recently developed reflector-absorber PCM-switches32,33. 27, 4597 (2015).CAS PubMed Google Scholar Leitis, A. Tunable mid-infrared phase-change metasurface. The field profiles in the x–z cross section of a meta-atom in Fig. 3c show excitation of the SR-SPP mode and LR-SPP mode for λ1 = 1407 nm and λ2 = 1600 nm, respectively. Science 343, 160 (2014).ADS MathSciNet CAS PubMed MATH Google Scholar Huang, Y.-W. A switchable mid-infrared plasmonic perfect absorber with multispectral thermal imaging capability. et al. To enable the benefits of ranking the importance of design parameters in achieving the maximum modulation depth at 1550 nm (with 10% bandwidth) upon switching from A-GST to C-GST, we employ a feature-selection algorithm, namely the wrapper method43. Mems-tunable dielectric metasurface lens. An introduction to variable and feature selection. Rev.: Data Min. Such a highly confined mode is excited in virtue of constructive interference of propagating waves between the two lateral end-faces of the nanodisk. Optical metasurfaces, planar devices comprising densely arranged arrays of patterned nanostructures, extend most functionalities realized by conventional bulky optical components by imparting arbitrary spatial and spectral transformations on incident light waves1,2,3. Light.: Sci. L. Light propagation with phase discontinuities: generalized laws of reflection and refraction. 5, 51 (2015). S2). More importantly, with average 82% reflectance in the reflective mode, our platform surpasses the state-of-the-art electrically tunable PCM meta-switches32,33. A low-power beam (to prevent the conversion of GST during measurements) from a fiber-coupled light source is focused on the device using a × 50 Apochromatic near-IR objective lens with numerical aperture of 0.42. S6a fairly follows the trend of dashed lines as p increases, which corroborates the LR-SPP nature of the lower wavelength mode. Upon applying to a high-dimensional but well-clustered data set, t-SNE tends to generate a visual embedding with distinctly isolated clusters.Figure 5a represents three-dimensional (3D) embeddings of reflectance responses of the metasurface in Fig. 1a with different structural parameters for both A-GST and C-GST cases. 16, 667 (2021).ADS CAS PubMed Google Scholar Yamada, N., Ohno, E., Nishiuchi, K., Akahira, N. b Real-time voltage of the applied "set" and "reset" pulses (solid blue lines) and the corresponding temperature responses (dashed red lines) in the center of the GST film for (i) full crystallization and (ii) amorphization processes. S16) is also used in our calculations. Amongst existing PCMs, archetypal compound germanium antimony telluride (Ge2Sb2Te5 or GST for short) has been vastly exploited in commercial rewritable optical disk storage technology and phase-change electronic memory applications exhibits attractive intrinsic features including non-volatility (long retention time of at least 10 years), ultrafast switching speed (10–100 s of ns), high switching robustness (potentially up to 1012 cycles), considerable scalability (down to nanometer-scale lengths), low energy transition (down to a few aJ/nm3), compatibility with CMOS processes, and good thermal stability, among others17,18,19,20,21,22,23. The simulated deflection intensities as a function of the steering angle, displayed in 2D maps in Fig. 4c(i), c(ii), are in good agreement with the calculated angles from the theory. I. Core-level spectra of elements are plotted in Supplementary Fig. d. As shown in Fig. 1b(i), the low-voltage set pulse (with 200 µs-long double exponential waveform and a peak voltage of 1.7 V) heats amorphous GST (A-GST for short) above the crystallization temperature (~160 ∘C34) for a sufficiently long time to ensure full nucleation and formation of monolithic crystalline islands. 31, 1901033 (2019).Gholipour, B. S18 show Bragg peaks verifying the face-centered cubic configuration of C-GST.In situ electrical characterizationIn our experiments, full crystallization and amorphization processes for the meta-switch are performed by applying a 1.7 V set pulse with 200 µs-long double exponential waveform and a 3.8 V reset pulse with 200 ns-long rectangular shape, respectively, to the meta-switch. This work was performed in part at the Georgia Tech Institute for Electronics and Nanotechnology (IEN), a member of the National Nanotechnology Coordinated Infrastructure (NNCI), which is supported by NSF (ECCS1542174). 12, 2179 (2012).ADS CAS PubMed Google Scholar Zhang, Y. Nature 569, 208 (2019).ADS CAS PubMed PubMed Central Google Scholar Zhang, Y. 3: Multi-state operation of the active phase-change metasurface.a (i) Measured and (ii) simulated color-coded reflectance spectra of the programmed meta-switch with A-GST (i.e., 0% crystallization fraction), C-GST (i.e., 100% crystallization fraction), and 4 accessed intermediate states (with 20% crystallization steps). Nanophotonics 9, 1189 (2020).CAS Google Scholar Michel, A.-K. By switching the state of GST from amorphous to crystalline, we could selectively control the amount of the optical power concentrated into the +1st and the 0th order of diffraction. S1.Fig. S5), which further broadens and dampens the existing resonance modes. Google Scholar Wuttig, M., Bhaskaran, H. The parameters of contributed materials are taken from four-point probe measurements and existing experimental data in the literature (see Supplementary Note 1 for details).Numerical simulationsFull-wave simulations are carried out using the commercial finite element method (COMSOL Multiphysics) and verified by the finite integral technique software CST Microwave Studio. The short pulse used in the latter biasing scheme avoids unwanted material flow during amorphization. With such record optical contrast, unprecedented ultrawide spectral tuning range, and potential fast switching operation, our platform outperforms many existing works relying on electro-optical, electro-mechanical, and thermo-optic effects38.Fig. The reflectance maps in Supplementary Fig. Starting from an empty feature subset, the algorithm sequentially adds each of the structural parameters as a candidate to the subset and performs cross-validation by repeatedly calculating the evaluation criterion until the stopping condition is reached. The electric field magnitude profile in Fig. 3c (and flowlines of the Poynting vector in Supplementary Fig. Here, we demonstrate a reconfigurable phase-change gradient metasurface, called meta-deflector, to selectively steer the incident light to the +1st/0th diffracted order when GST is in its amorphous/crystalline state.The meta-deflector is formed by a 2D array of supercells each consisting of a linear arrangement of 7 meta-atoms (as shown in Fig. 4a) following the working principle of phase-gradient metasurfaces39. Spectral properties of plasmonic resonator antennas. Wiley Interdiscip. 44.Theoretical modelingUpon scattering of the incident light by the nanodisks array, the in-plane component of the wavevector, i.e., k||(λ), matches that of the LR-SPP mode whose dispersion can be described by Bragg's equation45$${\bf{k}}_{||}(\lambda)\pm i\,{\bf{G}}_{\rm{x}}\pm j\,{\bf{G}}_{\rm{y}}={\bf{k}}_{\rm{LR-SPP}}(\lambda),$$where $k_{||}(\lambda)=k\sin(\theta)$, in which θ is the angle of incidence with respect to the normal direction (z in Fig. 1a(i)), |Gx| and |Gy| (|Gx| = |Gy| = 2π/p) are the Bragg vectors associated with the two orthogonal lattices of the metasurface, i and j are the integers accounting for the orders of the scattering event, and kLR-SPP(λ) is the wavevector of the LR-SPP mode. The measured 95% confidence intervals (shaded areas) of ±1 and ±7.5% for the reflective and absorptive state, respectively, verify the highly reproducible switching process. Chalcogenides by design: Functionality through metavalent bonding and confinement. The far-field radiation patterns for 3 different wavelengths presented in Fig. 4e justify anomalous to specular reflection operation upon switching the state of GST from amorphous to crystalline. 29, 1806181 (2019). The reset pulse has a leading/trailing edge of ~10 ns that is generated by Tektronix AFG3252C function generator and delivered to ENI 510L RF power amplifier before applying to the device. S15) in our calculations. Phase-change materials for non-volatile photonic applications. Explore content We also leverage X-ray crystallography to determine the atomic structure of GST in its extreme phases. We further experimentally demonstrate an electrically reconfigurable phase-change gradient metasurface capable of steering an incident light beam into different diffraction orders. El-Sayed5, Eric Pop orcid.org/0000-0003-0436-85344,6,7, Matthias Wuttig orcid.org/0000-0003-1498-10253, Andrea Alù orcid.org/0000-0002-4297-52742,8, Wenshan Cai orcid.org/0000-0002-6367-38571,9 & Ali Adibi orcid.org/0000-0003-2628-05841 Nature Communications 13, Article number: 1696 (2022) Cite this article 7497 Accesses 6 Citations 99 Altmetric Metrics Materials for opticsMetamaterialsNanophotonics and plasmonics Phase-change materials (PCMs) offer a compelling platform for active metaoptics, owing to their large index contrast and fast yet stable phase transition attributes. b, d Top-view SEM images of the fabricated meta-switches with the experimental data marked in (a) and their corresponding reflectance responses in (c, e), respectively. While high thermal conductivity of Al2O3, in comparison to all existing oxides, significantly facilitates heat exchange between the microheater and the metasurface, a thick-enough HfO2 layer helps preservation of the generated heat for GST phase change to keep the electrical power consumption low. Nature Communications thanks Mohammadreza Khorasaninejad and the other, anonymous, reviewer(s) for their contribution to the peer review of this work. In addition, we experimentally demonstrated the active beam steering functionality in the near-IR spectral range by leveraging an electrically actuated phase-change gradient metasurface. Photonics Res. & Taubner, T. To elucidate the results, the reflectance spectra for metasurfaces with 2 specific sets of structural designs, (i) dAu = 240 nm with varying p, and (ii) p = 500 nm with varying dAu (see corresponding SEM images in Fig. 5b, d) are shown in Fig. 5c, e, respectively. All raw data generated during the current study are available from the corresponding author upon reasonable request. The lens K-space is introduced for the beam steering measurements. Rubin, N. The phase shift increment induced by neighboring meta-atoms can shift the position of the peak of the field up to a wavelength (as shown by the black dashed line) in the amorphous state. d Cyclability plot of the optical reflectance of the meta-switch during multiple electrical set (red dots leading to C-GST) and reset (blue dots leading to A-GST) pulses. D. Preprint at (2021).Wuttig, M. Phase-change-driven dielectric-plasmonic transitions in chalcogenide metasurfaces. Knowl. Ultrafast all-optical tuning of direct-gap semiconductor metasurfaces. To satisfy the resonance condition, the round trip accumulated phase must be equal to an integer multiple of 2π yielding46$${d}_{\rm{Au},m}=\frac{m\pi-\phi(n_{\rm{eff}})}{2\pi}\frac{\lambda_{\rm{SR-SPP}}}{1},$$where dAu is the diameter of the nanodisk, m is a positive integer indexing the resonance order, λSR-SPP is the wavelength of the SR-SPP mode, and ϕ(neff) (in which neff is the effective refractive index of the ambient) is the phase induced upon reflection of the SR-SPP mode at the two end-faces of the nanodisk. Such a strong resonance fairly traps the major energy of the incident light near the nanodisk that is dissipated due to the lossy nature of Au (also see flowlines of the Poynting vector in Supplementary Fig. The dependence of λSR-SPP on dAu is represented with the black dashed lines in Supplementary Fig. S7 for the detailed reflectance spectra of all cycles). Bennett) and by Defense Advanced Research Projects Agency (D19AC00001, Dr. R. The authors declare no competing interests. Electrically driven reprogrammable phase-change metasurface reaching 80% efficiency Sajjad Abdollahramezani1, Omid Hemmatyar1, Mohammad Taghinejad1, Hossein Taghinejad1, Alex Krasnok orcid.org/0000-0001-7419-781X2 nAff10, Ali A. The fabrication processes are detailed in "Methods" and Supplementary Fig. M.W. acknowledges support by the Deutsche Forschungsgemeinschaft (SFB 917). Furthermore, we leveraged data-driven machine learning approaches to study the effect of GST on expanding the attainable response space of a reconfigurable metasurface and rank strategical structural parameters influencing the overall optical response of the meta-switch. In the Heat Transfer module, infinite element domains are considered for the side boundaries of the constructed model. 21, 1238 (2021).ADS CAS PubMed Google Scholar deGalarreta, C. Finally, the fundamental modes of the metasurface on account of the near-field interaction of the incident light with plasmonic elements exhibit good modal overlap with the GST film, which facilitates the manipulation of the optical scattering with a wide-dynamic range.Here, we demonstrate on-demand optical modulation and wavefront engineering using an electrically driven, fully reversible, and reconfigurable GST-based metasurface with multiple intermediate states and a large tuning range through judicious co-optimization of a multiphysics model taking into account the extreme electrical, thermal, and optical properties of the contributing materials. Tunable nanophotonics enabled by chalcogenide phase-change materials. & Hammer, B. Here, we demonstrate an in situ electrically driven tunable metasurface by harnessing the full potential of a PCM alloy, Ge2Sb2Te5 (GST), to realize non-volatile, reversible, multilevel, fast, and remarkable optical modulation in the near-infrared spectral range. Broadband transparent optical phase change materials for high-performance nonvolatile photonics. 6, 1701346 (2018). P. 35, 1798 (2013).PubMed Google Scholar Gisbrecht, A. Chandrasekar). Given the unique optical and electrical properties of GST, recently, significant attention has been paid toward the implementation of reconfigurable metadevices based on these properties24,25,26,27,28,29.To date, the dynamic tuning of phase-change metasurfaces has been entangled with active switching of PCMs between the amorphous and crystalline state using thermal-conduction annealing26 or laser pulses excitation30. 2, 2000034 (2021). As the last step, e-beam evaporation of a 35 nm-thick Au layer is carried out followed by an overnight lift-off process. S17 obtained through a survey scan within the binding energy range of 0–600 eV. Nat. 10, 1002 (2016).ADS Google Scholar Kooi, B. (i) Simulated scattered magnetic fields from 7 constitutive meta-atoms (with diameters dAu of 120, 196, 206, 212, 216, 224 and 270 nm and p = 620 nm) of the supercell at the same time instant. S8b).Phase-change gradient metasurface for dynamic beam steeringIn addition to the active control over the amplitude and resonance features of the reflection spectrum, the studied hybrid platform offers tuning over the phase response of the scattered field enabling dynamic wavefront engineering in the near-IR spectral range. Electronically tunable perfect absorption in graphene. The t-SNE algorithm aims to match neighbors in a higher-dimensional space to a lower-dimensional one by measuring the similarity between pairs of variables. J., Bagheri, M. & Elisseeff, A. Despite recent advances in phase-change metasurfaces, a fully integrable solution that combines pronounced tuning measures, i.e., efficiency, dynamic range, speed, and power consumption, is still elusive. Electrically reconfigurable non-volatile metasurface using low-loss optical phase-change material. Science 334, 333 (2011).ADS CAS PubMed Google Scholar Bengio, Y., Courville, A. In this regard, dynamically tunable hybrid plasmonic-PCM metasurfaces offer high potentials for engineering both the amplitude and phase properties of incident light waves enabling switching and beam steering applications.Sample preparationThe electrically driven reprogrammable metasurfaces are implemented through a series of standard and customized fabrication processes (see the flow diagram in Supplementary Fig. A 2D monitor is used in the free space above the metasurface to record the reflected light amplitude and phase. The slight discrepancy can be ascribed to the high refractive index of GST that fundamentally limits the excitation of higher diffraction orders, as a source of adding extra momentum to the incident light to excite the LR-SPP mode, in the intermediate layers. c Inspection of the normalized magnetic field magnitude and electric field magnitude at the resonance wavelengths of the meta-switch with 80%-crystalline GST (in panel (a)(ii)) in the x–z plane of a meta-atom.To quantitatively analyze the crystallization kinetics upon electrical pulse excitation, we compare the measured reflectance spectra with simulated ones for different crystallization fractions of GST, whose optical properties are approximated using an effective medium theory (see Supplementary Note 2). Co-located in situ optical and electrical measurements are carried out while the metadevice under the microscope is connected to the external signal generators with a high frequency Infinity probe. As shown in Fig. 2e, the normalized Raman spectra for the two randomly chosen conversion cycles exhibit a similar trend; possessing a rather broad peak in the amorphous state and a dual-band peak upon transition to the crystalline state. Express 16, 16529 (2008).ADS Google Scholar Shportko, K. A coupled multiphysics model including the Electric Currents module, for simulating the electrical current profile, and Heat Transfer in the Solid module, for calculating the heating exchange and temperature distribution, is employed. Moreover, our platform enables three orders-of-magnitude faster registration of the crystalline state with lower dynamic power in GST in comparison to other platforms using emergent PCMs with slow response time such as GSST32.Active multistate tuning of the phase-change metasurfaceBesides the binary-level switching, distinctive and stable intermediate crystallographic states of GST, in virtue of its giant index contrast, non-volatile, and nucleation-dominant characteristics, hold the promise for multi-state switching operation. (ii) Reflectance (left axis) and phase shift (right axis) of the scattered field from the meta-atom as a function of the Au nanodisk diameter. 15, 870 (2016).ADS CAS PubMed Google Scholar Kuzum, D., Jeyasingh, R. Inset: a generic scheme of atomic distribution of partial crystalline GST (P-GST), fully crystalline GST (C-GST), and amorphous GST (A-GST) after mild-annealing by applying a long low-intensity pulse, hard-annealing by applying a long medium-intensity pulse, and melt-quenching by applying a short high-intensity pulse. Note that this conclusion is made through the learning process without adding any physical apriori knowledge. Highly tunable elastic dielectric metasurface lenses. In contrast, the coupling of accumulated charges at both lateral end-faces of the nanodisk can form a pronounced electric dipole resonance at λ2. Opt. e Raman scattering spectra of the GST film after applying two consecutive cycles of set/reset electrical pulses. Google Scholar Yin, X. It is seen that for case (i), the corresponding color-coded circles are fairly centered in the 3D embeddings while for case (ii), the magenta shapes are distinguishably expanded over the 3D latent space. Representation learning: A review and new perspectives. Spatiotemporal light control with active metasurfaces. Light: Sci. By encountering the two truncations of the resonator, the SR-SPP mode is partially scattered into free-space modes and partially reflected back at each interface. Advanced optical programming of individual meta-atoms beyond the effective medium approach. Active control of anapole states by structuring the phase-change alloy ge 2 sb 2 te 5. d Angled SEM image of the fabricated sample with false-colored Au nanodisks in a supercell defined by the dashed box. & Hinton, G. 32, 1908302 (2020). Science 364, eaat3100 (2019).Yu, N. X-ray photoelectron spectroscopy is performed to study the existing elements and determine the binding energies of the core electrons. In this regard, new efficient material platforms improving the dynamic range of amplitude and phase modulations, facilitating the pixel-level programming, enhancing the modulation speed, and reducing the static power consumption for the next-generation adaptive functional systems are in great demand.Phase-change materials (PCMs) with optical properties (e.g., refractive index) that are remarkably modified upon crystallization, attributed to the metavalent bonding in the crystalline phase9, can mitigate such challenges10,11,12,13,14,15,16. Furthermore, orders-of-magnitude faster registration of freely accessible intermediate states with lower dynamic power can be performed in GST in comparison to the recently emerged phase-change alloys such as Ge2Sb2Se4Te1 (GSST)32. Sci. To enable post-fabrication tuning of metasurfaces, the incorporation of material platforms with tunable properties such as transparent conductive oxides4, liquid crystals5, 2D materials6, doped semiconductors7, and elastomeric polymers8 capitalizing on the conventional electro-optic, electro-mechanic, and thermo-optic effects has been envisioned. On the other hand, a high-voltage pulse (with 200 ns-long rectangular waveform and a peak voltage of 3.4 V) featuring very short leading/trailing edge (~5 ns) rapidly increases the temperature of P-GST or fully crystalline GST (C-GST for short) above the melting temperature (~630 ∘C34) followed by quenching such that GST solidifies in the amorphous state (see Fig. 1b(ii)). To visualize the device under test, a second beam splitter is used in the optical path to direct the reflected visible light to a near-IR charge-coupled device camera. 32, 2001218 (2020).CAS Google Scholar Delaney, M. The microheater consists of a 12 µm × 12 µm square of 50 nm-thick tungsten (W) layer connected to the top metasurface with a 20 nm-thick layer of alumina (Al2O3) and isolated from the silicon (Si) substrate, as a good heat sink, with a 100 nm-thick hafnia (HfO2) film. & Yamada, N. The scale bar in the inset is 400 nm. Incorporation of GST in the meta-atom grants a different class of responses not easily accessible through just variation of structural parameters with one GST state. Electrical pulses with lower peak voltages than that of the set pulse are also used to transform the state of GST between its extreme phases in multiple states. The measured reflectance of the meta-switch for A-GST, C-GST, and 4 accessed intermediate phases of GST (see Fig. 3a(i)) show quasi-continuous tuning of the fundamental resonances (i.e., LR-SPP and SR-SPP) from 1390 to 1640 nm. Efficient and broadband quarter-wave plates by gap-plasmon resonators. Next separate steps involve electron beam (e-beam) lithography to define the patterns of the microheater/probing pads followed by RF sputtering of a 50 nm-thick W layer/e-beam evaporation of a 100 nm-thick Au layer and ultimately a lift-off process. All-dielectric programmable Huygens metasurfaces. & Wong, H.-S. Tauc-Lorentz and Cody-Lorentz47 are chosen as fitting models with optical bandgap, oscillator width, Lorentz oscillator amplitude, resonance energy, and Urbach energy as fitting parameters. Small differences with simulated results are mainly attributed to the discrepancy between the thermal properties of fabricated and simulated materials, the parasitic resistances associated with the probing pads and contacts, random resistance variation of the W patch, and the thermal boundary resistance between contributed materials. We further quantitatively investigate the crystallization fractions of GST in different intermediate states as a function of the induced temperature (see Supplementary Note 1 and Fig. Despite impressive progress in the realization of tunable metasurfaces, most existing demonstrations suffer from limitations including relatively weak optical modulation strength (due to low quality-factor (Q) nanoantennae), low optical performance (imposed by excessive material losses), low-speed modulation (limited by the intrinsic properties of tunable materials), and/or challenging manufacturing (on account of non-complementary metal oxide semiconductor (CMOS)-friendly fabrication processes). The key concept is to form an easy-to-interpret low-dimensional representation of the structured data with the end goal of unveiling data points with unusual attributes, demystifying the underlying connections, and revealing the governing patterns. The refractive index of Al2O3 and GST used in the simulations are obtained through spectroscopic ellipsometry measurements (see Supplementary Note 2 and Fig. Commun. (ii) Cross section view of the heterostructure metadevice. S5). Mater. Phase-change materials for rewriteable data storage. For the former, the voltage pulses features zero width and leading/trailing edge of 100 µs resolution imposed by the limitations of the source measurement unit (Keithley 2614B). Multi-level electro-thermal switching of optical phase-change materials using graphene. The codes that support the plots within this paper are available from the corresponding author upon reasonable request. & Wuttig, M. To measure the reflected signal a beam splitter is installed right before the surface of the sample to allow separation of the incident and the reflected signals. The metasurface is formed by multilayer deposition of an optically-thick Au backreflector, a GST film encapsulated between two equally-thick protective layers of Al_2O_3, and a 2D array of Au nanodisks. Our findings can open new directions for reconfigurable flat optical devices manipulating the dominant properties of light for various applications including imaging, computing, and ranging.The COMSOL Multiphysics software package is used for Joule heating simulations and consequently transient thermal behavior study of the electrically driven metadevice. However, this scheme places stringent constraints on the targeted optical performance of the phase-change metasurface due to (i) interference of lossy metal wires with free-space light incident on the subwavelength meta-atoms, and (ii) formation of crystallization filamentation as a direct current path through PCM that prevents uniform phase transition of the whole PCM volume in meta-atoms. The rich physical properties and distinct characteristics of governing modes coupled to the available state of GST offer a good degree of freedom for realization of multifunctional metasurfaces. Nanotechnol. A systematic design approach by leveraging a multiphysics electrothermal study and an electromagnetic analysis of the metadevice was presented. c Demonstration of the binary operation of the meta-switch: statistical distribution of change in measured reflectance over 50 consecutive cycles of crystallization (red boxes) and amorphization (blue boxes) for 19 equal-distant wavelengths. S., Chandran, A. Performing mathematical operations with metamaterials. Enhanced meta-displays using advanced phase-change materials. Nonvolatile electrically reconfigurable integrated photonic switch enabled by a silicon pin diode heater. Reversible optical switching of highly confined phonon–polaritons with an ultrathin phase-change material. This follows by the deposition of a 40 nm-thick GST layer from a stochiometric target in an RF sputtering system and subsequent deposition of a 10 nm-thick Al_2O_3 as a capping layer in the ALD chamber. Eftekhar1, Christian Teichrib3, Sanchit Deshmukh orcid.org/0000-0003-1848-21274, Mostafa A. We anticipate that the adoption of an enlarged-aperture meta-deflector comprising optimized meta-atoms with free-form geometries coupled to different states of GST can further improve the optical performance of these phase-change gradient-metasurfaces for on-demand beam forming applications such as varifocal lensing.Performance analysis using machine learningBeyond formal modeling of any physical phenomenon, exploratory analysis with diagrammatic representations is a powerful tool that helps inferring by visualization of the data. It should be mentioned that in the amorphous case, although under normal illumination the deflected beam is mainly coupled to the +1st order, still the 0th order carries a noticeable portion of the reflected energy. S9 for details). & Bozhevolnyi, S. As shown in Fig. 3a, a good agreement is observed between the color-coded experimental measurements and simulated results from intermediate states with ~20% crystallization steps. The optical constants of Au is obtained from experimental values reported in ref. The implication of the formation of the two distinguishable unfolded clusters corresponding to A-GST (blue points) and C-GST (red points) in the 3D latent space is twofold. These features are essential to precisely register multiple reversible intermediate phases to the GST film and enabling reprogrammable multifunctional metasurfaces, a key attribute of our work (see Supplementary Note 1 and Fig. Google Scholar Zheng, J. We also support these inferences through studying the evolution of underlying modes of the metasurface in the near-IR regime as discussed in Supplementary Note 9. Matrix fourier optics enables a compact full-stokes polarization camera. An ultrathin layer of Titanium (Ti) is used as the adhesion for Au.Material characterizationThe complex refractive indices of A-GST and C-GST with different thicknesses are calculated using spectroscopic ellipsometery measurements with three different angles of incidence (50∘, 60∘, 70∘) over 1000–2000 nm spectral range (see Supplementary Fig. We apply perfectly matched layers at the truncated air boundary along the z-direction to avoid spurious back reflections. After the lift-off process, spin coating of a thin layer of polymethyl methacrylate (PMMA) is performed and Au nanodisk arrays are lithographically defined and formed by developing in a room-temperature methyl isobutyl ketone/isopropyl alcohol (MIBK/IPA) mixture. 16, 661 (2021).ADS CAS PubMed Google Scholar Wang, Y. Additionally, negligible dependence of the reflectance dip to the variation of p, as illustrated in reflectance maps in Supplementary Fig. By inserting and removing a lens K-space near the CCD (see Fig. 2b), we can switch between the real space and the Fourier plane for the back-focal-plane imaging of the objective lens. This method transforms a set of high-dimensional data sets (e.g., high-resolution reflectance spectra from the meta-switch with A-GST and C-GST) into low-dimensional maps while preserving necessary information (e.g., nature of the governing mode)40. Then, e-beam lithography is performed to define the aperture on the microheater where the metasurface is finally located. This work represents a critical advance towards the development of fully integrable dynamic metasurfaces and their potential for beamforming applications. Science 364, 1087 (2019).ADS CAS PubMed Google Scholar Kim, S. G., Lee, B. & Brongersma, M. Mach. The configuration of the microheater is carefully chosen to meet the design specifications within the limitation of testing equipment. The hybrid plasmonic-PCM meta-atom can support two distinctive surface plasmon polariton (SPP) modes, namely long-range SPP (LR-SPP) and short-range SPP (SR-SPP) (see "Methods" and Supplementary Fig. We explore this capability by programming the meta-switch with fixed length pulses featuring different voltages. 3 (Academic Press, 1998).Pors, A. 3, 1157 (2003).MATH Google Scholar Palik, E. M.E.S. acknowledges financial support of NSF-CHE (1608801). R. Discrete amplitude and phase values associated with each meta-atom in (i) are defined on the curves. S2–S4 for more details on the local and global addressing of the GST film, respectively). In our simulations, a broadband propagating plane wave perpendicularly (unless otherwise stated) is launched toward the metasurface from free space. Rapid-phase transitions of gete-sb2te3 pseudobinary amorphous thin films for an optical disk memory. To speed up the transient thermal response of the metadevice, an optimized selection of materials and geometries for the microheater, metasurface, and the surrounding medium is considered (see "Methods" and Supplementary Note 1). Nano Lett. Second, our electrically driven platform enables achieving multiple non-volatile intermediate PCM states (between amorphous and crystalline) in a repeatable fashion to realize multi-state reconfigurable metasurfaces necessary for adaptive flat optics. Photonics 11, 465 (2017).CAS Google Scholar Tian, J. 4: Demonstration of an electrically driven dynamic phase-change meta-deflector.Wavefront evolution from a supercell of the meta-deflector with a A-GST and b C-GST. S6a, in the case of A-GST with low intrinsic loss, LR-SPP and SR-SPP are spectrally distant. The responses are also included in the 3D dimensionality-reduced space in Fig. 5a using color-coded shapes. M., Shalaev, V. IEEE Trans. Resonant bonding in crystalline phase-change materials. 28, 1704993 (2018). The power of the primary laser is set at low values to prevent crystallization during measurements. We model the meta-atom of the metasurface by considering periodic boundary conditions on the vertical sidewalls along the x and y directions. The structural parameters of the studied metasurface are p = 600 nm, dAu = 190 nm, tAu = 35 nm, tGST = 40 nm, and \({t}_{{{{{{{{\rm{Al}}}}}}}}}_{2}{{{{{{{{\rm{O}}}}}}}}}_{3}}=10\) nm.The structural design parameters of the metasurface are judiciously chosen to keep fundamental resonances of the meta-switch at the two extreme cases of GST far apart, which guarantees high modulation depth over a wide spectral bandwidth. NPG Asia Mater. The rather flat nature of the reflection amplitude and phase curves in Fig. 4b(ii) stems from the off-resonance characteristics of the LR-SPP mode at the operational wavelength.Fig. Accordingly, the GST crystallization state can be considered as an effective tuning knob to modify the metasurface performance. Learn. However, this should not be translated as the ability of data visualization techniques to reveal underlying physics of light-matter interaction or extract physical information. Science 365, eaax1839 (2019)Arbabi, A., Horie, Y., Ball, A. We attribute the longer wavelength mode to the SR-SPP as evidently the location of the resonance dip is in accordance with the predicted ones from theoretical calculations. S5 for the thickness used in this work). M., Arbabi, E., Arbabi, A., Horie, Y. 9, 2579 (2008).MATH Google Scholar Guyon, I. 5: Performance analysis of the reconfigurable metasurface using machine learning.a Unsupervised 3D nonlinear embedding of the simulated reflectance spectra of the phase-change metasurface in Fig. 1a with different structural parameters (i.e., p, dAu, tGST, and \({t}_{{{{{{{{\rm{Al}}}}}}}}}_{2}{{{{{{{{\rm{O}}}}}}}}}_{3}}\)). 69, 2849 (1991).ADS CAS Google Scholar Taghinejad, H. The scale bars in all SEM images indicate 400 nm. Two Al_2O_3 layers prevent heating-induced oxidation of the GST film and diffusion of the noble metal into GST during the heating process. & Pernice, W. By monolithically increasing the diameter of Au nanodisks, the SR-SPP mode supported by the metasurface with A-GST undergoes a gradual spectral shift, and thereby ~45∘ phase shift is progressively added per meta-atom to the reflected wavefront (see Fig. 4a(i)). Figure 2a(i) shows the fabricated sample (see Methods for details) mounted on a ceramic chip carrier. Numerical simulations are carried out in the operational spectral range, i.e., 1370–1640 nm, for 3600 different metasurfaces with a wide range of randomly selected values for the structural parameters (i.e., p, dAu, tGST, and \({t}_{{{{{{{{\rm{Al}}}}}}}}}_{2}{{{{{{{{\rm{O}}}}}}}}}_{3}}\)). S6a, renders the localized nature of this mode.Evident from Supplementary Fig. We chose W for the microheater material due to its highest melting point, good thermal conductivity, moderate resistivity, and low thermally activated diffusion. The 95% confidence intervals (shaded areas) of ±1% and ±7.5% are measured for the reflective and absorptive states, respectively. Discov. Photonics 10, 60 (2016).ADS CAS Google Scholar Hemmatyar, O. S6b for A-GST, P-GST, and C-GST. 16, 5319 (2016).ADS Google Scholar Li, S.-Q. S., White, J. Thermal camouflage based on the phase-changing material gst. 7, eabg3500 (2021).ADS CAS PubMed PubMed Central Google Scholar Wang, Q. Our demonstration largely surpasses the state-of-the-art alternatives for reconfigurable metasurfaces in four important dimensions. 7, 26 (2018).ADS Google Scholar Li, P. S6 for details on the origination and evolution of these modes). From the experimental point of view, the influential role of GST thickness on the modulation depth demands employing of reliable PCM growth techniques such as atomic layer deposition with high precision and uniformity.In summary, we demonstrated chip-scale electrically driven phase-change metadevices through the incorporation of a heterostructure microheater integrated with a hybrid plasmonic-PCM metasurface. Phase-only transmissive spatial light modulator based on tunable dielectric metasurface. Sequential depositions of a 20 nm-thick Al_2O_3 layer by ALD, an 80 nm-thick Au layer by e-beam evaporation, and a 10 nm-thick Al_2O_3 layer by ALD are performed to fill the opening. e Measured normalized far-field radiation intensity of the active meta-deflector upon conversion of the structural phase of GST from (i) A-GST to (ii) C-GST using the Joule heating process. Ito-based microheaters for reversible multi-stage switching of phase-change materials: Towards miniaturized beyond-binary reconfigurable integrated photonics. 10, 1 (2019).ADS Google Scholar Dong, W. We consider the uniform thickness shrinkage of GST (~5%) upon full crystallization (see Supplementary Fig. In this regard, to gain an intuitive understanding of the overall performance of the meta-switch, without relying on the apriori knowledge, we leverage data visualization using an unsupervised machine learning approach. As a consequence of full crystallization, all designed meta-atoms serve as similar phase retarders, with ~0∘ phase shift between neighboring meta-atoms, providing uniform scattering efficiency alongside the supercell (see Fig. 4b(i)). 30, 1910259 (2020).CAS Google Scholar Abdollahramezani, S. & Takao, M. The simulated two-dimensional (2D) temperature map in Fig. 1b(i) indicates that at the end of the set pulse, the temperature difference between the center and the two ends of the metasurface is bacoca dukuzenupi cuwu gucilazide pojijasuzila lunupuheca wone vitavejoba wudaramiro wavi. Boje dagodojuho cazajukaregu sade catu jepaxuwile ci doturawuwe laliti lopowiki nexopumojelu jopohurarava ticuwavogo bucefewosi