Polaritons formed by the coupling of light and material excitations enable light-matter interactions at the nanoscale beyond what is currently possible with conventional optics. However, novel techniques are required to control the propagation of polaritons at the nanoscale and to implement the first practical devices. Here we report the experimental realization of polariton refractive and meta-optics in the mid-infrared by exploiting the properties of low-loss phonon polaritons in isotopically pure hexagonal boron nitride interacting with the surrounding dielectric environment comprising the low-loss phase change material Ge3Sb2Te6. We demonstrate rewritable waveguides, refractive optical elements such as lenses, prisms, and metalenses, which allow for polariton wavefront engineering and sub-wavelength focusing. This method will enable the realization of programmable miniaturized integrated optoelectronic devices and on-demand biosensors based on high quality phonon resonators.
Polaritons in van der Waals materials behave as confined optical modes, which extend as evanescent waves into the semi-spaces above and below\(^1\). Therefore, their propagation is affected by the refractive indices of the superstrate and substrate\(^3,4,6,8\). One notable example of these polaritons are phonon polaritons (PhPs) in hexagonal boron nitride (hBN). These are not interface modes as for plasmons in noble metals: they exist instead inside the volume of hBN. The permittivity values are of opposite signs along different principal axes and thus polaritons exhibit hyperbolic dispersion\(^3,8,12\). The degree to which the optical energy density of polaritons extends into the substrate and superstrate depends on the wavelength and thickness of hBN. The hBN-GST heterostructure used in this work. As PhPs are strongly confined, a thin layer of 55 nm of GST below hBN (195 nm of thickness) is sufficient to significantly alter polariton propagation. To create the heterostructure, we sputter a thin film of GST on a CaF\(_2\) substrate (in an amorphous phase as-deposited), protect it with a 15 nm layer of ZnS:SiO\(_2\) against oxidation and then transfer exfoliated hBN to form the top layer. A pulsed laser beam is used to write and reconfigure devices on GST underneath hBN (transparent at 405 nm). Longer, low-power laser pulses are used to crystallise GST and shorter high-power pulses are used to melt it to restore the amorphous phase.

### Results

#### Reconfigurable 2D refractive polariton lenses

Figure 1a shows the hBN-GST heterostructure used in this work. As PhPs are strongly confined, a thin layer of 55 nm of GST below hBN (195 nm of thickness) is sufficient to significantly alter polariton propagation. To create the heterostructure, we sputter a thin film of GST on a CaF\(_2\) substrate (in an amorphous phase as-deposited), protect it with a 15 nm layer of ZnS:SiO\(_2\) against oxidation and then transfer exfoliated hBN to form the top layer. A pulsed laser beam is used to write and reconfigure devices on GST underneath hBN (transparent at 405 nm). Longer, low-power laser pulses are used to crystallise GST and shorter high-power pulses are used to melt it to restore the amorphous phase. Electric field profile of polaritons for the a-GST and c-GST cases. The electric field confinement is larger in c-GST (due to its larger refractive index) than in a-GST. \(E_z\) represents the electric field along the direction of polariton propagation. Thicknesses for each layer are 195 nm for hBN, 15 nm for ZnS:SiO\(_2\), 55 nm for GST and 1 mm for CaF\(_2\), which is then considered semi-infinite. Refractive indices are 1.7 for ZnS:SiO\(_2\), 4.2 and 6.1 for GST in amorphous and crystalline phases, respectively, 1.37 for CaF\(_2\), while hBN is modelled with the Lorentz model presented for each layer are 195 nm for hBN, 15 nm for ZnS:SiO\(_2\), 55 nm for GST and 1 mm for CaF\(_2\), which is then considered semi-infinite.

#### Optical and s-SNOM images

Example of optical and s-SNOM images. Scale bar is 5 \(\mu\)m.
laser diode is used to write and erase patterns by selectively crystallising or re-amorphising GST\(^{22}\) (Fig. 1b).

The PhP mode profile is affected by the state (either crystalline or amorphous) of the GST beneath it (Fig. 1c), which can be quantified by using the effective index \(n_{\text{eff}} = c/\nu_{\text{ph}}\), where \(c\) is the speed of light and \(\nu_{\text{ph}}\) is the PhP’s phase velocity. Figure 1d shows the dispersion of \(n_{\text{eff}}\) for different hBN thicknesses on both a-GST \((n_{\text{eff,a}})\) and c-GST \((n_{\text{eff,c}})\), respectively. We use scattering-type scanning near field optical microscopy (s-SNOM) to characterise the polaritons launched at hBN edges, which propagate across the optical elements (Fig. 1e, f)\(^{8,13,18}\).

Polariton propagation in heterostructures with a- or c-GST is analogous to light propagation in two different materials (such as air and glass). The continuity of the electric field at the boundary between two regions implies Snell’s law\(^{32}\):

\[
\frac{n_{\text{eff,c}}}{n_{\text{eff,a}}} = \frac{\sin(\theta_1)}{\sin(\theta_2)},
\]

where \(\theta\) is the propagation angle in corresponding regions with respect to the interface normal.

Many conventional optical devices (such as lenses and prisms) are governed by Snell’s law, suggesting that similar components can be implemented in our hBN-GST heterostructure. The first example to illustrate this principle is a refractive lens, specifically, a plano-convex semi-circular lens to focus PhPs (Fig. 2a).

We write and erase a semi-circular plano-convex lens (radius \(R = 5 \mu\text{m}\)) twice and subsequently replace it with a plano-concave lens of the same radius (Fig. 2b–f). The straight hBN edge launches linear waves (the planar equivalent of three-dimensional plane waves), which are either focused by the plano-convex lens or diverged by the plano-concave lens (Fig. 1g, h). The lateral size of the focal spot is \(2 \mu\text{m}\) (29% of the free space wavelength), which is diffraction limited according to the Abbe limit computed for the 2D waves (i.e. 2.08 \(\mu\text{m}\)). The numerical aperture (NA) with respect to polaritons in a-GST is 0.55, while the NA with respect to vacuum is 2.11, which is higher than unity due to the high confinement of PhPs.

We performed phase-resolved s-SNOM measurements after each writing and erasing step. Using amplitude and phase information, the wavefronts of the polaritons can be clearly imaged (see Supplementary Note 4 for more details on measurements and image processing). The resulting images confirm focusing, which is shown by the narrow waist in the transmitted beam (Fig. 1i). Characteristic curved wavefronts can be seen before and after the focal spot. The position of the focal spot of the lens is measured from the images and compared with theoretical computation with two different methods (Fig. 2j).

The first method is based on computing the focal spot using ray optics, while the second, more accurate, method models the focused beam as a Gaussian beam, and identifies the focal spot as the beam waist\(^{32}\) (see more details in the Supplementary Note 2, Supplementary Fig. 1 and Supplementary Table 1).
After erasing, only polaritons with linear wavefronts that are launched by the hBN edge are visible, whereas focusing is fully restored when the lens is re-written (Fig. 2k, l). Furthermore, reconfiguring the same area to a plano-concave lens results in curved wavefronts associated with diverging PhPs (Fig. 2m).

Prisms and waveguides. The successful implementation of lenses can be extended to other common devices such as prisms and waveguides (Fig. 3). Planar prisms are simply triangles and follow Snell’s law (Fig. 3a). We wrote a prism and two waveguides (with different widths) close to the hBN edge so that edge-launched waves can interact with them (Fig. 3b–e). The prism is designed to be an isosceles right triangle with one side parallel to the hBN edge such that edge-launched waves enter orthogonal to it. When traversing the hypotenuse, the polariton propagation direction (k vector) is bent downwards (as expected from Snell’s law), as is clearly visible in the s-SNOM measurements in the form of bent fringes (Fig. 3f).

The waveguides consist of c-GST lines with widths (0.7 and 1.1 µm) smaller or comparable to the guided polariton wavelength. They provide additional in-plane confinement such that the propagating mode is truly one-dimensional and is confined along the waveguide. Here, the c-GST line acts as the waveguide core, while a-GST serves as cladding. The s-SNOM measurement in Fig. 3g shows that the wavefront spacing decreases inside the waveguides, as expected from confined modes. Furthermore, the compression is greater for the wider waveguide. This implies that the waveguide effective index \( n_{\text{eff,wg}} \) is larger when the width of the waveguide increases, which agrees with the behaviour known from conventional dielectric waveguides where the core size affects the effective index of the mode. In both the conventional and the polariton cases, the value of the waveguide effective index lies between the indices of the core and cladding material, that is, \( n_{\text{eff,a}} \leq n_{\text{eff,wg}} \leq n_{\text{eff,c}} \). We verified this behaviour by numerically calculating the waveguide dispersion relation (see Methods) and comparing the results to s-SNOM measurements taken at different frequencies (Fig. 3h). Figure 3i shows a cross-section of a guided mode obtained from numerical simulation, illustrating how polaritons are confined both vertically and laterally.

Reconfigurable polariton metalenses. Metasurfaces have recently emerged as a novel and versatile method for engineering light propagation by using arrays of discrete elements, which locally alter the phase of transmitted light. By changing the size and shape of these elements, arbitrary predetermined phase profiles can be implemented. Figure 4 shows the adaptation of this concept for polaritons and its implementation in an hBN-GST heterostructure. Our approach allows designing one-dimensional metalenses, which focus polaritons that propagate in two dimensions. The metalens elements are truncated c-GST waveguides defined in a-GST environment and create the hyperbolic phase profile.
range is to have a fraction of the polaritons transmitted without being focused, but the focusing power of the lenses is not affected.

**Discussion**

In summary, our results clearly establish that the hBN-GST heterostructure used in this work can serve as a versatile platform to arbitrarily control polaritons at the nanoscale to achieve freeform, transformation, and meta-optics. While we chose to integrate hBN with GST, it can be readily combined with other polaritonic vdW materials and other phase-change materials, thereby enabling a whole range of deeply sub-wavelength polaritonic devices, from visible to IR spectral regimes. Fully fledged polaritonic circuits can be cheaply fabricated without the need for traditional photolithography, allowing the low-cost realisation of biosensors and high-density optical storage, which benefit from the extreme volume confinement that can be achieved with polaritons. The challenges posed by the propagation losses to the implementation of optical circuits do not prevent the realisation of useful devices. For example, compact polarisers, biosensors and photodetectors could rely on the local enhancement due to resonant polaritons. Alternatively, optimising the layer thickness and materials can reduce the optical energy density inside hBN and therefore the losses. Alternative actuation mechanisms include using electrodes to locally heat GST electrically, as done in commercial GST memories. This approach could also be implemented with graphene, which is compatible with GST. The reconfigurability offered by GST-vdW heterostructures and the possibility of electrically switching GST-vdW material heterostructures paves the way to applications such as modulators, photodetectors and, more generally, programmable optical devices as optical counterparts to field programmable gate arrays.

**Methods**

**Sample fabrication.** A 55-nm GST-326 film (with 15 nm of ZnS:SiO2 protection layer) was sputter coated onto a 1-mm-thick CaF2 substrate. Lithography was performed to define alignment markers (positive tone photoresist S1813 spin coated at 3000 RPM and baked at 115 °C for 90 s), followed by Pt sputtering (30 nm) and lift-off at room temperature. Isotopically pure h-BN flakes were mechanically exfoliated onto the substrate after plasma activation (5 min of O2 plasma at 100 W) using a standard Scotch tape process. We removed traces of the glue from the Scotch tape by placing the sample in acetone for 10 min, followed by an isopropyl alcohol rinse for 5 min and drying with nitrogen. Afterwards, samples were further cleaned with O2 plasma (10 min of O2 plasma at 100 W). The thicknesses of the flakes and of GST were confirmed through atomic force microscope (AFM) measures (Cypher AFM from Asylum Research).

**Reconfigurable pattern writing.** See Supplementary Note 3, Supplementary Figs. 2, 3, 4 and Supplementary Table 2 for details on the technique used to write and erase patterns in GST.

**Lens and metalens parameters.** See Supplementary Table 1 for a summary of the fabricated lens parameters.

**Numerical simulations.** Numerical simulations were performed using Lumerical Mode solutions and Lumerical FDTD. One-dimensional (1D) simulations in mode solutions were used to calculate the effective indices $n_{eff,a}, n_{eff,c}$. A mesh size of 1 nm was used to compute the fundamental mode profile and effective indices of the hBN-GST-326 heterostructures in the RS2 band of h-BN. Here, hBN was modelled as an anisotropic dielectric with its permittivity values obtained from the Lorentz model (Supplementary Note 1). The effective indices of the waveguides were calculated via 2D simulations of their cross-sections, also done in Mode Solutions. Metalenses were designed by first simulating numerically each element in a periodic environment with full wave 3D simulations performed in FDTD. The result was a library of elements, which was used to implement the required phase profile. The final metalens was also completely simulated to verify the focusing performance. For 3D simulations, we used a mesh size smaller than 50 nm along x- and y-axis and 5 nm along the z-axis. A series of dipole sources were used to excite the polariton modes in hBN in the RS2 band.

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**Fig. 4 Reconfigurable metalenses.** a Adaptation of metalenses to the 2D case. Each discrete element changes the local phase of light, so the wavefronts converge to a focal spot. b, c Local phase (in degrees) of each element as a function of the element parameter and the frequency. b refers to unit cells with period 1.8 μm, 1 μm width and variable lengths. c refers to unit cells with period 1.2 μm, 9 μm length and variable widths. d Designed phase profile of the two metalenses (see Supplementary Note 2 for additional information). The design frequency was 1452 and 1448 cm$^{-1}$ for metalens 1 and metalens 2, respectively. e Optical images of the written metalenses. Metalens 1 was written, characterised, erased and subsequently the same area was reconformed into metalens 2. f $s$-SNOM image of metalens 1 showing focusing of polaritons at 1452 cm$^{-1}$. g $s$-SNOM image of metalens 2 at 1445 cm$^{-1}$. h Intensity profile (square of $s$-SNOM signal) at the cross-section of the diffraction-limited focused polariton beam for both lenses (dashed vertical lines in f, g). Scale bars are 5 μm.
s-SNOM measurements. The near-field scans were obtained using a commercial system from Nanospec. Tapping-mode AFM is used (tapping amplitude of 130 nm, Pt-Ir-coated tips with resonant frequency of ~300 kHz, tip diameter of ~0.2 nm). A quantum cascade laser array from Daylight Solutions was used as a tunable mid-IR source for imaging. The phase-amplitude images are obtained using a pseudo-heterodyne demodulation. The images of lenses and metalenses were processed using the technique shown in the Supplementary Note 4 to isolate the polaritons focused by the lenses. In all cases, polaritons are self-launched by the edges. See Supplementary Note 5 and Supplementary Figs. 6, 7, 8 for additional measurements.

Data availability

All data are available from the authors upon request. Please contact M.T. for any request of materials and data.

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Author contributions

K.C., M.T. and X.Y. conceived the project. M.T., K.C., X.Y., C.M.S., A.A. and F.C. devised experiments. X.Y. and C.S. designed and implemented the setup for writing patterns on GST-326 with help from R.L. and N.A.R. J.L. and J.H.E. provided isopropically pure hBN for final devices. C.P. and M.W. optimised and deposited the GST layer on the substrate. K.W., T.T., L.A.J. and P.K. provided natural abundance hBN for initial tests. X.Y. and C.M.S. wrote and erased patterns on h11BN/GST-326 heterostructures. K.C., M.T., S.L.O., T.T., L.A.J. and P.K. provided natural abundance hBN for initial tests. X.Y. and C.S. designed and implemented the setup for writing patterns on GST-326 with help from R.L. and N.A.R. J.L. and J.H.E. provided isopropically pure hBN for final devices. C.P. and M.W. optimised and deposited the GST layer on the substrate. K.W., T.T., L.A.J. and P.K. provided natural abundance hBN for initial tests. X.Y. and C.M.S. wrote and erased patterns on h11BN/GST-326 heterostructures. K.C., M.T., S.L.O., C.M.S. and A.A. performed s-SNOM and AFM scans. K.C., M.T., X.Y. and C.M.S. performed FDTD simulations. M.T. and K.C. analysed the experimental data. F.C. led the project. All authors contributed to discussions and manuscript preparation.

Competing interests

The authors declare no competing interests.