Chalcogenide material Ge$_2$Sb$_2$Te$_5$ (GST) has bistable phases, the so-called amorphous and crystalline phases that exhibit large refractive index contrast. It can be reversibly switched within a nanosecond time scale through applying thermal bias, especially optical or electrical pulse signals. Recently, GST has been exploited as an ingredient of all-optical dynamic metasurfaces, thanks to its ultrafast and efficient switching functionality. However, most of these devices provide only two-level switching functionality and this limitation hinders their application to diverse all-optical systems. In this paper, the method to expand switching functionality of GST metasurfaces to three level through engineering thermo-optically creatable hybrid state that is co-existing state of amorphous and crystalline GST-based meta-atoms is proposed. Furthermore, the novel hologram technique is introduced for providing the visual information that is only recognizable in the hybrid state GST metasurface. Thanks to thermo-optical complexity to make the hybrid state, the metasurface allows the realization of highly secured visual cryptography architecture without the complex optical setup. The phase-change metasurface based on multi-physical design has significant potential for applications such as all-optical image encryption, security, and anti-counterfeiting.

1. Introduction

Since we live in an age of overflowing information, there are growing interests to securely protect the vast amount of private information. To meet these needs, various computer-based cryptography techniques that exploit the chaotic combination of encryption algorithms have been studied for a long time to enhance the security level of information.[5–6] Apart from computer-based approaches, optical signal processing (OSP)-based cryptosystems have recently received a great deal of attention because of their inherent advantages, such as natural 2D imaging capabilities, multiple degrees of freedom, and high-speed parallelism.[6–11] Optical cryptographic techniques exploit the interaction between laser beam and complex combinations of various optical devices such as spatial light modulators and interferometers. They have proven to yield well-protected ciphered information in addition to extremely fast decryption thanks to the nature of photon-based optical communication. Nevertheless, the bulky system size resulting from the complex combination of optical components hinders its application to various OSP devices demanding the compact system size. As recent examples of efforts to miniaturize optical cryptosystems, the metasurfaces are in spotlights thanks to their large optical information handling capacity within small form factor.[12–16]

Representatively, the linear and nonlinear metasurface holograms (MHs) that modulate the reconstructed holographic image by adjusting the polarization state of the input and output lights have been proposed for optical information encryption and decryption.[17–20] Furthermore, metasurfaces that can dynamically modulate their scattering characteristics by applying external stimuli such as thermal and chemical biases have been suggested to enhance the complexity of the optical information visualization mechanism.[21–23] However, these approaches cannot take advantage of the ultrafast speed of photon-based data processing owing to their biased platform. Also, the encryption method is not sufficiently complex.

In this paper, we propose the unprecedented all-optical phase-change MH for dramatic enhancement of the encryption level of visual information while providing the ultrafast operation speed. The probe light (continuous-wave laser) is exploited to reconstruct the holographic image and the control light (pulse laser) is used as a thermal bias for phase change of metasurface that results in holographic image switching, that is, encryption and decryption of visual information. As the phase-change material, the chalcogenide glass Ge$_2$Sb$_2$Te$_5$ (GST)
is utilized that can reversibly switch its phase within the nanosecond time scale via applying the optical pulse signal. The GST has bistable phases called the amorphous and crystalline phases that exhibit large optical properties contrast. Thanks to its outstanding switching functionality, the various types of active metasurface exploiting GST have been demonstrated such as bifocal zoom lensing, vortex switching, holographic image switching, and so on. Though these devices provide high-contrast switching of optical information such as holographic image, the well-known switching mechanisms of GST make it hard for them to be applied to the field of cryptography. Here, the novel thermo-optical phenomenon to create a highly secured third stable state so-called hybrid state of GST metasurface is introduced. The hybrid state is a co-existence state of amorphous and crystalline GST meta-atoms is only creatable through applying specifically engineered control light source to the amorphous state GST metasurface. Furthermore, the novel hologram technique which generates deciphered visual information only in the hybrid state while providing ciphered information in the rest of the states is introduced. We call this three-level switchable phase-change metasurface the crypto-MH (Figure 1a). To design crypto-MH satisfying the above conditions, multiphysics analysis is done considering two important parts (Figure 1b). First, optical–thermal analysis is preceded to select the adequate size of GST meta-atoms that constitute crypto-MH. Second, based on selected meta-atoms, the hologram optimization process for reconstruction of the high-contrast dynamic holographic image is conducted through the unit cell structures design, and their arrangement optimization. Further details for meta-atom size selection, unit cell structure design, and arrangement optimization are dealt with in Section 2. The proposed crypto-MH assisted all-optical cryptography platform is expected to be applied to various information protection applications thanks to its ultrafast cryptographic optical data processing speed while providing high-security level encryption without a complex optical setup.

2. Results and Discussion

2.1. Nanorods Dimension Selection for Hybrid State Engineering

When the material is illuminated by the light, part of the light energy is lost through interaction with matter. The amount of lost energy is proportional to the inner product between the electric field and displacement current induced in the material which is heat generation density \( Q \) (\( W \text{ m}^{-3} \)). The \( Q \) affects temperature \( T \) of material as the following heat equation

\[
\rho C_v \frac{dT}{dt} = k \nabla^2 T + Q
\]

where \( C_v \) is volumetric heat capacity, \( k \) is the thermal conductivity, and \( \rho \) is density. This optically driven temperature increment can be usefully exploited when applied to metasurfaces that are composed of different shapes of temperature-dependent meta-atoms. Each meta-atom undergoes different scattering for incident light that results in different \( Q \) increment. Hence, meta-atom shape-dependent temperature increment can be induced even if the entire metasurface is illuminated by the uniform intensity of light.

In case when control light is incident on metasurface composed of different shape GST-based meta-atoms, the optically driven phase transition of each meta-atom occurs in a different manner: Some GST meta-atoms reach to phase transition temperature and the others do not. Therefore, when the appropriate condition of control light is incident to amorphous state GST metasurface, a co-existence state of amorphous and...
crystalline phase GST meta-atoms can be created. We call this phenomenon the selective crystallization and named this state as the hybrid state. In our study, an aluminum and GST stacked nanorod is utilized as a meta-atom of the metasurface. The thickness of each layer is set as 60 and 65 nm, respectively. The length of nanorod ($w_1$) is fixed to 330 nm and the period of single nanorods is 500 nm × 500 nm. And the pulse laser with a wavelength of 800 nm is exploited as a control light source. The polarization state is circular polarization (left circular polarization in this paper) to induce equivalent $Q$ for GST nanorods with an arbitrary rotation angle. And the beam profile is the flat-top shape rather than the Gaussian shape to ensure uniformly distributed illumination intensity to metasurface. To explore the possibility of selective crystallization, we interleave two different shapes of amorphous phase GST nanorods and calculate the $Q$ profile when the control light illuminates from the upper direction. The $Q$ profile in $xy$-plane perspective is observed in the middle of the GST part (Figure 2a). The width ($w_2$) of the left-side nanorod is 60 nm and that of the right-side nanorod is 150 nm. The calculation is conducted through the finite element method (FEM) in the periodic boundary condition. The calculated result shows an obvious $Q$ profile contrast between two nanorods. It means the selective crystallization can be induced once the appropriate energy of the control light is illuminated. To quantitatively compare the $Q$ difference according to nanorod dimension variance, the spatially averaged $Q$ of amorphous phase GST is calculated according to the variation of $w_2$ in the periodic boundary condition (Figure 2b). The power of the incident control light is set to 1 W. The calculated results show that the average $Q$ decreases as $w_2$ increases. And the inset of Figure 2b shows that the $Q$ is generated uniformly along the propagation axis of control light. It is noteworthy that $Q$ is barely induced in aluminum because most of the control light incident from the upper side is absorbed into GST following the Beer–Lambert law. For the more rigorous numerical demonstration of selective crystallization, the time-dependent temperature simulations is conducted based on calculated $Q$. Since the time-dependent FEM solution is required, the power profile of control light is defined as the following equation

$$P(t) = \frac{\ln 2}{\pi} \frac{2P_0}{\tau_p} \exp \left(-4 \ln 2 \frac{t^2}{\tau_p^2}\right)$$  \hspace{1cm} (2)$$

where $\tau_p$ is pulse width and $t$ is time.[25] Considering the computational load of the simulation, we assume single-pulse incidence condition and $\tau_p$ is set as 1 ns. The detailed simulation

![Figure 2. Optical–thermal analysis of GST nanorod. a) Schematic illustration of interleaved GST nanorods and its heat density profile in the condition of control light incidence. The heat density profile is observed in the middle of the GST part. b) Calculated average heat density of amorphous GST for control light incidence according to variation of $w_2$. The power of the incident control light is set to 1 W. The inset figure is a vertical plane (long-axis cut plane of left-side nanorod) heat density profile of GST nanorod observed in the center of nanorods. c) Calculated peak (temporal) average (spatial) temperatures of amorphous GST according to variation of $w_2$ and $P_0$. The white dotted line denotes the crystallization temperature of GST. And the condition of white circles denotes the selected size of nanorods and their required minimum power for crystallization.](image-url)
space and thermal properties of constituent materials are described in Section S1, Supporting Information. The spatially averaged temperature of the amorphous phase GST is calculated according to the variation of $w^2$ and $P_0$. The peak values of spatially averaged temperature are observed (Figure 2c). At the condition of the upper-left side of the dotted line which denotes crystallization temperature 423 K, we can assume that the GST nanorod is crystallized. On the other hand, the GST nanorod with the lower-right side condition keeps the amorphous phase. Based on the above assumption, two different sizes of nanorods corresponding to $w_2 = 60$ nm and $w_2 = 150$ nm are selected. The selected nanorods are referred to as N1 and N2 throughout this paper. Note that the required minimum $P_0$ for crystallization is $4.1 \times 10^{-13}$ W for N1 and $8.9 \times 10^{-13}$ W for N2 from the simulation results Figure 2c. It means that the required control light energy for crystallization is different for two nanorods. We call this energy difference region the hybridization energy that can induce selective crystallization when incident on metasurface composed of N1 and N2 (Section S2, Supporting Information).

To experimentally verify the simulation results, we construct a measurement setup and fabricate two metasurfaces that are distinguished by a constituent unit, N1, and N2 (Figure 3a). As a control light source, the femtosecond pulse laser (Mai Tai HP, Spectra-Physics) with 800 nm wavelength is utilized. For energy control, the combination of a half-wave plate, polarizing beam splitter, and circular polarizer is used. The half-wave plate modulates the power ratio of $x$-polarized light and $y$-polarized light. Then, polarizing beam splitter routes the $y$-polarized light to the blocker side while routing $x$-polarized light to the sample side. The number of pulses incident to the sample is fixed to $8 \times 10^4$ through considering the time interval of the motorized shutter (0.1 ms) and repetition rate (80 MHz) of control light source. To convert the polarization state of light routed to sample to left-circular polarization, the circular polarizer is used. And, we make use of a beam homogenizer that is composed of two microlens arrays and a planoconvex lens to make a spatial profile of control light as a flat-top shape. To confirm when phase transition of GST metasurfaces occur, the probe light with 1550 nm wavelength is utilized and its reflected light intensity is measured through an infrared camera. The power of control light that is routed to the sample is modulated through rotation of the half-wave plate. The half-wave plate is connected to the motorized controller that rotates the fast axis with an amount of $5^\circ$ at a time. At first, the initial fast axis is calibrated to send almost zero power of control light to the sample. And we rotate the half-wave plate nine times that result in fast axis variation ($\theta_f$) from 0° to 45°. It means the power routed to the sample increases following the function $\sin^2(2\theta_f)$ with ten discrete levels. The average power is measured through the power meter (OHM-6772B, Lightwave). We compare the reflected light intensity with simulation results to check whether the GST metasurface undergoes the phase transition (Figure 3b,c). From the results, the metasurface with N1 crystallizes when the average power with 1.06 W is applied to the sample. On the other hand, the crystallization of the sample with N2 occurs when a higher average power 2.26 W is applied. Hence, the metasurface that is composed of N1 and N2 can change its state from the amorphous to the hybrid state once control light with energy corresponding to average power between 1.06 and 2.26 W is incident.
In short, we introduce numerical and experimental demonstration about the method to create a third-stable state, that is, hybrid state GST metasurface, via optical–thermal analysis. Based on the demonstrated three-level switching of GST metasurface, the MH that provides high-contrast holographic image switching according to the state transition of GST is presented in Section 2.2.

Unfortunately, owing to the limitation of our control light source (weak power and the high repetition rate), the experiment about re-amorphization that requires the higher power and lower repetition rate optical pulse signal\(^{[25]}\) is not covered in this paper.

### 2.2. Hologram Design for Dynamic Image Encryption and Decryption

To take advantage of metasurfaces in the field of visual cryptography, it is required to design adjustable MH which provides the ciphered holographic image unless decryption conditions are satisfied. Here, based on the selected nanorods in Section 2.1, we design the three-level switchable MH that exploits the condition of control light inducing the hybrid state GST metasurface, as a decryption key. This MH, so-called crypto-MH, reconstructs the clear holographic image at a hybrid state while providing the perfectly damaged holographic image in the amorphous and crystalline states.

The crypto-MH is engineered through multiplying the binary computer-generated hologram (CGH) and the periodic square function whose amplitude can be dynamically switched through the phase transition of GST. The constituent number of pixels (unit cells) is \(200 \times 200\). The CGH is calculated through the weighted Gerchberg–Saxton algorithm to reconstruct the holographic image alphabet “\(S\)” and the binary values exhibit \(\pi\) optical phase difference\(^{[37,38]}\). The square function is arranged into a cross-configuration with a certain period \(\Lambda\) for both \(x\)- and \(y\)-direction. The constituent complex amplitudes of square function are \(A_p\) and \(A_p'\) whose subscript \(p\) means a state of GST metasurface (a is amorphous, \(h\) is hybrid, and \(c\) is crystalline state) (Figure 4a). Then, the complex amplitude profile of crypto-MH is determined as the following equation

\[
t(x, y) = \text{exp}(i \pi) \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \text{F}(k_x, k_y) e^{i(k_x x + k_y y)} \, dk_x \, dk_y \sum_{-\Lambda/2}^{\Lambda/2} \sum_{-\Lambda/2}^{\Lambda/2} C(n_x, n_y) e^{i(\frac{\Lambda}{2} + n_x \Lambda) + i(\frac{\Lambda}{2} + n_y \Lambda)}
\]

\[
C(n_x, n_y) = \frac{(A_p' - A_p)}{2\pi n_x n_y} (e^{i(\pi n_x \Lambda)} - e^{i(\pi n_y \Lambda)} + 1)
\]

\[
C(0,0) = \frac{A_p' + A_p}{2}
\]

\[\text{(3)}\]

whose \(F(k_x, k_y)\) is the Fourier transform of the CGH and the \(C(n_x, n_y)\) is the Fourier series of the square function. When the condition \(A_p = A_p'\) is met, the crypto-MH operates as a normal binary CGH that reconstructs a clear target holographic image “\(S\)” and its conjugate image (Figure 4b). This condition is a decrypted state that shows a clear target image in the detection area.

\[\text{Figure 4. Strategy for designing complex amplitude profile of crypto-MH. a) The complex amplitude profile of crypto-MH is the multiplication of the computer-generated hologram profile for reconstruction target image “\(S\)” and periodic square function for both \(x\)- and \(y\)-directions. b) The Fourier transform image of crypto-MH when condition } A_p = A_p' \text{ is met. c) The Fourier transform image when } \angle A_p - \angle A_p' = 2\pi/3 \text{ and } \Lambda = 20. \text{ The distance between the target image and the adjacent diffraction channel image is inversely proportional to } \Lambda. \text{ d) The Fourier transform image when } \angle A_p - \angle A_p' = 2\pi/3 \text{ and } \Lambda = 50. \text{ Owing to image overlap, the image distortion occurs at the detection area.}\]
area. In the other condition, the cross-talk images are generated at diffraction channels with intensity distribution corresponding to \( C(n_x, n_y) \) as shown in Figure 4c. We specify the conditions as \( \angle A_p - \angle A_p' = 2\pi /3 \) and \( \Lambda = 20 \) for calculation. The distance between the target image and cross-talk image at the first-order diffraction channel is inversely proportional to \( \Lambda \). Therefore, the image overlap occurs as the \( \Lambda \) increases, which results in image distortion (Figure 4d). This condition is an encrypted state that generates an unrecognizable ciphered image. Note that, the difference between \( A_p \) and \( A_p' \) is required to be sufficiently large for allocating energy to diffraction channels that induce image distortion. The degree of image distortion is defined as the root mean square error (RMSE) between the original target image and reconstructed image at the detection area after normalization of brightness. Therefore, the objectives in order to design crypto-MH that contains the well-protected visual image in the hybrid state GST metasurface, are cleared up as follows: 1) Design two phase-changeable unit cell structures that satisfy complex amplitude conditions \( A_p = A_p' \) and \( A_p \neq A_p' \) and design their \( \pi \) optical phase-shifted versions of each. 2) Based on the designed unit cell structures, select the optimized period \( \Lambda \) that exhibits near-zero RMSE for the hybrid state and large RMSE for the amorphous and crystalline states. 

For the probe light source of crypto-MH, the 1550 nm wavelength laser source is utilized. The polarization state of the probe light is right circular polarization and its reflected cross-polarized component is observed. Therefore, the unit cell structures with cross-polarized reflection coefficients (CPRC) \( A_p, A_p' \) are required as well as their optical phase-shifted versions of each. The unit cell structure that satisfies CPRC condition \( A_p \) is called S1, and the unit cell structure with CPRC \( A_p' \), is S2. Through rotating constituent meta-atoms of S1 and S2 by angle \( \pi /2 \), respectively, the \( \pi \) optical phase-shifted version of each can be designed by the principle of the Pancharatnam–Berry phase. The rotated version of S1 and S2 is called S1, and S2. As mentioned above, the objective for designing S1 and S2 is to meet condition \( A_p = A_p' \) and \( A_p \neq A_p' \). To achieve this condition, the S1 is optimized to exhibit large CPRC contrast between the hybrid state and the rest of the states. And the structure of S2 is adjusted to exhibit almost the same CPRC with CPRC of hybrid state S1 \( (A_p) \) while showing large CPRC deviations for the rest states of GST.

S1 is constructed through locating two N1 and N2 each into a 1 \( \mu \text{m}^2 \) scale unit cell structure with a cross-arranged configuration. The scattered electric field from S1 is determined by the summation of dipole sources that scatter electric fields from N1 and N2.\(^{[19]} \) Hence, cross-polarized electric field \( (E_{\text{cross}}) \) is determined by the following equation

\[
E_{\text{cross}} = e^{i2\pi} (r_1 + r_2e^{i2\pi})
\]  

where \( r_1 \) is the common rotation angle, and \( r_2 \) is the rotation angle difference between N1 and N2. The \( r_1 \) and \( r_2 \) are CPRC of N1 and N2, respectively, when the rotation angle is not considered. The calculated values of \( r_1 \) and \( r_2 \) for each phase of GST are shown in Figure 5a. The calculation for N1 and N2 is conducted in the periodic boundary condition with a period of 500 nm. From the calculation results, the assumption that \( r_1 = r_2 \) is reasonable for both amorphous and crystalline state GST. Under these assumptions, the abrupt \( \pi \) optical phase shift can be induced at the vicinity of \( \theta_1 = 90^\circ \) (Section S3, Supporting Information). On the other hand, in the hybrid state that N1 is the crystalline phase and N2 is the amorphous phase, the above assumption is not reasonable anymore. Hence, the dramatic optical phase shift cannot be induced at the vicinity of \( \theta_1 = 90^\circ \). To numerically confirm these conditions, we calculate the CPRCs by varying \( \theta_1 \) by 10° from 60° to 120° for each GST state of S1 (Figure 5b). Then the dramatic optical phase shift occurs when \( \theta_1 \) changes from 90° to 100° for both amorphous and crystalline states and not for the hybrid state. Hence, the condition of rotation angles of N1 and N2 is selected as \( \theta_1 = 0° \), and \( \theta_2 = 100° \) for satisfying the requirements of S1, that is, a large contrast between \( A_p \) and \( A_p' \).

For the next step, the S2 is designed through interleaving two N2s with different rotation angles and doubly sampling them with cross-arranged configuration to construct a 1 \( \mu \text{m}^2 \) scale unit cell structure. In case when two same dimension nanorods are placed in the sub-wavelength unit cell, the complex amplitude of cross-polarized light can be completely covered as the following equation

\[
E_{\text{cross}} \propto e^{i2\theta_1} + e^{i2\theta_2} = (e^{i(\theta_1-\theta_0)} + e^{i(\theta_2-\theta_0)}) e^{i(\theta_1+\theta_2)} = 2\cos(\theta_2 - \theta_1) e^{i(\theta_1+\theta_2)}
\]  

where \( \theta_1 \) and \( \theta_2 \) are the respective rotation angles of N2s that are different from each other.\(^{[40]} \) Hence, the strategy of adjusting the CPRC of hybrid state S2 \( (A_{p}) \) to CPRC of hybrid state S1 \( (A_p) \) is possible. We calculate the CPRCs of S2 in periodic boundary condition according to the variation of \( \theta_1 \) and \( \theta_2 \) when GST metasurface is in the hybrid state. From the simulation results, \( \theta_1 \) and \( \theta_2 \) are selected as 50° and −20° that meets the condition \( A_{p} = A_p \). Note that, because S2 is composed of only N2, S2 is a full amorphous state even when the GST metasurface is in the hybrid state: \( A_p \) is equal to \( A_p' \). The CPRC for the crystalline state S2 \( (A_{p}) \) is similar to \( A_p \) because \( r_2 \) exhibits almost the same value for each state of GST (Figure 5c). The CPRCs of \( A_p \) and \( A_p' \) are provided in Table 1.

Sequentially, the quality of the reconstructed holographic image (Fourier plain image) is assessed by calculating RMSE according to the variation of \( \Lambda \) based on CPRCs of designed unit cell structures. The RMSE is calculated for each state of the GST metasurface (Figure 5d). The RMSE values for the amorphous and crystalline states are highest when the \( \Lambda \) is 80 while exhibiting near-zero value for the hybrid state: The condition of \( \Lambda = 80 \) is desirable for the realization of high encryption level. Hence, the arrangement of the complex amplitude profile of crypto-MH is cleared up as shown in Figure 5e and their Fourier plane images for each state of crypto-MH are shown in Figure 5f.

For an experimental demonstration of our all-optical cryptography architecture, the crypto-MH is fabricated through an electron-beam lithography process and the optical measurement setup is constructed (Figure 6a). As the probe light source, the monochromated supercontinuum source with 1550 nm wavelength (Super K Select IR Tunable Filter, NKT Photonics) is exploited, and the circular polarizer is used to convert probe light to right circular polarized light. As a beam condenser, the combination of L1 and L2 is used. L2 acts as a Fourier
transform lens that forms the Fourier plane at the back focal plane. The target image plane, that is, the detection area of Fourier plane, is captured by an infrared camera (PA640F100TCL, NIP) through a 4-f imaging system. The image plane is switched with three levels through applying a control light source to crypto-MH as we experimentally proved in Section 2.1. The as-fabricated crypto-MH is the amorphous state that reconstructs the destroyed holographic image in the detection area. When we illuminate the control light with the energy of average power 1.5 W (called hybridization energy), the hybrid state crypto-MH, which is the co-existing state of crystallized N1 and amorphous phase N2, is created that reconstructs holographic image “S.” On the other hand, when the control light with over the hybridization energy corresponding to average power 2.5 W is incident to crypto-MH, the overall crystallization occurs that generates a destroyed holographic image (Figure 6b). In short, our all-optical cryptosystem experimentally provides decrypted information only when amorphous state crypto-MH is illuminated under the predefined condition of control light that satisfies the conditions of flat-top shape beam profile, circular polarization, and hybridization energy. For more durable operation of our crypto-MH, the SiO2 passivation layer can be easily adopted onto our metasurface to prevent degeneration induced by oxidation and thermal degradation.[28]

For the practical application of our crypto-MH to the visual cryptography system, the most desirable target image is the Quick Response Code (QR Code) that can contain a vast amount of information in a single image rather than simple letter “S.” Unfortunately, demonstration for QR Code image generation is not experimentally conducted owing to limitations of the numerical aperture of the Fourier transform lens and the sensor size of the infrared camera; QR Code image requires a wide range of spatial frequency space for high-resolution image

| Amplitude | \( A_a/A_a' \) | \( A_h/A_h' \) | \( A_c/A_c' \) |
|-----------|----------------|----------------|----------------|
| \( \theta \_d \) | 0.012/0.107 | 0.104/0.107 | 0.023/0.086 |
| \( \theta \_2 \) | -0.474/1.458 | 1.471/1.458 | -0.453/1.365 |
generation. If we can handle the abovementioned limitations of optical components, the target visual image can be changed from “S” to the QR Code by applying the crypto-MH design process straightforwardly.

Our work has great significance in that the switching functionality expansion method, that is, selective crystallization, of GST metasurface is introduced for the first time. Previously, there have been papers claiming multilevel switching of GST metasurface, but they relied on the partial crystallization of thick GST that cannot be quantitatively controlled owing to the nonprecise molecular dynamics of GST. Hence, their multilevel switchable functionality is limited to only spectrum modulation of input light that cannot be precisely predictable. On the other hand, our proposed GST metasurface can switch its state at will through applying specified conditions of control light as proven in Section 2.1. Therefore, apart from dynamic visual cryptography that proved in this section, other various multilevel switching devices can potentially be demonstrated such as an all-optical switch, router, and focus tunable lens.

3. Conclusion

In this paper, the design method of all-optical crypto-MH is introduced. First, optical–thermal analysis is preceded to find the condition of the control light source that can induce the hybridization of GST metasurface. Sequentially, the hologram optimization method is exploited to achieve high-contrast dynamic holographic image according to the state transition of GST metasurface: Optimized hologram generates an unrecognizable holographic image for the amorphous and crystalline states while reconstructs a clear target holographic image at the hybrid state. In other words, the crypto-MH provides deciphered visual information only when the hybridization of the GST metasurface is induced. As a proof of concept, the encryption and decryption of the target visual image “S” are demonstrated in both the numerical and experimental manner. The complex decryption mechanism of crypto-MH that requires multi-physical knowledge provides an unprecedented level of communication security. Even though the encryption level is dramatically increased, the advantage in the aspects of system compactness and communication speed is not degraded thanks to the large information capacity of our metasurface and inherent phase transition speed of GST. Our proposed all-optical crypto-MH is noteworthy in that it provides a novel type of hardware-assisted optical cryptography exhibiting outstanding functionality in every aspect.

4. Experimental Section

**Numerical Simulation:** Electromagnetic wave and heat transfer simulation results throughout this paper were performed by commercial software (COMSOL Multiphysics 5.3) based on the FEM. Periodic boundary conditions were used for x- and y-directions. The optical and thermal properties of constituent materials of meta-atom were dealt with at Section S1, Supporting Information. For temperature calculation, the time-transient solver was exploited and the time resolution was set to 0.3 ns.

**Device Fabrication:** Standard electron-beam lithography processes followed by the etching process were used. The aluminum was deposited on a quartz wafer using a thermal evaporator (MHS-1800, MUHAN) with a deposition rate of 1.5 Å s⁻¹. Amorphous phase GST film with 65 nm thickness was deposited consecutively using RF sputtering device (CS-200,
etched Ge$_2$Sb$_2$Te$_5$ with vertical etching profile while eliminating etching byproducts. Lastly, the BCl$_3$/Cl$_2$ plasma etched aluminum.

Supporting Information
Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest
The authors declare no conflict of interest.

Keywords
Ge$_2$Sb$_2$Te$_5$, holography, metasurface, optical cryptography, phase-change material

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