Polarization switching of thermal emissions based on plasmonic structures incorporating phase-changing material Ge$_2$Sb$_2$Te$_5$

YURUI QU, QIANG LI,* LU CAI, AND MIN QIU

State Key Laboratory of Modern Optical Instrumentation, College of Optical Science and Engineering, Zhejiang University, Hangzhou 310027, China

*qiangli@zju.edu.cn

Abstract: The ability to control the polarization of thermal emissions is important for fundamental science and many applications such as multichannel infrared emitters and chemical sensing. Most previous works on controlling the polarization of thermal emission are based on changing geometric sizes of the structures. The active control remains elusive so far. Here, we propose a design to actively switch the polarization of thermal emission. A metal-insulator-metal plasmonic thermal emitter with phase changing material Ge$_2$Sb$_2$Te$_5$ (GST) as the insulator is experimentally demonstrated. The thermal emitter with top GST and gold ellipses can excite third-order magnetic resonances with perpendicular polarization along both short radius and long radius. The polarization of the thermal emission can be rotated by 90° at 9.55 μm peak wavelength when GST phase changes from the amorphous phase to the 40% crystalline phase.

© 2018 Optical Society of America under the terms of the OSA Open Access Publishing Agreement

OCIS codes: (290.6815) Thermal emission; (160.3918) Metamaterials.

References and links


1. Introduction

The ability to control thermal emission has attracted growing interests in many applications including radiative cooling [1–3], thermophotovoltaics (TPV) [4–9], and thermal camouflage [10–12]. Thermal emission is a form of electromagnetic radiation and can be characterized by four fundamental properties: its emissivity, its frequency, its propagation direction and its polarization (apart from its phase). By controlling the geometric sizes of the structures, one can manipulate the emissivity and frequency [13–22], the propagation direction [23–26], and the polarization [27, 28] of the thermal emission. However, this method can only offer a static control over thermal emission.

Active control over emissivity and frequency has been demonstrated by changing carrier densities in materials (such as quantum wells [29], doped zinc oxide [30], and graphene [31]), mechanically changing the distance between the top metamaterial pattern and the bottom metallic film through applying heat [32], strain-induced buckling of the metallic layers [33], controlling the phases of phase changing materials such as vanadium oxide VOx [34], Ge$_2$Sb$_2$Te$_5$ (GST) [35–40], which is alloy of germanium (Ge), antimony (Sb), and tellurium (Te)). VOx behaves as an insulator at room temperature and changes into metallic state at above 343 K, and meanwhile its electrical resistivity varies from 0.1 to 3 × 10$^6$ Ω·m [41]. GST requires higher temperature (500 K for slow crystallization process and 750 K for fast crystallization process) for phase transition from amorphous phase to crystalline phase. The temperature distribution on a PCM cell can also be extracted using measured voltage-current characteristics and thermal modelling [42]. The electrical resistivity of GST sharply decreases during this phase transition process [43]. However, active control over the polarization or the propagation direction of thermal emission has remained elusive. Among them, switching the
polarization of thermal emission is one important aspect of active control, which can be used in many applications such as infrared thermal sources.

In this paper, we propose a method to switch the polarization of thermal emission based on a metal-insulator-metal (MIM) plasmonic thermal emitter consisting of phase changing material GST. Thermal emission polarization can be rotated by 90° at peak wavelength 9.55 μm when GST phase changes from the amorphous phase (termed as aGST) to the crystalline phase (termed as cGST) with a 40% crystallization fraction. Our design rests on the fact (i) that the thermal emitter with top GST and gold (Au) ellipses can excite third-order magnetic resonances with perpendicular polarization along both short radius and long radius and (ii) that the emission peak of the magnetic resonance excited along long radius at aGST phase coincides with that of the magnetic resonance excited along short radius at cGST phase with a 40% crystallization fraction at 9.55 μm wavelength.

2. Methods

2.1 GST/Au ellipse array fabrication

A 100-nm-thick Au film is deposited on a silicon substrate by magnetron sputtering. A 1.5-μm-thick photoresist (AR-P 5350) is then spun onto the Au film. The photoresist is exposed to define the nanohole array by photo lithography using a double sided mask aligner System (MA6 –BSA). The photoresist is then developed in 1:6 AR 300-26/ DI water followed by rinsing in DI water. After development, a 400-nm-thick GST and 100-nm-thick Au films are then deposited onto the sample by magnetron sputtering. The thermal emitter is realized after liftoff by ultrasonic processing in acetone for 1 minutes.

2.2 Numerical simulation

The corresponding simulated results were calculated by finite-difference time-domain method (FDTD Solutions v8.13, Lumerical). Light source was plane wave with amplitude 1 and phase degree 0. The wavelengths used were from 3 μm to 25 μm. Mesh sizes of the nanostructures were 140 nm for both x and y direction, and 20 nm for z direction. Simulation time was 50000 fs. Periodic boundary conditions for x and y directions, and perfectly matched layers for z direction were applied.

3. Results and discussion

The schematic of the MIM plasmonic thermal emitter is depicted in Fig. 1. The thicknesses of the bottom gold film, the intermediate GST ellipse and the top gold ellipse of the fabricated MIM thermal emitter are 100 nm, 400 nm and 100 nm, respectively. The array periodicity is 7 μm, and the long radius w1 (in y direction) and short radius w2 (in x direction) of the GST/Au ellipse are 4 μm and 3 μm, respectively. The total dimension of the nanostructure arrays is 10 × 10 mm2. The as-deposited GST is at the amorphous phase, as shown in Fig. 1(a). The 40% crystalline GST can be obtained by annealing it at 200 °C on a hot plate, as shown in Fig. 1(b). The relative permittivity of GST (2.5-15 μm) are obtained experimentally from the fabricated GST films [36], and the permittivities used in simulation (2.5-25 μm) are obtained by fitting experimental permittivities based on multi-coefficient models (MCMs) in FDTD Solutions. The 40% crystallization fraction is estimated by comparing experimental thermal emission peaks with the simulated peaks under different crystallization fractions in this paper. Other methods can also be used to estimate the crystallization ratio. One is to measure the resistivity during the phase changing process [43]. Another is to measure X-ray diffraction (XRD) patterns of GST film [44, 45]. Thermal emission polarizations have two orthogonal basis vectors: electric field E1 along long radius w1 (equivalent to magnetic field Hl along short radius) and electric field E2 along short radius w2 (equivalent to magnetic field Hl along long radius). For aGST-based thermal emitter, the dominant polarized thermal emission is
along long radius \( w_1 \) (in \( y \) direction). For 40\% cGST-based thermal emitter, the dominant polarized thermal emission is along short radius \( w_2 \) (in \( x \) direction).

![Diagram of polarization-dependent thermal emission](image)

**Fig. 1.** Schematic depiction of polarization-dependent thermal emission in the normal direction of the MIM thermal emitter incorporating (a) amorphous and (b) 40\% crystalline phase-changing material GST. \( E_L \) and \( E_S \) represent electric fields along long radius and short radius, respectively. For aGST-based and cGST-based thermal emitter, the dominant polarized thermal emission is along long radius \( w_1 \) (in \( y \) direction) and short radius \( w_2 \) (in \( x \) direction), respectively. Inset: an SEM image of the fabricated MIM thermal emitter.

The emissivities of the MIM thermal emitter in the normal direction are investigated in experiments (Fig. 2(a)) and simulations (Fig. 2(b)). The emission spectra are measured by a Fourier transform infrared spectrometer (FTIR) with a room-temperature doped triglycine sulfate (DTGS) detector. The black soot, which has high wavelength-independent emissivity, is chosen as a perfect reference. The relative permittivity of gold is obtained from Palik’s handbook [46]. According to Kirchhoff’s law of thermal radiation, the thermal emissivity of the sample is equal to its absorptivity [47], so the simulation is done by calculating the absorptivity.

For experimental results, there are two resonances corresponding to different polarizations for the aGST thermal emitter. The emission peaks at 8.31 \( \mu \)m with an emissivity of 0.15 and at 9.60 \( \mu \)m with an emissivity of 0.085 correspond to \( E_S \) and \( E_L \) polarization, respectively. For 40\% cGST thermal emitter, the emission peak at 9.32 \( \mu \)m with an emissivity of 0.097 corresponds to \( E_L \) polarization and 10.56 \( \mu \)m with an emissivity of 0.06 corresponds to \( E_S \) polarization. For simulated results, the peak wavelengths of aGST thermal emitter at two polarizations are 8.43 \( \mu \)m (with an emissivity of 0.66) and 9.55 \( \mu \)m (with an emissivity of 0.36), indicated by “A” and “B” in Fig. 2(b), respectively. For cGST thermal emitter, the peak wavelengths at two polarizations are 9.52 \( \mu \)m (with an emissivity of 0.31) and 10.78 \( \mu \)m (with an emissivity of 0.18), indicated by “C” and “D” in Fig. 2(b), respectively. When GST is in the amorphous phase, the thermal emission at \( E_L \) polarization is dominated at 9.55 \( \mu \)m wavelength. When GST gradually changes from aGST to cGST, the emission peak shifts to longer wavelength due to the increased real part of refractive index. When GST comes to a 40\% crystallization fraction, the thermal emission at \( E_S \) polarization is dominated at 9.55 \( \mu \)m wavelength. Therefore, the dominated emission polarization can be switched from \( E_L \) polarization to \( E_S \) polarization at 9.55 \( \mu \)m wavelength by controlling the GST phase.

The magnetic field patterns for the aGST and cGST thermal emitters at two polarizations are further investigated (A-D in Fig. 2(c)). The magnetic field is confined to the intermediate GST ellipse between the top Au ellipse and the bottom Au layer, signifying that a typical three-order magnetic resonance is generated. From the field patterns, we can see that all peaks (“A”–“D”) are the three-order magnetic resonances. The measured peak emissivities are
generally lower than the simulated ones for both aGST and 40% cGST thermal emitters because of the rough disk boundaries owing to the imperfection in fabrication (inset in Fig. 1(b)) and the error in fitting experimental permittivities based on multi-coefficient models (MCMs) [48].

Fig. 2. (a) and (b) are experimental and simulated thermal emissivities of the MIM thermal emitter, respectively. The black and red lines are for the aGST phase at polarization $E_s$ (electric field along short radius) and $E_l$ (electric field along long radius), respectively. The blue and green lines are for the cGST phase with a 40% crystallization fraction at polarization $E_s$ and $E_l$, respectively. When GST is at the amorphous phase, the thermal emission at $E_l$ polarization is dominated at 9.55 $\mu$m wavelength. When GST has a 40% crystallization fraction, the thermal emission at $E_s$ polarization is dominated at 9.55 $\mu$m wavelength since the emission peak wavelength shifts to longer wavelength due to the increased refractive index. (c) A-D represent the field at the peak wavelength of aGST and cGST thermal emitters at two polarizations. The colormaps represent the amplitude of magnetic field $|H|$.

Thermal emission polarization switching based on GST phases is explored in Fig. 3. To obtain the corresponding emissivities, the sample and the black soot are measured under the same conditions. Polarization-dependent emissivities are measured as a function of polarization angle from 0° to 360° in around 13° steps. The emissivities of different polarization angles at peak wavelength 9.55 $\mu$m are extracted from polarization-dependent emission spectrum. Both experimental and simulated thermal emission polarization angles at peak wavelength 9.55 $\mu$m rotate by 90° when GST changes from aGST to cGST with a 40% crystallization fraction. Degree of polarization (DOP) is used to describe the portion of an electromagnetic wave which is polarized. Degree of polarization (DOP) is defined by $(e_{\text{MAX}}$ -
\[ \frac{\varepsilon_{\text{MIN}}}{(\varepsilon_{\text{MAX}} + \varepsilon_{\text{MIN}})} \] where \( \varepsilon_{\text{MAX}} \) and \( \varepsilon_{\text{MIN}} \) are the maximum and minimum emissivities at two orthogonal angles [27]. A perfectly polarized wave has a DOP of 1, whereas an unpolarized wave has a DOP of 0. The measured polarized thermal emission has a DOP of 0.44 and 0.35 for the aGST and cGST thermal emitters, respectively (Fig. 3(a) and 3(b)). The simulated polarized thermal emission has a DOP of 0.82 and 0.74 for aGST and cGST thermal emitter, respectively.

To further explore the origins of thermal emission polarization rotation, the emissivities as functions of polarization angle and emission wavelength are calculated and measured. For aGST, mode A and mode B come from the three-order magnetic resonance excited along the elliptical short radius and long radius, respectively (Fig. 4(c)). Mode A gradually shifts to mode C at longer wavelength when GST changes from aGST to 40% cGST (Fig. 4(c) and 4(d)), because the crystallized GST has larger refractive index than that of aGST. Mode B goes through the same process. The thermal emission polarizations of mode B and mode C are perpendicular to each other because these two modes originate from the resonances along long radius and short radius, respectively. The experimental emissivities are in agreement with the simulated emissivities (Fig. 4(a) and 4(b)).
4. Conclusions

In conclusion, we introduce a MIM plasmonic thermal emitter incorporating phase changing material GST, which can switch the polarization of the thermal emission. The magnetic resonance excited along long radius at aGST phase coincides with the magnetic resonance excited along short radius at cGST phase at 9.55 μm wavelength. Therefore, thermal emission polarization can be rotated by 90° at 9.55 μm peak wavelength when GST changes from aGST to cGST with a 40% crystallization fraction. The phase transition of GST from crystalline to amorphous (reamorphization) can be achieved by laser pulse (fs or ns) [49–52] or electrical pulse [53, 54]. The required power and temporal variation of temperature of GST layer during the phase transition have also been investigated [55, 56] and is useful for optical and electrical switching. This MIM plasmonic thermal emitter paves the way towards the active thermal emission control in fundamental science and can significantly benefit a number of multichannel infrared emitters and chemical sensing.
Funding

National Key Research and Development Program of China (Nos. 2017YFA0205700 and 2017YFE0100200); National Natural Science Foundation of China (Grant Nos. 61425023, 61575177 and 61775194).