Tunable Metasurface for Phase Modulation Based on Silicon Nanobars and Phase Change Material

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***Abstract*—We propose an optical tunable metasurface based on an array of silicon nanobars and a phase change material layer. The device can achieve a wide phase modulation range (~ 2 rad) with low reflectivity variation (under 20%).**

Keywords—metasurface, tunable, phase change material, low reflectivity variation

I. Introduction

Over the years, optical devices controlling the phase and amplitude of light have been widely investigated to manipulate the light-wavefront, which are essential in optical phased arrays (OPAs) [1]. Among those optical devices, optical metasurface, as a subwavelength array, have attracted extensive attention due to their advantages such as small size and low cost [2,3]. For the optical metasurface, the modulation of light can be achieved by tuning active materials on metasurfaces. Recently, a great variety of active materials, such as transparent conducting oxides [4], liquid crystal (LC) [5], III-V semiconductor materials [6], and phase change materials (PCMs) [7], have been proposed to be integrated on the metasurface. Among the above mentioned active materials, PCM has the best balance between the tuning speed and the efficiency, so it has aroused widespread interest among researchers.

Currently, many kinds of metasurfaces based on PCM have been proposed to modulate the phase of light. A large range of phase modulation is demonstrated using an electrically tunable VO_2-based reflectarray metasurface [8]. However, the reflectivity of this device is very low, only about 20%. To solve the problem, a tunable metasurface based on $Ge_2Sb_2Te_5$ (GST) has been proposed [9], which enables a wide range of phase modulation with average reflectivity ~50%. However, it's lowest reflectivity is only 30%. And, during the phase modulation of the light, the reflectivity variation exceeds 150%.

To solve the above issue, we propose a metasurface based on an array of silicon (Si) nanobars and a GST layer. In this device, a large range of phase change ~2 rad can be obtained while the reflectivity variation is low (under 20%). In addition, the device can maintain low power consumption due to the non-volatility of GST. Furthermore, the device has a small size ~ 5 μm, which will be more conducive to integration. Therefore, we believe that such phase-changed merasurface is very promising in the field of wavefront control of light.

II. Design and Principle

The structure of the tunable metasurface is shown in the Fig. 1. The tunable metasurface is composed of an Au back reflector, a silicon dioxide (SiO_2) layer, an array of Si nanobars and a GST layer. As shown in Fig. 1, the SiO2 layer has a thickness (h_{SiO2}) of 2.45 μm and the Au back reflector is set at the bottom of SiO_2 layer to reflect light. An array of Si nanobars is immersed in the homogeneous SiO_2 environment. The array of Si nanobars has a period (*P*) of 630 nm , a width (*W*) of 400 nm and a height (h_{Si}) of 25 nm. Then, a PCM layer is placed on the top of the SiO_2. The distance between the PCM layer and the array of Si nanobars is 275nm. And the thickness of GST layer (h_{GST}) is set to 20 nm. Note that, the GST induced absorption loss can be effectively reduced since the GST layer is thin.

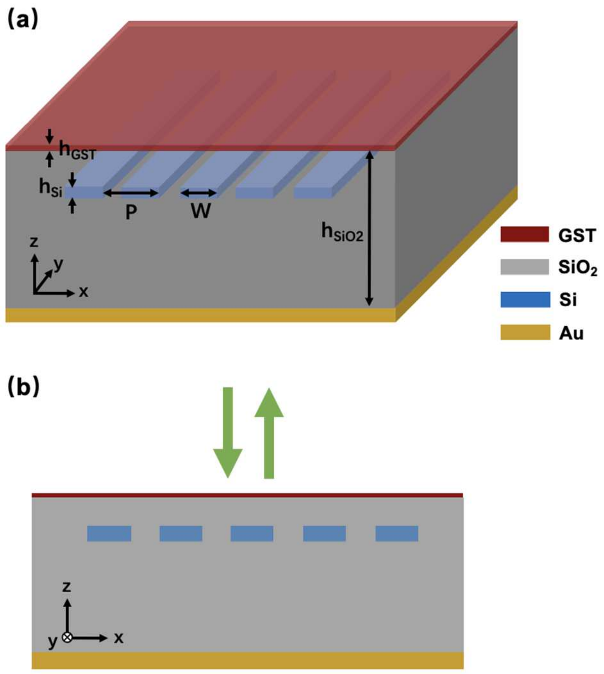

Fig. 1. The structure of the tunable metasurface based on an array of Si nanobars and a GST layer.

In the device, the phase modulation can be obtained for the reflected light. As shown in Fig. 1(b), normal incident light can be reflected in such device. Meanwhile, the refractive index of GST can be altered by changing the crystallization rate of GST. This could introduce a phase change on the reflected light and thus the phase modulation of reflected light can be performed.

To analyze the modulation process, we first use a classic model to calculate the real and imaginary parts of the refractive index of GST, which can be expressed as [10]:

$$\frac{\varepsilon_{eff}(p)-1}{\varepsilon_{eff}(p)+2} = p \times \frac{\varepsilon_c - 1}{\varepsilon_c + 2} + (1-p) \times \frac{\varepsilon_a - 1}{\varepsilon_a + 2} \quad (1)$$

where ε_c、 ε_a are the complex permittivity of cGST and aGST measured by ellipsometry, and p is the percentage of crystallization. Thus, p=0% corresponds to the fully aGST phase while p=100% corresponds to the fully cGST phase. The complex refractive index of the GST mesophase can then be calculated by $\sqrt{\varepsilon} = n + ik$.

Based on the above model, we study the reflectance spectra at different GST crystallization rates by using Finite-Difference Time-Domain (FDTD) simulations. As shown in Fig. 2(a), the calculated transmission spectra for two different crystallization rates are presented. One can find the reflectivity changes a little when the crystallization rate is 0%, since the absorption loss from aGST is low. Then, when crystallization rate increases to 50%, the notch wavelength will be shifted and the change of reflectivity will be larger. The corresponding phase change spectrum is shown in Fig. 2(b). For each spectrum, a phase change of 2π can be obtained in the simulated wavelength band. This indicates that the device works in the over-coupling condition under both two crystalline states. Thus, for a fixed wavelength in the simulation wavelength band, one can clearly find that the intensity and the phase of the reflected light can both be changed by tuning the crystalline rate of the GST material. And thus, a strong phase modulation can then implemented.

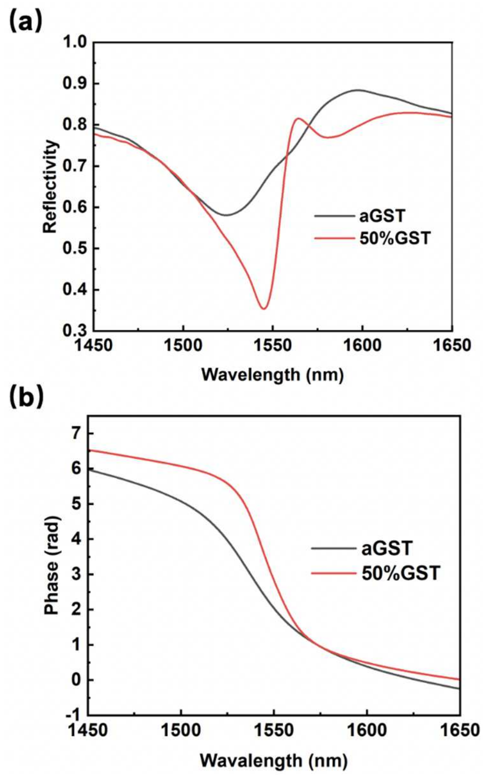

Fig. 2. Reflection spectra and phase change spectra of the device under different GST crystallization rates.

III. Results

In the application of OPA, a large phase change and a low reflectivity variation are highly desired. In the device, we thus set the light wavelength to 1530 nm and simulate the phase modulation performance of the device under different crystallization rates of GST. As shown in Fig. 3(a), the normalized electric field strength of the reflected light changes from 0.76 to 0.7 when the crystallization rate changes from 0% to 50%. Meanwhile, a strong phase change of the reflected light is obtained ~2 rad in the process, as shown in Fig. 3(b). These results show that our device can achieve a large range of phase change while keeping the reflectivity almost unchanged. Note that, the length of our device is only 5 μm in the direction of the x-axis . Such strong phase change and a small size would make the device useful in OPA.

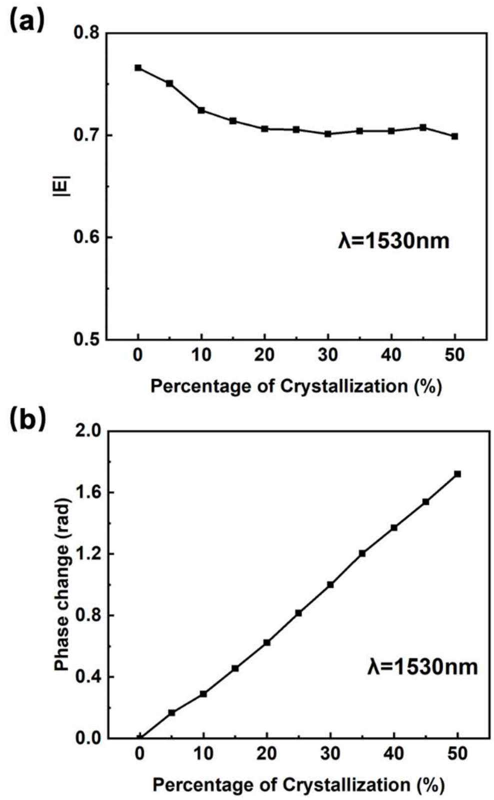

Fig. 3. The normalized electric field strength and phase changes of the reflected light under different GST crystallization rates.

IV. Conclusion

In summary, we propose an optical tunable metasurface based on an array of Si nanobars and a GST layer. The device can achieve a strong phase modulation of about 2 rad while keeping the reflectivity variation lower than 20% at 1530 nm. It is worth noting that due to the structure's small size and non-volatility, this structure is very beneficial for integration and low power consumption. We believe that this optical tunable metasurface with low reflectivity variation can be applied in highly integrated OPAs.

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