Miniature Silicon Nanobeam Resonator Tuned by GST Phase Change Material

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Abstract: We report a silicon optical nanobeam resonator with central hole infiltrated with a thin layer of $Ge_2Sb_2Te_5$ (GST) material. The resonances can be tuned when the GST changes its phases between the amorphous and crystalline states.

OCIS codes: (130.4815) Optical switching devices; (160.2900) Optical storage materials; (230.3120) Integrated optics devices; (250.6715) Switching.

1. Introduction

The active tuning of silicon photonic devices is usually realized by the thermo-optic (TO) effect or the electro-optic (EO) effect based on free-carrier injection [1, 2]. The refractive index tuning range is in the order of 0.01 and 0.001 for these two effects, respectively. Thus, in order to obtain a π phase change, a relative long waveguide of 100's μm to mm length is required. The tuning also consumes significant electrical power, given that the raised temperature in TO tuning or the electric current in EO tuning needs an external voltage source to maintain. In a photonic integrated circuit, the device size and power consumption gradually become the bottleneck for its further scaling-up in integration density. It is highly demanded to find a more efficient tuning method that should possess both high tuning efficiency and low power consumption. The $Ge_2Sb_2Te_5$ (GST) material, as a phase change material (PCM) commonly used in optical storage, exhibits distinct optical properties between its amorphous and crystalline states [3]. This feature can be utilized to manipulate light propagation and implement non-volatile optical devices [4, 5].

Here we present a nanobeam resonator structure with the GST as the active tuning material. A nanometer-size GST layer is enough to induce a large optical transmission power change at the resonance wavelength. The structure points to new ways of creating energy-efficient and miniature tunable optical components towards large-scale Si-PCM hybrid integration.

2. Device structure and simulation

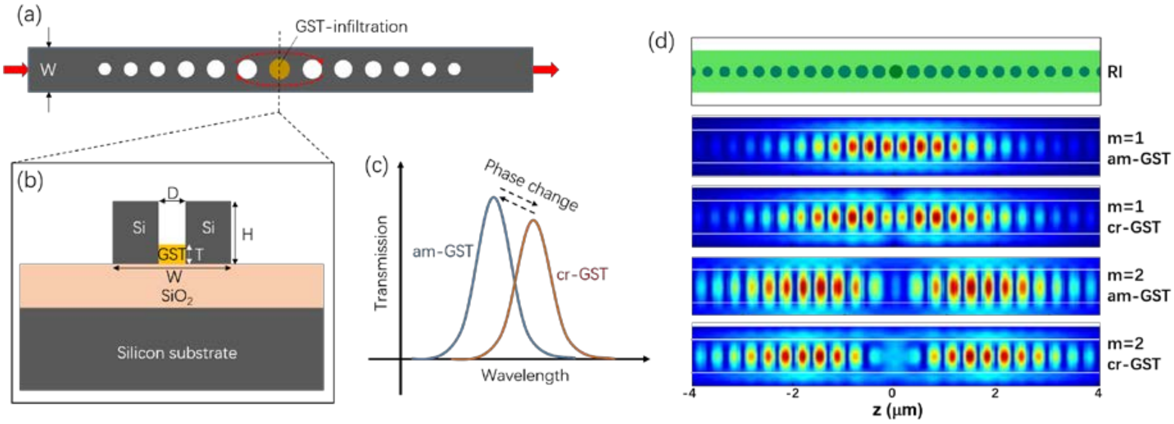

Fig. 1. (a) Schematic structure of the silicon nanobeam resonator. The center hole is infiltrated with GST. (b) Cross-section of the nanobeam waveguide. (c) Schematic illustration of the resonance tuning by GST upon phase change. (d) Simulated electric field |E| distribution at the top surface of the nanobeam resonator for the two lowest-order resonance modes.

Figure 1(a) shows the nanobeam resonator which is essentially a 1D photonic crystal waveguide with a sequence of holes etched in the silicon waveguide. The hole diameter first increases and then decreases with a symmetric arrangement along the waveguide. The center largest hole is infiltrated with a layer of GST as illustrated in Fig. 1(b). There is no additional cavity length in the nanobeam waveguide center. The holes have an equal separation spacing. High-Q resonances are formed by setting a quadratic tapering profile for the holes with linearly increasing and decreasing mirror strength along the waveguide [6]. The nanobeam resonator possesses dielectric resonance modes, implying that the optical energy is mostly concentrated in the silicon region. The optical field inside the hole is weak yet can still sense the refractive index variation of the GST material upon phase change. Therefore, the resonance can be tuned by the GST material, as schematically illustrated in Fig. 1(c). Change in the real and imaginary parts of the GST complex refractive index induces resonance wavelength shift and peak transmission variation, respectively. The phase change is bi-directional, making the tuning repeatable in both forward and backward directions.

Figure 1(d) shows the simulation results. The nanobeam waveguide width is W = 750 nm and the height H = 220 nm. The pitch of the holes is 330 nm, and the filing factor (hole area occupation ratio) reduces from 0.18 in the center to 0.09 towards the two ends. The first two longitudinal modes (m = 1, 2) have distinct optical field distribution profiles in the nanobeam resonator. The first mode has a higher optical confinement and the optical field reaches the maximum in the nanobeam center, while the second mode has a weaker confinement with a field trough in the center. They hence have different responses to the GST phase change, affected by the overlap between resonance mode and GST material.

3. Experimental results

The silicon nanobeam waveguide was fabricated using e-beam lithography (EBL) followed by reactive ion etch (RIE). The GST was deposited using radio-frequency (RF) sputtering and patterned with the lift-off method. Figure 2(a) shows the scanning electron microscope (SEM) image of the entire nanobeam waveguide. The design parameters are the same with those used in the simulation. Figures 2(b) and 2(c) are the zoom-in SEMs showing the center hole in the nanobeam. The bottom of the hole is covered with a GST film with a thickness of ~100 nm. The phase change from the as-deposited amorphous state to the crystalline state was induced by injecting a sequence of 10-μs-wide optical pulses (-5 dBm peak power) into the nanobeam cavity at the resonance wavelength.

Figure 2 shows the measured transmission spectra of the nanobeam resonator when GST switches from the amorphous to the crystalline state. Two resonance modes are observed in the broad stopband, with the Q-factor being ~14000 and ~4200 at the am-GST state. The high-Q mode experiences a larger resonance shift and a higher peak loss than the low-Q mode as expected from the simulation. The on-off switching extinction ratio at 1543.1 nm wavelength is >10 dB.

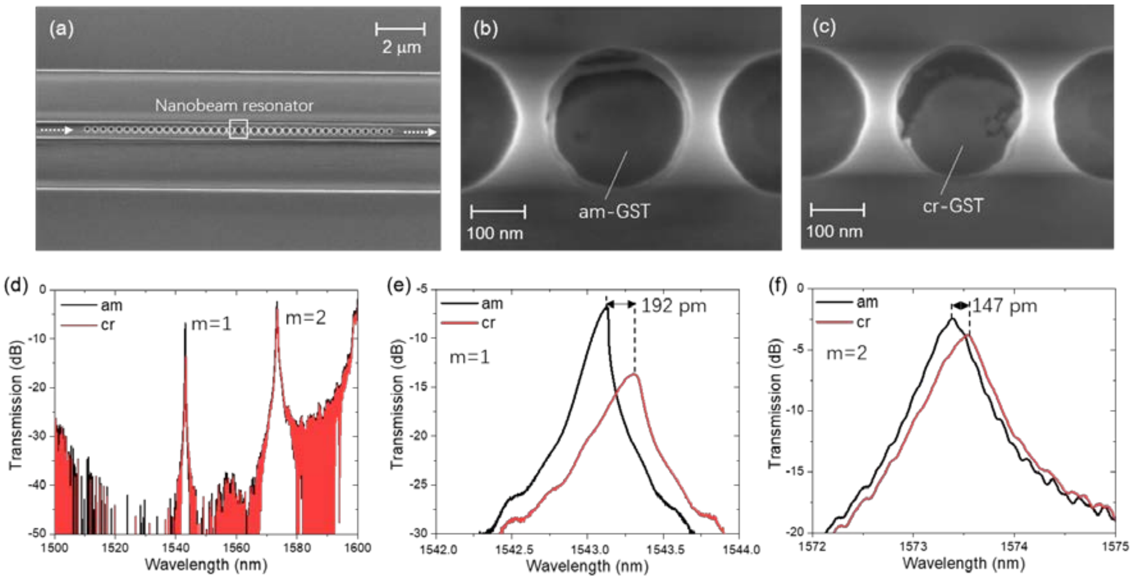

Fig. 2. (a) SEM image of the fabricated nanobeam resonator. (b) and (c) Zoom-in SEM images of the nanohole infiltrated with GST material when it is in the (b) amorphous and (c) crystalline states. (d) Measured transmission spectrum of the nanobeam resonator. (e) and (f) Magnified spectra showing the resonance peaks for two modes with (e) m = 1 and (f) m = 2.

4. References

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