Energy-efficient nonvolatile switching of silicon microring resonator with suspended phase-change waveguide

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***Abstract*—We have proposed and designed a partially suspended silicon microring resonator (MRR) to improve the energy efficiency for inducing phase change of Sb_2Se_3. Only 10.8 nJ is required to amorphize the Sb_2Se_3, about half of that for a nonsuspended MRR.**

***Keywords*—energy-efficient, microring resonator, suspended waveguides, Sb_2Se_3**

I. Introduction

Phase change materials (PCM), such as GST [1] and Sb_2Se_3 [2] have been under extensive investigations for implementation of nonvolatile and reconfigurable integrated photonic devices and circuits. Nonvolatility is highly desired for applications such as photonic switching and computing. However, the phase change of such materials require thermal quenching and annealing processes that consume considerable energy. For example, 620 °C is required for Sb_2Se_3 to be amorphized, which consumes tens of nJ of thermal energy in silicon photonic devices with doped heaters [3]. The energy consumption should be significantly reduced to enable large-scale photonic circuits [4].

To improve the energy efficiency, we have proposed to drastically decrease the thermal dissipation by removing the buried oxide (BOX) layer below the waveguide with PCM, so that a section of the waveguide becomes suspended in air. Because of the low thermal conductivity of the air compared with the BOX layer, the proposed device with suspended PCM waveguide is much more energy-efficient.

Here we have proposed and simulated the structure of a partially suspended microring resonator (MRR) with a small piece of PCM on top. In_2O_3 electrodes are employed to electrothermally induce the phase change of Sb_2Se_3. The simulation results show that only 10.8 nJ is required to amorphize the Sb_2Se_3, which is only about half of that for a nonsuspended MRR of otherwise the same design. Our simulations have validated the improved energy efficiency of reconfigurable photonic device with suspended PCM waveguides, which paves the way to highly scalable photonic switching and computing.

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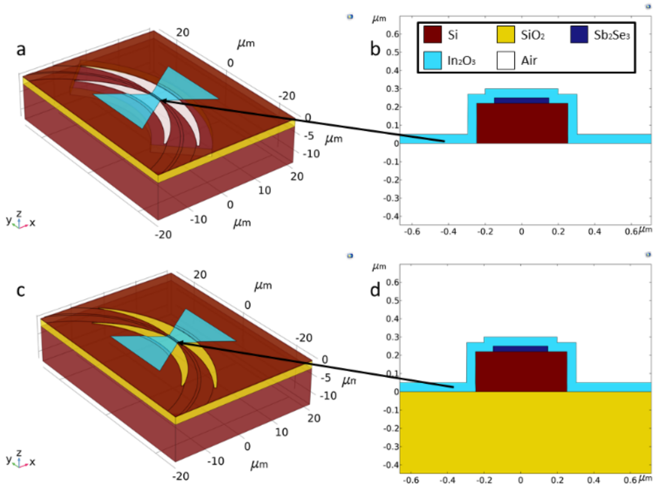

Fig. 1. (a) Structure and (b) cross section of partially suspended microring. (c) Structure and (d) cross section of non-suspended microring.

II. Structure and Simulation

The structure of our partially suspended MRR is shown in Fig. 1a, with the cross-section in Fig. 1b to show the position of Sb_2Se_3. Only the part of the MRR with Sb_2Se_3 on it is suspended because the temperature is the highest here during the phase change of Sb_2Se_3. For the rest of the MRR, shallow-etched waveguide is used as a hard mask to prevent the vapor of hydrofluoric acid to undercut the waveguide. In order to covert the mode in shallow-etched waveguide into/from the mode in suspended waveguide efficiently, two curved adiabatic tapers are used. In_2O_3 electrodes are patterned directly on top of Sb_2Se_3 as a heater. In order to show the improved energy efficiency of the suspended waveguide, we have also simulated the MRR without the suspended waveguide for comparison. The nonsuspended structure is shown in Fig. 1c and the cross-section is also shown in Fig. 1d. The only difference of the two MRRs is whether the waveguide with Sb_2Se_3 on it is suspended or not. The geometry parameters of the designed MRR are summarized in TABLE I. From [5-8] and our own measurement, the material parameters are determined as summarized in TABLE II.

We have used COMSOL Multiphysics for the electrothermal simulation. The results are shown in TABLE III and Fig. 2. Stationary simulation results are shown as Result a and Result b in TABLE III for suspended and nonsuspended MRRs, respectively. The corresponding temperature distribution are shown in Fig. 2a and Fig. 2b. We use the same voltage (2 V) for both kinds of MRRs. Since the heaters in both kinds of MRRs are the same, the current is also the same (2.2 mA). Result a indicates that, for partially suspended microring, the temperature of the Sb_2Se_3 reaches 529 K, which is higher than Sb_2Se_3 crystallization temperature (200 °C) [3], so that Sb_2Se_3 can be crystallized after sufficient heating time. While in Result b, for nonsuspended MRR, the temperature of the Sb_2Se_3 can only reach 351 K, so that Sb_2Se_3 cannot be crystallized. Time-dependent simulation results for electrical pulses are shown as Result c and Result d in TABLE III. The corresponding temperature distribution are shown in Fig. 2c and Fig. 2d. We use the same pulse duration (100 ns) and the same voltage (10 V), resulting in the same current (10.8 mA). Result c indicates that, for the partially suspended MRR, the temperature of the Sb_2Se_3 reaches 911 K, which is higher than the Sb_2Se_3 melting point (620 °C) [3], so that Sb_2Se_3 can be amorphized. While in Result d, for the nonsuspended microring, the temperature of the Sb_2Se_3 can only reach 581 K, so that Sb_2Se_3 cannot be amorphized.

Therefore, for both stationary and pulsed heating, the partially suspended MRR reaches much higher temperature than the non-suspended MRR, validating the significantly improved energy efficiency of the former than the latter. Only 10.8 nJ is required for amorphizing the Sb_2Se_3 in the partially suspended MRR.

TABLE I. GEOMETRY PARAMETERS

Name	Parameter
Silicon height	0.22 μm
Silica height	2 μm
In_2O_3 height	50 nm
Sb_2Se_3 height	30 nm
Sb_2Se_3 length	4 μm
Suspended waveguide width	0.5 μm
Shallow-etched waveguide width	0.7 μm

TABLE II. MATERIAL PARAMETERS

σ: electrical conductivity C_p: heat capacity at constant pressure
ε_r: relative permittivity ρ: density k: thermal conductivity

Material	σ (S/m)	C_p (J/(kg*k))	ε_r (1)	ρ (kg/m^3)	k (W/(m*K))
Silicon	$1*10^{-12}$	700	11.7	2329	130
Silica	$1*10^{-14}$	703	3.75	2203	1.38
In_2O_3	$6*10^4$	340	3.9	7100	11
Sb_2Se_3	$7*10^{-2}$	636	29	5843	3

TABLE III. SIMULATION RESULTS OF DIFFERENT MICRORINGS

t: heating time U: voltage I: current ∞: infinity

No.	Suspended	t (ns)	U (V)	I (mA)	Sb_2Se_3 temperature (K)
a	Yes	∞	2	2.2	529 K
b	No	∞	2	2.2	351 K
c	Yes	100	10	10.8	911 K
d	No	100	10	10.8	581 K

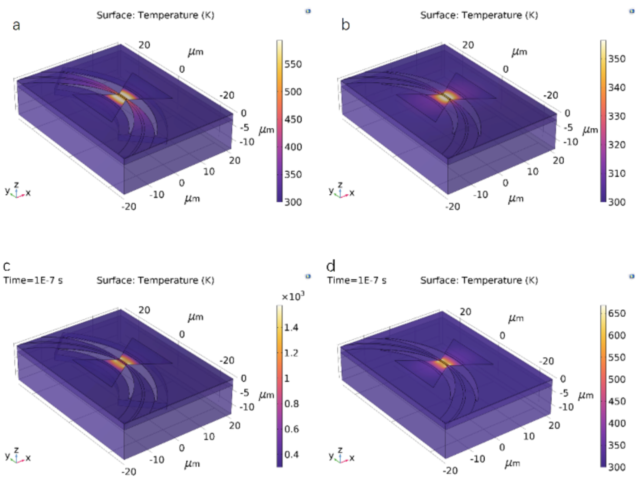

Fig. 2 Temperature distribution of the microrings mentioned in TABLE III

III. CONCLUSION

In conclusion, we have proposed and designed a partially suspended MRR. The suspended waveguide is used to decrease the thermal dissipation to reduce the energy consumption. Simulation results show that for both stationary and pulsed heating, the temperature of the partially suspended MRR is much higher than the nonsuspended one, validating the significantly improved energy efficiency. Only 10.8 nJ is required to amorphize the Sb_2Se_3, which is only about half of that for a nonsuspended MRR of otherwise the same design.

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