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RESEARCH ARTICLE

Thermal analysis for fast thermal-response Si waveguide wrapped by SiN

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Abstract A new type of Si waveguide wrapped by silicon nitride (SiN) is designed, and its optical and thermal analysis are presented. The thickness of SiN up-cladding should be larger than 1 μm in order to prevent the absorption of optical field by metal heater. Thermal response of the proposed waveguide structure is enhanced by the high thermal conductivity of SiN. Moreover, this thermal response can be further improved by a fast heat dissipation channel created in this structure. Our simulation results indicate that a rise time of about 110 ns can be achieved for the proposed waveguide structure, which is about two orders of magnitude less than that of the conventional Si waveguide. The influences of the thickness of up-cladding and the stretching width and etching depth on the thermal performance are also discussed. The simulation shows thin up-cladding, large stretching width and etching depth are critical to enhance the thermal response speed.

Keywords thermo-optic, SiN, Si, waveguide, rise time

1 Introduction

Silicon-on-insulator (SOI) is a popular material platform for photonic devices and photonic integrated circuits. Due to its large thermo-optic coefficient and high thermal conductivity, many silicon thermo-optic devices have been designed and fabricated [1–5]. Conventional Si waveguide is wrapped by silica (SiO_2), which has a very low thermal conductivity (k = 1.27 W/(m·K)) [6], thus its thermal response is very slow. The rise time of the conventional Si waveguide is usually several microseconds [3,7], which seriously affects its application in high-speed photonic devices. However, SiN can be fabricated with a complementary-metal-oxide-semiconductor compatible process, it has a relatively low refractive index (n = 1.91 at 1.55 μm) and a relatively large thermal conductivity (k = 30 W/(m·K)) [8]. Therefore, it could be an effective way by replacing SiO_2 claddings with SiN claddings to improve the thermal response of the Si waveguide devices.

Here we propose a waveguide structure based on SiN-Si-SiO_2 system. The high index contrast between a core (Si) and a claddings (SiO_2 [9] and SiN [10]) provides a good confinement to optical field. The SiO_2 bottom-cladding is deeply etched [11] and a trench is formed and filled with SiN. Since the thermal conductivity of SiN is much higher than that of SiO_2, therefore a fast heat dissipation channel is created. Our simulation indicates that the rise time of the proposed waveguide structure is about 110 ns, which is about two orders of magnitude less than that of the conventional Si waveguide.

2 Structure and modeling

Cross-section of the Si waveguide wrapped by SiN is shown in Fig. 1. There are four layers stacked on the Si substrate, which are SiO_2 bottom-cladding, Si core, SiN up-cladding and metal heater (e.g. Cr). It should be noted

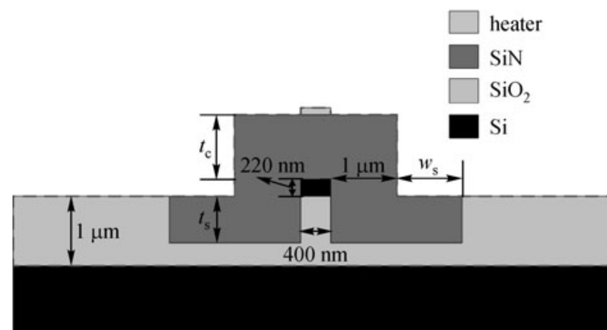

Fig. 1 Cross-section of Si waveguide wrapped by SiN

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Table 1 Thermal and optical parameters of materials used in calculation

material	refractive index at 1.55 μm	extinction coefficient at 1.55 μm	thermal conductivity /(W·(m·K)$^{-1}$)	specific heat /(J·(kg·K)$^{-1}$)	density /(kg·m^{-3})
Si	3.476	–	148	710	2.33×10^3
SiO_2	1.445	–	1.27	745	2.3×10^3
SiN	1.91	4.9×10^{-6}	30	170	2.5×10^3
Cr	3.674	4.19	93.7	450	7.14×10^3

that the SiN up-cladding is stretched into the SiO_2 bottom-cladding and three sides of the Si core are covered by SiN. That is, the Si waveguide is wrapped by SiN. The SiO_2 bottom-cladding is 1 μm in thickness. The Si core is 400 nm × 220 nm. The metal heater is 400 nm in width and 50 nm in thickness. There are three parameters: etching depth t_s, stretching width w_s and up-cladding thickness t_c. When the Joule heat is generated in the metal heater, it goes through the SiN up-cladding and establishes a stable temperature field in the Si waveguide quickly. The computation domain is indicated by the dashed lines in Fig. 1. We assume a constant temperature of 300 K at the bottom of the computation domain and heat convection boundary condition at the interface of the structure with air. The heat convection coefficient of air is 5.0 W/(m^2·K) at 300 K (the same as that in Ref. [7]). The thermal and optical parameters of the materials used in the calculation are listed in Table 1.

In this paper, we use two-dimensional (2D) finite element method (FEM) for thermal analysis and three-dimensional (3D) beam propagation method (BPM) for optical analysis. Noted that rise time refers to the time required for the temperature to change from 300 K to $(0.9\times(T_{\max}-300)+300)$ K, where $T_{\max}$ is the value of its maximum.

3 Simulation results

In order to improve the response speed of the proposed structure, the SiN up-cladding should be as thin as possible. However, much too thin SiN up-cladding cannot confine the optical field effectively and results in large optical loss. So the thickness of the SiN up-cladding should be optimized. We use 3D BPM to calculate the effective extinction coefficient of the proposed structure. As shown in Fig. 2, firstly, the effective extinction coefficient decreases rapidly as the up-cladding thickness t_c increases, which is mainly due to the absorption of metal heater to the optical field, and then saturates to about 2×10^{-6} when the up-cladding thickness t_c further increases, which is mainly due to the absorption of SiN to the optical field. Therefore, the up-cladding thickness t_c is chosen to be larger than 1 μm. Since optical loss is mainly caused by the absorption of the metal heater to the optical field, the etching depth t_s and stretching width w_s

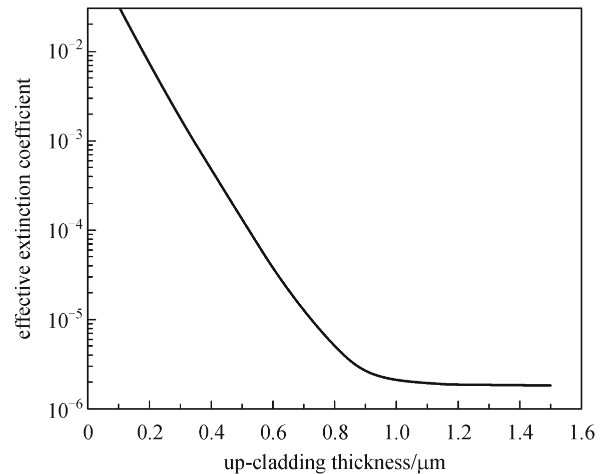


Fig. 2 Calculated effective extinction coefficient of Si waveguide wrapped by SiN with different up-cladding thicknesses

hardly affect the optical loss and are fixed to be 0.5 μm and 1 μm respectively during the above calculation.

Since the thermal conductivity of Si is much larger than those of SiO_2 and SiN, the temperature distribution is almost flat in the Si core. Therefore we use the temperature at the centre point of the Si core to evaluate the whole core. Power consumption is measured via area heat generating rate (AHGR) in the heater with a unit of W/m^2. We use 2D FEM for the following thermal analysis and the AHGR is chosen to be 5×10^{15} W/m^2.

When we calculate the temperature response of the Si waveguide wrapped by SiN with different etching depths t_s (0.1 to 1.0 μm with an interval of 0.1 μm), the up-cladding thickness t_c is fixed to be 1 μm and the stretching width w_s is fixed to be 1 μm. When we calculate the temperature response of the Si waveguide wrapped by SiN with different up-cladding thicknesses t_c (1.5 to 3 μm with an interval of 0.5 μm), the etching depth t_s is fixed to be 0.1, 0.5 and 0.9 μm respectively, and the stretching width w_s is fixed to be 1 μm. When we calculate the temperature response of the Si waveguide wrapped by SiN with different stretching widths w_s (0 to 1.5 μm with an interval of 0.5 μm), the etching depth t_s is also fixed to be 0.1, 0.5 and 0.9 μm respectively, and the up-cladding thickness t_c is fixed to be 1 μm.

For comparison, the thermal behavior of the conventional Si waveguide wrapped by SiO_2 with the same Si

core size and SiO_2 bottom-cladding thickness is also simulated (Fig. 3). The thickness of the SiO_2 up-cladding is also set to be 1 μm and the width of the heater is set to be 12.5 μm, which is the same as the value used in Ref. [1]. As the heater of the conventional Si waveguide wrapped by SiO_2 is wider than that of the Si waveguide wrapped by SiN, the AHGR loading on the heater of the conventional Si waveguide is set to be 1.6×10^{14} W/m^2 in order to get the same power consumption as the Si waveguide wrapped by SiN does.

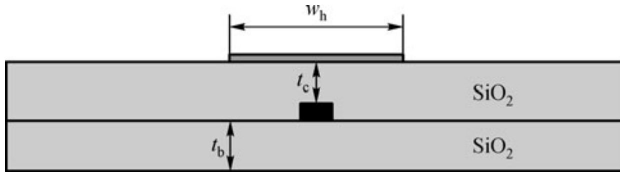
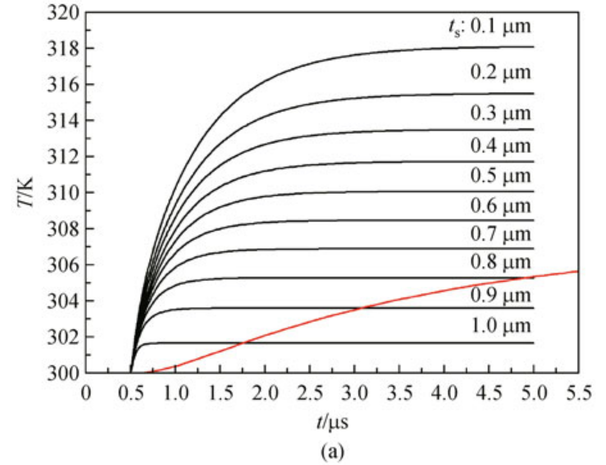
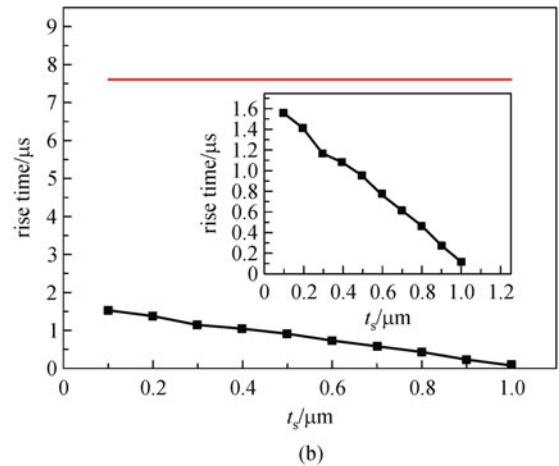


Fig. 3 Cross section of conventional Si waveguide

Figure 4(a) shows the temperature response of the Si waveguide wrapped by SiN with different etching depths t_s. It is clearly seen that increasing the etching depth t_s impoves the temperature response of the Si waveguide wrapped by SiN greatly (from 2.5 μs for t_s = 0.1 μm to 117 ns for t_s = 1 μm) with the sacrifice of reducing the temperature change greatly (from 318 K for t_s = 0.1 μm to 302 K for t_s = 1 μm). However, the temperature response time of the conventional Si waveguide wrapped by SiO_2 is 7.6 μs (as shown in the red line in Fig. 4(b)), which is about two orders of magnitude larger than that of the Si waveguide wrapped by SiN with t_s = 1 μm.

Figures 4(b) and 4(c) show the rise time and temperature change for different etching depths t_s. It is clearly seen that the rise time and temperature change decrease almost linearly as the etching depth t_s increases, which means that high response speed comes together with high power consumption. When the etching depth t_s increases from 0.1 to 1.0 μm, the rise time of the Si waveguide wrapped by SiN reduces from 1.55 μs to 117 ns. Considering the situation of the etching depth t_s = 1.0, the rise time of the Si waveguide wrapped by SiN is just 1/65 that of the conventional Si waveguide (7.6 μs). The Si waveguide wrapped by SiN has a same temperature change with the conventional Si waveguide when the etching depth t_s is 0.68 μm. The temperature change reduces to about 1.8 K for the etching depth t_s = 1.0 μm, which is only 1/4 that of the conventional Si waveguide. While for the etching depth t_s = 0.1 μm, the temperature change is about 18 K, which is about two times that of the conventional Si waveguide.





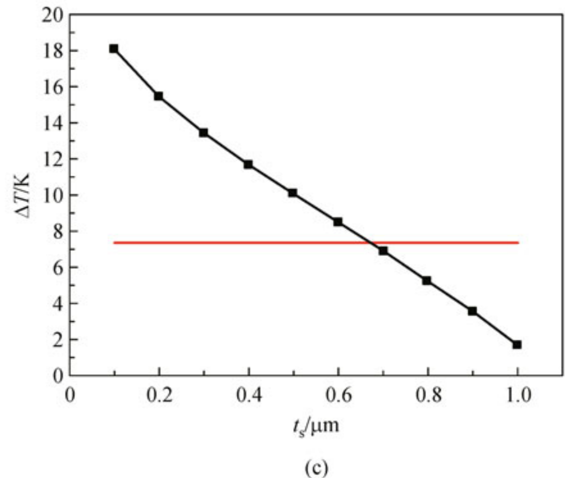


Fig. 4 (a) Temperature response of Si waveguide wrapped by SiN with different etching depths t_s; (b) rise time versus etching depths t_s; (c) temperature change versus etching depths t_s. Corresponding curves of conventional Si waveguide are shown in red lines as references

It can be seen from Fig. 5(a) that increasing the stretching width w_s is a good way for improving the response speed, but demands for more power consumption. How much the stretching width w_s affecting the rise time and temperature change depends on the etching depth t_s. When the etching depth t_s is 1.0 μm, the Si waveguides wrapped by SiN with different stretching widths w_s have almost same rise time and temperature change, which means that the influence of the stretching width w_s on the

rise time and temperature change is weak. When the etching depth t_s is 0.1 μm, the influence of the stretching width w_s on the rise time and temperature change is much stronger. Figure 5(b) shows the rise time of the Si waveguide wrapped by SiN with different stretching depths w_s and etching depths t_s. It is clearly seen that the etching depth t_s plays a dominant role in determining the response speed of the Si waveguide wrapped by SiN. The influence of the stretching width w_s on the response speed of the Si waveguide wrapped by SiN is strong for small etching depth t_s and weak for large etching depth t_s. For example, the rise time change is 0.28 μs for t_s = 0.1 μm, 0.27 μs for t_s = 0.5 μm and 33.5 ns for t_s = 1.0 μm when the stretching width w_s increases from 0 to 1.5 μm. It is clearly seen from Fig. 5(c) that the etching depth t_s also plays a dominant role in determining the temperature change of the Si waveguide wrapped by SiN. The influence of the stretching width w_s on the temperature change of the Si waveguide wrapped by SiN is strong for small etching depth t_s and weak for large etching depth t_s. For example, the temperature change is 7.4 K for t_s = 0.1 μm, 5.4 K for t_s = 0.5 μm and 0.34 K for t_s = 1.0 μm when the stretching width w_s increases from 0 to 1.5 μm.

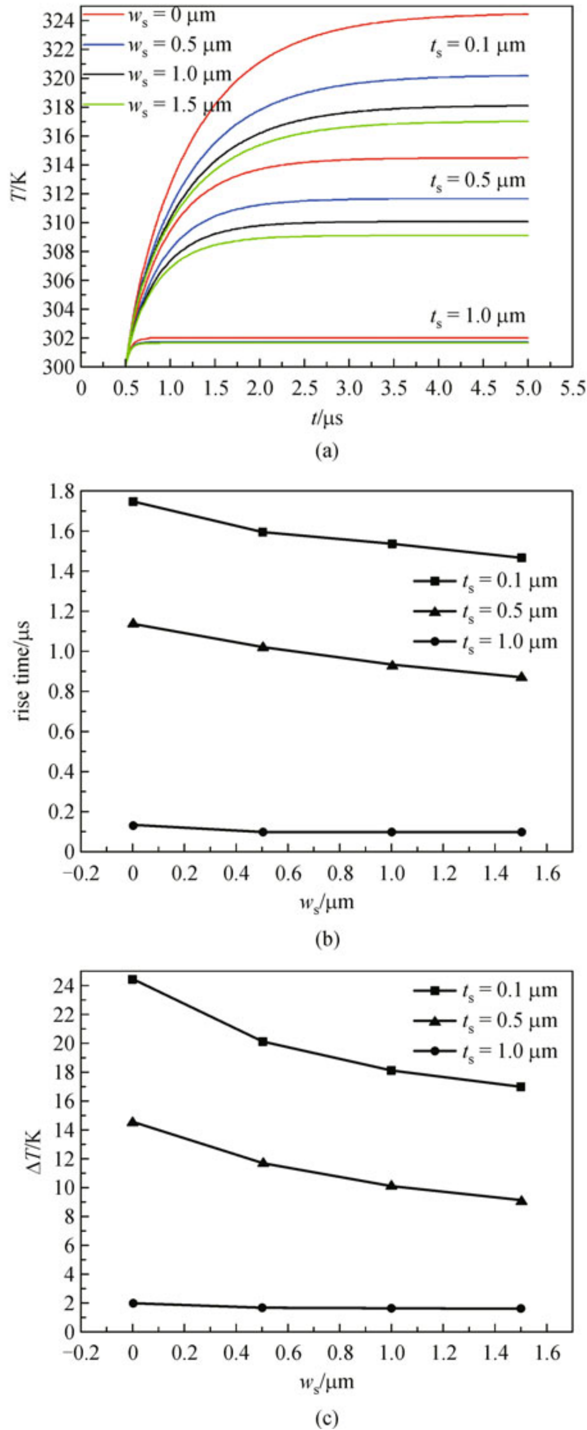


Fig. 5 (a) Temperature response of Si waveguide wrapped by SiN with different stretching widths w_s and etching depths t_s; (b) rise time versus stretching width w_s for different etching depths t_s; (c) temperature change versus stretching width w_s for different etching depths t_s

Figure 6(a) shows the temperature response of the Si waveguide wrapped with SiN for different up-cladding

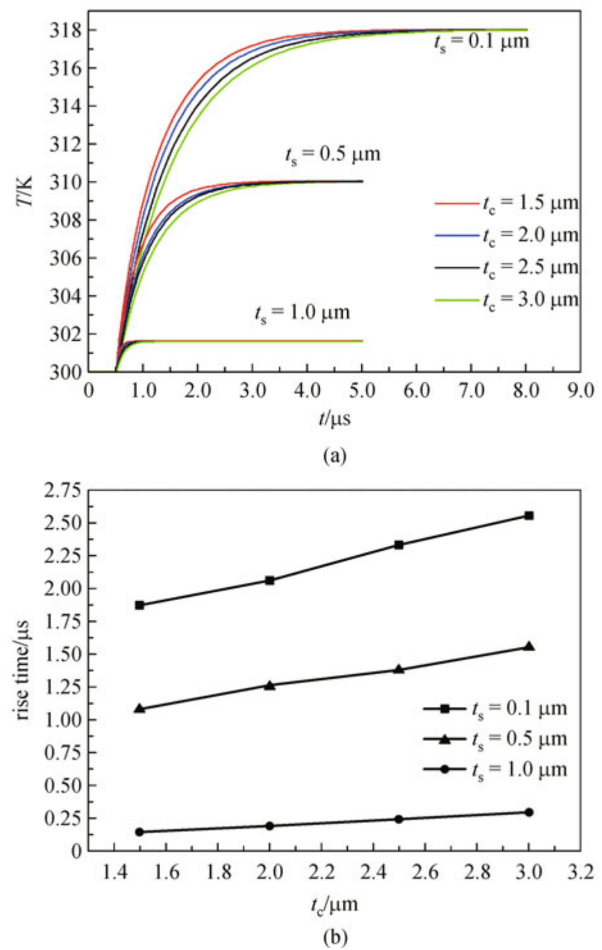


Fig. 6 (a) Temperature response of Si waveguide wrapped by SiN with different up-cladding thicknesses; (b) rise time versus up-cladding thicknesses t_c

thicknesses (t_c = 1.5, 2.0, 2.5 and 3.0 μm). Here etching depth t_s is chosen to be 0.1, 0.5 and 1.0 μm respectively, and stretching width w_s is chosen to be 1 μm. We can see that for the same etching depth t_s, the temperature change is same for different up-cladding thicknesses. However, the rise time increases almost linearly as the up-cladding thickness increases (see Fig. 6(b)). When up-cladding thickness t_c changes from 1.5 to 3.0 μm, the rise time changes from 1.87 to 2.55 μs for t_s= 0.1 μm, from 1.076 to 1.557 μs for t_s = 0.5 μm, and from 147 to 300 ns for t_s = 1.0 μm. It means that when the etching depth t_s is smaller, the up-cladding thickness t_c has a larger influence on the response speed.

4 Conclusions

A new type of Si waveguide wrapped by SiN and associated optical and thermal analysis are presented. The thickness of SiN up-cladding should be larger than 1 μm in order to prevent the absorption of the metal heater to the optical field. Because of the high thermal conductivity of SiN, the thermal response of the proposed waveguide structure is improved. Moreover, its thermal response can be further improved by creating a fast heat dissipation channel. Our simulation indicates that a rise time of about 110 ns can be achieved for the proposed waveguide structure, which is about two orders of magnitude larger than that of the conventional Si waveguide. The influence of the thickness of up-cladding and the stretching width on the thermal performance are also discussed. Due to the high response speed of the presented waveguide structure, it can be used to improve the response speed of varies thermo-optic devices, such as thermo-optic MZI [1], RODAM [4] and optical logic gate [5] based on tunable micro ring-resonator.

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