Graphene-based Transparent Nano-heater for Thermally-tuning Silicon Nanophotonic Integrated Devices

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Abstract— For the traditional metal heaters used for SOI (silicon-on-insulator)-nanowire devices, a thick SiO_2 upper-cladding layer is usually needed between the metal heater and the silicon core to isolate metal absorption, which makes the thermal tuning be with low response speed, low heating efficiency, and low maximal temperature. In this paper, we propose and demonstrate a graphene-based transparent nano-heater for SOI nanowires. The present transparent graphene nano-heater is designed to contact directly with the silicon core of an SOI nanowire by utilizing the transparency of graphene. The lack of the thick SiO_2 upper-cladding layer between the heater and the core region helps make fast thermally-tuning nanophotonic integrated devices. It is also beneficial to improve the heating efficiency because the heating volume is shrunk significantly. The graphene nano-heater is designed optimally to avoid any significant excess loss for the guided modes in the SOI nanowires. For example, the theoretical propagation losses of TE- and TM-polarization modes of a 600 nm-wide SOI nanowire with a 100 nm-wide graphene nano-heater are as low as ~ 0.005 dB/μm and ~ 0.013 dB/μm respectively. With this graphene-based transparent nano-heater, we present a thermally-tuning silicon Mach-Zehnder interferometer (MZI). The power consumption to have π phase-shift is ~ 5.2 mW and ~ 5.7 mW for TE- and TM-polarization modes, respectively. The theoretical response time is ~ 4.4 μs, which is about twice faster than that for the case of using a traditional metal heater. In addition, the temperature of the silicon core is almost the same as that of graphene nano-heaters. In contrast, for the case of traditional metal heaters, the silicon core has much lower temperature than the metal heater while the metal heater has a limited maximal operation-temperature. This indicates that one can achieve higher achievable temperature for the silicon core with the present graphene nano-heater than the traditional metal heater. Graphene can also be used as a heat conductor (other than heater) by utilizing its high thermal conductivity of up to 5300 W/mK. The excellent thermal properties of graphene make it very useful to enable efficient thermally-tuning nanophotonic integrated devices including optical switches, optical filters, etc..

1. INTRODUCTION

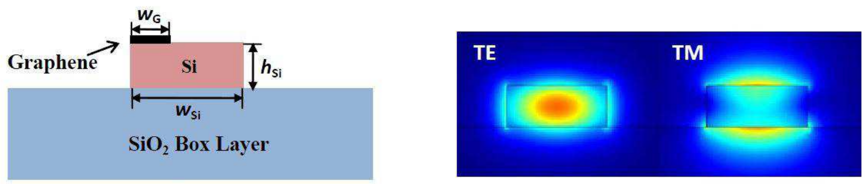
Silicon photonics has been regarded as one of the most promising technologies to realize low-cost large-scale photonic integrated circuits (PICs) because of the ability for ultra-small bending and the compatibility with CMOS fabrication processes [1]. It is well known that silicon has a large heat conductivity and a large thermo-optical (TO) coefficient ($\sim 1.8 \times 10^{-4}$/K at the wavelength of 1.55 μm), which are beneficial to realize efficient thermally-tuning nanophotonic integrated devices [2]. Traditional metal heaters used for SOI nanowires usually require a thick SiO_2 upper-cladding layer between the metal heater and the silicon core to isolate metal absorption. However, this will introduce some disadvantages, e.g., low response speed, low heating efficiency, and low maximal temperature.

Graphene has attracted strong interest for both fundamental studies and applications since the two-dimensional sheet was first exfoliated in 2004 [3]. Due to its unique structure, graphene has many extraordinary mechanical, electronic, photonic, and thermal properties [4]. A single-layer graphene is only 0.34 nm-thick, and it only absorbs $\sim 2.3\%$ of the vertically incident light. Thermal conductivity of up to 5300 W/mK is observed in graphene at room temperature [5, 6]. Graphene is also suggested to have a high value of optical damage threshold and excellent mechanical stability [5].

In this paper, we propose and demonstrate a graphene-based transparent nano-heater on SOI nanowires for the first time. The graphene nano-heater is designed to contact directly with the silicon core and there is no significant excess loss for the light propagating along the SOI nanowire because of the graphene transparency. By removing a thick SiO_2 upper-cladding layer (needed for a traditional metal heater), the graphene nano-heater has improved heating efficiency, response speed and maximal operation-temperature. Based on the graphene nano-heater, a thermally-tuning silicon Mach-Zehnder interferometer (MZI) is also presented. The excellent thermal properties of graphene make it very useful to enable efficient thermally-tuning nanophotonic integrated devices including optical switches, optical filters, etc..

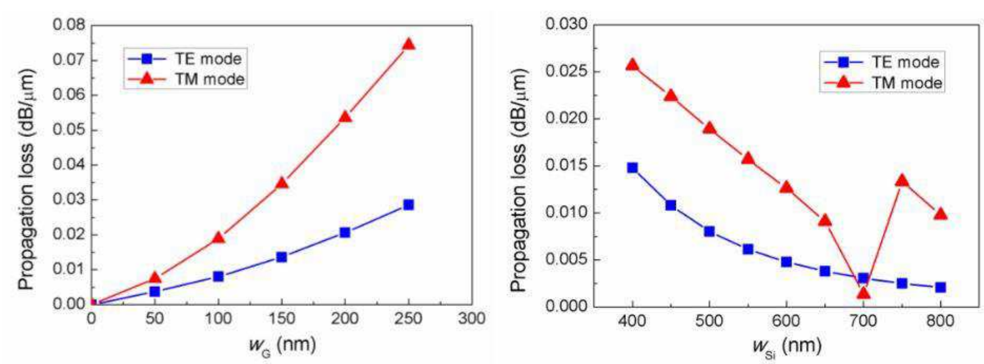
2. STRUCTURE AND DESIGN

The cross-section view of an SOI nanowire is shown in Figure 1(a). We choose an SOI wafer with a 250 nm-thick top silicon layer ($h_{Si} = 250$ nm) and a 3 μm-thick SiO_2 box layer. Graphene is transferred directly to the core of the SOI nanowire and is then patterned to a nanoribbon [7], which is located at the edge of the SOI nanowire. The propagation losses for TE- and TM-polarization modes (see Figure 1(b)) are mainly due to the absorption of graphene [7, 8], and thus they are significantly dependent on the widths (w_{Si}, w_G) of the SOI nanowire and the graphene nanoribbon. A finite element simulation (FEM) mode-solver is used to evaluate the propagation losses of SOI nanowires with graphene nano-heaters and the waveguide parameters are optimized to reduce the excess loss for the guided modes.



(a) (b)

Figure 1: (a) Cross-section view of an SOI nanowire and a graphene nano-heater. (b) TE- (left) and TM- (right) polarization modes of an SOI nanowire.



(a) (b)

Figure 2: Propagation losses for TE- (blue squares) and TM- (red triangles) polarization modes (a) as w_G varies when $w_{Si} = 500$ nm and (b) as w_{Si} varies when $w_G = 100$ nm.

Figure 2(a) shows the calculated propagation losses for TE- and TM-polarization modes as the width w_G of the graphene nanoribbon varies when $w_{Si} = 500$ nm. With the increase of w_G, the propagation loss for both polarization modes gets an increase as well. Therefore it is desired to have a narrow graphene nanoribbon. Here we choose $w_G = 100$ nm regarding the fabrication process. In Figure 2(b), we show the calculated propagation losses for the case of $w_G = 100$ nm as the width w_{Si} of the SOI nanowire varies. It can be seen that the propagation losses get a significant decrease for both TE- and TM-polarization modes when w_{Si} increases from 400 nm to 600 nm. When $w_{Si} =\sim 700$ nm, the TM polarization mode is hybridized, which makes the absorption loss reduced significantly (see Figure 2(b)). Regarding the single-mode condition, we choose $w_{Si} = 600$ nm. Then the corresponding propagation losses are only ~ 0.005 dB/μm for TE polarization mode and ~ 0.013 dB/μm for TM polarization mode, which are much smaller than those of previous graphene-silicon hybrid SOI nanowires [7, 8]. And a graphene transparent nano-heater is achieved.

3. CHARACTERIZATION OF GRAPHENE TRANSPARENT NANO-HEATER

The thermal behaviors of the present graphene transparent nano-heater are modeled by using Poisson equation with FEM tools (similar to that in Reference [9]. The input power per unit length is 0.2 mW/μm, and the room temperature is 300 K. Figure 3 shows the results for 250 nm × 600 nm SOI nanowires with a 100 nm-wide graphene nano-heater, as well as a traditional metal heater (for which the metal is 1 μm-wide and the SiO_2 upper-cladding layer is 1 μm-thick).

From Figure 3, it can be seen that the temperatures in the silicon core are $T =\sim 449.8$ K and $T =\sim 376.9$ K when using a graphene nano-heater and a traditional metal heater, respectively. The power consumption for a nanowire in unit length to increase temperature by 1 K is ∼ 0.00134 mW/ μmK and ∼ 0.00260 mW/μmK, respectively. The power consumption of a graphene nano-heater is 50% smaller than that of a traditional metal heater. The improved heating efficiency of graphene nano-heaters results from the lack of the thick SiO_2 upper-cladding layer between the heater and the silicon core region, which reduces the heating volume significantly. Figure 3 also indicates that the temperature of the silicon core is almost as same as that of the heater for the case of using a graphene nano-heater. In contrast, when using a traditional metal heater, the temperature of the silicon core is much lower than that of the heater (e.g., $\Delta T =\sim 73$ K in the present case). Therefore, graphene nano-heaters are beneficial to achieve a higher operation-temperature and a larger tunable range in thermally-tuning nanophotonic devices.

Temporal responses of temperature for SOI nanowires with a graphene nano-heater and a metal heater are also calculated and compared as shown in Figure 4. The 90% rise time, which is defined as the time it takes for the change of temperature to reach 90% of the maximum value from zero, is

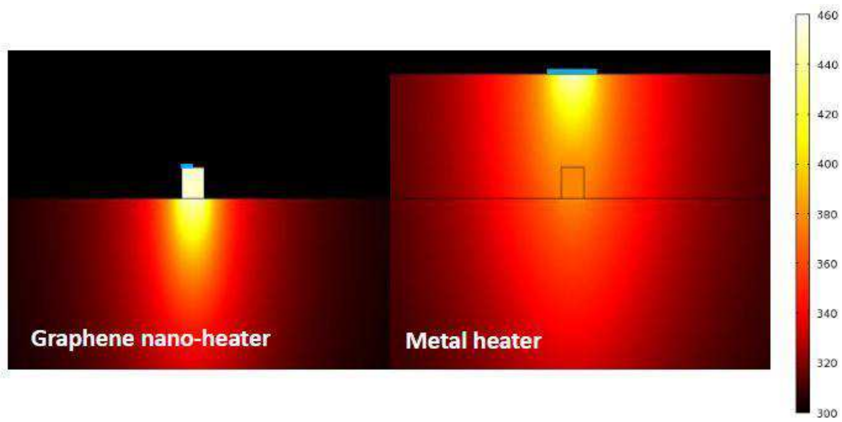


Figure 3: Temperature distribution of a 250 nm × 600 nm SOI nanowire. Left, using a 100 nm-wide graphene transparent nano-heater. Position of graphene is shown in blue line. Right, using a traditional 1 μm-wide metal heater with a 1 μm-thick SiO_2 up-cladding layer. Position of metal is shown in blue line.

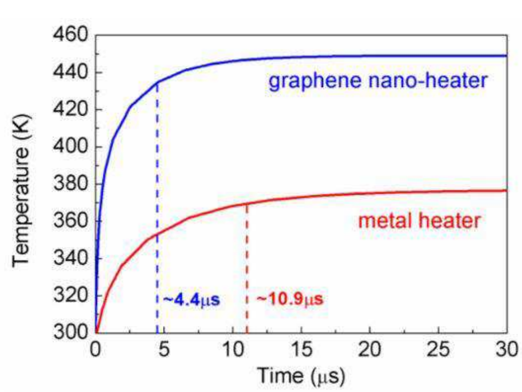


Figure 4: Temporal responses of temperature for SOI nanowires with a graphene nano-heater and a traditional metal heater. The 90% rising times are ∼ 4.4 μs and ∼ 10.9 μs respectively.

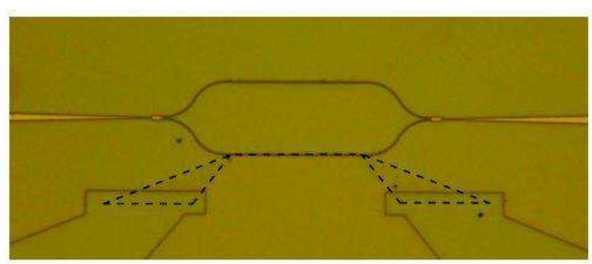


Figure 5: Microscopy picture of a Mach-Zehnder interferometer (MZI). One arm is heated by a graphene transparent nano-heater (dash line).

$\sim 4.4\,\mu s$ for graphene nano-heaters and $\sim 10.9\,\mu s$ for traditional metal heaters. This is because the SiO_2 upper-cladding region has poor thermal conductivity. For traditional metal heaters, it will take some time to transport heat from the heater to the silicon core, while for graphene nano-heaters, this problem is removed since graphene nano-heaters contact the silicon core directly.

The present graphene transparent nano-heater is then used to realize a thermally-tuning silicon Mach-Zehnder interferometer (MZI). As shown in Figure 5, one of the two MZI arms is heated and a phase difference $\Delta\varphi$ between the two arms is introduced. It indicates that the power consumption for $\Delta\varphi = \pi$ is ~ 5.2 mW and ~ 5.7 mW for TE- and TM- polarization modes respectively, which is half of that by using traditional metal heaters.

4. CONCLUSION

We have demonstrated a graphene-based transparent nano-heater for thermally-tuning silicon nanophotonic devices. The excess loss of graphene nano-heaters are minimized by optimizing the structure design. The theoretical calculation has shown that the present graphene nano-heaters have better performance than traditional metal heaters in terms of heating efficiency, response speed and maximal operation-temperature. It will help to enable efficient and fast thermally-tuning nanophotonic integrated devices, such as optical switches, optical filters, and so on. Based on the high thermal conductivity of graphene and the structure design, graphene can also be used as a heat conductor instead of a heater in the future.

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