Ultracompact On-chip Long-wave Photodetector Based on Hybrid Plasmonic Waveguides

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Abstract— An ultra-small on-chip long-wave photodetector by utilizing the thermal resistance effect of the metal strip on a hybrid plasmonic waveguide structure. When light propagates along a hybrid plasmonic waveguide, the metal strip is heated due to the light absorption. Accordingly, the resistance of the metal strip increases due to the thermal-resistance effect of metal and the resistance change can be measured accurately with a Wheatstone bridge so that the photodetector is with very high sensitivity. Owing to the nano-scale confinement of light in a hybrid plasmonic waveguide, the temperature increase of metal due to the metal absorption is enhanced in comparison with the conventional long-range plasmonic waveguide. A theoretical responsivity of as high as 74 mV/mW is obtained with a low bias voltage of 1 V. The photodetector also has a fast response ($< 1\,\mu$s) and works in a very broad wavelength range (e.g., $1.5 \sim 7.5\,\mu$m).

1. INTRODUCTION

Photodetection plays an important role in many applications, including optical interconnects [1] and optical sensing [2]. Particularly, photodetectors for long-wave (e.g., mid-infrared wavelength) are becoming increasingly attractive, regarding the significant applications of long-wave in temperature measurement, environment monitoring, human health, etc. [3–5]. Long-wave photodetector can be realized by utilizing the photo-electric effect of semiconductor materials [6]. However, the operation wavelength range of a photodetector based on the photo-electric effect is limited by the bandgap of the semiconductor [6, 7]. Although a mid-IR photodetector based on the quantum effect has a high resposivity, it has to be operated at a very low temperature (< 100 K) [6–8] so that the thermal noise is depressed.

In recent years, silicon photonics for long-wave applications has been attracting lots of attention due to the great potentials in on-chip biochemical detections and environment monitoring [9]. Nevertheless, long-wave photodetection on silicon is still a big challenge since silicon is transparent for the wavelength larger than 1.1 μm [10]. To develop long-wave photodetectors on silicon, germanium has been utilized as the active material due to its favorable absorption coefficient [11–15]. However, the operation wavelength is still concentrated on the communication band around 1310 nm and 1550 nm. Furthermore, it is not easy to grow another semiconductor film with high quality on silicon due to the large lattice mismatch between them [16].

Long-wave photodetector can also be achieved based on the photo-thermal effect. When light is absorbed, the temperature will increases and the temperature variation can be measured with various techniques. For example, the resistance of a metal strip changes as the temperature increases according to the thermal resistance effect while the resistance can be measured in an electrical way. An integrated power monitor with a long-range surface plasmonic waveguide on silicon was reported [17], and the responsivity is about 0.15 mV/mW with an active length as long as 1 mm.

In this paper, we propose a long-wave photodetector with a silicon hybrid plasmonic waveguide (HPW), which consists of a metal strip, a silicon core and a sandwiched silica nano-layer [18]. The silicon HPW is with a nanoscale light confinement. The ultrasmall volume of the proposed photodetector helps improve the responsivity significantly. Furthermore, the silica nano-layer in such a structure also plays an important role as a thermal insulator, which can prevent the heat convection from the metal strip to the silicon region. In this way, heat generated due to the metal absorption is confined well in the metal region and consequently the responsivity is improved further. For example, the theoretical responsivity of the proposed photodetector with a footprint of $10\,\mu\text{m} \times 300\,\text{nm}$) is as high as 74 mV/mW.

2. STRUCTURE AND DESIGN

Figure 1(a) shows the three-dimensional view of the proposed photodetector based on a silicon HPW, whose cross-section is illustrated by the inset. The silicon HPW consists of a metal strip, a silicon core and a silica nanolayer sandwiched between them. The thickness of the silica layer is usually tens of nanometers to have a nanoscale light confinement. When light propagates in the silicon HPW, heat is generated due to the light absorption in the metal strip. As an example, a silicon-on-insultor (SOI) wafer with 340 nm-thick top-silicon is chosen. The SOI wafer is oxidized to produce a 20 nm-thick silica layer (i.e., 4 nm-thick silicon sacrificed), which not only helps to confine light tightly but also prevent the heat flow from the metal region to the silicon core. The waveguide width is chosen as $w = 300$ nm and a 20 nm-thick metal strip is covered on top of the waveguide. Here copper is chosen as the metal due to the COMS compatibility and high stability.

Figure 1(b) show the calculated field distribution of the silicon hybrid plasmonic waveguide in the proposed photodetector by using a finite-element method (FEM) mode solver. It can be seen that light is confined strongly in the silica nano-layer. Fig. 1(c) shows the calculated temperature profile of the silicon HPW when a power is applied in the metal strip. One sees that the metal strip has a peak temperature, which is attributed to the thermal isolation of the silica layer. In the present case, the applied power is actually the heat generated from light absorption. Since the resistivity of the metal is temperature dependent, one can figure out the temperature change by measuring the variation of the metal resistance by utilizing an electrical way with, e.g., the Wheatstone bridge circuit.

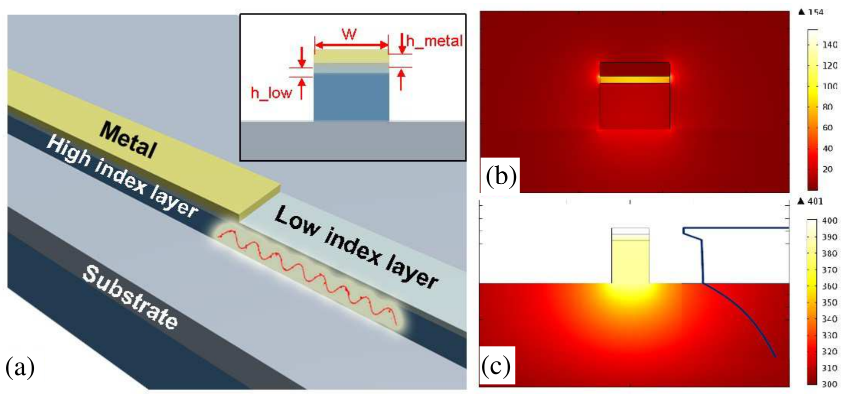

Figure 1: (a) The configuration of the proposed photodetector based on a silicon hybrid plasmonic waveguide (HPW). Inset shows the cross-section of the silicon HPW. (b) Field distribution of the silicon HPW with $w = 300$ nm @ $\lambda = 3.39\,\mu$m. (c) The temperature distribution of the silicon HPW when 1 mW power is applied in the metal strip.

3. RESULT AND ANALYSIS

It is well known that both the light absorption [18] and the thermal response [19] of a hybrid plasmonic waveguide are dependent on the waveguide size. Since light is well confined in the low-index nanolayer, we focus on the dependence of the light absorption and the thermal response on the thickness of metal and the silica nanolay, as well as the width of the waveguide.

Figure 2(a) show the maximum of the calculated temperature in the metal strip as the input power varies. Here the metal thickness $h_metal = 0.02\,\mu$m, the silica-nanolay thickness $h_low = 0.02\,\mu$m, and the waveguide width $w = 0.3\,\mu$m. With the optimized structure, the theoretical responsivity is as high as 91 K/mW. Fig. 2(b) shows the calculated temporal response and the rise time and the decay time are as short as 0.95 µs.

Figure 3 shows the wavelength dependence of the calculated propagation length and the 90% absorption length of the photodetector. It can be seen that the 90% absorption length of the photodetector is shorter than 10 µm in the wavelength range of $[1.5, 7.5]$ µm, which indicates a ultracompact footprint of the photodetector. The operation can be broadened by choosing a longer absorption length.

In order to readout the temperature increase resulting from the input light, an electric circuit with the Wheatstone bridge is achive an accruate measurement for the resistant change. Considering the calculated thermal responsivity 91 K/mW mentioned above, the responsivity of the Wheatstone bridge circuit is as high as 148 mV/mW for a bias voltage of 2 V, which is 1000 times larger than that reported in the previous work [17]. The dynamic range is about 6.5 mW due to the electrical current heating. The sensitivity, mainly limited by thermal fluctuation, is estimated as

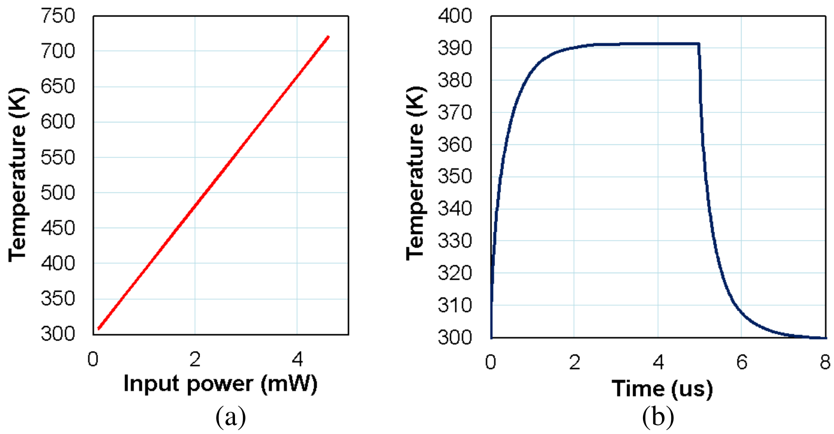

Figure 2: (a) The maximal temperature in the metal strip as the input power varies. Here, $h\_metal = 0.02\,\mu\text{m}$, $h\_low = 0.02\,\mu\text{m}$ and $w = 0.3\,\mu\text{m}$. (b) The temporal response of the temperature of the metal strip with an applied power 1 mW.

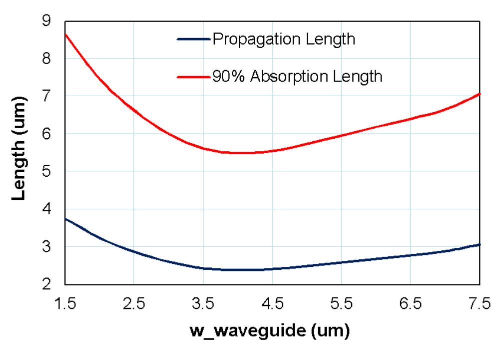

Figure 3: The wavelength dependence of the propagation length and the 90% absorption length. Here $h\_metal = 0.02\,\mu\text{m}$, $h\_low = 0.02\,\mu\text{m}$ and $w = 0.3\,\mu\text{m}$.

low as 0.5 nW for a bias voltage of 1 V, which is four order of magnitudes smaller than the previous work [17].

4. CONCLUSION

In this paper, an ultra-small on-chip long-wave photodetector is proposed by utilizing thermal resistance effect of the metal strip on a hybrid plasmonic waveguide, which consists of a metal strip, a silicon core and a sandwiched low-index nanolayer. The metal strip is heated due to the light absorption and the resistance of the metal strip increases. An electric circuit with a Wheatstone bridge is used to measure the resistance change accurately so that the photodetector is with very high sensitivity. The designed long-wave photodetector has a theoretical responsivity of as high as 74 mV/mW when operating at 1 V. This photodetector also enables a sub-μs response due to a compact volume (e.g., 10 μm). Moreover, the present on-chip photodetector is available for an ultra-broad wavelength range (from 1.5 μm to 7.5 μm), which makes it useful for many optical sensing systems.

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