Silicide Schottky-Barrier Phototransistor Integrated in Silicon Channel Waveguide for In-Line Power Monitoring

Shiyang Zhu, G. Q. Lo, M. B. Yu, and D. L. Kwong

***Abstract*—An in-line power monitor with a thin nickel silicide layer placed on a silicon channel waveguide for optical absorption is proposed. A two-terminal Schottky-barrier collector phototransistor configuration is used to amplify significantly the primary photocurrent, and the Ni silicide thickness is thinned down to ∼5 nm using a two-step rapid thermal annealing procedure to reduce the insertion loss. The demonstrated in-line detectors exhibit ∼24-mA/W responsivity around 1550 nm with the insertion loss of ∼0.8–1.2 dB. The approaches to further increase the responsivity and simultaneously decrease the insertion loss are addressed.**

***Index Terms*—In-line power monitor, near-infrared, phototransistor, Schottky-barrier, silicide, silicon waveguide.**

I. INTRODUCTION

MONOLITHIC integration of near-infrared detectors on the existing silicon complementary metal–oxide–semiconductor technology platform is highly desirable for low-cost silicon-based photonic integrated circuits. In addition to the well-developed photodetectors based on germanium-on-silicon [1] or implanted silicon waveguide [2], [3], the silicide Schottky-barrier photodiode (SBPD) is also an attractive alternative, in which light propagating along the Si-waveguide is absorbed by a thin silicide layer placed on it and the cutoff wavelength is solely determined by the Schottky barrier height (SBH) at the silicide–Si interface [4], [5]. The SBPD offers the advantages of low cost, ease of fabrication, small footprint, and long cutoff wavelength, etc., but suffers a big issue of low responsivity due to its inherent low Fowler yield. To overcome this drawback, a novel detector named silicide Schottky-barrier collector phototransistor (SBCPT) was recently proposed, in which the primary photocurrent can be inherently amplified through the transistor action [6]. A two-terminal n-p-metal (NPM)-SBCPT for terminal detection was demonstrated with responsivity of ∼150 mA/W and 3-dB bandwidth of ∼0.44 GHz. Here, a p-n-metal (PNM)-SBCPT for in-line power monitoring is reported, which provides the same functions as a waveguide tap coupler and an integrated detector.

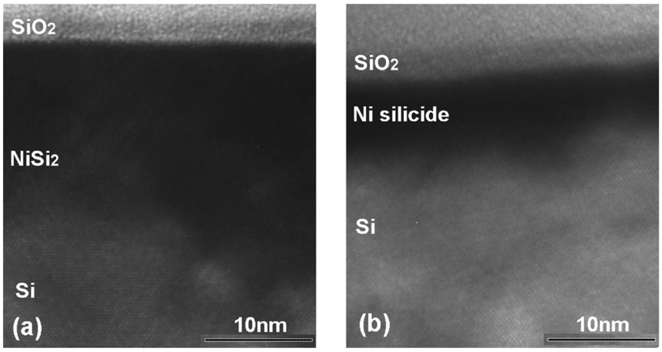

Fig. 1. XTEM images of Ni silicide on SOI formed by solid-state reaction of Ni(∼5 nm)/Ti(∼1 nm)/Si systems by (a) one-step RTA and (b) two-step RTA. The formed Ni silicides have thicknesses of ∼16 and ∼5 nm, respectively.

II. FABRICATION

Ni silicide for optical absorption was formed by a titanium-intermediated solid-state epitaxy [7]. The silicide thickness was controlled by the rapid thermal annealing (RTA) procedure after deposition of ∼1-nm Ti and ∼5-nm Ni sequentially on silicon-on-insulator (SOI) substrates in a sputtering system: In one procedure, RTA at 450 °C for 30 s, followed by selectively etching in Pirahna solution at 90 °C for 10 min to remove the unreacted metal; in the other procedure, first RTA at 240 °C for 30 s, followed by the selectively etching, and then second RTA at 450 °C for 30 s. The cross-sectional transmission electron microscopy (XTEM) images of the final Ni silicides are shown in Fig. 1. Their thicknesses are ∼16 and ∼5 nm, respectively, and the latter exhibits smoother silicide–Si interface than the former. The Ni : Si ratio of the 16-nm-thick silicide is very close to 1 : 2, as determined from energy dispersive X-ray fluorescence spectroscopy (EDX), confirming that the formed phase is $NiSi_2$, while the 5-nm-thick silicide is too thin for the EDX analysis. In the following, these two kinds of silicides were referred to as the thick silicide and the thin silicide, respectively.

The channel SOI waveguides employed in this study have a width of 1 μm, height of ∼0.2 μm, and length of ∼5.5 mm, and have an inverted taper at both facets. The buried SiO_2 and top cladding SiO_2 are ∼2 and ∼1.5 μm thick, respectively. A 1550-nm laser light was coupled into the waveguide using a lensed fiber and out of it using another lensed fiber. The fiber-to-fiber loss through a reference waveguide without silicide is ∼15 dB. The excess loss (in decibel scale) induced by a 0.56-μm-wide Ni silicide layer placed on the SOI channel

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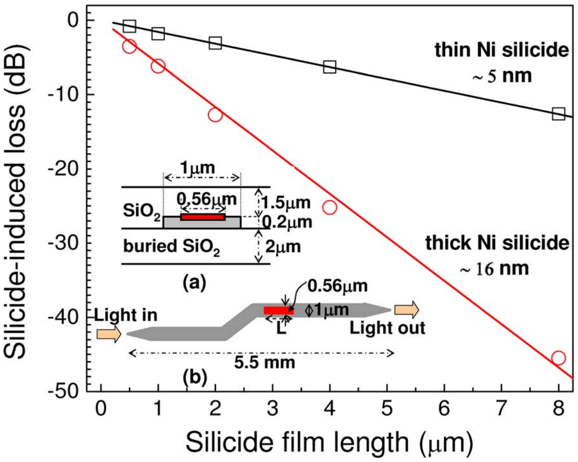

Fig. 2. Excess loss induced by Ni silicide layer (= loss of waveguide with silicide—loss of reference waveguide, measured at 1550 nm) versus its length and their linearly fitting. The inset shows the cross sectional and top views of the SOI channel waveguide with the 0.56-μm-wide silicide layer placed on it.

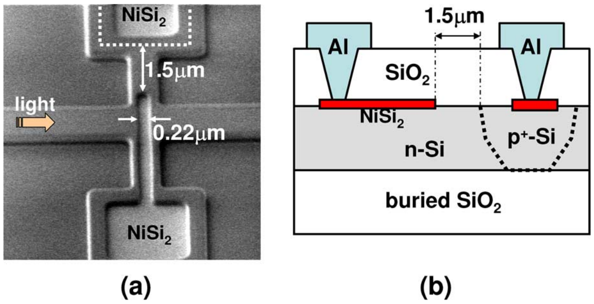

Fig. 3. (a) Scanning electron microscope (SEM) image of the in-line detector just after Ni silicide formation; (b) schematic cross-sectional view of final detector. The dotted square area is highly p$^+$-doped to form the emitter region in the PNM-SBCPT and is highly n$^+$-doped to form Ohmic contact in the n-type SBPD.

waveguide (as shown schematically in the inset of Fig. 2) is depicted in Fig. 2 as a function of its length (L). The plots exhibit a good linearity, obeying an equation of Loss $= -A \times L$, the factor $A = 4.34 \times \alpha$ (the absorption coefficient of NiSi$_2$) $\times\Gamma$ (the confinement factor) is extracted to be ~5.85 and ~1.58 dB/μm for the thin and the thick silicides, respectively. To minimize the insertion loss for in-line monitoring, the absorbing silicide layer needs to be both thin and short enough.

Fig. 3(a) shows the configuration of silicide absorber in our in-line monitor. The Si stripe orthogonal to the Si waveguide has a width of 0.66 μm and the silicide absorber placed on it across the waveguide has a width of 0.22 μm. The excess loss induced by the orthogonal Si stripe without silicide is ~0.1–0.3 dB. The silicide-induced loss is ~2.3–3.0 dB for the thick one and ~0.7–0.9 dB for the thin one. Therefore, the total insertion loss of our in-line detector is ~0.8–1.2 dB with the thin silicide and ~2.4–3.3 dB with the thick silicide. Fig. 3(b) shows the schematic cross-sectional view of PNM-SBCPT. The NPM-SBCPT also works and draws similar results. The top Si of SOI was initially implanted by 50-keV 5×10^{11} cm^{-2} phosphorus, followed by 1000 °C 60-s RTA to form the n-type base. The dotted region shown in Fig. 3 was implanted by 15-keV 3×10^{15} cm^{-2} boron, followed by 1000 °C 60-s RTA to form the p$^+$ emitter region. The lateral distance between the p$^+$ emitter and the silicide absorber (collector) is 1.5 μm, which can be roughly regarded as the base width. The corresponding n-type SBPDs were also fabricated simply by replacing the boron implantation with the 30-keV 3×10^{15}-cm^{-2} phosphorus implantation. More details of device fabrication can be found in [4]–[6].

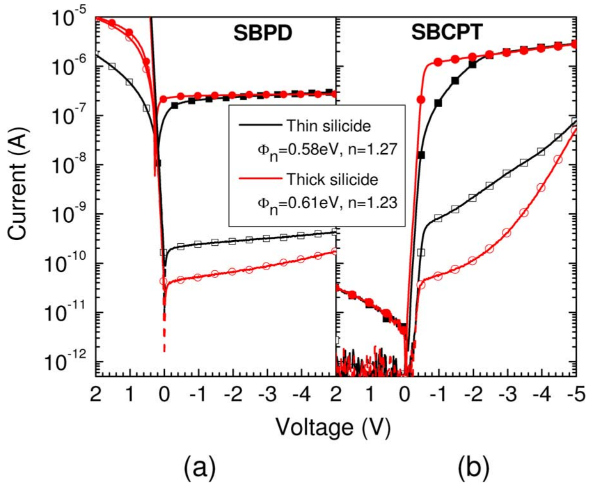

Fig. 4. Dark (open symbols) and photocurrent (solid symbols) for the in-line detector of (a) n-type SBPD and (b) PNM-SBCPT illuminated by 1550-nm 0-dBm light coupled from a lensed fiber to the waveguide. The optical loss before reaching the detector is assumed to be ~9 dB. The linearly fitting based on the TE model is also shown for SBPDs to extract their SBH and ideality factor.

III. CHARACTERIZATION AND DISCUSSION

Fig. 4 shows the current–voltage (I–V) curves of SBPD and SBCPT at the dark environment and illuminated with 1-mW 1550-nm light. The optical loss before reaching the detector is roughly assumed to be ~9 dB because the detector is located near the end facet of the waveguide. Therefore, the photocurrent read from Fig. 4 divided by 0.126 W (optical power incident upon the detector) gives the responsivity ~2.5 and ~24 mA/W for the −5-V biased SBPD and SBCPT, respectively, almost independent of the silicide thickness. The SBCPT has a relatively low 3-dB bandwidth of ~0.5 GHz due to the base floating, similar to the previous report [6].

However, the plots of photocurrent–light power exhibit quite poor linearity for both SBPD and SBCPT, as shown in Fig. 5. The responsivity decreases with the light intensity increasing, especially for the thin silicide and/or at low bias. The transistor-induced gain, defined as $(I_{\rm photo} - I_{\rm dark})_{\rm SBCPT}/(I_{\rm photo} - I_{\rm dark})_{\rm SBPD}$, also depends on both the light power and the bias voltage. This behavior may be attributed to the large series resistance of the Ni–silicide/Si Schottky contact: $\sim 1.1 \times 10^6\ \Omega$ for the thin silicide and $\sim 1.7 \times 10^5\ \Omega$ for the thick silicide, as extracted from the linearly fitting of the forward biased I–V curves of SBPDs.

From linearly fitting of the slightly forward biased log (I)–V plots of SBPDs based on the thermionic emission (TE) model, the SBH and ideality factor are extracted to be 0.58 eV and 1.27 for the thin Ni silicide and 0.61 eV and 1.23 for the thick Ni silicide, respectively, The lower SBH of the thin silicide detector

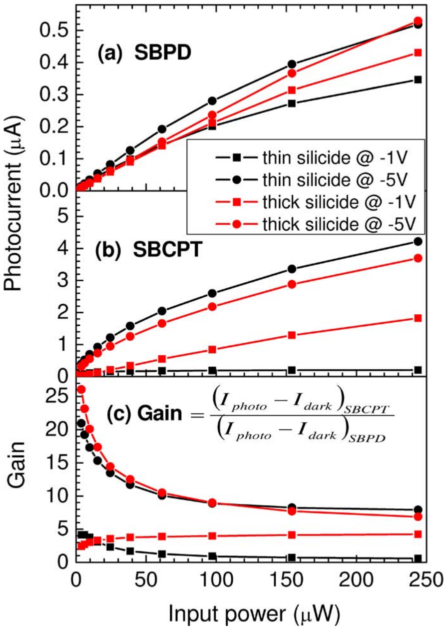

Fig. 5. (a) Photocurrent of SBPD, (b) photocurrent of SBCPT, and (c) the transistor gain defined as $(I_{\rm photo} - I_{\rm dark})_{\rm SBCPT}/(I_{\rm photo} - I_{\rm dark})_{\rm SBPD}$ at -1 and -5-V bias as a function of the light power incident upon the detector.

results in the larger dark current than the thick silicide counterpart, which may arise from phase variation of the thin Ni-silicide and/or the impact of subsequent dry and wet-etching procedures for the contact hole opening. The SBCPTs at low bias have similar or only slightly larger dark current than the SBPD counterparts, while it increases quickly after a certain voltage. This behavior can be explained as follows: for PNM-SBCPT at negative bias, the p-n junction is forward biased and the silicide/n-Si Schottky junction is reversely biased. Therefore, the applied voltage is mainly dropped at the Schottky junction and the depletion region extends from the silicide deeply into the n-Si base with the applied voltage increasing. If the depletion region reaches to the p^+ emitter, namely "punching through" the base region, the device behaves somewhat like the forward biased $NiSi_2$/i-Si diode and the dark current will increase abruptly.

Assuming that the thin and the thick silicides absorb $\sim$17% and $\sim$46% light (corresponding to -0.85- and -2.65-dB insertion loss, respectively), the apparent internal quantum efficiencies ($\propto$ photocurrent/absorbed light power) are $\sim$0.11 and $\sim$0.04 for PNM-SBCPTs at -5-V bias and 0.126-W 1550-nm light incidence with the thin and the thick silicides, respectively. The larger quantum efficiency for the thin silicide detector can be attributed to the larger yield gain induced by multiple reflections of photoexcited carries in the silicide layer because this yield gain is approximately inversely proportional to the silicide thickness [8], and also the smaller SBH for the thin silicide. For comparison, the NPM-SBCPT in [6] (with responsivity of $\sim$150 mA/W and assuming 100% light absorption) has the apparent internal quantum efficiency of $\sim$0.12, which may benefit from the lower hole SBH of $NiSi_2$–Si contact ($\sim$0.49 eV) than its electron SBH.

Although the lower SBH provides the higher quantum efficiency, the dark current increases exponentially with the SBH decreasing. Therefore, a more promising method to improve the quantum efficiency and simultaneously reduce the insertion loss of in-line monitor is to thin down the silicide thickness. However, the thin silicide will lead to the large series resistance, which will remarkably restrict the increase of photocurrent, especially at low bias, as mentioned above. This conflict may be circumvented by using a two-layer silicide configuration, i.e., the silicide is as thin as possible in the region for optical absorption while the other region (e.g., for interconnection and/or contact) being thick enough to reduce the resistance. Furthermore, the transistor gain of SBCPT can be further improved by optimizing the base width, the base doping profile, and the layout design. However, because the "punch-through" voltage is also determined by these parameters, a tradeoff between the transistor gain and the "punch-through" voltage has to be considered.

IV. CONCLUSION

In summary, a two-terminal PNM SBCPT for in-line optical monitoring is demonstrated with insertion loss of $\sim$0.8–1.2 dB and responsivity of $\sim$24 mA/W around 1550-nm. The responsivity may be further increased and the insertion loss may be reduced simultaneously by thinning down the thickness of the silicide absorber and increasing the transistor gain, indicating that the silicide SBCPT is a promising candidate for in-line optical monitoring.

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