Monolithic integration of complementary metal oxide semiconductor compatible waveguides (WGs) and photodetectors (PDs) is one of the most important technologies in the emerging Si-based integrated photonics. A bottom-WG-coupled structure has been commonly adopted in most III-V compound semiconductor-based WG-integrated PDs and more recent Ge PDs integrated with Si WGs, as the WG and PD materials are sequentially grown by a heteroepitaxial process. On the other hand, a top-WG-coupled structure may fit better into the intrachip optical interconnection architectures because it retains the general Si chip structure, where active devices are fabricated on the substrate and the passive interconnections are built in the upper levels.

In addition to a recent report of top-WG-integrated Ge PD, there have been a few previous reports of Si PDs integrated with upper dielectric WGs. However, most of them exhibited slow evanescent wave coupling rates and amorphous silicon detectors, which also suffered from low quantum efficiency and high bias voltage requirements. In this paper, we present crystalline p-i-n silicon PDs integrated with compact SiON channel WGs, which demonstrated high coupling efficiency and high responsivity with relatively small device size due to high evanescent coupling rates.

A top-WG-integrated structure provides great flexibility in the materials choices and device designs. Therefore, it is critical to understand the trends in coupling behavior and device performance dependency on design parameters, which were not addressed in previous studies as reported on specific material and design choices. In our current work, we report the dependence of coupling efficiency on WG design and the resulting impact on PD performance. The results can provide design guidance for a broader range of evanescent coupling structures with various materials in silicon micro photonics.

For device fabrication, Si p⁺ wafers (0.01–0.02 Ω cm) with a 5 μm thick epitaxial Si layer (16–24 Ω cm) were used. After the epitaxial layer was etched down to 0.5 μm thickness, phosphorus was implanted with a dose of 3 × 10¹⁵/cm² at 100 keV, followed by an activation annealing at 1000 °C for 30 s. Silicon vertical p-i-n diodes were patterned and a 2.2 μm depth was plasma-etched. This was done in order to ensure optical isolation of the WGs from the Si substrate. Then, 35 μm SiO₂ was deposited over the Si PD mesas and then planarized and polished down by chemical mechanical polishing, leaving a thin oxide above the Si mesas. Patternning and opening of oxide windows followed in order to expose the top surface of the silicon PDs. Next, the single-mode WGs were formed by plasma enhanced chemical vapor deposition of SiO₂, followed by etching to define the WGs. Both relatively low index-contrast WGs (1.2 μm² with ncore=1.52) and higher index-contrast, smaller WGs [1.2 μm(width,W)×0.4 μm(height,H)] with ncore=1.58 and 0.9 μm(W)×0.3 μm(H) were prepared. The dimensions of the WGs were chosen for single-mode operation and to stay within the resolution limit of the available lithography tool. The index contrast is defined by Δn=ncore−nclad. A 2.2 μm thick SiO₂ cladding layer (nclad=1.45) was deposited, followed by opening contact holes at least 3 μm away from the WG in order to prevent the metal from interacting with the optical mode. After depositing and patterning Al contact pads, the wafers were annealed in N₂/H₂ forming gas. For testing, while coupling 830 nm transverse-electric light to the cleaved WG input facets, we simultaneously measured the photocurrent Iph at −2V reverse bias and the remaining optical power from the output facet of the through WGs Pout. The device structures are shown in Fig. 1.

Figure 2(a) shows the transmitted optical power Pout(WG-PD) normalized to the power at the reference WG Pout(ref-WG), as a function of detection length L. As the data show the dependence of exponential decay on the coupling length L, we can fit the data with the following equation:

\[
\frac{P_{\text{out}}(\text{WG-PD})(L)}{P_{\text{out}}(\text{ref-WG})} = \frac{P_{\text{in}} \eta \text{exp}(−\alpha_{\text{coupling}} L)}{P_{\text{in}} \eta \text{exp}(−\alpha_{\text{WG}} L)}\frac{10^{−\alpha_{\text{WG}} L/10}}{10^{−\alpha_{\text{WG}} L/10}} = \eta^2 \text{exp}(−\alpha_{\text{coupling}} L),
\]

where P_in is the optical power at the point of entering the
Because the optical mode in the WG on top of the PD is different from the mode in the bus WG, we introduced mode coupling efficiencies $\eta_m$ and $\eta_{out}$ that describe the coupling from the bus WG mode to the mode in the WG on top of the PD and vice versa. In approximation, it was assumed that $\eta_m$ and $\eta_{out}$ are equal and that the term $10^{-\alpha_{WG}/10}$ is negligible, as the propagation loss in the WG $\alpha_{WG}$ is small.

Fitting the measurement data to Eq. (1) suggests that incoming photons from the input bus WG are coupled to a mode in the WG on the PD with $\eta_{in} \approx 86.3\%$ mode-matching efficiency and the power in the WG on the PD decreases at a rate of $1/\alpha_{coupling} = 52 \mu$m due to the evanescent wave coupling to the Si PD. We can also conclude that the total coupling efficiency of photons from the input bus WG to silicon PD is well above 90% because nearly all of the photons that are coupled to the WG mode on the PD ($\sim P_{in} \times \eta_m$) will be coupled to the Si PD via evanescent wave coupling in a sufficiently long PD [e.g., $L > 3 \times (1/\alpha_{coupling})$], and some portion of the remaining 14% photons ($\sim P_{in} \times (1-\eta_m)$) also can contribute to the photocurrent by being directly coupled to the Si detector.

The measured quantum efficiency as a function of detector length $L$ is shown in Fig. 2(b) and can be described as follows:

$$QE(L) = \frac{h\nu}{qP_{in}} \times I_{ph}(L) = \frac{h\nu}{qP_{out(ref-WG)}10^{-\alpha_{WG}/10}} \times I_{ph}(L) = A + C[1 - \exp(-\alpha_{det}L)].$$

The saturated quantum efficiency, represented by the term $(A+C)$ in Fig. 2(b), was about 46%, slightly higher than the efficiency of Si PD when measured with surface-normal illumination (41\%).

The results of coupling from high index-contrast WGs, shown in Fig. 3, reveal two significant differences compared to low index-contrast WGs. First, the evanescent coupling to the detector occurs much faster than for low index-contrast WGs. The greater index-contrast between core and cladding of a WG ($n_{core} - n_{clad}$) leads to smaller refractive index difference between the PD and WG core ($n_{PD} - n_{core}$). In addition to the smaller index difference between WG and detector, the geometrical factors of these WGs, such as smaller WG dimensions to maintain the single-mode condition and reduced height, also affect the impedance of the WG layer.
through an effective index change (i.e., $Z \approx 1/\sqrt{n_{core}^2 - n_{eff}^2}$) and thus lower the impedance barrier between WG and PD. As a result, a leaky mode has more evanescent field penetrating into silicon and the evanescent coupling rate $\alpha_{coupling}$ is higher, as demonstrated by much shorter $1/\alpha_{coupling}$ and quicker rise in the quantum efficiency within short coupling lengths (e.g., $<40 \; \mu m$) as shown in Fig. 3.

The second significant difference between low versus high index-contrast WGs is the observed direct coupling from the bus WG to modes inside the Si PD. Figure 4(a) shows the simulation results for such a scenario. The simulation clearly shows that the light is coupled to modes in the Si PD. Simulations for the low-index-contrast case [Fig. 4(b)] show that the light remains in the WG and generally does not couple directly into the Si PD. The direct coupling into the Si PD explains the relatively low $\eta$ in Fig. 3(a), indicating that only a small fraction of the light from the bus WG remains in the WG on top of the detector.

The lower quantum efficiencies for the low-index-contrast WGs are mainly due to the fact that during evanescent coupling, photons enter the PD nearly perpendicular to the WG-detector interface. Due to the long absorption length of $13 \; \mu m$ for 830 nm light in Si, only $41\%$ of the photons can be absorbed in the top $7 \; \mu m$ thick layer (given the vertical $p-i-n$ geometry of our silicon PD, only the photons absorbed within a certain depth of the PD—top $7 \; \mu m$ in our devices—can contribute to the photocurrent). Therefore, the quantum efficiency of the PD coupled with low index-contrast WG is close to the efficiency of the PD when measured with surface-normal illumination. In contrast, for the high index-contrast WG cases, the modes, excited due to direct coupling to the Si PD, travel in the horizontal direction and therefore are not limited by absorption length of Si. As the absorption length limitation is lifted, the quantum efficiency increases significantly.

In summary, we have demonstrated WG-integrated silicon PDs that employ a top-to-bottom evanescent-wave coupling structure, achieving over 90% coupling efficiency. PD devices integrated with single-mode, low index-contrast WGs exhibit relatively slow evanescent coupling rates and a slightly higher quantum efficiency than that of surface-illuminated device. In the case of single-mode, high index-contrast WGs, coupling to PDs occurred mainly by mode-matching of the input WG mode and modes in the Si PD, leading to an enhanced $80\%$ quantum efficiency. The observed trend can generally be extended to a wider variety of top WG-coupled vertical $p-i-n$ PDs, as was recently demonstrated by an integrated Ge PD coupled with silicon nitride WGs.$^7$

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