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Evanescent Coupling Device Design for Waveguide-Integrated Group IV Photodetectors

Donghwan Ahn, Member, IEEE, Lionel C. Kimerling, Senior Member, IEEE, and Jurgen Michel, Member, IEEE

Abstract—We have fabricated vertical p-i-n silicon photodetectors that are monolithically integrated with compact silicon-oxynitride channel waveguides. By comparing the evanescent coupling from low index-contrast waveguides and compact, high index-contrast waveguides, the dependence of evanescent coupling behavior on the waveguide index and geometry designs was analyzed. The effects of fabrication variations in the coupling structure have been studied and it was found that an offsetting step in the waveguide can help compensate for the mode mismatch at the transition interface from the input bus waveguide to the waveguide on top of the photodetector. Finally, we present a design map, built by drawing the evanescent coupling rate contour lines in the waveguide design space, which well predicts the evanescent coupling trends.

Index Terms—Integrated optoelectronics, photodetectors, waveguides.

I. INTRODUCTION

Silicon microphotonics has emerged with great interest recently [1]–[3], due to its potential to enable large-scale integration of photonic devices for applications such as low-cost telecommunication or on-chip optical interconnects. One of the key elements for its success is the viable and efficient integration of waveguide and high-performance photodetector.

Traditionally, waveguide-photodetector integration has been primarily focused on III-V compound semiconductor devices [4]–[7]. Only since 2007 have there been experimental reports of waveguide-integrated germanium photodetectors [8]–[17].

In most III-V compound semiconductor-based waveguide-integrated photodetectors [4]–[7], a bottom-waveguide-coupled structure, where the evanescent-wave coupling occurs from a bottom waveguide to an upper photodetector, has been a typical design, as the waveguide and photodetector materials can be sequentially grown by a heteroepitaxial process. The majority of recently demonstrated Ge photodetectors integrated with a Si waveguide also adopted this structure [9]–[13], [16]–[18] as the direct epitaxy of germanium on Si can be utilized [19], [20].

On the other hand, a top-waveguide-coupled structure has the advantage of being flexible in choosing the waveguide material, unlike bottom-waveguide-coupled photodetector where waveguide material and substrate, on which the photodetector is epitaxially grown, have to be identical. A top-waveguide-coupled design also retains the general Si CMOS chip structure where active devices are fabricated on the substrate and the passive interconnections are built in the upper levels. A top-waveguide-coupled structure may fit better with the on-chip optical interconnection architectures where global optical interconnects are envisioned to be located in or above the metal interconnect levels [21], [22].

In our current work, we adopted a top-waveguide-coupled structure and demonstrated the integrated structure of SiON channel waveguides and Si photodetectors. There have been a few previous reports of Si photodetectors integrated with upper dielectric waveguides [23]–[26]. However, most of them exhibited slow evanescent coupling rates and amorphous [25] or polycrystalline [26] silicon detectors, which also suffered from low responsivity and high bias voltage requirements. In this paper, we present crystalline p-i-n silicon photodetectors integrated with compact SiON channel waveguides, which demonstrated high coupling efficiency and high responsivity with relatively small device size, due to high evanescent coupling rates.

A top-waveguide-integrated structure provides great flexibility in the materials choices and device designs. Therefore, it is critical to understand the coupling behavior dependency on design parameters and the resulting impact on photodetector performance, which were not addressed in previous studies [9]–[17], [23]–[26] as they reported on specific material and design choices. In this paper, we developed general design rules for waveguide-photodetector coupling by systematically studying the trend of change in the evanescent-wave coupling behavior and device performance, as influenced by coupling structure design and waveguide materials. The results will provide useful information particularly for silicon microphotonics, where a large range of possible materials choices for waveguides (SiO$_2$N$_x$ (n = 1.45–2.0), Si$_3$N$_4$ (n ~ 2.0), Si-rich nitride (n > 2.0), Si (n ~ 3.5)) and photodetectors (Si, SiGe, and Ge) exist.

We furthermore developed a methodology that extracts key coupling parameters such as coupling efficiency, coupling rate, and mode-matching parameters from the experimental measurement data as a function of photodetector coupling length, and studied the change of such parameters as a result of waveguide design change. We also investigated mode-matching issues at the entrance/exit interface between the photodetector and the
bus waveguide. The observed trends were used to predict the evanescent coupling performance in a broad range of group IV photodetector devices.

II. DEVICE FABRICATION AND MEASUREMENT

For device fabrication, Si p+ wafers (0.01–0.02 Ω cm) with a 5 μm epitaxial Si layer (16–24 Ω cm) were used. After the epitaxial layer was etched down to 0.5 μm thickness, phosphorus was implanted at a dose of 3 x 10^{15} cm^{-2} at 100 keV, followed by an activation annealing at 1000°C for 30 sec. Silicon vertical p-i-n diodes were defined by patterning mesa structures and dry-etching to remove 2.2 μm of silicon. This was done in order to ensure optical isolation of the waveguides from the Si substrate. Then, 3.5 μm SiO₂ was deposited by Plasma-Enhanced Chemical Vapor Deposition (PECVD) (Fig. 1(a)), followed by a Chemical-Mechanical Polishing (CMP) process to planarize the top surface. The thickness of the remaining oxide layer on top of the silicon photodetector, t, was evaluated by ellipsometry measurements on larger monitor features positioned close to the photodetectors. The oxide layer was further reduced to the desired thickness by timed plasma etching (Fig. 1(b)). This step was followed by patterning and opening an oxide window to expose the top silicon surface such that the waveguide could be in direct contact with the silicon photodetector for efficient coupling (Fig. 1(c)).

The opening of the oxide window following the CMP process, in Fig. 1(c), results in an abrupt step in the waveguide at the transition interface to the coupling region. We fabricated samples with various step heights t of 0, 0.1 μm, 0.2 μm and 0.3 μm (samples I–IV).

Next, the single-mode waveguides were formed by PECVD deposition of SiO₂Nₓ, followed by etching to define waveguides. The refractive index of the SiO₂Nₓ material was varied by adjusting N₂/N₂O gas ratio. A 2.2 μm-thick SiO₂ cladding layer was deposited, followed by opening contact holes at least 3 μm away from the waveguide 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. The final device structure is shown in Fig. 1(d).

On a chip, reference waveguides and the waveguides integrated with the photodetectors of different lengths L were placed parallel to each other, as shown in Fig. 1(e). In order to prevent any uncoupled stray light from the fiber or weakly-guided leaky modes from entering the devices and affecting the measurements, the waveguide input facet was offset 50 μm by employing two 90° bends [Fig. 1(e)]. While coupling 830 nm transverse-electric light to the cleaved waveguide input facets, we simultaneously measured the photocurrent from the photodetector, I phot, at −2V reverse bias and the remaining optical power from the output facet of the through waveguide, Pout. We selected and used for this study only those samples in which the standard variation of Pout through multiple reference waveguides, σ(Pout), is less than 5% of the average Pout, in order to assure that all the waveguides on a sample have consistent light propagation performance and uniform fiber coupling efficiency.

Mode matching efficiency η, coupling rate αcoupling and the quantum efficiency were defined as follows. Pout(WG→PD)(L), the measured optical power at the output of the waveguide coupled with a photodetector of length L is expressed as follows:

\[
P_{out}(WG→PD)(L) = P_{in}\eta_{in}\exp(-\alpha_{coupling}L)\eta_{out}10^{-\alpha_{WG}t/L/(10T)} \tag{1}
\]

where P_{in} is the optical power at the point of entering the photodetector. η_{in} and η_{out} are the mode coupling efficiencies between the bus waveguide mode and the mode in the waveguide on top of the photodetector in the coupling region, at the beginning and at the end of the photodetector, respectively. L is the detector coupling length and α_{coupling} is the evanescent coupling rate from the waveguide to the Si photodetector. α_{WG} is the waveguide loss per length in unit of dB/cm, measured by a cut-back method from paper clip structures on the same chip, and L is the distance in cm from the photodetector to the output facet of the through waveguide. T is the power transmittance at the output facet. Some notations are also shown in the schematic chip layout, Fig. 1(e).

P_{out}(WG), the optical power from the reference waveguide without photodetector is given by

\[
P_{out}(WG) = P_{in}10^{-\alpha_{WG}t/L} \tag{2}
\]

Normalizing (1) by (2), we obtain

\[
P_{out}(WG→PD)(L)/P_{out}(WG) = \eta_{in}^2\exp(-\alpha_{coupling}L) \tag{3}
\]

where η_{in} and η_{out} are assumed to be equal and L and t are set equal as well because the difference (L−t') is negligible in our samples (≤160 μm).
We define three coupling mechanisms. Contributions to photocurrent from Mechanism I, \( I_{\text{ph}1}(L) \), can be expressed as follows:

\[
I_{\text{ph}1}(L) \approx P_{\text{in}}(1 - \eta_{\text{in}})C_1 R_{11} f(L)
\]

(5)

where \( C_1 \) is the undetermined ratio of the photons coupled to silicon that did not couple to the waveguide mode on top of the photodetector, \( R_{11} \) is the internal responsivity of the detector resulting from this process. Since absorption is a function of path length in silicon, \( f(L) \) is the function that increases from zero and saturates at 1 with detector length \( L \). Since Mechanism I consists of many different absorption paths, \( C_1, R_{11}, \) and \( f(L) \) should reflect the combined effect of each absorption process.

Mechanism II: This mechanism occurs when the photons in the input bus waveguide reaches the Si detector. Mode matching conditions between the waveguide mode and Si radiation modes allow photons to couple directly into the Si layer. This mechanism also describes scattering into the Si layer due to the abrupt effective index change in the bus waveguide. Contribution to photocurrent, resulting from Mechanism I, \( I_{\text{ph}1}(L) \) can be expressed as follows:

\[
I_{\text{ph}2}(L) \approx P_{\text{in}} \eta_{\text{in}}(1 - \exp(-\alpha_{\text{det}} L)) R_{2}
\]

(6)

where \( R_{2} \) is the responsivity of the photodetector at 830 nm.

Mechanism III: At the end of the Si photodetector, the remaining light in the waveguide experiences a modal discontinuity because of the abrupt change in structures and effective index. Part of the light that is still remaining in the waveguide can be scattered back into the Si layer.

Contributions to photocurrent from Mechanism III should be significantly smaller than from Mechanisms I and II. The photocurrent due to Mechanism I levels off much more quickly with detector length than the photocurrent due to Mechanism II, because the coupling to silicon in Mechanism I occurs nearly instantaneously at the input interface of the photodetector and the absorption length inside silicon in the lateral direction, \( 1/\alpha_{\text{det}} \), cannot exceed \( 1/\alpha_{\text{Si}} \), which is about 14 \( \mu \)m at 830 nm. Therefore, we
can create a simplified equation by assuming that the photocurrent from Mechanism I is approximately constant. Therefore

\[
Q \cdot E(L) = \frac{hv}{qF_{in}} \times I_{\text{ph},M}(L) \\
\approx \frac{hv}{qF_{in}} \times (I_{\text{ph},r}(L) + I_{\text{ph},t}(L) + I_{\text{ph},r,l}(L)) \\
\approx A + C(1 - \exp(-\alpha_{\text{det}}L)), \quad (7)
\]

The term \(A/(A + C)\) represents the saturated quantum efficiency when the photodetector length \(L\) is sufficiently large. In addition, \(A/(A + C)\) can be used as a parameter that indicates how dominant Mechanism I is, compared to the other two coupling mechanisms, and in turn shows how large the mode-mismatch between the input bus waveguide and the waveguide on the photodetector is. These parameters for sample A are shown in Fig. 2(a). We used various sample sets with three different waveguide designs and additional step height \(t\) variations. The measured and fitted data are summarized in Table I.

### III. EFFECT OF STEP HEIGHT VARIATION

As Fig. 2(c) shows, Mechanisms I and III contain photon scattering due to the mode-mismatch between input or output bus waveguide and the waveguide on top of the photodetector in the coupling region. In general, it is desirable to minimize photon scattering in order to reduce optical energy loss and prevent carrier generation due to scattered photons in nearby devices. We therefore studied the influence of the step height \(t\) [see Fig. 1(c)] on the scattering loss. Comparison between samples with identical waveguide design but varying step heights \(t\) (samples I–IV in Table I) shows the maximum mode-matching efficiency parameter \(\eta\) for the sample with \(t = 0.2 \mu m\) (Sample II). More apparently, the value of the mode-mismatch indicator \(A/(A + C)\), as defined in Fig. 2(a) and re-plotted as a function of step height \(t\) in Fig. 3, reaches a minimum when \(t = 0.2 \mu m\). This result shows that more optical power from the input bus waveguide is coupled into the mode in the waveguide on the photodetector, when a 0.2 \(\mu m\) step is intentionally introduced at the interface where the bus waveguide reaches the photodetector.

We can analytically calculate and compare the mode profile of the waveguide in the input bus region and that in the photodetector-coupled region, as shown in Fig. 4.

![Fig. 3. Mode-mismatch indicator \(A/(A + C)\), as defined in Fig. 4, from the samples with different step height \(t\).](image)

![Fig. 4. The mode profiles calculated in a multilayer structure where the waveguide material is in contact with the bottom oxide cladding layer (dashed line, \(E_1\)) or silicon absorbing layer (solid line, \(E_2\)). As an approximation, the 1D multilayer structure was obtained by applying the Effective Index Method (EIM) to 2D waveguide structure. The transfer matrix method with complex refractive indexes [27] was used for mode calculations. The inset shows the change of overlap integral between \(E_1\) and \(E_2\) as a function of the mode offset \(t\).](image)
The overlap integral between these two modes can be calculated with the following equation:

$$\Gamma = \frac{\int E_1^*(x)E_2(x)dx}{\sqrt{\int E_1^*(x)E_1(x)dx \int E_2^*(x)E_2(x)dx}}.$$  \(8\)

Then, replacing \(E_2(x)\) with \(E_2(x - t)\) in the above equation, we can estimate the dependence of the mode overlap integral as a function of the mode offset \(t\). The inset of Fig. 4 shows that the mode offset of 0.23 \(\mu m\) can increase the mode-matching between the two modes by about 5.5%. This mode offset can be implemented in the device fabrication process by introducing a controlled step height \(t\) in the waveguide at the transition to the coupling region [Fig. 1(c)].

The experimental observations and analytical estimations of the coupling offset are also supported by optical simulations. 3D finite-difference time-domain (FDTD) simulation results in Fig. 5(a) show that the propagation mode in the waveguide experiences an upward shift as it enters the coupling region. In contrast, optical simulation with a step of 0.2 \(\mu m\) in the waveguide as shown in Fig. 5(b) demonstrate that the light propagation mode experiences less disruption as it enters the coupling region and scattering losses are reduced.

This effect applies to a broad range of integrated photodetector designs, especially the ones in which Coupling Mechanism II is important. The optimal step height \(t\) in the photodetector device with different design parameters (wavelength, refractive index, etc.) can be generally calculated in the same way as described above.

**IV. EVANESCENT COUPLING DESIGN MAP**

The device sample sets presented in this paper had significant variations of the waveguide index-contrast \(\Delta n = n_{cladding} - n_{core}\), the main parameter of waveguide design, from low (samples I–IV in Table I) to relatively high values (samples V, VI). The measured quantum efficiency data from various sample sets as functions of waveguide-detector coupling length are drawn in Fig. 6(a).

A clear trend of quantum efficiency saturation dependency on different waveguide designs is that, as the index-contrast \(\Delta n\) of single-mode waveguides increases, the quantum efficiency tends to saturate more quickly within shorter detector coupling length and the parameter \(A/(A + C)\), defined in (7) and Fig. 2(a), increases. Increasing value of \(A/(A + C)\) in higher \(\Delta n\) waveguides indicates relative dominance of coupling Mechanism I, which is also verified from Fig. 6(b) in comparison to Fig. 6(c). Coupling Mechanism I is responsible for enhanced total quantum efficiency through direct optical coupling from the bus waveguide to the modes inside the Si photodetector and thus enables the high \(\Delta n\) waveguide integrated photodetector to achieve the efficiency well beyond that of surface-illuminated photodetector devices. The detailed explanation and supporting evidences for the physical background for this trend were previously reported in [28].

The experimental results in this paper clearly show that the difference in waveguide design, even if integrated with the same Si photodetectors, significantly changes the evanescent coupling phenomenon and the overall device performances. Therefore it is worthwhile to generalize the observed trends in an extended design map and understand key design factors in evanescent coupling device design.

The two most significant design factors that are considered in the waveguide design process would be 1) the choice of waveguide core material (SiO\(_2\) cladding is given in most group IV photonic devices) and 2) the determination of waveguide geometry and dimension. The first factor can be parameterized...
The above definition is based on the ray-optics perspective of the waveguide mode propagation [as shown in Fig. 7(a)]. That is, we postulate that two main geometrical factors of the mode are the reflection angle $\theta$ and the frequency at which the light ray hits the interface, $1/l$, once the waveguide structure is converted to slab structure by the Effective Index Method (EIM). As $1/l$ and $\theta$ are larger, light rays will make more frequent attempts to enter the photodetector material with higher transmission efficiency.

After running 3-dimensional FDTD simulations, we fitted the monitored optical power in the waveguide into the exponential function and extracted the rate of exponential decay. We then drew the contour lines of the constant evanescent coupling rate in the 2-dimensional space that consists of $(n_{PD} - n_{WG, core})$ and the WG geometrical factor [Fig. 7(b)]. The contours, the solid lines shown in the design map, were obtained by interpolating the simulation results from 16 different waveguide design cases, some of which are shown in the map along with the index-scaling lines for the square-type (A1–A4) and the rectangular-type (B1–B4) single-mode waveguide designs.

The contour lines of $1/\alpha_{coup, center} = 60, 35, 20, 10 \mu m$ shown in Fig. 7(b) indicate that the evanescent coupling from waveguide to photodetector becomes faster when the waveguide design has the smaller $(n_{PD} - n_{WG, core})$ and a larger WG geometrical factor. We also have seen the trend that as the $1/\alpha_{coup, center}$ decreases (the coupling rate increases), coupling Mechanism I becomes more significant than coupling Mechanism II. Therefore, we can define two different regimes of coupling behavior in the design map, i.e., 1) the regime where the coupling Mechanism II is dominant and the evanescent coupling from the waveguide to the waveguide is slow due to low $n_{PD} - n_{WG, core}$ and low waveguide geometrical factor and 2) the regime where the coupling Mechanism I is dominant and the evanescent coupling from waveguide to photodetector is fast due to low $n_{PD} - n_{WG, core}$ and high waveguide geometrical factor. These regimes are indicated in the coupling design map.

The design map agrees well with the observed coupling trend from the experimental data of the Sample set I–VI (in Fig. 6). In particular, it is noteworthy that, in addition to the index-contrast parameter $\Delta n$ of the waveguide, the geometry of the single-mode waveguide plays a very significant role in affecting evanescent coupling behavior. That is, with a given material, we can further enhance the coupling rate by increasing the waveguide geometrical factor, e.g., by simply shrinking the waveguide dimensions or choosing a flat rectangular shape. In fact, the design map explains that the significant increase of the evanescent coupling rate and quantum efficiency achieved by Samples V and VI (case B2 and B3), relative to Samples I–IV (case A1), was the outcome of the waveguide geometry change from square-type to flat-rectangular type (i.e., a jump from the index-scaling line A to the line B in the design map), in addition to a $\Delta n$ increase. The simple $\Delta n$ scaling from 0.07 (design case A1, sample I) to 0.12 (design case A2) to 0.22 (design case A3) without change of waveguide geometry shape [i.e., following the index-scaling line A as indicated in Fig. 7(b)], would increase the evanescent coupling rate only modestly.

The trend indicated in the above design map can extend to a wide variety of Group IV waveguide-integrated photodetectors.
and even beyond the shown 850 nm wavelength cases. For example, as we continue moving in the direction towards high $\Delta n$ and larger WG geometrical factor, one of the extreme experimental cases would be the sub-micron scale, Si channel waveguide coupled to a Ge photodetector [11]–[13], [16]–[18], [29]. Such structures have very low $n_{\text{FD}} - n_{\text{VG,core}}$ of 0.5 and a very high waveguide geometrical factor ($\sim$1.1) because of the high refractive index of the silicon waveguide core and the very small, flat rectangular single-mode waveguide dimensions (e.g., 500 nm (W) $\times$ 200 nm (H)). Just as the above design map helps us anticipate very fast, nearly Mechanism I dominant coupling for such structures, the simulation in Fig. 8(a) shows the photons from Si channel WG couple to Ge PD almost immediately at the onset of the detector coupling. In case of the thin-film Ge photodetector [i.e., $t_{\text{Ge}} \ll 1/\alpha_{\text{Ge}}$ (absorption length of Ge)], the coupling to a Ge photodetector is still immediate at the onset of the detector coupling, but, because a single pass of photons inside Ge layer is not enough to absorb all the photons, the unabsorbed photons are reflected back into silicon. They continue propagation while oscillating between the Si and Ge layer until being fully absorbed (Fig. 8(b) [30]), extending the coupling length to 10 $\mu$m. This behavior was experimentally confirmed by our previous report on Ge photodetectors vertically coupled to Si channel waveguides [18], which showed that all photons were coupled and absorbed within 5 $\mu$m length (or within 20 $\mu$m at longer wavelength beyond the Ge direct bandgap where absorption in Ge becomes less efficient).

Meanwhile, other research groups have strategically adopted Si rib waveguides as their building blocks for silicon-based photonic chips [10], [31], [32]. Single-mode rib waveguide design has its effective index very close to the core refractive index, as nearly all of the waveguide mode is contained in the waveguide core material, and has relatively large waveguide dimensions. Such characteristics of Si rib waveguide design lead to very small waveguide geometrical factors ($\sim$0.01) for the design used in [10], i.e., much smaller than any channel waveguide designs we considered in our experiments and simulations. Being placed at the left end of the design map (Fig. 7(b)), in opposition to Si channel waveguide design, Si rib waveguides are expected to have slow evanescent coupling rates when integrated to Ge photodetectors. In addition to our simulation result for such structure (Fig. 8(c)), the experimental report by Intel researchers [10] indicated their devices required the detector coupling length of about 100 $\mu$m for full responsivity saturation. Their unique results, different from faster responsivity saturation within short coupling length in other Ge photodetectors integrated Si channel waveguides, are well explained by the coupling behavior trend identified in our design map, Fig. 7.

V. Conclusion

We have demonstrated waveguide-integrated silicon photodetectors that employ a top-to-bottom evanescent-wave coupling structure. We achieved over 90% coupling efficiency from SiON waveguides to Si photodetectors. We identified three different coupling mechanisms and investigated the impact of the coupling device design on the coupling mechanisms. A two-step process that consists of 1) mode-coupling from a guided mode in the input bus waveguide to a leaky mode in the waveguide on top of the photodetector and 2) gradual evanescent wave coupling from the waveguide into the photodetector, was a main coupling mechanism in the case of devices with low index-contrast waveguides. Such designs with small waveguide geometrical factors will be useful for applications like optical power taps, due to slower evanescent coupling rates in the coupling region and efficient mode-coupling at the entrance of the photodetector between input bus waveguide and the waveguide on top of the photodetector. We showed that intentional introduction of a step in the input bus waveguide as it enters the Si photodetector further improves the mode-matching efficiency between the input bus waveguide and the waveguide on top of the photodetector. The total quantum efficiency of the integrated photodetector ($\sim$41–46% for the low index-contrast waveguide) was limited by partial collection of carriers generated by the evanescently coupled photons in the silicon photodetector ($\sim$41% quantum efficiency with 830nm surface-normal illumination). In the case of high index-contrast waveguides with large waveguide geometrical factor, coupling to the photodetector occurred mainly by mode matching of the input waveguide mode and radiation modes in the Si photodetector, leading to 78% quantum efficiency. The coupling structure designs with high index-contrast waveguides may serve well for end-node photodetectors that require short coupling length for high bandwidth.

We built a design map, which maps out the key single-mode waveguide materials and geometrical design factors onto 2-dimensional space and visualizes the trend of evanescent coupling behavior change as a result of waveguide designs. In addition to good agreement with the trend found in different kinds of SiON waveguide-integrated Si photodetector device sets we demonstrated in this paper, the design map well explains the evanescent coupling trend in a wide variety of group IV waveguide-integrated photodetector.
REFERENCES


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