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Low-Optical-Return Multimode Interference Photodiodes with Small Capacitance for Polarization-Diverse Optical Receivers

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Abstract *We designed and characterized a waveguide photodiode with a multimode interferometer. The photodiode with two light input ports showed high sensitivity, small junction capacitance, and low optical coupling between the two light input ports, which enables high-speed and polarization-diverse optical receivers with low optical returns.*

Introduction

Recent increasing demands for high density optical inter-connection requires high-bandwidth-density and low-energy-consumption optical receivers, such as silicon photonics with wavelength division multiplexing. One of the important features for such an optical receiver is being operable with existing optical-fiber networks. Most of those optical fibers used in datacenters are single mode fibers and are not supposed to maintain polarization of light. Therefore, optical receivers are expected to operate in the same manner for different polarizations of optical input[1,2]. On the other hand, optical devices in silicon photonics generally show large polarization-dependent characteristics, originating from the rectangular shape of silicon waveguides and a large index difference between silicon and cladding materials. In order to actualize polarization-diverse optical receivers with silicon photonics, several approaches have been proposed, using photodiodes (PDs) with two light input ports for the optical-electrical (OE) conversion[1,2]. Concerning PDs, there are several important characteristics for high-speed-operation and low-energy consumption optical receivers. One is the sensitivity, or OE conversion efficiency. Another is the junction capacitance C_{pd}, which limits the operation bandwidth of PDs connected to transimpedance amplifiers (TIAs). At the same time, the light reflection from optical receivers should be kept small[4], for avoiding unstable operations of light sources in transmitters. In this paper, we introduce a multimode-interference photodiode (MMI-PD) and the characteristics of fabricated devices. Compared to other conventional PDs, the MMI-PD showed high sensitivities and small C_{pd}. It is also shown that the MMI-PD was able to reduce the amount of optical reflection from the receiver circuits.

Circuit overview

Figure 1(a) shows the schematic of our optical receiver circuit. It is assumed that the polarization of the input light is not maintained and that the input light is a mix of four different wavelengths, which correspond to coarse wavelength division multiplexing grids in the O-band. First, the input light is connected from a single mode fiber to the photonic circuit through a low polarization-dependent-loss spot-size converter[3]. After that, the transverse electric (TE) polarization component and the transverse magnetic (TM) polarization component are separated through a polarization splitter and rotator (PSR). Then, each of the four wavelengths contained in the separated lights are split into four different waveguides through wavelength demultiplexers (DeMUXs). The separated lights are directed to silicon p-i-n variable optical attenuators (VOAs) and waveguide PDs. Here, each PD has two light-input ports and each PD is used for the OE conversion of a wavelength, summing the intensity of a TE polarization component and that of a TM polarization component. Each PD is respectively connected to a TIA. Thus, a single PD converts optical signals carried by a wavelength to corresponding electrical signals. Figure 1(c) is a photograph of the fabricated integrated circuit, a block from a PSR to PDs.

In this photonic circuit, the two ports of a PD

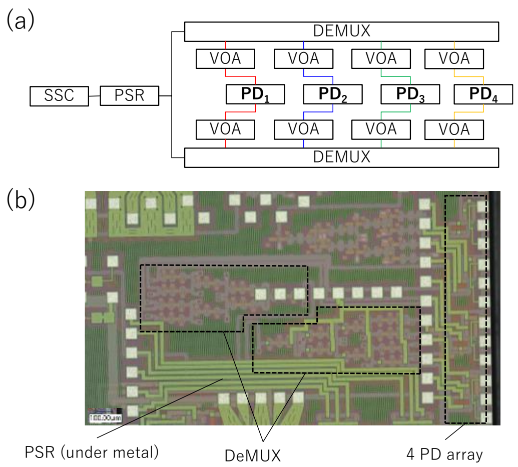

Fig. 1: (a) The schematic of the photonic circuit of the polarization-diverse optical receiver.(b) A photograph of the circuit, from PSR to PDs.

could be optically couple to each other. In other words, part of the input light from a port, which is not completely absorbed in the photodiodes, could transmit to the other port and go back through the circuit. This optical return, which we hereafter call the inter-port crosstalk (*XT*), behaves similarly to the light reflection from PDs and leads to the unstable operation of light sources used in transmitters.

Therefore, the critical characteristics of the two-port PDs are considered as not only high sensitivities and small capacitances but also small *XT*s.

Device design and operation principle

Figure 2(a) shows the cross-sectional structure of the PDs. The layer structure is the same as conventional waveguide photodiodes, epitaxial germanium (Ge) on silicon (Si). The top of Si adjacent to Ge was n-doped and silicided so as to reduce the contact resistance of cathodes. Figure 2(b) and 2(c) show the conventional structure of two-port waveguide photodiodes. In the structure of Figure 2(b), hereafter referred to as “straight”, two light input ports are placed in the opposite side of the Ge region. In the structure of Figure 2(c), hereafter referred to as “cross”, two light input ports are placed in an orthogonal manner. In both structures, Si waveguides are tapered between the input waveguides and the Ge region because the width of single mode Si waveguides is 400 nm and the width of Si waveguides under the Ge region must be larger than 1 µm for the epitaxial growth of Ge and for Si cathodes. Figure 2(d) shows our MMI-PD proposal, in which Si waveguides construct an MMI and Ge is placed on a small part of the MMI. The operation principle of the MMI-PD is as follows.

First, Figure 3(a) shows the simulated beam propagation of a silicon waveguide MMI without the Ge layer. Light input from port1 propagates along the waveguide and is focused at the middlepoint of the MMI. Here, the width of the

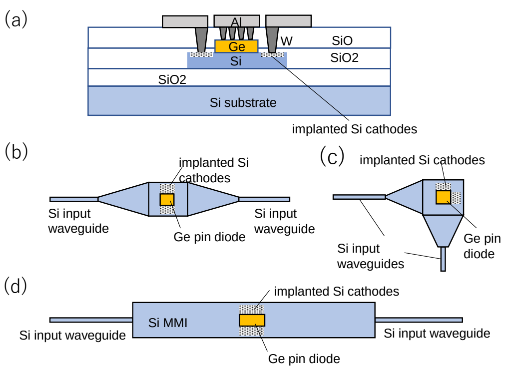

Fig. 2: The schematics of (a) the layer structure of PDs, (b) a “straight” PD, (c) a “cross” PD, and (d) an MMI-PD.

focued beam is less than 2 microns, so we can place the narrow Ge for absorbing the focused light. Simultaneously, we can place wide Si cathodes adjacent to the Ge without additional absorption of light by heavily doped Si cathodes, which generally degrades the sensitivity of waveguide PDs. As a result, the MMI-PD enables a small Ge region with large Si cathodes, enabling small junction capacitances as well as high sensitivities of the PD.

As for *XT*, Figure3(b) and Figure3(c) show the effect of Ge, placed at the focus point of the MMI, on optical propagation and *XT*s. Here, in order to show the operation principle visually, the absorption coefficient of Ge , was set to zero hypothetically. In Figure 3(b), the length of Ge is 13.8 µm. Input light from port1 does not couple to port2, because the multimode waveguide consisting of Si and Ge changes the focusing distance shorter. On the other hand, when the length of Ge is 17.5µm, as shown in Figure3(c), input light from port1 couples to port2, leading to the increase of *XT*. This results shows that *XT* can be reduced by designing the appropriate length of Ge. In order to estimate the proper length of Ge, the optical coupling ratio between port2 and port1 were calculated, taking into consideration the absorption coefficient of Ge. The results is shown in Figure3(d). In this case,

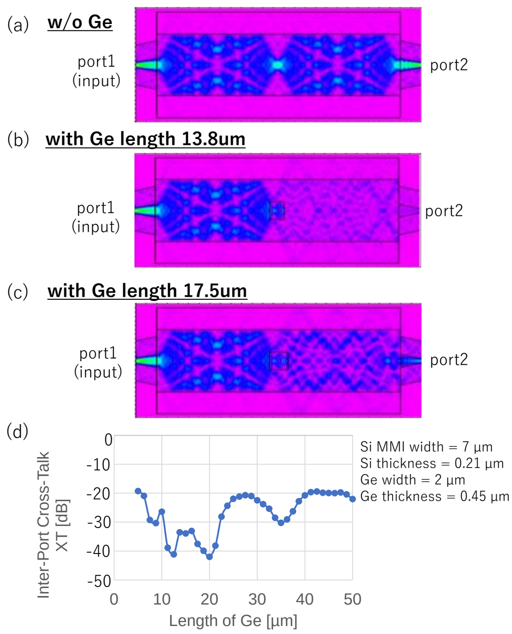

Fig. 3: Simulated beam propagations of (a) an Si MMI without Ge, (b) an Si MMI with a Ge 2 µm wide and 13.8 µm long, and (c) an Si MMI with a Ge 2 µm wide 17.5 µm long. The absorption coefficient of Ge was hypothetically set to the zero for the visibility of the operation principle. (d) The PD length dependence of optical coupling ratio *XT* between port2 and port1, taking the absorption coefficient of Ge into consideration.

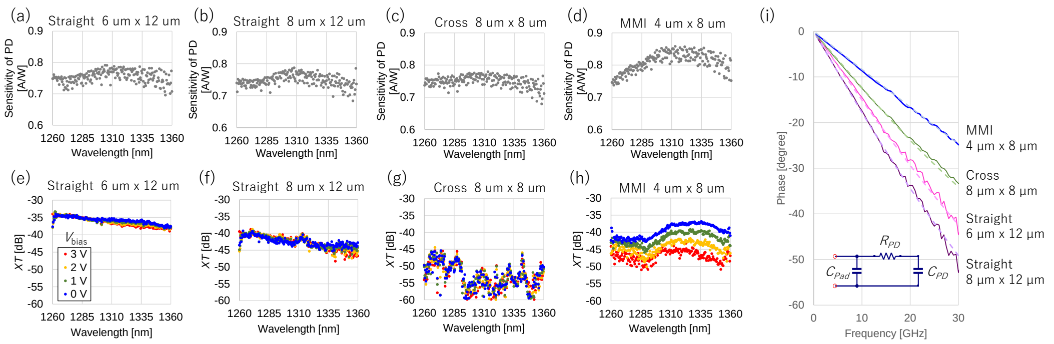

Fig. 4: The wavelength dependence of measured sensitivities and *XT*s of (a, e) "straight PD" (6 um x 12 um), (b, f) "straight" PD (8 um x 12 um), (c, g) "cross" PD (8 um x 8 um), and (d, h) MMI-PD (4 um x 8 um). (i) The measured phases of S11 parameters of fabricated PDs (solid lines), and the results of fitting analysis by the equivalent circuit model drawn in the inset (dashed lines). C_{pad} was fixed to 12 fF, estimated from the measurement of the pattern without a PD

the magnitude of *XT* is as low as <-30 dB when the lengh of Ge is shorter than 20 µm.

Characteristics of fabricated devices

We fabricated Ge PDs with a width of 4 µm and length of 8 µm on an Si MMI with a width of 6 µm and length of 160 µm. For comparison, "straight" PDs with a 6 µm width and 12 µm length, and with an 8 µm width and 12 µm length, and a "cross" PD with an 8 µm width and length were also fabricated. Here, it should be noted that the lengths of Ge were more than 8 µm for the sake of sufficient light absorption.

First, the wavelength dependences of sensitivities are shown in Figure4(a-d). The amount of input light was estimated from the input light power and the optical loss of edge couplers, which is estimated to be 1.5 dB. The sensitivities were more than 0.75 A/W without large wavelength dependences for all PDs. The sentivity of the MMI-PD was around 0.8 A/W, slightly higher than the other two types of PDs, even though the area of Ge was the smallest.

Figure 4(e-h) shows the wavelength dependence of *XT*s. Reverse bias voltages V_{bias} were applied between 3 V to 0 V. The "straight" PDs showed large *XT* values and *XT* became larger when the width of Ge was smaller. It is thought that the narrower the Ge width is, the larger amount of light goes through the cathodes and couples to the opposite input port. The "cross" PD showed quite small *XT*, less than -45dB. Concerning the MMI-PD, *XT* values changed by V_{bias}. When 3 V was applied, the *XT*s were less than -45dB for the entire wavelenth range of the O-band. The variation of *XT*s on V_{bias} will originate from the change of the refractive index of Ge, which will cause the change of focusing position of transmitted light.

Concerning C_{pd}, Figure 4(i) shows the phases of S11 of the PDs. Smaller values of phases qualitatively indicates smaller C_{pd}. These results were quantitatively analyzed based on an equivalent circuit model shown in the inset of Figure 4(i)[5]. The resultant values of C_{pd} are summarized in Table 1. The C_{pd} of the MMI-PD was as low as 11 fF due to the compact Ge.

Table 1 shows a comparison of the characteristics of fabricated PDs. The MMI-PD showed high sensitivity, small *XT* under bias voltages, and small C_{pd} at the same time. Those values are desirable for high-speed optical receivers with small optical returns.

Conclusions

We designed and fabricated a two-port MMI-PD. We demonstrated that the MMI-PD showed high sensitivities and small junction capacitances without the increase of inter-port crosstalk. We believe that the MMI-PD can be applied to polarization-diverse optical receivers in combination with photonic circuits consisting of polarization splitters and rotators and wavelength demultiplexers.

Table 1: Summary of the characteristics of the fabricated PDs

Wavelength 1310 nm V_{bias} = -3.0 V	straight 6 µm x12µm	straight 8 µm x 12µm	Cross 8 µm x 8 µm	MMI 4 µm x 8 µm
Sensitivity	0.77 A/W	0.77 A/W	0.74 A/W	0.81 A/W
Inter-port crosstalk *XT*	-37 dB	-42 dB	< -50 dB	-46 dB
Capacitance C_{pd}	30 fF	38 fF	22 fF	11 fF

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