Ultra-compact integrated silicon photonics balanced coherent photodetector

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ABSTRACT

In this paper, the performance simulations of a novel ultra-compact balanced coherent photodetector for operation at a wavelength of 1.5 μm are presented and design proposals for future fabrication processes are provided. It consists of a compact 2x2 MMI that is evanescently coupled into a germanium MSM photodetection layer. The simulations demonstrate dark current less than 10 nA, capacitance less than 20 fF, and optical bandwidth in the 10-30 GHz range. We propose utilizing the simplicity of direct wafer bonding to bond the detection layer to the output waveguides to avoid complicated epitaxial growth issues. This ultra-compact device shows promise as a high-speed, low-cost integrated silicon photonics solution for the telecommunications infrastructure.

Keywords: Silicon photonics, balanced coherent photodetectors, metal-semiconductor-metal (MSM) photodetectors, multimode interference (MMI) coupler, germanium photodetectors, homodyne, integrated optics.

1. INTRODUCTION

High-speed, low-power, low-cost integrated silicon photonics devices are of great interest to the telecommunications industry as the demand on its infrastructure continues to grow^{1,2,3}. Balanced detectors enable ideal coherent detection by eliminating relative intensity noise (RIN) while also increasing the sensitivity of the system due to the utilization of all of the input and local oscillator signal^{4,5}. Germanium has gained increasing popularity in these devices due to its low cost of integration and excellent absorption characteristics at standard telecom wavelengths⁴. However, the large lattice mismatch that exists between silicon and germanium provides a challenge for fabrication, requiring special techniques to reduce defects between these two layers^{6,7,8}. We propose a novel solution that is a combination of a 2x2 multimode interference (MMI) device and a pair of balanced metal-semiconductor-metal (MSM) photodetectors. The MMI will mix a signal of interest containing phase information with a local oscillator. The mixed signal will then be evanescently coupled up into a pair of germanium MSM photodetectors, which have been bonded on top of the output waveguides using liquid capillary bonding. The pair of MSM photodetectors utilizes balanced coherent detection, which enables the extraction of phase information from the mixed signal, thus increasing capacity by enabling polarization multiplexing techniques⁹. The MSM photodetector is ideal due to its ability to provide high bandwidth at a low cost, while still being simple to fabricate^{1,8,10}. The final design seen in Figure 1 of the device will have a length of approximately 110 μm , giving it an extremely small footprint.

Figure 1. Top-down view of the MMI to MSM silicon-germanium hybrid device.

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2. SIMULATIONS

2.1 Compact 2x2 Multimode interference device

The silicon 2x2 multimode interference (MMI) device consists of two input and two output waveguide ports. The two input ports are used to mix a local oscillator with a signal of interest in the MMI. At specific interval lengths of the MMI device, the mixed signal can be split in half with each half sent down a separate output waveguide path. Using Optiwave OPTIBPM simulation software, it was determined that the optimal length of the MMI was $14.6\text{ }\mu\text{m}$ with a width of $3\text{ }\mu\text{m}$. The input and output silicon waveguides have a height of $0.22\text{ }\mu\text{m}$ and a width of $0.5\text{ }\mu\text{m}$, which ensures single mode operation at $1.5\text{ }\mu\text{m}$. The waveguides also had a center-to-center separation of $1.0\text{ }\mu\text{m}$. The wave propagation results in Figure 2 demonstrate good coupling between the input signal and local oscillator and 50/50 splitting of the mixed signal down the two output waveguides.

Figure 2. OPTIBPM simulation of the compact 2x2 MMI device. The scale is in microns.

2.2 Metal-semiconductor-metal photodetector

Metal-semiconductor-metal (MSM) photodetectors are commonly used to detect incoming signals. However, they are typically used in surface illumination applications, which cause the electrode fingers to create a shadowing effect, reducing the external quantum efficiency and responsivity of the device. Furthermore, devices utilizing surface illumination can be limited to a short total absorption depth. Our device utilizes evanescent coupling to couple the mixed signal from the output waveguides of the MMI, up into the germanium MSM photodetection layer bonded on top. This allows us to take advantage of a significantly longer absorption length with no adverse shadowing effects.

A simple model of external quantum efficiency of the MSM was analyzed to determine the optimal length of the device. This model used confinement factor values of 0.075, 0.1, and 0.125, which are very conservative compared to other typically assumed confinement factors around $0.40^{11,12}$. The results shown in Figure 3 allowed us to determine that a total MSM device length of $40\text{--}50\text{ }\mu\text{m}$ was ideal to obtain external quantum efficiency in the 70-80% range when using an absorption coefficient of 4000 cm^{-1} for germanium. This absorption coefficient corresponds to a signal wavelength of $1.5\text{ }\mu\text{m}$. If the signal wavelength is changed slightly from $1.5\text{ }\mu\text{m}$ to $1.55\text{ }\mu\text{m}$, the absorption coefficient drops sharply from 4000 cm^{-1} to 400 cm^{-1} . This has a large negative impact on the external quantum efficiency of the device, which can be seen in Figure 3. Therefore, it is vital to maintain operation around the design wavelength of $1.5\text{ }\mu\text{m}$. The length of the device could be made longer to continue to increase its efficiency, but the results are diminishing due to its exponential nature.

Figure 3. External quantum efficiencies using absorption coefficients of 4000 cm^{-1} (left) and 400 cm^{-1} (right). These absorption coefficients correspond to wavelengths of 1.5 μm and 1.55 μm , respectively.

The responsivity of the MSM is also determined largely by the confinement factor, absorption coefficient, and total device length, since it is directly proportional to the external quantum efficiency. Utilizing the same values mentioned above, we obtain the responsivity results shown in Figure 4. Using the specified MSM length of 40 μm , we can obtain a responsivity of $0.8\text{--}1.0 \text{ A/W}$, depending on confinement factor. This will result in a photodetector that has a large photocurrent output for given optical input.

Figure 4. Responsivity versus MSM device length using an absorption coefficient of 4000 cm^{-1} for germanium.

The performance of the MSM photodetector is also limited by the dark current, since low dark current is necessary to detect the incoming signal. The MSM structure is basically two Schottky barriers connected back to back, with the semiconductor material in the middle. The bandgap energy of germanium is 0.66 eV , which is a combination of the electron and hole barrier heights. The electron barrier height is approximately 0.50 eV while the hole barrier height is approximately 0.16 eV . The low hole barrier height means that the dark current is dominated by thermionic emission over this barrier. Barrier enhancement techniques have been developed, such as placing a silicon-carbon layer between the metal electrodes and the germanium semiconductor layer¹³. This has been reported to enhance the hole barrier height

from 0.16 eV to 0.52 eV. Assuming use of this barrier enhancement with TiAu electrodes with a spacing of 500 nm, we obtain the dark current results observed in Figure 5.

Figure 5. Dark current as a function of bias voltage for MSM photodetector. This assumes silicon-carbon barrier enhancement.

The capacitance of the detector was modeled using a detector length of 10-50 μm with a finger spacing of 500 nm and a finger period of 1.0 μm . Around the design length of 40 μm , the capacitance is approximately 15 fF and does not change appreciably within the simulation window. Capacitance in the low fF range allows for a greater optical bandwidth during operation. Using the aforementioned design values, the optical frequency is simulated to be approximately 30 GHz. If the spacing between electrodes is increased, there is a detrimental effect on the optical bandwidth due to the increase in capacitance, as observed in Figure 6.

Figure 6. 3dB optical bandwidth versus interdigitated electrode spacing.

3. FINAL DESIGN

The previous discussion regarding various performance metrics have guided the overall design of the ultra-compact balanced coherent photodetector. The resulting design parameters can be observed in Table 1 for the MMI and Table 2 for the MSM, below. It is important to note that the output waveguides from the MMI will need to be bent away from one another to allow for enough spacing for proper electrode patterning on the MSM layer over the absorption region. The ideal shape is an S-bend that is gradual enough to prevent the optical wave from escaping the waveguide. Our design had an initial center-to-center output waveguide separation of $1.0\text{ }\mu\text{m}$ and we used S-bends to allow for a final separation of $10\text{ }\mu\text{m}$ over a propagation distance of $30\text{ }\mu\text{m}$. The simulations performed in OPTIBPM demonstrated good wave confinement, as seen in Figure 7.

Figure 7. OPTIBPM simulation of the 2x2 MMI outputs being bent away from each other. The propagation distance is in microns.

Table 1. Design parameters of the MMI.

2x2 MMI Device	
Material	Silicon
Input/Output Waveguide Width	$0.5\text{ }\mu\text{m}$
Input/Output Waveguide Height	$0.22\text{ }\mu\text{m}$
MMI Width	$3.0\text{ }\mu\text{m}$
MMI Length	$14.6\text{ }\mu\text{m}$
MMI Height	$0.22\text{ }\mu\text{m}$

Table 2. Design parameters of the MSM.

MSM Device	
Semiconductor Material	Germanium
Electrode Material	TiAu
Electrode Finger Width	0.5 μm
Electrode Finger Length	4.0 μm
Electrode Finger Spacing	0.5 μm
Total MSM Length	40 μm

4. PRELIMINARY FABRICATION

4.1 Compact MMI and MSM Fabrication

The MMI was fabricated by first spin-coating a layer of negative photoresist on a silicon wafer followed by baking at 90°C for 2 minutes. The wafer was then loaded into an Elionix ELS-7000 electron-beam lithography system, which is capable of writing patterns as small as 5 nm. After exposure in the ELS-7000, the silicon wafer was developed and etched using a combination of O₂ and CF₄ gases. The remaining photoresist was removed in a final processing step. The resulting MMI can be observed in the SEM image in Figure 8.

Figure 8. SEM image of the fabricated MMI.

We propose that the MSM be fabricated by spin-coating a positive photoresist layer on a suitably sized piece of germanium. The ELS-7000 can then be used to write the appropriate pattern for the interdigitated electrode fingers and contact pads on the photoresist layer. After development, appropriate layers of Si:C and TiAu can be deposited. If the output silicon waveguides are planarized, along with the opposite side of the germanium, we propose utilizing direct wafer bonding to bond the fabricated germanium photodetection layer on to the top of the output silicon waveguides. This will allow for evanescent coupling from the silicon waveguides up into the germanium photodetector. This bonding step will effectively avoid the epitaxial growth issues that will arise due to the lattice mismatch between silicon and germanium. One of the most significant sources of error would be during placement of the MSM layer on the waveguides. If there is too much tilt, the photodetector will no longer operate as a balanced device.

4.2 MSM Layer Tilt Error Analysis

One of the most significant sources of error would be during placement and bonding of the MSM layer on the waveguides. If there is too much tilt, the photodetector will no longer operate as a balanced device. If the power of the incoming signal is given by P_s and the power of the local oscillator is given by P_{LO} , then the mixed signal exiting the MMI down each of the two waveguides is given by⁵

$$P_1 = \frac{P_s}{2} + \frac{P_{LO}}{2} + \sqrt{P_s P_{LO}} \cos[(\omega_s - \omega_{LO})t + \varphi_s - \varphi_{LO}] \quad (1)$$

$$P_2 = \frac{P_s}{2} + \frac{P_{LO}}{2} - \sqrt{P_s P_{LO}} \cos[(\omega_s - \omega_{LO})t + \varphi_s - \varphi_{LO}] \quad (2)$$

where ω_s and ω_{LO} are the frequencies of the signal and local oscillator, respectively, and φ_s and φ_{LO} are the phases of the signal and local oscillator, respectively. After these optical signals are evanescently coupled into the germanium waveguides, the optical power will be converted into respective photocurrents, given by⁵

$$I_1 = \frac{I_s}{2} + \frac{I_{LO}}{2} + R\sqrt{P_s P_{LO}} \cos[(\omega_s - \omega_{LO})t + \varphi_s - \varphi_{LO}] \quad (3)$$

$$I_2 = \frac{I_s}{2} + \frac{I_{LO}}{2} - R\sqrt{P_s P_{LO}} \cos[(\omega_s - \omega_{LO})t + \varphi_s - \varphi_{LO}] \quad (4)$$

where R is the responsivity of the photodetector, I_s and I_{LO} are the photocurrents of the signal and local oscillator, respectively. If the detector is balanced, we can subtract I_2 from I_1 , which results in the expression

$$I_1 - I_2 = 2R\sqrt{P_s P_{LO}} \cos[(\omega_s - \omega_{LO})t + \varphi_s - \varphi_{LO}] \quad (5)$$

Operation as a homodyne receiver means that the signal and local oscillator frequencies will be the same, which results in the final expression for the photocurrent for our balanced coherent detector

$$I = I_1 - I_2 = 2R\sqrt{P_s P_{LO}} \cos[\varphi_s - \varphi_{LO}] \quad (6)$$

It is immediately obvious that the detected photocurrent is primarily a function of the phases of the signal and local oscillator. However, if there is any tilt on the photodetection layer, it will add an increased propagation distance to one of the mixed signals prior to detection. This added propagation distance will result in phase error. A simple schematic of this situation can be observed in Figure 9.

Figure 9. Demonstration of effect of tilt of the MSM photodetector layer on the output waveguides from the MMI.

The phase error will modify equation (6), resulting the expression

$$I = I_1 - I_2 = 2R\sqrt{P_s P_{LO}} \cos[\varphi_s - \varphi_{LO} + \delta\varphi] \quad (7)$$

$$I = 2R\sqrt{P_s P_{LO}} \cos[\varphi_s - \varphi_{LO} + (\delta\varphi_1 - \delta\varphi_2)] \quad (8)$$

where $\delta\varphi_1$ and $\delta\varphi_2$ are the phases in each of the output waveguides and $\delta\varphi$ is the total phase error, which is the difference between $\delta\varphi_1$ and $\delta\varphi_2$. If there is no tilt, the two phases will be the same and will simply subtract out of equation (8), resulting in equation (6). However, if there is tilt, these phases will be different and can be modeled as¹⁴

$$\delta\varphi_1 = \delta L_1 \beta_1 = y \beta_1 \tan \theta, \quad (9)$$

$$\delta\varphi_2 = \delta L_2 \beta_2 = y \beta_2 \tan \theta, \quad (10)$$

where y is the separation distance between the two waveguides, θ is the tilt angle, δL_1 and δL_2 are the extra propagation distances caused by the tilt angle, and β_1 and β_2 are the propagation constants of each waveguide section. These equations were used to determine the maximum amount of tilt angle that could be tolerated before phase error would result in misreading a bit. For simplicity, the local oscillator phase was assumed to be 0 and the signal phase was assumed to be 180°. Another assumption was that a positive photocurrent would represent a 1 bit and a negative photocurrent would represent a 0 bit, although this assignment is entirely arbitrary. If there is no phase error, the subtraction of the local oscillator phase from the signal phase will result in a negative photocurrent. The tilt angle was then increased until the negative photocurrent turned positive, which represents an error. It was determined that the

maximum tolerance on the tilt angle for our device with a waveguide separation of 10 μm was approximately 2.14° , which seems very reasonable for possible future surface-mount technology.

5. CONCLUSION

We proposed a novel ultra-compact silicon-germanium hybrid balanced coherent photodetector capable of achieving low dark current of less than 10 nA, low capacitance of less than 20 fF, and high optical bandwidth in the range of 10-30 GHz. This has been simulated for a total device length of approximately 110 μm . To the author's knowledge, this is the smallest device capable of this functionality to date. Direct wafer bonding can be used to bond the photodetection layer to the output MMI waveguides, thus eliminating a complicated growth step. Finally, we detailed error analysis necessary to determine the maximum tilt tolerance on the MSM photodetection layer, which is necessary for successful hybrid integration of this device.

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