InGaAs MSM photodetector monolithically integrated with InP photonic-wire waveguide on III-V CMOS photonics platform

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Abstract: An InGaAs metal-semiconductor-metal (MSM) photodetector (PD) monolithically integrated with an InP photonic-wire waveguide has been demonstrated by using III-V CMOS photonics platform. Owing to a Schottky contact between Ni and p-InGaAs, the MSM PD operation is obtained with a dark current of 270 nA at 1 V bias voltage. The 20-µm-long waveguide InGaAs PD exhibits responsivity of around 0.4 A/W and broadband operation covering the C- and L-bands, enabling wavelength division multiplexing (WDM) optical interconnects.

Keywords: waveguide photodetector, III-V CMOS photonics

Classification: Optoelectronics, Lasers and quantum electronics, Ultrafast optics, Silicon photonics, Planar lightwave circuits

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1 Introduction

Since optical interconnects can resolve the tradeoff between the bandwidth and transmission distance imposed by electrical interconnects [1, 2], the optical interconnections are widely used for rack-to-rack interconnections in high-performance computers and date centers [3, 4, 5]. To meet further demands of wide-bandwidth, low-power, and dense optical interconnects, photonic integrated circuits (PICs) based on silicon (Si) photonics including modulators [6, 7] and photodetectors [8, 9] have gained a lot of popularity [10, 11] because low cost, high volume, and compact PICs can be realized on Si-on-Insulator (SOI) platform by using wafer-scale complementary metal oxide semiconductor (CMOS) process lines. However, Si is an indirect-bandgap semiconductor, intrinsically not suitable for realizing active photonic devices such as lasers. On the other hand, conventional III-V compound semiconductor-based photonics is much suitable for lasers, modulators, and photodetector. However, in the conventional III-V photonics, there is no photonic-wire like optical waveguide structure which enables a two-dimensional strong optical confinement. This is the reason why the drastic reduction in the waveguide geometry is not allowed for the III-V photonics.

To overcome the constraints above, we have investigated the III-V CMOS photonics platform [12, 13] by using a III-V-on-Insulator (III-V-OI) wafer. The strong optical confinement of the III-V-OI structure enables micro bends, ultra-small arrayed waveguide gratings [14], grating couplers [15], and high-efficient optical switches [16] by using InGaAsP photonic-wire waveguides so...
far. Since high-performance InGaAs MOS transistors have also been successfully demonstrated on the III-V-OI wafer [17], monolithic integration of InGaAs MOS transistors and InP-based photonic-wire devices is possible with same thermal budget. Hence, the III-V CMOS photonics platform enables ultimately high-performance electronic-photonic integrated circuits (EPICs) for optical interconnects.

In this paper, we have firstly demonstrated a waveguide InGaAs metal-semiconductor-metal (MSM) photodetector (PD) on the III-V CMOS photonics platform as shown in Fig. 1. The InGaAs MSM PD with interdigitated electrodes is monolithically integrated with an InP-on-Insulator rib waveguide. The responsivity more than 0.4 A/W has successfully been obtained for the 20-µm-long InGaAs PD. The broadband operation, which can fully cover the C-band and L-band, has also been demonstrated with a nearly flat wavelength dependence of the responsivity, suitable for wavelength-division-multiplexing (WDM) optical interconnects.

### 2 Design of InGaAs MSM PD on III-V CMOS photonics platform

The numerical simulation by the two dimensional time-domain beam propagation method (TD-BPM) [12] is performed to design the waveguide InGaAs MSM PDs on the III-V CMOS photonics platform. Fig. 2(a) gives a cross-sectional structure of the InGaAs PD integrated with the InP waveguide. We assume that a 200-nm thick InGaAs absorbing layer is on a 350-nm thick InP waveguide layer. The refractive indices of InP and InGaAs is assumed to 3.17 and 3.6, respectively. At first, the reflection at the edge of the InGaAs PD section is calculated by assuming the extinction coefficient of InGaAs $K_{\text{InGaAs}} = 0$. It is found from the transmission power that the reflection is approximately less than 3% at a 1550 nm wavelength. Then, the absorption of the PD is simulated by assuming $K_{\text{InGaAs}} = -0.093$. Fig. 2(b) shows the
simulation result of beam propagation when an input light is injected to the InP waveguide. Due to the thin InGaAs layer, evanescent coupling with an oscillating pattern similar to a multimode interference coupler is observed. Fig. 2(c) shows the normalized optical power along the waveguide. It is found in Fig. 2(c) that the PD length of 20 µm is enough for optical absorption at a 1550 nm wavelength.

![Simulation Result](image)

Fig. 2. TD-BPM simulations of waveguide InGaAs PD on III-V CMOS photonics platform. (a) cross-section of waveguide structure, (b) beam propagation, and (c) optical power along the waveguide.

### 3 Evaluations of bulk and surface leakage currents of Ni/p-InGaAs junction

To form InGaAs MSM PDs, Ni/p-InGaAs Schottky barrier junctions (SBJs) are used. To understand the origin of dark current of the InGaAs MSM PDs, we evaluate junction bulk leakage current density ($J_b$) and surface leakage current density ($J_s$) using the Ni/p-InGaAs SBJs.

![Process Flow](image)

Fig. 3. (a) Process flow of Ni/p-InGaAs SBJs and (b) Plan-view photograph of SBJs with the same junction area ($S = 22500 \, \mu m^2$) but different junction perimeters ($L = 600 \, \mu m, 1200 \, \mu m, 2400 \, \mu m$, and $3600 \, \mu m$).
Fig. 3(a) shows a fabrication procedure of the SBJs. First, a 1-µm-thick p-In$_{0.53}$Ga$_{0.47}$As layer is grown on a p-InP wafer by metal-organic vapor phase epitaxy (MOVPE). The doping concentration of the InGaAs layer is $10^{16}$ cm$^{-3}$. Then, a 30-nm-thick Al$_2$O$_3$ passivation layer is deposited on the top by using atomic layer deposition (ALD). After forming contact holes for the SBJs, Ni electrodes are formed by lift-off. Finally, Ni and Al contact pads are formed.

Since the bulk leakage current and surface leakage current are proportional to the junction area ($S$) and peripheral length ($L$), respectively, the total leakage current of the SBJ can be expressed by

$$I = J_s \times L + J_b \times S.$$  

(1)

To extract $J_b$ and $J_s$ values from current-voltage (I-V) characteristics of the SBJs, we prepare SBJs with the same junction area ($S = 22500$ µm$^2$) but different junction perimeters ($L = 600$ µm, 1200 µm, 2400 µm, and 3600 µm) as in Fig. 3(b).

Fig. 4(a) shows I-V curves of the four SBJs. It is clearly seen in Fig. 4(a) that the leakage current increases as the peripheral length increases due to the surface leakage current. Thus, $J_s$ is evaluated to 0.5 µA/cm by subtracting the bulk leakage currents. $J_b$ can also be extracted by dividing total leakage current $I$ by $L$. Since $I/L$ is expressed as a formula in Fig. 4(b), we obtain $J_b$ of 1.1 mA/cm$^2$ from a slope in the relationship between $I/L$ and $S/L$ in Fig. 4(b).

Using the obtained $J_b$ value, we calculate Schottky barrier height (SBH) $\Phi_B$ by

$$J_b = A^*T^2 \exp\left(-\frac{e\Phi_B}{k_BT}\right) \left[\exp\left(\frac{eV_D}{k_BT}\right) - 1\right],$$  

(2)

where $T$ is absolute temperature, $e$ is electronic charge, $k_B$ is Boltzmann constant, $V_D$ is applied voltage. We assume effective Richardson constant $A^*$ to be 60 A cm$^{-2}$ K$^{-2}$ [18]. From (2), the SBH of Ni/p-InGaAs is evaluated to be 0.58 eV, which is a similar value reported in Ref. [18].
4 Device fabrication

First, the III-V-OI wafer for InGaAs MSM PDs is prepared by direct wafer bonding as shown in Fig. 5(a)–(c) [13, 14, 15, 16, 17]. A 340-nm-thick i-InP waveguide layer and 210-nm-thick absorbing p-InGaAs layer are grown on an InP wafer. A 2.3-µm-thick SiO2 layer is also thermally grown on a Si wafer for a buried oxide layer (BOX) of the III-V-OI. After Al2O3 is deposited on both wafers by ALD, the two wafers are bonded together; Finally, the InGaAs/InP on SiO2/Si wafer is obtained by etching the InP substrate as shown in Fig. 5(c).

Using the III-V-OI wafers, we fabricate InGaAs MSM PDs monolithically integrated with InP rib waveguides in Fig. 5(d)–(g). First, the III-V PD mesa and waveguide are defined by deep ultra-violet (DUV) lithography and reactive ion etching (RIE). Then, the InGaAs layer on the InP waveguide is selectively removed by wet etching. An Al2O3 layer is deposited by ALD as a passivation layer. Finally, interdigitated electrodes are formed by Ni deposition and lift-off.

Fig. 6(a) shows a plan-view of the waveguide InGaAs MSM PDs fabricated on the III-V-OI wafer. Fig. 6(b) is a cross-sectional transmission electron microscopy (TEM) image of the InGaAs PD region. It is clearly seen that the InGaAs and InP layers are well bonded on the 2.3-µm-thick SiO2 BOX layer. The bonded interface shown in Fig. 6(b) is smooth owing to the ALD Al2O3 interlayer.

5 Measurement results

To evaluate the intrinsic photo-response of the fabricated PD, the propagation loss of the InP rib waveguide on the SiO2/Si wafer is considered by the cut-back method as shown in Fig. 7.

A 1550-nm continuous-wave (CW) light is coupled into the waveguide through a lensed fiber. The polarization is controlled to the transverse-electric
(TE) mode by a polarization controller. The output light from the waveguide is coupled again into a single-mode fiber through an objective lens. From Fig. 7, the propagation loss of the InP rib waveguide is evaluated to be approximately 1.2 dB/mm. We estimate that the coupling loss between the lensed fiber and the waveguide is 6.5 dB from the previous result in Ref. [12]; thus the total insertion loss of the InGaAs MSM PD with the 1-mm-long InP waveguide is approximately 8 dB. In the following experiments, the 8-dBm CW light is injected to compensate the coupling and insertion losses of the devices for ensuring approximately 0-dBm launched power to the InGaAs PD.

Fig. 8(a) shows the measurement results of the photocurrent and dark current of the InGaAs MSM PD. Owing to the Schottky contact between Ni and p-InGaAs, the dark current is below approximately 270 nA when the bias voltage is 1 V. The photocurrent at 1 V bias voltage is approximately 400 µA when the 1550-nm CW light with the 0-dBm launched power to the PD is injected. Thus, the $I_{on}/I_{off}$ ratio is approximately more than $10^3$. We also give the wavelength dependence of the responsivity of the InGaAs MSM PD in
The 20-µm-long InGaAs PD exhibits nearly flat wavelength dependence of the responsivity, suitable for wavelength division multiplexing (WDM) operation. When the bias voltage is 1 V, the responsivity of >0.4 A/W is obtained for the wavelength from 1520 nm to 1630 nm, covering the C- and L-bands.

6 Conclusions

A waveguide InGaAs MSM PD monolithically integrated an InP rib waveguide on III-V CMOS photonics platform is successfully demonstrated. Since a Schottky barrier height of 0.58 eV is obtained between Ni and p-InGaAs, the dark current of 270 nA at 1 V bias is obtained in the waveguide InGaAs PD. We also estimate the intrinsic responsivity to be around 0.4 A/W when the bias voltage is 1 V. The 20-µm-long waveguide InGaAs MSM PD also exhibits flat responsivity for the wavelength range covering the C- and L-band which enables WDM optical interconnects monolithically integrated with high-performance InGaAs MOS transistors on the III-V CMOS photonics platform.

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