High-performance waveguide unitraveling carrier photodetector based on GaAs0.5Sb0.5/InP type-II heterojunction

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**ABSTRACT**

Heterogeneous III-V/silicon photonic integrated circuits promise to integrated dissimilar materials without compromising their own properties. InP-based high-power and high-speed In$_{0.53}$Ga$_{0.47}$As modified uni-traveling carrier photodiodes (UTC-PDs) heterogeneously integrated on silicon-on-insulator waveguides have been demonstrated. In this paper, we will propose a novel GaAs$_{0.5}$Sb$_{0.5}$/InP type-II waveguide UTC-PD. The p-type In$_{0.53}$Ga$_{0.47}$As absorption layer is replaced by a p-type GaAs$_{0.5}$Sb$_{0.5}$ layer. Due to the type-II interface between p type GaAs$_{0.5}$Sb$_{0.5}$ absorber and InP collector, photo-generated electrons generated in the absorption layer are injected into the collection layer with enhanced kinetic energy, which aids their transport toward the collector and minimizes the current blocking effect. Our device shows a significant improvement in the responsivity (1.14A/W) and bandwidth (40.3GHz) compared with that of waveguide UTC-PD with the same thickness of pure In$_{0.53}$Ga$_{0.47}$As absorber. The demonstrated type-II PD offers a record overestimated saturation current-bandwidth product 4473.3 mA*GHz . These promising results suggest that our proposed GaAs$_{0.5}$Sb$_{0.5}$/InP type-II waveguide UTC-PD structure can fundamentally overcome the trade-off among bandwidth, responsivity, and length of high-speed waveguide PDs.

**Keywords:** photodiodes, uni-traveling-carrier, type-II heterojunction, silicon-on-insulator

1. INTRODUCTION

High speed, high efficiency and high power photodiodes are critical components in digital and analog photonic systems [1]. III-V materials are preferred for high performance photodiodes, since they allow complex bandgap engineering. Previously, many studies [2-4] have demonstrated that In$_{0.53}$Ga$_{0.47}$As/InP based uni-traveling carrier photodiodes (UTC-PDs) can achieve high performance, including high saturation photocurrent, large bandwidth and low dark current, because UTC-PD has only photo-generated electrons that travel in the drift region, which significantly suppresses the space charge effect and increases the bandwidth in contrast to that of conventional PIN photodiodes. Though bandgap-graded InGaAsP layers are used to smooth the abrupt band barrier at the InGaAs-InP heterojunction interface of UTC-PDs, the minority electrons tend to accumulate at the absorption/collection band discontinuity causing RF output power saturation under high optical intensities [5]. Besides InGaAs, the lattice-matched GaAs$_{0.5}$Sb$_{0.5}$ alloy is also an interesting candidate for the absorbing layer in UTC-PDs. Its staggered band lineup with InP forces photon-generated electrons injecting from the p-type absorber GaAsSb layer into the InP collector so as to alleviate the space charge effect. Recently, photodiodes with type-II band structures (GaAs$_{0.5}$Sb$_{0.5}$/InP and GaAs$_{0.5}$Sb$_{0.5}$/In$_{0.53}$Ga$_{0.47}$As ) have been reported [6-8]. The high electric-field provided by the band stagger drive electrons from the p-type GaAs$_{0.5}$Sb$_{0.5}$ layer to the depleted collector layer with high excess energy and thereby minimize the current blocking effect. The surface-illuminated GaAs$_{0.5}$Sb$_{0.5}$/InP UTC-PD exhibits an extremely wide bandwidth 170GHz but low DC responsivity 0.09A/W [8] because of a trade-off between bandwidth and responsivity regarding the thickness of the absorber. This trade-off can be relaxed in waveguide photodiodes and the responsivity is no longer limited by the thickness of the absorber. In this way, we can achieve both high responsivity and bandwidth.

In this paper, we will study a GaAs$_{0.5}$Sb$_{0.5}$/InP waveguide UTC-PD. Three-dimensional (3D) Finite Difference Time Domain (FDTD) tool is used to simulate light absorption in the waveguide PD and photogeneration rate. Then the photogeneration rate is imported to TCAD for electrical stimulation.

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2. PD STRUCTURE

The photodiode we studied is a type-II (GaAs0.5Sb0.5/InP) UTC-PD wafer bonding on top of a silicon-on-insulator (SOI) waveguide as shown is Fig.1. Here, GaAs0.5Sb0.5/InP type-II absorption-collector interface is used. The absorber consists of undepleted p-type and depleted GaAs0.5Sb0.5 layers. The undepleted p-type GaAs0.5Sb0.5 absorption layer with a thickness of 250nm and a linearly graded doping profile (bottom: 8.0E19 cm⁻³ to top: 5.0E18 cm⁻³) is designed to induce built-in electric filed in order to accelerate the carrier diffusion process. This type of band alignment can provide injected electrons from the p-type absorber layer to the InP collector layer with high excess energy and minimize electrons accumulation at the absorption/collection band discontinuity, which will be discussed in detail in section 4. A 700nm n.i.d InP electron drift layer is designed to reduce junction capacitance and thus increased the RC-bandwidth limitation. A n+ doped (1.0E17cm⁻³) InP charge layer among these intrinsic layers at around the type II absorption/collector junction is used to drop the electron potential and maintain high electric field in the depleted absorber. A 10nm thick InP bonding layer and an InP/GaAsP super lattice are integrated below the InP matching layer to facilitate wafer bonding onto SOI waveguide and to block the propagation of defects into the absorber. The type-II UTC-PD is evanescently coupled to an underlying SOI optical waveguide. The thickness of the Si rib and the buried oxide layer are 0.7 μm and 1 μm, respectively. To match the 10 μm width of the active PD region, a tapered single-mode input Si waveguide can be used to couple the PD to a signal-mode optical fiber. The input taper is not shown in this figure. Figure 1 (a) show the 3D structure of the GaAs0.5Sb0.5/InP type-II waveguide photodiode and Figure 1 (b) show a cross-sectional view and detailed layer structures of the photodiode.

![Figure 1](image_url)

3. OPTICAL FIELD AND GENERATION RATE SIMULATIONS

In this work, the optical field was simulated by FDTD. The optical field in the absorber was used to calculate photogeneration rate of electron and hole pairs. Then, the photogeneration rate is imported to TCAD software to calculate the electrical characteristics.

A TE mode of 1.55 μm wavelength was launched to the silicon rib waveguide shown in Fig. 2(a). The major portion of the optical field is confined within the waveguide. Along with the light transmission in y direction, the light is gradually evanescently coupled to the photodiode active layers and then absorbed by the photodiode, as shown in the Fig.2(b). It is indicated that most of the light is absorbed within the 50-micron length of the photodetector.
As the optical field propagates down the device, the light is absorbed in the GaAs$_{0.5}$Sb$_{0.5}$ layers and the generation rate is calculated accordingly, assuming that each absorbed photon generates one electron-hole pair. Fig. 3 shows photogeneration rate distribution of the type-II waveguide photodiode in case of 10mW optical power. As shown in the Fig. 3(a), the optical field is mainly confined in the absorber layer, only small portion of optical field leak to the n-contact GaAs$_{0.5}$Sb$_{0.5}$ layer.

Compared to the absorption of absorber layer, the GaAs$_{0.5}$Sb$_{0.5}$ n-contact layer exhibits less light absorption because of its location far from the SOI waveguide. The same conclusion can be drawn for the photogeneration rate. Fig. 3(b) shows the photogeneration rate in the x-y plane of the absorber layer at z=1.109 $\mu m$. A non-uniform absorption profile can be seen. To perform a 2D electrical simulation instead of 3D in TCAD, the generation rate profile is averaged in the y direction to export the results in the XZ cross section and is given in Fig. 3(c).

Figure 3. Photogeneration rate distribution of the type-II waveguide photodiode: (a) side (y-z plane at x=0 $\mu m$ ) view. (b) top (x-y plane at z=1.109 $\mu m$ ) view. (c) averaged in the direction of optical propagation (y).

### 4. PHOTODETECTOR CHARACTERIZATION

Type-II GaAs$_{0.5}$Sb$_{0.5}$/InP UTC-PD provides a favorable alternative to Type-I In$_{0.53}$Ga$_{0.47}$As/InP UTC-PD, especially waveguide-coupled photodetector. As shown in Fig. 4(a), GaAs$_{0.5}$Sb$_{0.5}$/InP UTC-PD has a type-II absorber/collection heterojunction. This property help to inject the electrons generated in the absorption layer into the collection layer with enhanced kinetic energy, which aids their transport towards the collector. This makes the device fast in responding to AC modulation of the injected light. In our simulation, the value of the conduction band offset has been incorporated in by specifying the electron affinity parameter to reflect the desired value of conduction band offset. A slightly conservative value of conduction band offset of 0.11 eV has been adopted. Fig. 4 (b) shows the simulated band diagram for the type-II GaAs$_{0.5}$Sb$_{0.5}$/InP UTC-PD. As shown in Fig. 4(b), a quasi-electric field is induced that assists electron transport. No abrupt conduction band barrier should be flattened between the GaAs$_{0.5}$Sb$_{0.5}$ absorption and InP collection layer, which is much different from the type I In$_{0.53}$Ga$_{0.47}$As/InP UTC-PDs.
As we have mentioned before, the averaged photogeneration rate is imported to TCAD. It then calculates the corresponding photocurrent. The photocurrent of the type-II GaAs$_{0.5}$Sb$_{0.5}$/InP waveguide photodiode with a reverse bias voltage from 0 to 10V is shown in Fig. 5. At different injected optical powers, the photocurrent is 1.14 mA, 11.4 mA, 22.8 mA, and 34.2 mA. The corresponding responsivity is 1.14A/W. Quantum efficiency is up to ~91.2%. Compared to the responsivity of previous structures reported in ref.[8], our structure exhibits a significant increase in responsivity. It is worth noting that, in all cases, the device photocurrent reaches its maximum at low bias voltage, even zero bias. This is a desired feature in integrated waveguide photodetectors for low-power consumption operation of nanophotonic receivers.
For type-I In$_{0.47}$Ga$_{0.53}$As/InP UTC-PD, photo-electrons pile up at the absorption/collection heterojunction when under high power illumination. The accumulation of carriers not only increases the carrier recombination probability and reduces the responsivity but also reduces the carrier velocity and contributes to saturation. With type-II A/C heterojunction, high electric field inside the depleted GaAs$_{0.5}$Sb$_{0.5}$ absorber of the GaAs$_{0.5}$Sb$_{0.5}$ UTC-PD and staggered band alignment aid electrons transport towards the collector providing more margins for carrier accumulation. Therefore, a higher saturation current is achieved and bandwidth reduction is not observed until a higher photocurrent level is reached. Fig.6(a) show the photocurrent responses under different DC illuminations. The deviation from a linear increase with incident power is observed when the carrier accumulation occurs. The decrease of slope suggests a reduction in bandwidth and thus saturation under high power illumination. It can be inferred that the inflection points indicate beginning of saturation. In Fig.6(a), a responsivity of 1.14A/W is extracted from the slope of the linear part, which agrees with the value of 1.14A/W described in Fig.5. Assuming an optical sinusoidal signal with a 100% modulation depth, the peak current is 222mA. A mid-range current of 111 mA was determined from the Fig.6(a). An increase of the average photocurrent beyond 111 mA will take the PD further into saturation. Therefore, this average photocurrent is estimated to be the operating DC photocurrent point under -1 dB compression. Fig.6(b) shows the small-signal response. The simulated 3 dB bandwidth is 40.3 GHz. Compared with the result reported for the traditional InGaAs/InP waveguide UTC-PD, having exactly the same 300nm absorption layer [9], there is significant improvement in the bandwidth. Saturation current-bandwidth product is 4473.3 mA*GHz . In reality, as shown in Fig.2(b), the optical intensity peaks on the first 10 μm and remains considerably lower beyond 30 μm . If we assume that the carrier generation is proportional to the optical intensity, a non-uniform photocurrent distribution follows that can result in localized areas of strong saturation at high optical input powers. The saturation current calculated by TCAD with generation rate profile averaged in the y direction of optical propagation(y) is overestimated. And therefore the Saturation current-bandwidth product is overestimated.

5. CONCLUSIONS

In conclusion, we demonstrate a novel GaAs$_{0.5}$Sb$_{0.5}$/InP type-II waveguide UTC-PD on silicon-on-insulator with improved speed and responsivity. The type-II UTC-PD takes full advantage of a staggered band alignment, together with a waveguide PD structure. We obtain a PD which exhibits a high responsivity of 1.14 A/W and a wide bandwidth 40.3 GHz. A record overestimated saturation current-bandwidth product 4473.3 mA*GHz is demonstrated under excitation by an optical signal with a 100% modulation depth. This achievement opens up a promising alternative route towards advance integration schemes for heterogeneous silicon based photonic integrated circuits, which are particularly attractive for the microwave photonic applications.
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