High performance silicon lateral PIN photodiode

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Abstract. Start Photodetectors with high responsivity in Si-related processes are required for high speed optoelectronic applications such as fiber optic data communication systems. In this paper, the performance of a virtual lateral PIN photodiode with intensity response in the 200-1000 nm wavelength range was demonstrated. The results obtained for responsivity, total quantum efficiency and frequency response were 0.62 A/W and 13.1 GHz respectively for design parameters of intrinsic region length of 6 µm, photoabsorption layer thickness of 50 µm, incident optical power of 1 mW/cm² and bias voltage of 3 V. As a conclusion, the decrease in device size enabled the realization of a high performance lateral p-i-n photodiode.

1. Introduction

PIN photodiode is the most widely used detector in optical applications because it has high sensitivity at the operating wavelength, high response speed, and low noise. This is because the depletion region thickness (the intrinsic layer) can be tailored to optimize the quantum efficiency, transient response and frequency response [1]. The development of a lateral PIN photodiode based on silicon absorption layer is pursued because of its compatibility in monolithic integration of CMOS-based photonic devices as well as low cost and robustness of the silicon material itself. The lateral PIN photodiodes can be fabricated in this technology [4], giving incident light direct access to the active intrinsic region of the device.

The main properties of a photodiode often considered in analysis are its responsivity and frequency response. In previous research [2], it was reported that a frequency response of 4.38 GHz at 5-V bias for a 7.4 µm intrinsic width of photodetector on silicon-on-insulator (SOI) substrate was achieved. The Si photodiode in standard 0.18 µm CMOS technology exhibited frequency response of 8.7 GHz and responsivity of 0.018 A/W at 11.4-V bias [3]. In another research [4], the silicon nano-photodiodes produced, a frequency response of 5 GHz at 850 nm optical wavelength. Feng et.al [5] produced a PIN modulator on silicon-on-insulator (SOI) substrate, with a frequency response of 12 GHz at 8-V bias voltage. Totsuka et. al [6] reported a responsivity of 0.34 A/W at 590 nm optical wavelength for the dimension of 1.18 mm (width) x 3.8 mm (length) x 5.0 mm (thickness). The active photoabsorption layer of a PIN photodiode must be as thick as 1 µm to obtain high quantum

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efficiency and low bias voltages from 2 to 7 V and can be used for optimum operation with low dark current and high speed [7].

In this paper, an investigation on the effect of device size reduction on the frequency response, responsivity and total quantum efficiency of a Si lateral PIN photodiode was explored and the device design is based on the device which was developed in the previous paper [8]-[10]. A two dimensional model of a Si lateral PIN photodiode operating at the 800 nm optical wavelength was developed using an industrial based numerical software.

In this paper, numerical modeling was used to design and characterize the device. In terms of simulation for the fabrication and device electrical characterization, ATHENA and ATLAS software from Silvaco Int. were used respectively. In this way a more physical insight into the device operation can be obtained. The models in bulk silicon material which were used are the Shockley-Read-Hall (SRH) recombination model, the concentration dependent mobility model, the Auger model and the Fermi-Dirac statistic model [8]-[12].

2. Methodology

The Si lateral PIN photodiode was simulated on silicon substrate (n+ type) in two dimensional using ATHENA software from Silvaco Int. Then, the n-well was developed using phosphorus diffusion with dopant concentration of 2.02 x 10^{19} cm^{-3} on the left side of the photodiode with diffusion temperature of 1000 °C for 50 seconds. Whilst the p-well was diffused with boron concentration of 8.09 x 10^{19} cm^{-3} on the other side of the photodiode with temperature of 1000 °C for 120 seconds. SiO_2 layer with thickness of 280 nm was deposited on the silicon substrate to act as a passivation layer. The electrode contacts with thickness and length of 500 nm and 6000 nm respectively, were processed by depositing aluminum on the n-well and p-well areas of the silicon photodiode.

The responsivity of a pin-photodiode is given by [10]:

\[
R = \frac{I_s}{I_T} \left( \frac{\lambda}{1.24} \right)
\]

where \( I_s \) is the source photocurrent, \( I_T \) is the cathode current and \( \lambda \) is the optical wavelength.

The frequency response is defined as [10]:

\[
\mathcal{F}_{2dB} = 20 \log \left( \frac{I_R}{I_{Ro}} \right)
\]

where \( I_R \) is the real cathode current and \( I_{Ro} \) is the real component current.

3. Results and discussion

The developed device structure is shown in Figure 1. The p+ region resides beneath the anode electrode whereas the n+ region resides below the cathode electrode. The area between the p+ and n+ region is the intrinsic (or i) region. The device’s electrical and optical characteristics were executed using the ATLAS module from Silvaco Int.

![Figure 1. The device structure of Si lateral pin-photodiode](image)
The simulation results for the frequency response of 13.1 GHz is obtained for the structure with 6 intrinsic region, whereas the value drop to 2.27 MHz for 30 μm intrinsic length at optical wavelength of 800 nm as shown in Figure 2 [12]. The result of frequency response for Si lateral PIN photodiode with intrinsic width of 6 μm is increased because of the photoresponse and the speed in the device [13]. The frequency response could be further increased by increasing the and bias voltage and reducing the intrinsic width [12].

Figure 2. The -3dB frequency response at optical wavelength 800 nm.

Figure 3 shows the responsivity as a function of reverse bias with optical wavelength from 200 nm until 1000 nm. At a small bias of 3 V, the Silicon PIN photodiode for the device with 30 μm and 6 μm intrinsic length produced responsivities of 0.62 A/W and 0.45 A/W at 800 nm, respectively [12]. The result of responsivity for Si lateral PIN photodiode with intrinsic width of 6 μm is increased because of the recombination rate and photoresponse in the device [13]. The responsivity could be further increased by increasing the photoabsorption thickness and bias voltage [12].

Figure 3. Responsivity for 30 μm and 6 μm intrinsic length of silicon lateral PIN photodiode

4. Conclusion
As a conclusion, the Si lateral PIN photodiode with a high responsivity in the visible spectrum (200 – 1000 nm) is reported. The PIN photodiode device structure is similar to PIN photodiode developed in previous work except for the size reduction of the device. The fabrication of Si lateral PIN photodiode is compatible with complementary metal-oxide semiconductor (CMOS) technology processes, which makes the device reliable and suitable for CMOS integration. In order to make a faster and smaller device in the future, we need to optimize the design of the device including the layer thicknesses, the intrinsic region width and the power intensity.
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