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High Speed Waveguide Integrated Lateral P-I-N Ge on Si Photodiode with very Low Dark Current

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Abstract

We present here waveguide integrated lateral PIN Ge photodiode exhibiting 32GHZ -3dB zero bias bandwidth, 1nA dark current under -1V reverse bias and 0.64A/W responsivity at 1550nm as well as Franz-Keldysh enhanced responsivity in the L-band.

1. Introduction

Silicon photonics integrated circuits development considerably spread in the last past years, and telecommunications and datacom applications are now clearly seen as its targets. With the increasing need of data rates, Si photonics components will have to offer very high speed as well as very low power consumption at lowest costs. The recent developments in photodetection have led to high speed and high responsivity waveguide integrated Ge photodetectors [1-3], with various configurations: butt coupling vs. evanescent coupling, vertical vs. lateral PIN junction. Nevertheless, Germanium absorption beyond 1550nm is limited, and long devices are needed, thus prohibiting Ge based photodiode use in the L-band (1565-1625) used in telecommunication. One way to solve this is to make use of Franz-Keldysh effect [4] or resonant metallic cavity to enhance Ge absorption in this range [5].

In this paper, we report on very low dark current and high speed lateral PIN Germanium photodetectors integrated with Si waveguides for telecom and datacom applications. Obtained dark current is of the order of 1nA under 1V reverse bias, which is the lowest achieved value for lateral PIN Germanium photodiodes fabricated by ion implantation, to our knowledge. The zero bias opto-electrical -3dB bandwidth is measured at 32GHz, and photodiode exhibit repsonsivity up to 0.64A/W at 1550nm. We also show extended absorption in the L-Band, with Franz-Keldysh enhanced responsivity of 0.18A/W at 1610nm.

2. Device Design and Fabrication

The photodiode is integrated with Si waveguide using butt coupling for efficient absorption, thus the device length can be reduced to minimize the capacitance. The waveguide as well as the grating coupler (to couple light from a fiber) are designed for 1550nm wavelength. A lateral p-i-n junction configuration has been chosen in order to simplify the integration and reduce the process steps: contacts are on the same level and topology is limited. To allow fast speed photodiode operation at low reverse bias or zero bias, the internal build-in electric field must be as high as possible. Hence, intrinsic region has to be narrow enough without degrading too much the responsivity.

200mm SOI wafers with 2µm Buried OXide (BOX) and 220nm top Si are used for the fabrication of the devices. The waveguides and fiber couplers are defined using 193nm Deep-UV lithography and dry etching down, resulting in 500nm wide and 220nm height Si waveguides. A thick SiO2 layer is deposited and polished prior to the definition of the cavity for the Germanium growth. 10x10µm cavities are etched in oxide and underlying Si layer. The Si layer is partially etched in order to let a Si seed layer for the Ge selective epitaxy. Germanium is grown by Reduced-Pressure Chemical Vapor Deposition (RPCVD). Ge layer are thick enough to avoid faceting inside the cavity and to reduce the Threading Dislocation Density (TDD) [6]. To further increase the quality of the epitaxied Ge, the growth is followed by an optimized annealing step [7], favoring low TDD without degrading absorption by Si-Ge interdiffusion. Chemical Mechanical Polishing (CMP) step allows flattening of the surface and obtaining of the desired Ge layer thickness. The P and N region are obtained by ion implantation of the Ge layer with Boron and Phosphorous respectively. Implantation conditions are optimized to obtain deep and homogeneous doping profiles to favor homogeneous electric field along the depth of the photodiode. Rapid thermal annealing is used to activate the dopants. Ge is contacted with W plugs and electrodes are defined after metal deposition and pattering. A SEM cross-section is shown in Fig. 1 (a) as well as a top view (b) of the fabricated device.

3. Results and discussion

First, the grating couplers losses are measured function of the wavelength in order to accurately extract the responsivity of the photodiode. The measurements were done from 1550nm to 1620nm using tunable laser and polarizer. The coupler losses are measured to be -5dB at 1550nm. Fig. 2 shows the measured dark current function of applied bias: only 1nA is obtained under 1V reverse bias, and 12.5nA at -5V. Photocurrent measurements are carried out from 1550nm to 1620nm. The maximum responsivity of the photodiode is about 0.64A/W at zero bias at 1550nm. At 1610nm, zero bias responsivity is about 0.1A/W as shown in Fig. 3. The voltage dependency of the photocurrent has also been measured for several wavelengths and is shown in Fig. 4. The photocurrent is double between 0V and -5V for 1620nm wavelength, indicating an enhancement of the absorption above the Ge absorption band edge, which can be attributed to Franz-Keldysh effect. Under -5V, responsivity is calculated to be around 0.18A/W at 1610nm and 0.12A/W at 1620nm.

The opto-electrical bandwidth is measured using 40GHz calibrated lightwave component analyzer at 1550nm wavelength. As seen from Fig. 5, the zero bias -3dB bandwidth is measured to be around 32GHz, allowing 40Gb/s operation at zero bias. With increasing bias, the bandwidth increase and is already over 40GHz under -1V reverse bias. Based on analytical model, calibrated with the zero bias bandwidth and resistance extracted from I-V measurement in high injection regime, the bandwidth versus bias dependency have been calculated and is shown in Fig. 6. Maximum bandwidth is estimated to be around 52GHz and is reached at -5V bias.

4. Conclusions

Very low dark current waveguide integrated lateral p-i-n Ge on Si photodiodes were fabricated and characterized. Dark current as low as 1nA under -1V bias was measured. At wavelength of 1550nm, responsivity of 0.64A/W was achieved, and L-band responsivity reached 0.12A/W at 1620nm with only 10µm long device, due to field enhanced absorption. The measured bandwidth of 32GHz should allow 40 Gbps operation at zero bias and even faster data rate operation at low bias. By increasing the photodiode length, higher responsivity should be achievable without compromising 40Gbps operation.

Acknowledgements

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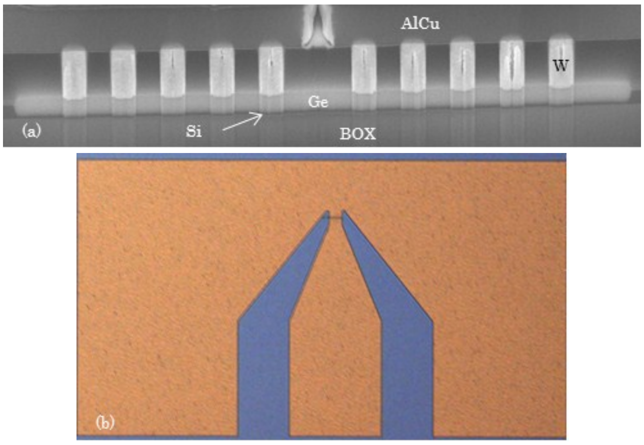

Figure 1. SEM cross-section (a) and top-view (b) of fabricated Ge photodiode.

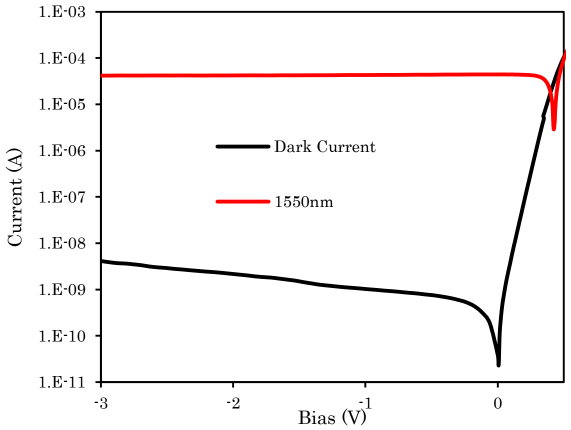

Figure 2. Dark current and photocurrent under 1550nm wavelength illumination.

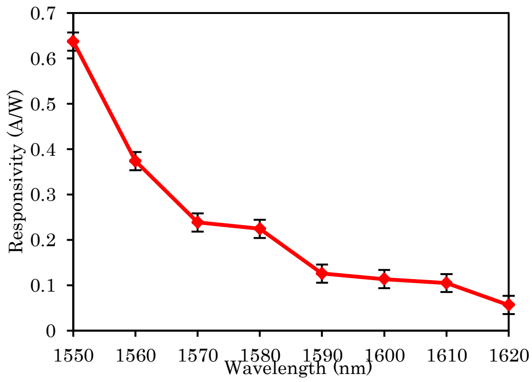

Figure 3. Zero bias responsivity function of the wavelength.

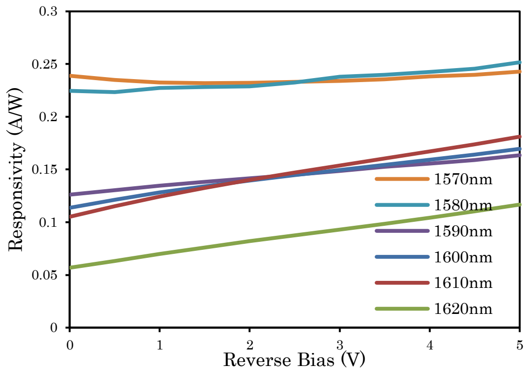

Figure 4. Responsivity-voltage characteristics in the L-band.

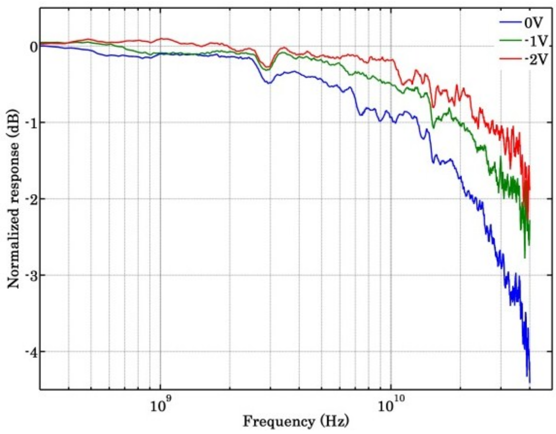

Figure 5. Normalized opto-electrical frequency response of the photodiode up to 40GHz at 1550nm under 0V, -1V and -2V applied bias.

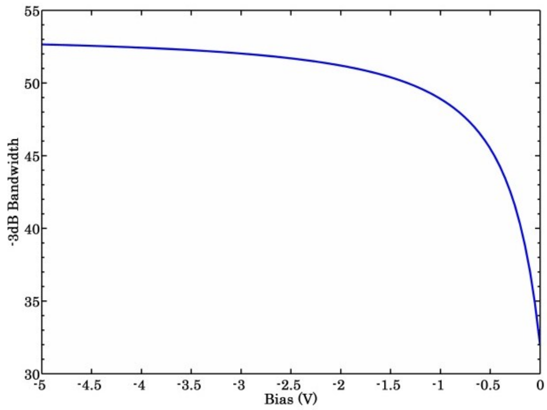

Figure 6. Simulated analytical -3dB bandwidth function of applied bias.