A Compact Evanescently-coupled Germanium PIN Waveguide Photodetector

Zhijuan Tu, Kaibo Liu, Huaxiang Yi, Runxi Zhou, Xingjun Wang*, Zhiping Zhou*, and Zhangyuan Chen
State Key Laboratory of Advanced Optical Communication Systems and Networks, School of Electronics Engineering and Computer Science, Peking University, Beijing, 100871, China

ABSTRACT

A compact 1.6×10μm² germanium pin waveguide photodetector was demonstrated on a Silicon-on-Insulator substrate. The dark current of the photodetector was measured to be 0.66μA at -1V bias voltage, which is much lower than recently reported. The photodetector exhibited a 3-dB bandwidth of 20GHz at the wavelength of 1.55μm. A clear open eye diagram at 10Gb/s was also obtained.

Keywords: Germanium photodetector, Silicon photonics, Evanescently-coupling, Waveguide integration

1. INTRODUCTION

In recent years, numerous progresses have been made in silicon photonics, which reveals more increasing interest in this area¹. The main reason of this worldwide concern lies in that silicon photonics can firstly overcome the bottlenecks of metallic interconnects by using optics and secondly reduce the cost and foot-print of Electro-Photonic integrated circuits (EPIC) circuits². With its potential integration with complementary metal oxide semiconductor (CMOS) electronics, silicon photonics represent one of the most promising platforms for next generation optical interconnect and communication solutions³. Up to now, enormous efforts have been made in Si photonics technologies and critical milestones have been achieved⁴. Many developments of silicon based photonic components have been carried out with impressive breakthroughs, such as passive components⁵, active devices like lasers⁶, high speed modulators⁷-⁸, and high performance photodetectors⁹-¹⁷. In light receiving systems, photodetectors play an important role in converting the incident light into electrical signals. They can be used to either monitor light intensity variations or detect high speed optical signals⁷.

For many majorities of long-distance data transition, the wavelength that is usually used is in the 1.55μm range, which corresponds to the minimum loss window of silica optical fiber. As a result, photodetectors working in the 1.55μm wavelength range have become aggressively pursued by researchers worldwide. Due to their relatively large bandgap of 1.12eV, bulk Si photodetectors demonstrate an absorption cutoff wavelength of ~1.1μm. But in order to utilize the mature Si CMOS technology, people tried to use Si as a platform to fabricate the heterojunction PDs by bonding or epitaxing the material on the Si substrate.

Germanium has an indirect bandgap of 0.67eV, so it can offer much higher optical absorption in 1.55μm wavelength range than silicon. Since Germanium is a group IV material like silicon, its fabrication process is compatible with CMOS technology. Owing to their excellent properties, Germanium photodetectors have become promising candidates for Si photonics integration at low cost and low power consumption.

*Corresponding authors: zjzhou@pku.edu.cn and xjwang@pku.edu.cn
There are two kinds of photodetectors with different light incidence manners. The normal incident (free space) structure and the side incident (waveguide integrated) structure. As to the former, there is a trade-off between quantum efficiency and bandwidth. When we want to improve the efficiency by increasing the intrinsic layer thickness, the 3dB bandwidth will drop down as the transit time becomes longer. In contrast, the trade-off can be overcome by using the Germanium detector as part of a waveguide. Since the light propagates and is absorbed along the direction of the waveguide, while the motion of the carriers is perpendicular to the waveguide. Therefore, the waveguide integrated photodiode can obtain high quantum efficiency and high bandwidth at the same time.

Generally, two schemes to couple light to the Germanium region are reported, namely the evanescently coupled and the butt-coupled methods. Usually the evanescently coupled scheme is preferred because of the easy fabrication process. In the past years, significant progress has been made for the waveguide integrated silicon based Germanium photodetectors in various application occasions. Some people are trying to reduce the dark current by surface passivation. Some people are trying to enhance the bandwidth of the photodetectors without reducing their dimensions. While others are trying to tune the responsivity roll-off wavelength from 1520nm to beyond 1620nm by using localized stressor.

In this paper, we report our recent works on evanescently coupled Germanium waveguide photodetectors. For high speed optical communication applications, we designed and fabricated a compact (1.6×10^{-6} μm^2) Germanium PIN photodetector. The photodetector demonstrated a dark current of 0.66μA and a 3dB bandwidth of 20GHz, which was ready to be used in future high speed coherent receiving systems.

### 2. DEVICE DESIGN AND FABRICATION

The 3-D schematic structure of the reported Germanium photodetector is presented in Fig. 1. It shows that the Germanium absorption layer is integrated on the top of a SOI rib waveguide. This forms a vertical PIN structure. The light in the silicon rib waveguide is evanescently coupled to the overlying Germanium layer and this configuration confirms a good overlap of the guide mode in the silicon waveguide with the Germanium absorption layer.

In order to analyze the light coupling and absorption in the evanescently coupled photodetector, we simulated the structure by using the beam propagation method. Germanium with a width of 1.6μm and a thickness of 500nm was defined. Fig. 2 shows the field distribution along the device longitudinal direction by simulation. By comparing three monitors which were put in three different layers, we found out that nearly 95% of the light power is absorbed when the Germanium length reaches about 8μm.
The fabrication process began with an SOI wafer with a 220nm thick top silicon. The rib waveguide had a total height of 220nm, a width of 600nm and an etching depth of 160nm. Two tapers were also formed to improve the coupling efficiency. Then the wafer was lightly implanted with boron and then heavily implanted to form the p-type ohmic contacts. The dopants in Si were activated using a rapid thermal annealing (RTA) process at 1030°C for 5 seconds prior to Germanium epitaxy. The Germanium layer was selectively grown above the silicon rib waveguide using the combined SiGe buffer layer with the two step growth approach. The final thickness of the Germanium layer was 500nm. A post epitaxy annealing step was undertaken at 750°C for 30 minutes to reduce the threading dislocations in the Germanium layer. Soon afterwards, an ion implantation with phosphorus was then performed on top of the Germanium layer to form the n-type ohmic contact area. The dopants referred to just now were activated by annealing at 500°C for 5 minutes. After the cladding oxide deposition, the fabrication process ended up with the formation of contact vias and aluminum interconnects.

3. EXPERIMENTAL RESULTS

The dark current-voltage (I-V) characteristics of the photodetector is presented in Fig. 3. A low dark current of 0.66μA at the bias of -1V is achieved. The corresponding dark current density is 4.125 A/cm². The two main sources of this dark current are the bulk dislocations which relieve the stress caused by the lattice mismatch between Germanium and Silicon, and the surface defects of the Germanium layer.
The 3-dB bandwidth was measured using a vector network analyzer (VNA) which provided measurement capability to 20GHz. The reverse bias was applied to the photodetector with a bias-tee. A high speed RF signal from the VNA was applied to a high performance modulator which is inside the E/O module of the VNA. The modulated light at 1550nm was coupled to the device using a lensed fiber, and the electrical output was measured with 50Ω high speed RF probes. The RF cables, probes, and bias-tee were calibrated before the measurement. The extracted normalized optical response as a function of frequency is plotted in Fig. 4.

Fig. 4. Normalized optical response versus frequency for the reported germanium photodetector under 3.8V reverse bias at 1550nm wavelength.

The measured series resistance was 568Ω, and the capacitance was calculated to be 4.5fF. Considering the 50Ω cable impedance, the RC time constant limited bandwidth was estimated to be 57GHz. Taking the following equation into account:

\[ f_{\text{transit}} = \frac{0.45 \cdot v_{\text{sat}}}{d_{\text{in}}} \]

where \( v_{\text{sat}} \) is carriers saturation drift velocity in Germanium, and \( d_{\text{in}} \) is the thickness of the intrinsic region, we obtained a 54GHz transit time limited bandwidth. Comparing the measured 20GHz bandwidth and the calculations in theory, we found that the limitation of the RF signal of the VNA might have an effect on the performance of our photodetector. It is possible that we could achieve a higher photodetector bandwidth by using a higher bandwidth VNA.

In order to check the viability of our photodetector, an eye-diagram measurement was undertaken. A 27-1 pseudo-random binary sequence (PRBS) NRZ signal at a 12.5Gb/s transmission rate was applied to the device. The PRBS signal was amplified by a RF Amplifier, and then applied to a commercial 10Gb/s LiNbO3 modulator. The reversed biased photodetector received the modulated light and output the corresponding electrical signal. The signal was then fed into a digital communication analyzer (DCA). An eye diagram was obtained at under -4V and it was shown in Fig. 5. The eye diagram is clearly open, although there were many limitations of the testing equipments, such as the DCA and the modulator. Since the measured bandwidth of our photodetector is 20GHz, we are sure that it is capable of much higher speed occasions.
4. CONCLUSION

In summary, we report a high performance evanescently coupled Germanium PIN photodetector. It is integrated on an SOI wafer with a 220nm thick top silicon. The fabrication process is compatible with the CMOS technology. The dark current measured is 0.66μA and the bandwidth is 20GHz. Although 10Gb/s is the maximum capability of the DCA that is in our hand, a clearly open eye diagram at 10Gb/s is obtained. By calculation in theory and comparing the measured 3-dB bandwidth, we are confirmed that our photodetector will show much better performance if higher speed DCA is available. Moreover, our photodetector has great potential to be used in future high speed coherent receiving systems.

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