31GHz Ge $n$-$i$-$p$ waveguide photodetectors on Silicon-on-Insulator substrate

1st & Corresponding author : Tao Yin (Intel Corporation)
Last author : Marion J. Paniccia (Intel Corporation)
Times Cited : 160 (from Web of Science, 2012-11-25)
Contents

- Introduction
- Device Structure and Fabrication
- Schematics
- Results
- Discussions
- Summary and Conclusion
- References
Introduction

Why Ge-on-Si photodetectors?

- Crystalline Si does not exhibit linear absorption in the telecommunication wavelength bands.
- Ge crystalline detectors are usually cooled to around 77 K to reduce dark currents, making them expensive and of limited use, particularly for spectroscopy.
- The ability to grow Ge epitaxially on Si.
- The effect of tensile strain on the structure of Ge.

Introduction

Why *n-i-p* configurations?

- The **depletion region** of *p-n* is very thin. \( I = \frac{n_{\text{int}}^p q}{\eta} \)
- In *n-i-p* structure **two depletion regions form**.
- Both depletion layers can be made to overlap so that a single, large depletion layer and corresponding electric field extends entirely across the intrinsic region of the device.
Why waveguide based photodetectors?

- The waveguide: the most basic silicon photonic component, used to carry high speed optical data.
- Crystalline Si photonic waveguide: be capable of transporting wavelength-parallel optical data with terabit-per-second data rates across the entire chip.
- To use a waveguide based detector: breaks the trade-off between bandwidth and responsivity present in surface normal detectors, and is much easier to integrate with other types of devices.
Device Structure and Fabrication

100Ω-cm SOI wafer
1 μm thick BOX (Buried Oxide) layer and
1.5 μm thick Si layer

Locally implanted with
Boron

Etching the substrate

1.4 μm for waveguide

0.6 μm

1.4 μm for waveguide

4.5 μm for Input width

Oxide Deposition and Patterning

Ge Selective Epitaxial Process – CMP-Anneal- Phosphorous Implanted

Tapered Coupling Waveguide Sectional Plane

Si

SiO2 BOX (Buried OXide)
P-doped (Boron Doped) Si

P-doped (Boron Doped) Si to contact metal pad

Al (Metal Contact)

Ge intrinsic epitaxial processed layer

N-doped (Phosphorous Doped) Ge

Optics and Metamaterials Lab
The edge of the phosphorous implantation in the Ge film was intentionally pulled in from the Ge sidewalls by 0.4 μm on each side.

To minimize the E-field at these trap-laden interfaces

Thereby reducing the level of surface leakage current.

Beamprop modeling → optimized Ge thickness at 1550 nm
The measured **average transmission loss** of the Si rib waveguide, together with input taper and reverse taper, was calculated to be $-0.55 \pm 0.05$ dB/cm at 1550 nm.

The **average coupling loss** was measured to be $-3.0$ dB $\pm 0.3$ dB.
Results

Coupling to the Ge layer can be improved by optimizing Ge layer thickness and reducing the rib waveguide height, allowing for even shorter detectors.

Reducing the rib height Trade-off Increased polarization sensitivity (reduce viability)

For the detectors discussed in this paper, the measured polarization dependence is smaller than 1dB.
Results

The corresponding electrical (power) bandwidths $\propto \frac{1}{\text{Device Area}} \propto \frac{1}{\text{RC delay}}$

<table>
<thead>
<tr>
<th></th>
<th>Detector A</th>
<th>Detector B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured Optical Bandwidth ($\text{GHz}$)</td>
<td>31.3</td>
<td>29.4</td>
</tr>
<tr>
<td>Measured Electrical Bandwidth ($\text{GHz}$)</td>
<td>26</td>
<td>24.1</td>
</tr>
<tr>
<td>Calculated Electrical Bandwidth ($\text{GHz}$)</td>
<td>27</td>
<td>26</td>
</tr>
</tbody>
</table>
Discussions

The issues in this setup

- Electrical reflections due to impedance mismatch, as can be seen from the double traces on the rising and falling edges.
- A very high average power of 1.2mW had to be launched into the detector due to the limited gain from the RF amplifier, and this could have lead to carrier screening and a slightly slower response time.

To further improve

- Properly packaging the Ge waveguide photodetector with a high speed trans-impedance amplifier (TIA) with impedance matching, expect the high speed data transmission at 40Gb/s.
By Ge n-i-p waveguide photodetectors on Silicon

### Summary and Conclusion

Report evanescently coupled Ge waveguide photodetectors’ performance:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Detector A</th>
<th>Detector B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width (μm)</td>
<td>7.4</td>
<td>4.4</td>
</tr>
<tr>
<td>Length (μm)</td>
<td>50</td>
<td>100</td>
</tr>
<tr>
<td>Dark Current at −2V (nA)</td>
<td>169</td>
<td>267</td>
</tr>
<tr>
<td>Dark Current Density (mA/cm²)</td>
<td>51</td>
<td>74</td>
</tr>
<tr>
<td>Responsivity at -2V (A/W)</td>
<td>0.89 ±0.06</td>
<td>1.16 ±0.08</td>
</tr>
<tr>
<td>Quantum Efficiency(%) at 1550nm</td>
<td>71</td>
<td>93</td>
</tr>
<tr>
<td>Measured Optical Bandwidth(GHz)</td>
<td>31.3</td>
<td>29.4</td>
</tr>
<tr>
<td>Measured Electrical Bandwidth(GHz)</td>
<td>26</td>
<td>24.1</td>
</tr>
<tr>
<td>Calculated Electrical Bandwidth(GHz)</td>
<td>27</td>
<td>26</td>
</tr>
</tbody>
</table>


G.T. Reed and A.P. Knights, Silicon photonics. (Wiley Online Library, 2008).

http://www.leb.eei.uni-erlangen.de

Thank you.