

# 42 GHz p.i.n Germanium photodetector integrated in a silicon-on-insulator waveguide

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**Abstract:** A compact pin Ge photodetector is integrated in submicron SOI rib waveguide. The detector length is reduced down to 15  $\mu\text{m}$  using butt coupling configuration which is sufficient to totally absorb light at the wavelength of 1.55  $\mu\text{m}$ . A -3 dB bandwidth of 42 GHz has been measured at a 4V reverse bias with a responsivity as high as 1 A/W at the wavelength of 1.55  $\mu\text{m}$  and a low dark current density of 60 mA/cm<sup>2</sup>. At a wavelength of 1.52  $\mu\text{m}$ , a responsivity of 1 A/W is obtained under -0.5 V bias. The process is fully compatible with CMOS technology.

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**OCIS codes:** (230.5160) Photodetectors; (130.3120) Integrated optics devices; (130.0250) Optoelectronics; (130.1750) Components; (200.4650) Optical interconnects

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## 1. Introduction

Numerous works have been reported on silicon-based photonics for several years with a strong evolution in the field of active components in the last years [1]. The main reason of such an increasing interest is due to the possibility firstly to use optics to overcome the bottlenecks of metallic interconnects and secondly to reduce the cost and foot-print of circuits for optical telecommunication applications. Silicon is a good candidate thanks in particular to the possibility to monolithically integrate photonics with CMOS circuits. Various passive [2-3] and active building blocks have been experimentally demonstrated with impressive breakthroughs on optical modulators [4-5] and germanium photodetectors [6-11]. The latter is one of the main building blocks for numerous applications either to monitor slow light intensity variations or to detect high speed optical signals. Two kinds of approaches can be considered to detect near-infrared light in the silicon-based platform: surface illuminated photodetectors and integrated photodetectors. Since 2007, significant results have been reported on high speed germanium-on-silicon photodetectors integrated in silicon-based waveguides [6-11], using either pin or MSM structures, at the wavelengths of 1.55 $\mu\text{m}$  and 1.3  $\mu\text{m}$ .

We report here recent works on compact Ge-on-Si pin photodetectors integrated in silicon-on-insulator rib waveguide with improved performances: low dark current, high cut-off frequency and high responsivity at the wavelength of 1.55 $\mu\text{m}$ .

## 2. Description and fabrication

Schematic views of the waveguide Ge photodetector integration and cross section of pin diode are presented in fig. 1(a) and 1(b). Ge-on-Si photodetector is integrated at the end of a SOI rib waveguide. This configuration allows a good overlap of the guided mode in the SOI waveguide with the absorbing Ge layer.

Furthermore, such an integration insures a low wavelength dependence and the coupling efficiency from the waveguide to the Ge film is the same in the whole telecom range. The rib waveguide has a total height of 0.38  $\mu\text{m}$ , a width of 660 nm and an etching depth of 110 nm. Single-mode propagation for TE polarization at a wavelength of 1.55  $\mu\text{m}$  is achieved with this waveguide geometry.

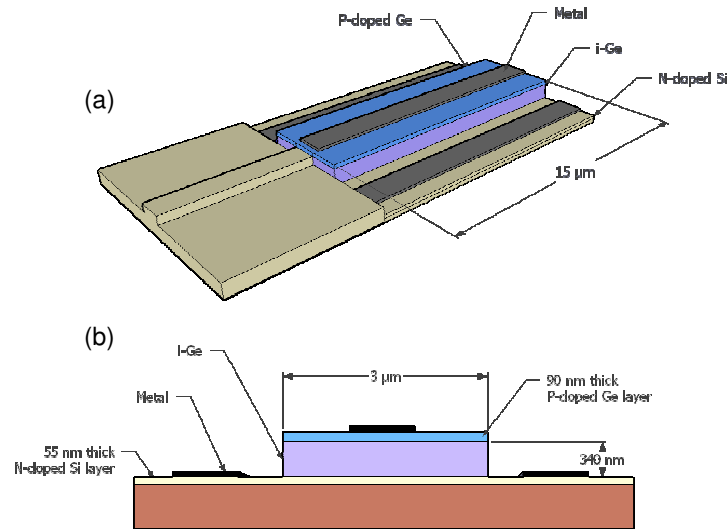


Fig. 1. (a) Schematic views of pin germanium photodetector integrated in SOI waveguide. The photodetector length and width are  $15\ \mu\text{m}$  and  $3\ \mu\text{m}$ , respectively. (b) cross section of the pin diode.

Passive photonic devices like waveguides and beam splitters are processed on a 8-inch SOI wafer with  $1\ \mu\text{m}$  thick buried oxide layer and a  $0.4\ \mu\text{m}$  thick silicon film using Deep-UV lithography followed by dry etching. A silicon recess is etched in the silicon film down to  $55\ \text{nm}$  residual thickness. Its length is  $15\ \mu\text{m}$  and the width is  $10\ \mu\text{m}$ . The photodetector length has been chosen to allow a total absorption of the light at the wavelength of  $1.55\ \mu\text{m}$ . This recess is locally implanted with phosphorus followed by thermal annealing at  $1050^\circ\text{C}$  for 30 seconds to form the P+ ohmic contact. Germanium is then selectively grown by Reduced Pressure Chemical Vapour Deposition (RP-CVD) in the silicon recess. A  $40\ \text{nm}$  thick Ge buffer layer at low temperature ( $400^\circ\text{C}$ ) is followed by a  $300\ \text{nm}$  thick Ge film at higher temperature ( $730^\circ\text{C}$ ) and finally by a  $90\ \text{nm}$  thick P-doped Ge layer. An annealing step is performed to reduce the threading dislocation density in the Ge layer. Bottom contacts are defined by UV lithography followed by an etching step down to the P+ silicon region which defines simultaneously a  $3\ \mu\text{m}$  wide Ge mesa in between, as shown in fig 2b. A  $300\ \text{nm}$  thick silicon dioxide ( $\text{SiO}_2$ ) layer is then deposited onto the wafer using plasma-enhanced chemical vapour deposition (PECVD). Openings on both top P+ and bottom N+ regions are patterned in the silicon dioxide and a Ti/TiN/AlCu metal stack is deposited to form top and bottom contacts. A top view and a SEM cross section of the complete device is shown in Fig. 2(a) and 2(b).

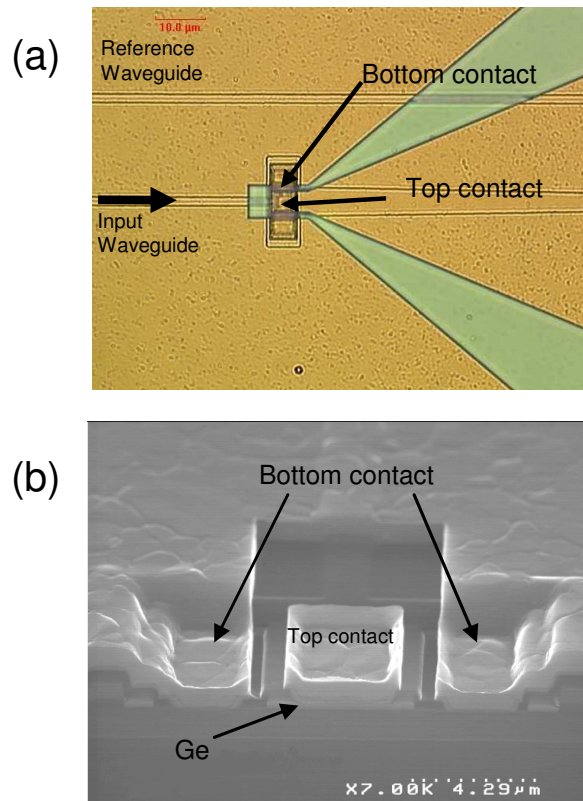


Fig. 2. (a) Optical microscopy top view of the photodetector integrated at the end of SOI waveguide. The reference waveguide is a rib waveguide of the same dimensions as the input waveguide, covered by SiO<sub>2</sub>, and that is used for optical responsivity calibration (b) SEM cross-section view of the complete pin Ge photodetector.

### 3. Experimental results

The dark current-voltage (I-V) characteristics of the 15 μm long and 3 μm wide pin Ge photodiode are reported in fig 3. A dark current as low as 18 nA at a reverse bias of 1V has been obtained which corresponds to a current density of about 60 mA/cm<sup>2</sup> (figure 3). The leakage current is mainly due to dislocations in the Ge layer and sidewall roughness of the Ge mesa.

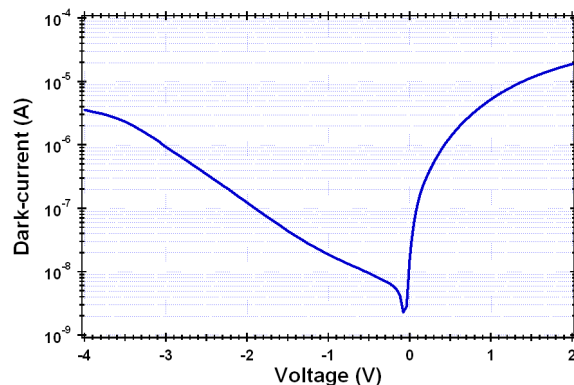


Fig. 3. Dark current as a function of voltage of Ge pin diode integrated in SOI waveguide. The Ge mesa width and length are 3 μm and 15 μm, respectively.

Under illumination, photocurrent is then generated. A tunable laser source centered at a wavelength of  $1.55\ \mu\text{m}$  at TE polarization is coupled into the SOI waveguide using a lensed fiber.

The guided light beam is then equally divided using a star coupler [13] into two branches. The detector is inserted in the first branch and the second branch is used as a reference which by measuring the optical output power, allows evaluating the power at the photodetector input. The responsivity is defined as the ratio of the generated photocurrent by the input power estimated from the reference branch. The input power measurement takes into account the propagation loss of the rib waveguide ( $\sim 1\ \text{dB/cm}$ ) and the waveguide length difference. The measured responsivity is given in fig. 4(a) as a function of the reverse bias and as a function of the wavelength in fig. 4(b).

The responsivity value at  $1.55\ \mu\text{m}$  is  $0.2\ \text{A/W}$  at  $0\text{V}$  bias and rapidly increases to about  $0.9\ \text{A/W}$  at  $0.3\ \text{V}$  reverse bias to finally reach  $1\ \text{A/W}$  at  $4\text{V}$  reverse bias which corresponds to an external quantum efficiency of  $80\%$ . At  $-0.5\ \text{V}$ , the responsivity is  $1\ \text{A/W}$  at the wavelength of  $1.52\ \mu\text{m}$  and is still  $0.2\ \text{A/W}$  at  $1.6\ \mu\text{m}$ . The external responsivity considering a good fiber coupler ( $<1\text{dB}$ ) [14], low propagation loss ( $\sim 0.1\ \text{dB/cm}$ ) [15] and internal photodetector responsivity ( $\sim 1\ \text{A/W}$ ), is still higher than  $0.8\ \text{A/W}$ .

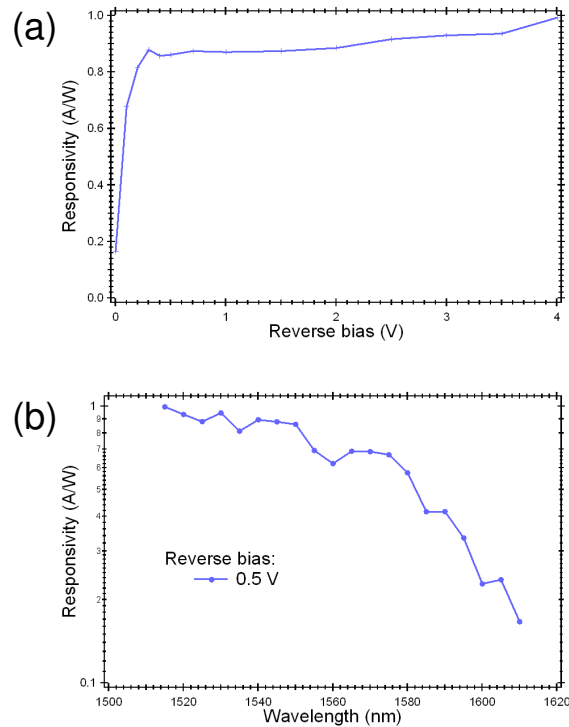


Fig. 4. Responsivity of the pin Ge photodetector integrated in SOI waveguide (a) as a function of the reverse bias at  $1.55\ \mu\text{m}$  and (b) as a function of the wavelength at  $-0.5\ \text{V}$  bias. The photodetector length and width are  $15\ \mu\text{m}$  and  $3\ \mu\text{m}$  respectively.

The  $-3\ \text{dB}$  bandwidth is determined using a classical RF experiment set-up. A linearly TE polarized light beam at the wavelength of around  $1.5\ \mu\text{m}$  is butt-coupled into the waveguide using a polarization-maintaining lensed fiber. The integrated Ge-on-Si pin photodetector is biased using  $50\ \text{GHz}$  microwave probes. The photocurrent is measured using a lightwave component analyzer which provides measurements from  $0.1\ \text{GHz}$  to  $50\ \text{GHz}$ . The normalized optical responses as a function of frequency, from  $0.1\ \text{GHz}$  to  $50\ \text{GHz}$ , are plotted in fig. 5.

The measured optical bandwidths are 12GHz, 28GHz and 42 GHz at 0V, -2V and -4V biases, respectively.

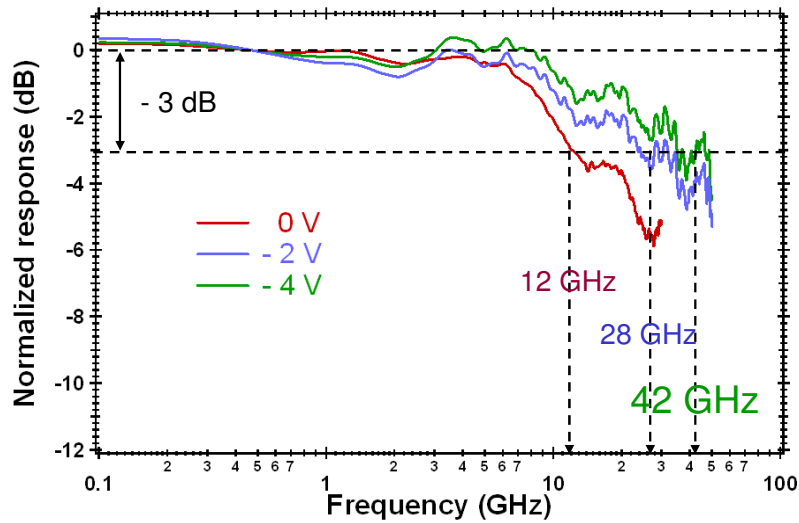


Fig. 3. Normalized optical responses versus frequency for pin diode integrated in SOI rib waveguide under 0V, -2V, and -4V biases at the wavelength of 1.53 $\mu$ m. The photodetector length is 15  $\mu$ m and the mesa width is 3  $\mu$ m.

The product of the quantum efficiency by the bandwidth is usually used as a figure of merit in order to evaluate the photodetector performances. At 4V reverse bias, this product reaches 33.6 GHz at 1.55  $\mu$ m. It is the highest value reported in the literature for any Ge photodetectors (surface illuminated and integrated configurations) at the wavelength of 1.55  $\mu$ m.

#### 4. Conclusion

For a few years, significant and impressive works have been performed on the design, fabrication and characterization of silicon-based photonic components especially on germanium photodetector. We have experimentally demonstrated a high speed and compact Ge photodetector integrated in SOI rib waveguide. A record -3 dB bandwidth of 42 GHz has been obtained at -4V with a responsivity as high as 1 A/W at the wavelength of 1.55  $\mu$ m and a low dark current density of 60 mA/cm<sup>2</sup>. The technological process used to fabricate such a photodetector is fully compatible with complementary-metal-oxide-semiconductor (CMOS) technology developed for microelectronic circuits. The results presented here demonstrate that efficient waveguide detectors now exist for Silicon-based microphotronics development towards applications in the field of optical interconnects for CMOS circuits or for low cost optical telecommunication systems.

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