Zero-bias high-responsivity high-bandwidth top-illuminated germanium p–i–n photodetectors

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We report efficient zero-bias high-speed top-illuminated p–i–n photodiodes (PDs) with high responsivity fabricated with germanium (Ge) films grown directly on silicon-on-insulator (SOI) substrates. For a 15 μm-diameter device at room temperature, the dark current density was 44.1 mA/cm^2 at −1 V. The responsivity at 1.55 μm was 0.30 A/W at 0 V. The saturation of the optical responsivity at 0 V bias revealed that this photodetector allows a complete photo-generated carrier collection without bias. Although the 3-dB bandwidth of the 15-μm-diameter detector was 18.8 GHz at the reverse bias of 0 V, the detector responsivity was improved by one order of magnitude compared with that reported in the literature. Moreover, the dark current of the detector was significantly reduced.

Keywords: germanium, photodetectors, integrated optoelectronics, optical interconnections

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1. Introduction

Optical interconnects will be more advantageous for the next-generation inter-chip data communication beyond 10 Gb/s compared with the current copper interconnections, which suffer with resistance-capacitance-limited slow speed and high heat dissipation.[1] The application of silicon photonics technologies to optical telecommunications requires the development of near-infrared detectors monolithically integrated to the Si platform. Top-illuminated photodiodes (PDs) are widely used in the next-generation data communication, especially in board-to-board and chip-to-chip optical interconnects, because of their simple process and fiber alignment. Ge-based PDs on Si or silicon-on-insulator (SOI) have attracted much attention because of their compatibility with the CMOS technology and favorable absorption coefficients. Much effort has been made to grow high-quality Ge films for devices with high responsivity and high bandwidth.[2–4]

The main drawback of Ge-on-Si PDs is the high dark current. The average value reported in the literature is approximately 1 μA under −1 V.[1–4] This rather high dark current is due to the lattice parameter mismatch between Ge and Si (i.e., the presence of numerous threading dislocations in the Ge layer). A high dark current leads to a high stand-by power consumption in addition to a degraded signal-to-noise rate (SNR). Moreover, the detector and receiver circuit is preferred to operate on a single power supply, which often restricts the bias voltage for PDs to be less than 1.5 V.[1,2] A high-speed operation under zero bias will also be of great significance because a system without a power supply will simplify the packaging, reduce the dimensions, ease the maintenance, and lower the cost.[5] As a result, interest in the development of low-bias or even zero-bias PDs to decrease the dark current and the power consumption has increased.

Moreover, top-illuminated PDs also suffer from an inherent drawback of bandwidth–efficiency tradeoff because of the opposite requirement of the thickness of the photo absorption layer for high bandwidth and high efficiency. Only a few studies have demonstrated zero-bias Ge PDs in top-illuminated configurations with a high bandwidth. An overview of the performances obtained by zero-bias Ge-on-Si top-illuminated PDs is shown in Table 1. A record high zero-bias 3-dB bandwidth of 39 GHz was obtained by Klinger in 10-μm-diameter top-illuminated p–i–n Ge PDs. Although the detectors have a record high 3-dB bandwidth, the reported responsivity at 1.55 μm is only ∼0.04 A/W because it is limited by the small device active area and the relatively thin absorption layer. The dark current density is as high as 130 mA/cm^2, which makes it difficult to be used in practical data communication. In terms of high responsivity, the dark current density is important for detectors with thick Ge absorption layer and proper photosensitive surface.

Table 1. An overview of the performances obtained by zero-bias Ge-on-Si top-illuminated photodiodes.

	Dark current density/mA·cm^{-2}	Wave length/nm	Diameter/μm	Band width (0 V)/GHz	Responsivity (EQE)/A·W^{-1}
Ref. [6]	100 (−1 V)	1552	10	25.1	0.035 (2.8%) (−2 V)
Ref. [7]	130 (−1 V)	1550	10	39	0.04 (3.2%) (0 V)
This work	44.1 (−1 V)	1550	15	18.8	0.30 (24%) (0 V)

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In this paper, we report an efficient zero-bias high-speed top-illuminated p–i–n PD with high responsivity fabricated with Ge films grown directly on SOI substrates using ultra-high vacuum chemical vapor deposition (UHV/CVD). The device area and the thickness of the absorption layer have been optimized based on a theoretical analysis and practical applications. For a 15-μm-diameter device at room temperature, the dark current density is about 44.1 mA/cm^2 at the reverse bias of 1 V. The responsivity at 1.55 μm is 0.30 A/W, corresponding to a quantum efficiency of 24%. Although the 3-dB bandwidth of the 15-μm-diameter detector is 18.8 GHz at a reverse bias of 0 V, the detector responsivity is improved by one order of magnitude compared with that reported in the literature. Moreover, the dark current of the detector is also significantly reduced.

2. Device design

The most relevant figures of merit for a photodetector are the responsivity (in units of A/W), the speed (in terms of response time or bandwidth), and the dark current (or signal-to-noise ratio). The p–i–n PDs have a double-junction semiconductor arrangement for high-speed receivers; their responsivity R at normal incidence (i.e., light impinging perpendicularly to the junctions) can be expressed as[4]

$$R = \frac{\lambda}{1.24}\eta_{\rm ex} = \frac{\lambda}{1.24}(1-\theta_{\rm R})\eta_{\rm in}(1-{\rm e}^{-\alpha d_{\rm i}}), \qquad (1)$$

where λ is the vacuum wavelength in units of μm, $\eta_{\rm ex}$ is the external quantum efficiency (EQE), $\theta_{\rm R}$ is the reflectivity due to the Fresnel index mismatch at the input interface, $\eta_{\rm in}$ is the internal quantum efficiency, α is the optical absorption coefficient in units of cm^{-1}, and $d_{\rm i}$ is the thickness of the active layer (i.e., the Ge region of the p–i–n photodiode).

The electrical 3-dB bandwidth is an important figure of merit for evaluating high-speed PDs. It specifies the frequency range from DC to the cut-off frequency $f_{\rm 3dB}$. The latter is defined as the frequency at which the electrical output power has dropped by 3-dB below that at DC. The bandwidth of a lumped element PD, in which the device length is much shorter than the electrical signal wavelength, might be limited mainly by the *RC*-time constant and the carrier drift time in the depletion region. These bandwidth constraints lead to a 3-dB bandwidth that can be approximated by the following equation:[8,9]

$$f_{\rm 3dB} = \sqrt{\frac{1}{f_{\rm T}^{-2}+f_{RC}^{-2}}}. \qquad (2)$$

One limitation of the bandwidth is the *RC* delay of the detector. The *RC* bandwidth f_{RC} can be calculated by

$$f_{RC} = \frac{1}{2\pi RC} = \frac{1}{2\pi\varepsilon R}\cdot\frac{d_{\rm i}}{\pi(D/2)^2}, \qquad (3)$$

where D is the mesa diameter, ε is the permittivity, and $d_{\rm i}$ is the thickness of the intrinsic zone. The *RC* frequency increases linearly with the increasing thickness of the intrinsic region, assuming a constant device area. We have to assume a load resistance, which is chosen in this paper to be 50 Ω in agreement with the used measurement system and the standard microwave waveguides.

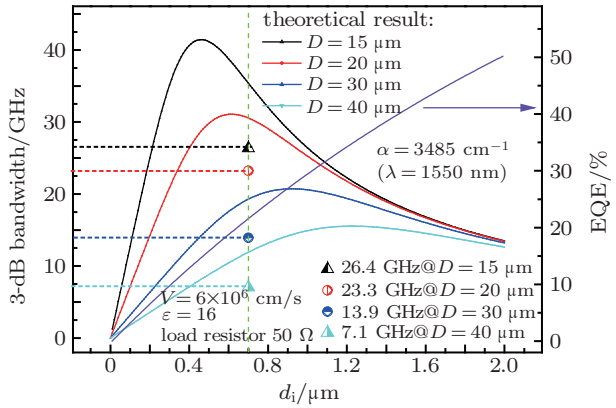


Fig. 1. (color online) Theoretically calculated external quantum efficiency, 3-dB bandwidth and measured 3-dB bandwidth $f_{\rm 3dB}$ versus the thickness of the intrinsic zone $d_{\rm i}$ for different device diameters D ranging from 15 μm to 40 μm. The frequency curves have maxima which depend on the device area and the thickness of the absorption layer.

Another limitation of the bandwidth is the transit time of the carriers in the intrinsic region. The minimum time is determined by the saturation drift velocity $v_{\rm sat}$, which is a material constant (Ge: $v_{\rm sat} = 6\times10^6$ cm/s), and $d_{\rm i}$. The carrier transit frequency $f_{\rm T}$ can be calculated by[9]

$$f_{\rm T} = \frac{\sqrt{2}}{\pi}\frac{v_{\rm sat}}{d_{\rm i}} = \frac{0.45 v_{\rm sat}}{d_{\rm i}}. \qquad (4)$$

The theoretically calculated external quantum efficiency, 3-dB bandwidth, and measured 3-dB bandwidth are plotted in Fig. 1 as a function of the thickness of the intrinsic zone, $d_{\rm i}$, for different device diameters ranging from 15 μm to 40 μm. The frequency curves have maxima which depend on the device area and the thickness of the absorption layer. Figure 1 shows that the bandwidth maxima (31 GHz) of the p–i–n Ge PDs with 20-μm diameter can be obtained by using a very thin absorber layer (about 600 nm). A bandwidth above 40 GHz can be obtained by using a very thin absorber layer (about 450 nm) and small detector areas (15 μm). However, the quantum efficiency is reduced to 14.5%, corresponding to 0.18 A/W, and the tolerances for the alignment of the fiber are tighter as the mesa sizes are smaller. The single-mode optical fiber core diameter is usually 9 μm or 10 μm. In order to obtain larger fiber alignment tolerance and higher responsivity, the device photosensitive surface diameter must be larger than 10 μm. The device area and the thickness of the absorption layer must be optimized based on the practical applications and the process conditions. In this paper, the mesa diameter is chosen to be 15 μm.

3. Material growth and device fabrication

A schematic cross-section view of the reported Ge-on-SOI PD is shown in Fig. 2. Germanium films were deposited on an n+ SOI (001) layer using germane (GeH_4) by cold wall UHV-CVD with a background pressure lower than 10^{-7} Pa. To minimize the dislocation density, a thin relaxed Ge buffer layer was grown first at low temperature (290 °C) and followed by an additional 800-nm thick Ge film at high temperature (600 °C).[10]

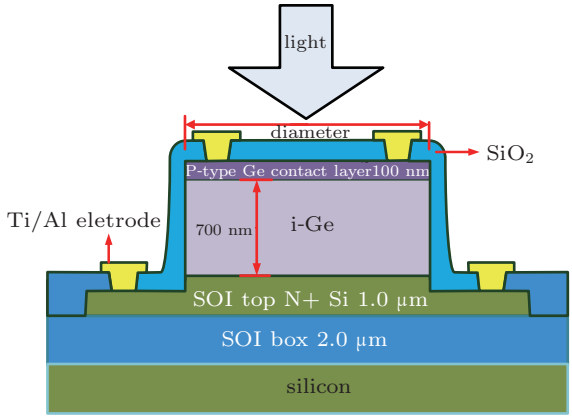


Fig. 2. (color online) Schematic cross-section view of the reported Ge-on-SOI photodetector.

Normal incidence p–i–n PDs were realized with a top p-type contact layer, an intrinsic layer of epitaxial Ge, and a bottom n-type contact on highly phosphorus doped SOI. For the top contact layer, BF^{2+} was implanted at a dose of 4×10^{15} cm^{-2} and the energy of 40 keV to reduce the contact resistance. After thermal activation, the thickness of the intrinsic Ge layer was about 700 nm. The Ge p–i–n detectors were realized with a double-mesa structure, which were fabricated by dry etching.[11] The first mesa process defined the dimensions of the photodiode; the second one isolated the photodiodes from each other. The hetero-junction devices with different mesa diameters from 15 μm to 100 μm were fabricated. A 650-nm thick SiO_2 was deposited by plasma enhanced CVD on the sidewall to reduce the surface leakage current. Ti/Al for the pad contacts were deposited by e-beam evaporation and patterned by lift-off. The top and the bottom electrical contact pads consisted of ring-shaped regions based on 900-nm thick Al films. Finally, a passivation/antireflection layer was coated to reduce the incidence light loss.

4. Results and discussion

The PDs were characterized by their electrical and optical properties. The setup for current–voltage characteristics and optical responsivity measurements consisted of an Agilent B1500A semiconductor analyzer, a probe station, and a special laser of 1550-nm wavelength. Light was coupled into the detector perpendicular to the surface with a single-mode fiber probe. The laser output was measured with a calibrated reference detector. The DC responsivity was measured with a monochromatic light source of 0.50 mW at the 1550-nm wavelength.

Figure 3 demonstrates the currents of the device without and with the light at normal incidence on the top surface, where the input optical power was 0.5 mW at 1550 nm for the 15-μm-diameter detector. At a reverse bias of 3 V, the dark current was 197.8 nA, corresponding to a current density of 111.9 mA/cm^2. If the photodetectors were operated under a low bias or even zero bias, the dark current decreased significantly. For example, at a reverse bias of 1 V, the dark current was 78 nA, corresponding to a current density of 44.1 mA/cm^2. Compared with the operation at the reverse bias of 3 V, the dark current was decreased by 60.6%. When the detector bias voltage decreased to 0.1 V, the dark current was only 2.5 nA, corresponding to a current density of 14.4 mA/cm^2. Compared to the result at the reverse bias of 3 V, the dark current was decreased by 98%. The results showed that reducing the operating voltage can significantly reduce the dark current. The optical responsivity was 0.30 A/W at 1550 nm. The quantum efficiency was 24%. The reported responsivity at 0 V bias was more than 98% of the saturated value at 1 V reverse bias, which was attributed to the high-carrier collection efficiency resulting from the high built-in electric field in the depletion region of the diode. The saturation of the optical responsivity at 0 V bias reveals that this photodetector configuration allows a complete photo-generated carrier collection without bias.

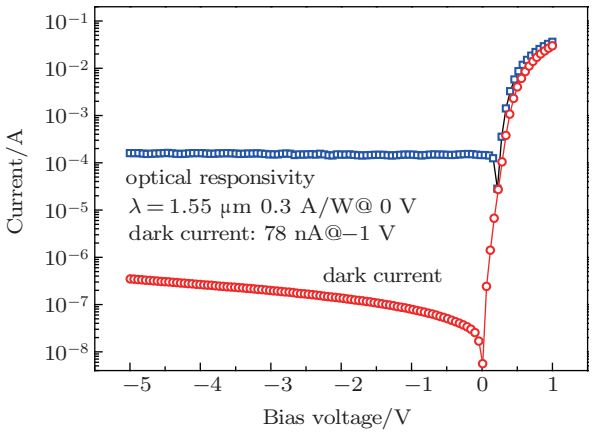


Fig. 3. (color online) Measured dark current and photocurrent with input optical power of 0.5 mW at 1550 nm for the 15-μm-diameter detector.

The dark current density of the photodiode indicates the material quality and determines the optical receiver sensitivity. One of the origins of the dark current is the junction bulk leakage current J_{bulk} due to the defects induced by threading dislocation and the ion implantation process. The bulk dark current in Ge PDs has been proven to scale linearly with threading dislocation density N_{TDD}.[12] The surface leakage current J_{surf}

is also expected to be another source of the dark current. The bulk leakage $J_{\rm bulk}$ and the peripheral surface leakage $J_{\rm surf}$ components of the dark current were also investigated. The dark current as a function of the applied bias voltage was measured for different mesa PDs. Figure 4 shows the total dark current density $J_{\rm dark}$ versus $1/D$ at the reverse biases of 0.1 V, 1 V, and 3 V. To extract $J_{\rm bulk}$ and $J_{\rm surf}$ separately, numerical fitting was performed using[13]

$$I_{\rm total} = J_{\rm bulk}\pi(D/2)^2 + J_{\rm surf}\pi D. \tag{5}$$

Then the dark current density, $J_{\rm total} = I_{\rm total}$ /area, can be written as

$$J_{\rm total} = J_{\rm bulk} + \frac{4J_{\rm surf}}{D}. \tag{6}$$

For the PDs operating at 1 V reverse bias, $J_{\rm bulk}$ and $J_{\rm surf}$ can be extracted from Fig. 4. The $J_{\rm bulk}$ and $J_{\rm surf}$ are 21.73 mA/cm^2 and 8.23 μA/cm, respectively. The best results were reported in the Ref. [9]. The extracted $J_{\rm bulk}$ and $J_{\rm surf}$ were 0.032 mA/cm^2 and 0.27 μA/cm, respectively. This bulk current density of 0.032 mA/cm^2 is one of the lowest values for Ge PDs reported so far. The present bulk dark current density of 21.73 mA/cm^2 at the reverse bias of 1 V confirms that the dark current density can be reduced with a further improvement on the Ge epitaxial growth quality and gas-phase doping. As is well known, the surface passivation of Ge is more difficult than that of an SiO_2/Si system. Thus, a more effective surface passivation of Ge is required for further reduction in the surface leakage current of Ge PDs, such as the GeO_2 passivation.[13]

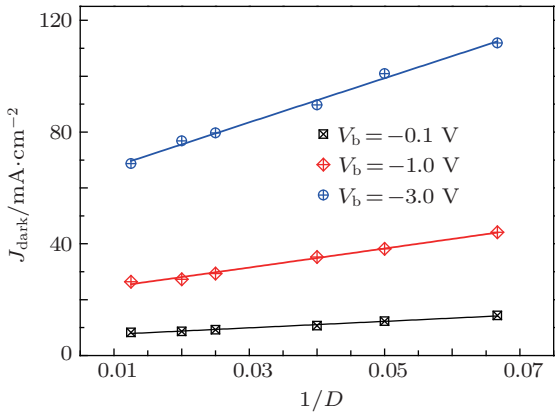


Fig. 4. (color online) Dark current density $J_{\rm dark}$ versus $1/D$ at different reverse bias $V_{\rm b}$, where D is the device mesa diameter.

Figure 5 illustrates the normalized frequency responses of the detectors with different diameters at 1550 nm under a bias of 0 V. A 3-dB bandwidth as high as 18.8 GHz is obtained for the 15-μm-diameter device under a bias of 0 V. The normalized optical responses for the 15-μm-diameter photodetector under biases of −1 and −3 V are also shown in Fig. 5. With a modest reverse bias of 3 V, a good response is obtained at an even higher frequency of 26.4 GHz.

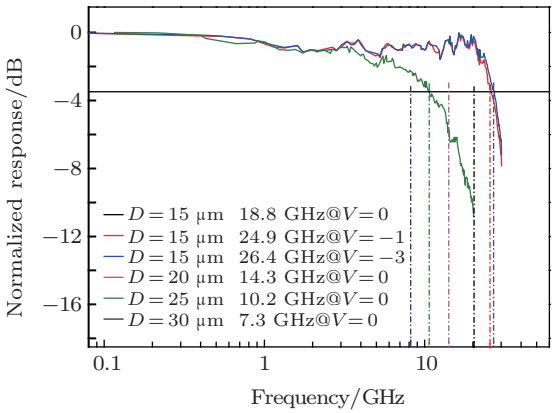


Fig. 5. (color online) Normalized frequency responses of the detectors with different diameters at 1550 nm and 0 V, and normalized frequency responses at the external biases of 0 V, −1 V, and −3 V for a Ge detector with a diameter of 15 μm.

Assume that the Ohmic resistance R is equal to the system impedance of 50 Ω, with a 0.7-μm-thick and 15-μm-diameter detector, the theoretical band width is almost 30 GHz for a photodiode. Due to the Ohmic contact resistance of the pad electrodes and the parasitic capacitance in the device, the experiment value should be lower than the theoretical result. The measured 3-dB bandwidth is in good agreement with the theoretical values, as illustrated in Fig. 1. According to the previous research, a large contact resistance due to the Fermi level pinning effect at the interface between metal and Ge strongly restricts the 3-dB bandwidth of Ge photodetectors. Therefore, an Al/TaN stack electrode could be a good choice to improve the bandwidth.[14]

5. Conclusion

The vertical incidence high-speed top-illuminated Ge-on-SOI p–i–n PDs with different mesa diameters were fabricated by Si CMOS-compatible technology. For a 15-μm-diameter device at room temperature, the dark current density was about 44.1 mA/cm^2 at the reverse bias of 1 V. The responsivity at 1.55 μm was 0.30 A/W. Although the 3-dB bandwidth of the 15-μm-diameter detector was 18.8 GHz under the bias of 0 V, the detector responsivity improved by one order of magnitude compared with that reported in the literature. The saturation of the optical responsivity at 0 V bias revealed that this photodetector configuration allows a complete photo-generated carrier collection without bias. Moreover, the dark current of the detector was significantly reduced. The dark current density can be reduced with a further improvement on the Ge epitaxial growth quality and the fabrication process. For further improvement of the bandwidth and responsivity, a resonant cavity design could be used to improve the external quantum efficiency while maintaining the thin intrinsic region for high-speed operation.

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