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Ge-on-insulator lateral p - i - n waveguide photodetectors for optical communication

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We report high-performance lateral p - i - n Ge waveguide photodetectors (WGPDs) on a Ge-on-insulator (GOI) platform that could be integrated with electronic-photonic integrated circuits (EPICs) for communication applications. The high quality Ge layer affords a low absolute dark current. A tensile strain of 0.144% in the Ge active layers narrows the direct bandgap to enable efficient photodetection over the entire range of C- and L bands. The low-index insulator layer enhances optical confinement, resulting in a good optical responsivity. These results demonstrate the feasibility of planar Ge WGPDs for monolithic GOI-based EPICs.

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Ge is a group-IV semiconductor that is widely used in Si-based electronics because the unique advantages including compatibility with standard complementary metal-oxide semiconductor (CMOS) processing, excellent carrier mobility, relative abundance, and low toxicity [1]. Recently, Ge has attracted increasing research interests for the fabrication of cost-effective and efficient functional electronic-photonic integrated circuits (EPICs) [1, 2]. The direct bandgap of Ge is 0.8 eV at room temperature, which corresponds to an absorption edge at 1,550 nm. Strong optical absorption between 1,300 nm and 1,500 nm makes Ge an ideal photodetector (PD) material for fiber-optic telecommunication devices [3]. However, it is challenging to directly integrate Ge on Si substrates due to the 4.2% lattice mismatch between Si and Ge. Intensive efforts have been made to directly grow Ge layers on Si substrates using different approaches including two-step growth [4, 5] and graded SiGe buffers [6] for the fabrication of high-performance Ge normal-incident PDs [3, 7] and waveguide (WG) PDs (WGPDs) [8, 9]. However, the Ge active layers and Ge/Si interfaces are relatively defective, which degrades device performance. In addition, the

direct absorption edge at 1,550 nm makes the optical response of Ge PDs negligible in the C-band (1,530–1,560 nm) and L-band (1,560–1,625 nm), which are the most important bands for fiber-optic telecommunications, thereby hindering their applications in telecommunications. Furthermore, the relatively small difference between the refractive indices (RIs) of Si (~ 3.45) and Ge (~ 4.2) 10 limits optical confinement for light-matter interactions.

Ge-on-insulator (GOI) platforms are promising for the development of CMOS-compatible EPICs. As defective regions are absent, the material quality of the top Ge layers in GOI structures are superior to those of Ge layers in Ge-on-Si structures [11]. In addition, the insulator layer provides stronger optical confinement for the Ge active layer than Si due to its small refractive index (~ 1.45) [12]. Based on this development, normal incidence Ge PDs on GOI platforms have been recently demonstrated with enhanced device performance [12–15]. However, to meet the requirements of EPICs, planar WGPDs are highly desired for cooperating with various photonic devices. In addition, the photo-absorption path in WGPDs can be much longer than that in normal incident PDs, allowing for high-responsivity photodetection. Although there are a few successful demonstrations of planar GOI WGPDs [16, 17], the optoelectronic properties are not yet fully understood. Thus a deeper understanding of the optoelectronic properties is crucial in designing and fabricating high-performance GOI WGPDs for enabling high-performance and functional GOI-based EPICs.

In this study, we demonstrate planar Ge WGPDs on GOI platforms as key enablers for GOI-based EPICs. The optoelectronic properties of the planar Ge WGPDs were systematically characterized and analyzed. Device characterization results show low absolute dark currents, an extended photodetection range, and excellent responsivity, making them suitable for communication applications

The GOI platform used in this study was prepared using wafer bonding and layer transfer techniques, and the defective Ge regions were removed via chemical-mechanical polishing (CMP) techniques [15]. A cross-sectional transmission electron microscope (XTEM) image of the GOI platform is shown in the

inset of Fig. 1. It consists of a 960 nm thick Ge layer, and an insulator consisting of a 312 nm thick SiO₂ layer, a 50 nm thick SiN layer, and a 215 nm thick SiO₂ layer on a silicon substrate. The average threading dislocation density (TDD) was estimated to be $2.5 \times 10^7 \text{ cm}^{-2}$ based on etch-pits experiments; this value is comparable to, or even better than, typical TDD values in the range of 10^7 - 10^8 cm^{-2} in high-quality Ge-on-Si structures with proper thermal annealing treatments [11]. Fig. 1 shows the (004) 2θ - ω scans of the GOI sample and a bulk Ge reference. The x-ray diffraction pattern of the GOI sample is clearly shifted relative to that of bulk Ge, evident for the existence of tensile strain in the Ge layer. Following the procedures described in Ref. [18], the residual in-plane tensile strain in the Ge layer was found to be 0.144%. This 0.144% tensile strain is caused by the mismatch of thermal expansion coefficient between Si and Ge during the epitaxial growth of Ge-on-Si structures [9, 11], and it can narrow the direct bandgap to extend the photodetection range (discussed later).

Fig. 1. (004) 2θ - ω scans of the GOI platform and a bulk Ge reference sample. Inset: a XTEM image of the GOI platform.

A schematic diagram of our designed Ge WGPd on the GOI platform is shown in Fig. 2(a). The device contains a Ge ridge waveguide structure and a lateral *p-i-n* homojunction to collect photocurrents. The devices were fabricated using a CMOS-compatible processing method. Strip mesas with a height (h) of 470 nm and variable ridge widths (w) were defined using standard optical lithography and reactive ion etching (RIE) techniques. *p*-Ge and *n*-Ge regions were created by implanting boron and phosphorous ions, respectively, at 20 keV and doses of 10^{15} cm^{-2} . The samples were then annealed in a microwave annealing system at a power of 1650 W for 100 s to activate the dopants. A 200 nm thick SiO₂ passivation layer was then deposited on each sample via plasma-enhanced chemical vapor deposition (PECVD). Trenches were subsequently introduced using a RIE technique to expose the *n*- and *p*-Ge regions. Metal pads with a Cr/Au multilayer (20/200 nm) were then deposited using an electron beam evaporator. The pads were patterned using a lift-off technique. The samples were cleaved into several devices with a length (L) of 2.1 mm. A scanning electron microscope (SEM) image of the device is shown in Fig. 2(b).

To evaluate optical confinement, the guiding modes of the WG structures with different ridge widths were analyzed by performing finite element method (FEM) simulations, and multiple guiding modes were found. Figure 2(c) shows the calculated optical confinement factor (OCF) of the quasi-TE fundamental (TE₀₀) mode at $\lambda=1,550 \text{ nm}$ for the Ge active region as a function of the ridge width; and the insets show the simulated energy

distribution for the device with different ridge widths. The deposited SiO₂ and insulator layers provide excellent optical confinement for the Ge active region due to the large differences between their respective RIs. The OCF increases with increasing ridge width, and a high OCF of >95% can be achieved for $w>1 \mu\text{m}$, which is much higher than those of active regions in Ge vertical *p-i-n* WGPds on silicon substrates ($\sim 40\%$) [19]. This analysis indicates that the Ge active layer is highly responsive, and that it could efficiently absorb photons to generate a photocurrent.

Fig. 2. (a) Schematic diagram of our designed Ge WGPd. (b) SEM image of a fabricated Ge WGPd with $w=5 \mu\text{m}$. (c) Calculated optical confinement factor for the quasi-TE fundamental mode of the Ge active region as a function of the waveguide width at $\lambda=1,550 \text{ nm}$. The inset shows the simulated energy distribution for the quasi-TE fundamental mode with different ridge widths.

The current-voltage (I - V) curves of a Ge WGPd with $w=5 \mu\text{m}$ recorded at room temperature in darkness and under illumination by a 1,498 nm laser are shown in Fig. 3(a). The dark current voltage (I_{dark} - V) characteristics exhibit clear rectifying behavior with an excellent on-off ratio of 85.4 at $\pm 1 \text{ V}$. Despite its length, the I_{dark} of the device at -1 V is only 1.20 μA . This value approaches the leakage current requirement for high-speed optical receivers ($<1 \mu\text{A}$) [9]. As the reverse bias voltage increases, I_{dark} increases slightly. The reverse bias current is considerably higher under illumination, which confirms photodetection capability. The I_{dark} - V curves of Ge WGPds with different ridge widths are shown in Fig. 3(b); I_{dark} at -1 V as a function of width (w) is plotted in Fig. 3(c). As w increases, I_{dark} increases. To better understand the origin of the dark current, the surface leakage density (J_{surf}) and bulk leakage density (J_{bulk}) of each Ge WGPd are extracted using [20]

$$I_{\text{dark}} = 2(L + w)J_{\text{surf}} + J_{\text{bulk}}wL. \quad (1)$$

Fitting the experimental data yields a J_{bulk} value of 9.11 mA/cm^2 and a J_{surf} value of 1.70 $\mu\text{A/cm}$. The J_{bulk} value is considerably smaller than the value of 59.49 mA/cm^2 for a Ge PD with a TDD of $\sim 10^8 \text{ cm}^{-2}$ [21]. This observation confirms the suppressed Shockley-Read-Hall (SRH) process in the Ge active layer, indicating the good quality of the Ge active layer. The J_{surf} value is also smaller than the typical values reported for Ge-on-Si PDs (5–60 $\mu\text{A/cm}$) [22], indicating reduced interfacial trapping sites by appropriate surface passivation. The contributions of the bulk leakage and surface leakage currents to I_{dark} at -1 V are 59.7% and 40.3%, respectively. To further understand the origin of the dark current, temperature-dependent I_{dark} - V characteristics of a Ge WGPd $w=5$

μm were recorded in the range from 300 K to 340 K, and the results are shown in Fig. 3(d). The results show that I_{dark} in reverse bias increases with increasing temperature. The activation energy (E_a) of the device was then obtained using [18, 23]

$$I_{\text{dark}} = BT^{3/2} \exp\left(\frac{-E_a}{kT}\right) \times \left[\exp\left(\frac{qV}{2kT}\right) - 1 \right], \quad (2)$$

where B is a constant, and k is the Boltzmann constant. An Arrhenius plot of the device at -1 V is shown in Fig. 3(e). Fitting the experimental data using Eq. (2) yields an E_a of 0.397 eV. The E_a value is approximately half the direct bandgap energy of the Ge active layer (discussed later), which suggests that the SRH process is predominantly responsible for the dark leakage current. These results are consistent with those of the bulk and surface leakage current analyses.

Fig. 3. (a) I - V curves of a Ge WGPd with $w=5 \mu\text{m}$ in darkness and under illumination by a 1,498 nm laser with a power of 5 mW. (b) I_{dark} - V curves of Ge WGPds with different widths. (c) I_{dark} as a function of device width. (d) Temperature-dependent I_{dark} - V curves of a Ge WGPd with $w=5 \mu\text{m}$. (e) Arrhenius plot of the Ge WGPd at -1 V.

For optical characterization, light was directed onto one facet of the Ge WGPd using a fiber focuser [19]. The optical responsivity (R_λ) spectra of the Ge WGPd ($w=5 \mu\text{m}$) recorded at different reverse bias voltages are shown in Fig. 4. At zero bias, the responsivity remains nearly constant up to 1,540 nm. Subsequently, the responsivity decreases with increasing wavelength and becomes negligible at $\sim 1,620$ nm, corresponding to the direct-gap absorption edge, from which the direct bandgap of the Ge layer is estimated to be 0.765 eV. The direct bandgap is narrower than that of bulk Ge (0.8 eV), because the 0.144% tensile strain reduces the bandgap. The responsivity is weak beyond 1,620 nm, because optical absorption is dominated by inefficient indirect-gap absorption. As the reverse bias increases, the responsivity increases considerably, then tends to saturation. This observation is attributed to strengthening of the electric field at the junction, which enhances carrier collection efficiency. The photodetection cutoff wavelength undergoes a redshift as the reverse bias increases, which is likely due to the Franz-Keldysh effect. These results suggest that the photodetection range of the Ge WGPds encompasses the O-, E-, S-, C-, and L-bands. The optical responsivity at 1,550 nm is 0.61 A/W at -7 V, which corresponds

to an external quantum efficiency (EQE) of 48%. Note that there is a significant reflection loss (38.3%) on the Ge WGPd facet at 1,550 nm obtained by FEM simulations. This reflection loss could be significantly reduced by applying an anti-reflective coating or an evanescent wave coupling technique [7]. Thus, the EQE could thus potentially exceed 80% to enable sensitive photodetection. In addition, it is anticipated that that tensile strain in the Ge active layer could be further increased by different methods such as application of stressors [24], and strain concentration of nanostructures [25] to reduce the bandgap for further extending the photodetection range of the Ge WGPds. Furthermore, alloying Ge with Sn can also significantly reduce the bandgap to extended the photodetection range [5, 18].

Fig. 4. Measured room-temperature optical responsivity spectra of the Ge WGPd with different reverse bias voltages.

Another unique advantage of WGPds is the decoupled carrier-collection path and photon-absorption path that allows for simultaneous high-speed and high-responsivity operation, thus particularly suitable for communication applications. Next, we theoretically analyze the responsivity and 3-dB bandwidth of the device as a function of the device width and length. The theoretical 3-dB bandwidth ($f_{3\text{dB}}$) of PDs is determined by the carrier transit time limited bandwidth (f_{trans}) and RC time delay limited bandwidth (f_{RC}), given by [7]

$$f_{3\text{dB}} = \left(f_{\text{trans}}^{-2} + f_{\text{RC}}^{-2} \right)^{-1/2}. \quad (3)$$

The transit time limited bandwidth can be estimated by $f_{\text{trans}} = 0.44 v_{\text{sat}} / w$, where $v_{\text{sat}} = 6.0 \times 10^6$ cm/s is the saturation drift velocity in Ge [7]. The RC limited bandwidth is given by $f_{\text{RC}} = (2\pi RC)^{-1}$ [7], where R is the load resistance and its value is set to 50Ω which is the most commonly used microwave transmission line; and C is the capacitance of the device which is calculated using FEM simulations. On the other hand, the responsivity of the Ge WGPd can be calculated by [26]

$$R_\lambda = \frac{q\lambda}{hc} \eta \Gamma (1 - R) [1 - \exp(-\Gamma \alpha L)] \quad (4)$$

where η is the internal quantum efficiency and its value is set to 1 in the calculation, h is the Planck constant, c is the speed of light in free space, R is the reflectance at the input port of the WGPd which is calculated using FEM simulations, α is absorption coefficient of the Ge active layer which is calculated using the theoretical models

in Refs. [12, 27, 28]. Figure 5(a) depicts the calculated f_{trans} , f_{RC} , and $f_{3\text{dB}}$ for the Ge WGPd with $L=20\text{ }\mu\text{m}$ as a function of the ridge width. The results show that, as w increases, f_{RC} increases due to the reduced capacitance, while f_{trans} decreases due to the increased depletion region width. As a result, $f_{3\text{dB}}$ is dominated by f_{trans} for $w>0.16\text{ }\mu\text{m}$. Figure 5(b) shows the calculated 3-dB bandwidth for the Ge WGPd as a function of WG width and length. The $f_{3\text{dB}}$ value significantly increases with decreasing WG width, but is less dependent on the device length because f_{trans} dominates the 3-dB bandwidth. These observations are consistent with the experimental results in lateral Si/Ge/Si WGPds [29]. With $w<2.5\text{ }\mu\text{m}$, a 3-dB bandwidth of $>10\text{ GHz}$ is achievable. Figure 5(c) shows the calculated absorption spectra for 0.144% tensile-strained Ge and bulk Ge at $T=300\text{ K}$. With the introduction of 0.144% tensile strain, the direct bandgap is reduced from 0.8 eV to 0.773 eV, thereby significantly enhancing the absorption coefficient at $\lambda=1,550\text{ nm}$ to 2859 cm^{-1} . Figure 5(d) shows the calculated responsivity at $\lambda=1,550\text{ nm}$ for the Ge WGPd as a function of WG width and length. As w increases, the responsivity slightly increases because of the increased OCF for the Ge active layer (Fig. 2c). As L increases, the responsivity increases rapidly due to a longer photon-absorption path, and then tends to saturate. Thus a device length of $L=11\text{ }\mu\text{m}$ is sufficient to achieve 95% of the maximum responsivity. These analyses indicate that, with $L=11\text{ }\mu\text{m}$ and $w=1\text{ }\mu\text{m}$, a high 3-dB bandwidth of 26 GHz and a high responsivity of 0.71 A/W at $\lambda=1,550\text{ nm}$ can be simultaneously achieved in the Ge WGPds. Given the low absolute dark current, high responsivity, extended photodetection, planar structures, and CMOS-compatibility, we conclude that the Ge WGPds hold promises for efficient optical receivers on GOI-based EPICs for telecommunication applications.

Fig. 5. (a) Calculated bandwidths of the Ge WGPd with $L=20\text{ }\mu\text{m}$ as a function of waveguide width. (b) Calculated 3-dB bandwidth of the Ge WGPd as a function of waveguide width and length. (c) Calculated absorption spectra for bulk Ge and 0.144% tensile-strained Ge at $T=300\text{ K}$. (d) Calculated responsivity at $\lambda=1,550\text{ nm}$ of the Ge WGPd as a function of waveguide width and length.

In conclusion, new planar Ge waveguide photodetectors on a GOI platform have been fabricated and characterized. The high quality of the Ge active layer reduces the generation of dark current. The insulator layer provides excellent optical confinement for the Ge active layers, thereby enhancing optical responsivity. The 0.144% tensile strain extends the photodetection range to completely encompass the C- and L-bands, which are the most important bands for telecommunications. These results demonstrate new planar Ge waveguide photodetectors that can be monolithically

integrated on a GOI platform for communication applications.

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