GeSn Waveguide Photodetectors with Vertical $p$–$i$–$n$ Heterostructure for Integrated Photonics in the 2 μm Wavelength Band

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The 2 μm wavelength band (1800–2100 nm) emerges as a promising candidate for next-generation optical communication. As a result, silicon photonic platforms acquire great interest since they offer the ultimate minimization of photonic systems for 2 μm band applications. However, the large bandgap and indirectness of the band structure of the conventional SiGe alloy prevent their utilization for efficient photodetection in the 2 μm wavelength band. To overcome this drawback, complementary metal-oxide semiconductor (CMOS)-compatible GeSn waveguide photodetectors (WGPDs) with a vertical $p$–$i$–$n$ heterojunction configuration that can operate in the 2 μm wavelength band is demonstrated. The proposed photodetector incorporates 5.28% Sn into the GeSn active layer, which redshifts the photodetection range to 2090 nm. In addition, the longer light–matter interaction length and good optical confinement of the proposed GeSn WGPD enhance the optical responses significantly. As a result, the proposed GeSn WGPD achieves a responsivity up to 0.52 A W$^{-1}$ and a detectivity up to $7.9 \times 10^{15}$ cm Hz$^{1/2}$ W$^{-1}$ in the 2 μm wavelength band at room temperature. These promising results indicate that the developed GeSn WGPDs are promising candidates for integrated photonics in the 2 μm wavelength band.

1. Introduction

Fiber-optic telecommunication systems have been progressively advancing to fulfill the capacity demand for tremendously increasing data transmission volume in a wide range of applications such as cloud computing, IoV, IoT, big data, and 5 G.[1–3] However, the data-hungry future is driving new radical solutions to fulfill the requisite demands of high spectral efficiencies and high bandwidth. Since the current standard single-mode fiber (SMF) bandwidth capacity is approaching the theoretical capacity limit at the 1310 and 1550 nm wavelength bands,[4] they cannot help achieve the additional gain in the bandwidth capacity. Therefore, to subsequently increase the wave of internet modernization, novel technologies are required to further boost the bandwidth capacity.

To address the issue of limiting bandwidth capacity, low-loss hollow-core photonic bandgap fibers operating in the 2 μm wavelength band (typically defined in the spectral range of 1800–2100 nm) are aimed to reduce latency while increasing power and reducing nonlinearities in the persuasive technology as they offer a high propagation speed of ≈98% of the speed of light in vacuum, low thermal sensitivity in the aforementioned range, and a minimum loss of ≈0.1 dB km$^{-1}$,[4–6] which is even lower than the lowest loss of 0.1484 dB km$^{-1}$ in conventional SMF fibers. This minimal loss and elongated nonlinear threshold value enhanced the capacity by three to four times when compared with the SMF capacity limit. Therefore, the aforementioned merits paved the way toward next-generation development of optical communication systems based on the 2 μm technology. In addition, optical components based on III–V semiconductors working in the 2 μm wavelength band are becoming more commercially available owing to their benefits in other sectors, including sensing and biomedical applications. More recently, research attention has been directed toward utilizing complementary metal-oxide semiconductor (CMOS) mature technology to realize cost-effective, compact, and functional electronic–photonic-integrated circuits (EPICs) for 2 μm optical communication systems on silicon photonics platforms to address the current internet bottleneck of bandwidth capacity.[4–7]

However, to realize the 2 μm based optical communication technology, various passive and active photonic devices are necessary. In addition to Si-based light emitters[8,9] and optical modulators[10,11] that can operate at the 2 μm band, efficient CMOS-compatible photodetectors (PDs) are crucial for
optical–electronic data conversion. Owing to the limitation of relatively large bandgaps and the indirect band structures of Si and Ge, it is challenging to realize efficient group-IV PDs that can operate in the 2 μm wavelength band. To address this issue, group-IV binary GeSn alloys have gained remarkable attention in silicon photonics research due to their unique compatibility with standard CMOS processes and higher carrier mobilities than Ge, Si, and their alloys.\cite{1,2} In addition, theoretical analysis and recent experiments have revealed that the direct bandgap of GeSn can be modulated by incorporating the Sn content to extend the photodetection range and enhance its quantum efficiency by enhancing the absorption coefficient in the 2 μm band.\cite{15,16} This advancement has opened up a new avenue for developing different types of high-performance GeSn normal-incidence PDs that cover a broad photodetection range in the mid-infrared range\cite{18,19,20,21} and even up to λ = 4600 nm.\cite{22} However, the responsivity of the developed GeSn normal-incidence PDs in the 2 μm wavelength band is not yet satisfactory, thereby limiting the signal-to-noise ratio for practical applications. Meanwhile, planar GeSn waveguide PDs (WGPDs) are necessary for constructing EPICs. Although a few attempts have been made to fabricate GeSn WGPDs on Si,\cite{23,24,25} presently the performance remains unsatisfactory at the 2 μm wavelength band. For example, lateral GeSn p–i–n WGPDs with a Sn content of 4.3% have shown a good responsivity of 0.292 A/W at λ = 1800 nm, but the photodetection range only reaches 1950 nm.\cite{26} GeSn/Ge multiple-quantum-well p–i–n WGPDs can operate at λ = 2000 nm, but its responsivity and detectivity are only 0.119 A W–1 and 1.1 × 107 cm Hz1/2 W–1, respectively.\cite{27} Therefore, it is crucial to improve the performance of GeSn WGPDs for practical applications at the 2 μm wavelength band.

Silicon on insulator (SOI) is an ideal platform for developing 2 μm optical communication systems.\cite{6} In SOI, the top Si layer can be fabricated into stripe or ridge Si waveguides clad by the buried oxide (BOX) layer due to the large difference in refractive index between Si (n ≈ 3.45) and SiO2 (n ≈ 1.45). The Si waveguide can serve as the communication channels between various photonic devices, and be further co-integrated with electronics to form EPICs. In addition, SOI waveguide are transparent up to λ = 2500 nm, making it ideal for 2 μm optical communication systems. SOI waveguides with a low loss of ∼0.89 dB cm–1 at λ = 2000 nm have been demonstrated.\cite{8} In addition, SOI technology is readily available in Si CMOS foundries. Thus, it is attractive to develop photonic devices on SOI platform for 2 μm optical communication systems.

In this study, we demonstrated GeSn WGPDs based on a vertical p–i–n heterostructure configuration on SOI platform that can operate in the 2 μm wavelength band. By further increasing the Sn content in the GeSn active region to lower the direct bandgap effectively, the photodetection range of the GeSn WGPD is extended 2090 nm, nearly covering the entire 2 μm wavelength band. The waveguide structure significantly increases the photon-absorbing length to enhance the responsivity, and allows for cooperating with other photonic devices to construct EPICs. Furthermore, the proposed device exhibited an enhanced responsivity of 0.52 A W–1 at λ = 1800 nm, which is 185% higher than that of the previously reported GeSn WGPDs at room temperature.\cite{28} In addition, the spectral detectivity of our GeSn WGPDs was one order of magnitude larger than the previously reported GeSn WGPDs\cite{28} and was comparable with, or even better than, the commercially available infrared PDs at room temperature, thereby confirming the feasibility of the device in the 2 μm wavelength band. These results confirm the suitability of the CMOS-compatible GeSn WGPDs for the 2 μm wavelength band EPIC applications.

2. Results and Discussion

Figure 1a illustrates the layer structure of the sample grown on an SOI substrate using the low-temperature molecular-beam epitaxy (MBE) growth technique (described in Experimental Section). The heterostructure consisted of 1) a 120 nm thick strain-relaxed Ge virtual substrate (VS), 2) a 410 nm thick B-doped p-type Ge layer, 3) a 320 nm thick intrinsic GeSn layer, 4) a 110 nm thick Sb-doped n-type Ge layer, and 5) a 3 nm thick Si cap layer. The structural properties of the grown samples were evaluated using secondary-ion mass spectroscopy (SIMS), X-ray diffraction (XRD), and ultraviolet (UV) Raman microscopy. Figure 1b displays the SIMS atomic distribution of the Ge, Sn, B, and Sb atoms along the growth direction for the grown samples. The SIMS depth profile results revealed sharp interfaces between the intrinsic GeSn layer and the Ge layers. The incorporation of B and Sb atoms in the respective p- and n-Ge layers was visible as well. For the GeSn active layer, a uniform Sn distribution was observed. The average Sn composition in the GeSn active layer by calibrated SIMS is determined to be 5.12% and 5.28% respectively.\cite{29,30,31} Therefore, it is crucial to improve the performance of GeSn WGPDs for practical applications at the 2 μm wavelength band.
Experimental Section). The fabricated sample was then cleaved into the devices; the device investigated in this study had a length of \( L = 3 \) mm. A schematic plot of the fabricated device is illustrated in Figure 2a, and a scanning electron microscope (SEM) image of the fabricated device is displayed in Figure 2b, showing smooth facet of the GeSn WGPD. To obtain the optical confinement factor (OCF) of the GeSn active region and field distribution of the GeSn WGPDs, mode analysis was performed on the fabricated device using the finite element method (FEM) modeling wherein the wavelength-dependent refractive index and absorption coefficient of the materials were taken from refs. [34] and [35]. The simulated energy distribution of the quasi-transverse-electric fundamental mode obtained at \( \lambda = 2000 \) nm is displayed in Figure 2c. The obtained energy distribution results indicate that the deposited SiO\(_2\) layer and the Si layer offered good optical confinement for the Ge/GeSn heterostructure due to the large contrast in refractive indices between the Ge \((n = 4.11)\) and Si substrate \((n = 3.45)\), and the SiO\(_2\) \((n = 1.45)\) layers. This analysis revealed excellent OCF of \( \Gamma \approx 38\% \) for the GeSn active layer through the vertical \( p-i-n \) WGPD design, enabling the proposed GeSn WGPDs to be highly responsive for 2 \( \mu \)m band photodetection.

Figure 3a displays the measured room-temperature dark current–voltage \( (I_{\text{dark}}-V) \) characteristics of the vertical GeSn \( p-i-n \) WGPD. In a dark environment, the dark current \( (I_{\text{dark}}) \) featured different trends in the forward and reverse-bias regions, thereby exhibiting a clear rectifying behavior of the diode. The \( I_{\text{dark}}-V \) curve was modeled using the Shockley equation.[36]

\[
I_{\text{dark}} = I_0 \times \exp \left[ \frac{q(V - R_{\text{sh}} I_{\text{net}})}{\eta kT} \right] + \frac{V}{R_{\text{sh}}}
\]  

(1)

where \( k \) is the Boltzmann constant, \( \eta \) is the diode ideality factor, \( I_0 \) is the reverse-saturation current of the diode, \( T \) is the temperature, and \( R_{\text{sh}} \) and \( R_s \) are the shunt and series resistances of the device, respectively, and \( I_{\text{net}} = I_{\text{dark}} - V/R_{\text{sh}} \) represents the net current flowing through the diode. The shunt resistance obtained near zero-bias voltage yielding \( R_{\text{sh}} = 0.16 \) k\( \Omega \) for GeSn WGPD was comparable to \( 0.08 - 0.85 \) k\( \Omega \) value of the GeSn vertical \( p-i-n \) WGPDs having the Sn content of 7–10\%. [36] Ideally, reducing thermal noise current requires an infinite \( R_{\text{sh}} \). Therefore, the obtained value of the shunt resistance indicated the existence of a leakage current in the device. With the extracted \( R_{\text{sh}} \), we can determine \( R_s \) and \( \eta \) using Equation (1). An ideality factor of \( \eta = 1.509 \) for the proposed GeSn WGPD was obtained, which is within the typical range of 1–2 for diodes. In contrast, we obtained a series resistance of \( R_s = 75.3 \) \( \Omega \), which was comparable to the value of \( \approx 50 \) \( \Omega \) for the GeSn normal-incidence \( p-i-n \) PDs,[36] thereby exhibiting good ohmic contact and low resistance between the semiconductor and metal interface for the proposed GeSn WGPD devices. In addition, obtaining a high operational device speed requires a low series resistance due to the reduced resistance capacitance (RC) delay.[37] The dark

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**Figure 1.** Material characterization. a) Sample layer structure (not to scale). b) Secondary-ion mass spectroscopy (SIMS) atomic distribution of B, Ge, Sn, and Sb. c) X-ray diffraction (XRD) \( \omega-2\theta \) scan for the grown GeSn/Ge heterostructure sample. The vertical dashed line represents the position of bulk Ge. d) Raman spectra of the grown sample and bulk Ge. The solid lines fit to the experimental data and the vertical dashed lines represent the fitted peak positions.

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**Figure 2a** shows the sample layer structure of the fabricated GeSn WGPD, whereas **Figure 2b** displays a scanning electron microscope (SEM) image of the fabricated device. **Figure 2c** presents the obtained energy distribution of the GeSn WGPD. **Figure 2d** illustrates the Raman spectra of the grown sample and bulk Ge.
Figure 2. a) Schematic diagram, b) scanning electron microscopy (SEM) image, and c) simulated energy distribution for the quasi-transverse electric fundamental mode of the proposed vertical p–i–n GeSn waveguide photodetectors (WGPD) at $\lambda = 2000$ nm.

Figure 3. Electrical characterization of the fabricated GeSn WGPDs. a) $I_{\text{dark}}$–$V$ curve measured at room temperature. b) Time response with illumination using a 1900 nm broadband light source with various optical powers. c) Temperature-dependent $I_{\text{dark}}$–$V$ curves of the fabricated device. d) Plot of $\ln(I_{\text{dark}}T^{-3/2})$ versus $k^{-1}T^{-1}$ at $-1$ V bias for extracting the activation energy.
current density ($I_{\text{dark}}$) at $-1$ V was 27.23 A cm$^{-2}$, which is relatively high compared to the typical value of 0.1–30 A cm$^{-2}$ of normal-incidence GeSn PDs with similar Sn contents$^{[25,37]}$. The relatively high dark current density is attributed to the long device length that leads to higher peripheral leakage current$^{[38,39]}$. As $I_{\text{dark}}$ is proportional to the device length $L$,$^{[39]}$ shortening the device length could significantly suppress the dark current density. As per our observations, as the applied reverse-bias voltage increased, $I_{\text{dark}}$ increases monotonously. This observation may be attributed to the Shockley–Read–Hall and/or trap-assisted tunneling (TAT) processes, which are more significant for higher reverse-bias voltages.$^{[39]}$

Figure 3b displays the time response of the GeSn WGPD with illumination under a 1900 nm broadband light source (ASE 1900, Thorlabs) with various optical powers modulated by an optical chopper at 200 Hz and then coupled to one facet of the device. The results provided vital evidence for photocurrents and confirmed the photodetection capacity of the proposed device in the 2 μm wavelength band. As the optical power increased, the photocurrent increased correspondingly. To better understand the leakage current mechanism, the temperature-dependent $I_{\text{dark}}$–$V$ characteristics of the device were measured in the temperature range of 280–340 K, and the results are presented in Figure 3c. According to the figure, as the temperature increased, $I_{\text{dark}}$ increased monotonically. Therefore, the activation energy ($E_a$) of the device could be extracted from the temperature-dependent $I_{\text{dark}}$–$V$ characteristics using$^{[40]}

$$I_{\text{dark}} = B T^{3/2} \exp \left( -\frac{E_a}{kT} \right) \times \exp \left( \frac{qV}{2kT} \right) - 1$$

where $B$ is a constant. Figure 3d displays the Arrhenius plot of the device at $-1$ V. The Arrhenius plot fitting using Equation (2) yielded $E_a = 15$ meV, which was much lower than the half value of the direct bandgap of the GeSn active region (discussed later). The activation energy analysis revealed that $I_{\text{dark}}$ may be anticipated by the presence of shallow traps caused by sidewall and surface defects$^{[41]}$ rather than by band-to-band tunneling through the deep-level defect states within the direct bandgap of the GeSn layer. Therefore, proper passivation of the device could further lower $I_{\text{dark}}$.$^{[42]}

Figure 4a demonstrates the room-temperature optical responsivity characteristics of the GeSn WGPD devices measured at zero-bias voltage. With the increase of wavelength, the optical responsivity increased with increasing wavelength. This observation is attributed to the fact that the photon energy per photon becomes smaller with increasing wavelength, so a watt of light energy contains a larger number of photons. As a photon

![Image](https://www.advancedsciencenews.com/figure4.png)

**Figure 4.** Optical characteristics. a) Responsivity spectrum measured at room temperature for the proposed GeSn WGPD. b) Schematic band structure of the GeSn active layer. c) Calculated absorption spectra for the GeSn active layer, top n-Ge layer, and bulk Ge. d) Comparing the responsivity of the proposed GeSn WGPD with previously reported GeSn photodetectors (PDs) in the 2 μm wavelength band.
absorbed by the active layer can ideally generate an electron–hole pair to form photocurrents, the responsivity increases linearly with increasing wavelength. The responsivity then reached a peak value of 0.33 A W⁻¹ at λ = 1770 nm. The high responsivity of the device was due to the ability of the long interaction length of the WGPD and the proper OCF of the GeSn active layer to absorb more photons that were then converted into photocurrents. As the wavelength increased further, the responsivity decreased, finally becoming small at λ = 2090 nm, corresponding to cutoff wavelength of the photodetection range and the direct bandgap of E_D = 0.593 eV for the GeSn active layer. Therefore, based on the optical characteristic responsivity curve, the photodetection range of the proposed device covered the entire telecommunication bands (1265–1675 nm) as well as the near entire 2 μm wavelength band, proving its usefulness for conventional telecommunication networks and the emerging 2 μm wavelength band communications. To further confirm the direct bandgap, the band structure was calculated using a multiband k·p method considering the strain effect. A schematic of the band diagram is displayed in Figure 4b. The introduction of Sn into the active layer lowered the bandgap, whereas the presence of the compressive strain lifted the heavy-hole (HH) band above the light-hole (LH) band. As a result, HH→cΓ transition was the lowest direct-gap transition that defined the direct-gap absorption edge. The calculated HH→cΓ transition energy was 629 meV, which was in reasonable agreement with the experimental results. Figure 4c displays the calculated direct-gap absorption spectra for the GeSn active layer and bulk Ge. Since introducing Sn into the active layer lowered the bandgap, it increased the absorption coefficient in the 2 μm wavelength band significantly. In contrast, the tensile strain in the top n-Ge layer also lowers the bandgap from 800 to 733.6 meV (LH→cΓ transition), thereby redshifting the direct-gap absorption edge from λ = 1550 to λ = 1690 nm. When photons are absorbed by the top n-Ge layer, the photo-generated holes within a diffusion length away from the depletion region will diffuse into the intrinsic region, swept by the build-in electric field, and then converted to photocurrents. Thus, the responsivity for λ < 1690 nm can be enhanced. For λ > 1690 nm, the top n-Ge layer is transparent, so it does not contribute to photocurrents. Figure 4d displays a comparison of the proposed GeSn WGPD responsivity with previously reported works with different Sn compositions in the 2 μm wavelength band, and the responsivity decreased with increasing wavelength. In contrast, the proposed GeSn WGPD exhibited outstanding responsivities of 0.520, 0.124, and 0.018 A W⁻¹ at λ = 1800, 2000, and 2100 nm, respectively; these values were higher than those of the reported GeSn PDs with similar Sn contents and active layer thicknesses. These results confirmed that the proposed GeSn WGPDs subsequently enhanced the optical responsivity and enable photodetection in the 2 μm spectral range. It is worth mentioning that there were no grating couplers and/or antireflection-coating layers at the facet of the GeSn WGPD, resulting in a significant reflection. From our FEM simulation, the calculated reflection loss was 36.9%. This reflection loss can be minimized to nearly zero by introducing grating couplers and/or antireflection coatings. As a result, the responsivity of the proposed GeSn WGPD can possibly achieve > 1 A W⁻¹ for efficient photodetection in the entire 2 μm wavelength band.

From the I–V and responsivity characteristics, we further extracted the spectral detectivity (D*) of the proposed vertical p−i−n GeSn WGPD (Supporting Information). Figure 5a depicts a comparison of D* at T = 300 K with the selected GeSn PDs reported in the literature. The value of D* for the proposed GeSn WGPD increased with increasing wavelength, and the highest D* in the 2 μm wavelength band was 7.9 × 10⁸ cm Hz¹/₂ W⁻¹ at λ = 1800 nm. The comparison revealed that the D* of the proposed GeSn WGPD was comparable and even better than some of the reported normal incidence GeSn PDs with higher Sn contents and/or thicker active layers due to the long photon-absorbing path that results in high-quantum efficiency. In addition, the D* value of our GeSn WGPD is also significantly higher than that of the GeSn/Ge multiple-quantum-well p−i−n WGPD by a factor of ≈17 because of the higher OCF. Figure 5b shows the D* of the

![Figure 5. Comparison of detectivity of the proposed GeSn WGPD with a) the reported GeSn PDs, and b) several commercially available detectors.](Image)
proposed GeSn WGPD at $T = 300$ K compared with various commercially available infrared PDs at $T = 300$ K. The $D^*$ value of the proposed GeSn WGPD was higher than that of the commercially available PbSe and InSb PDs having $D^* = 4.38 \times 10^5$ cm$^2$Hz$^{-1/2}$ W$^{-1}$ and $D^* = 8.73 \times 10^7$ cm$^2$Hz$^{-1/2}$ W$^{-1}$ at $\lambda = 1800$ nm, respectively. With increasing wavelength, $D^*$ decreased rapidly as the absorption coefficient was smaller at wavelengths close to the direct-gap absorption edge. However, it was still better than that of the PbSe and InSb PDs till $\lambda = 1895$ and $\lambda = 2050$ nm, respectively. When compared with InGaAs and Ge PDs, the proposed GeSn WGPD exhibited a wider spectral response with a much lower $D^*$ value. Therefore, $D^*$ and the responsive spectral range of the proposed GeSn WGPD were smaller than those of the extended InGaAs and PbS PDs. In addition, the CMOS compatibility of the proposed GeSn WGPDs made it ideal for Si- or SOI-based EPICs. Therefore, considering the good detectivity, wide photodetection range in the 2 μm wavelength band, CMOS compatibility, and planar waveguide structure suitable for integrated photonics, we summarized that the developed GeSn WGPDs are suitable for EPICs that can operate in the 2 μm wavelength band.

Having demonstrated the good responsivity and detectivity of the proposed GeSn WGPDs, the performance can be further improved by several approaches. First, the dark current can be further lowered by improving the material quality and/or passivation. Second, the responsivity can be significantly enhanced by increasing the OCF and/or Sn content of the GeSn active layer. In addition, it is also possible to significantly enhance the responsivity by integrating SOI waveguides with the GeSn WGPDs. In this way, efficient coupling between the SOI waveguides and GeSn WGPDs via end-fire or evanescent-wave coupling schemes could considerably reduce the reflection loss, thereby significantly enhancing the responsivity. Third, the responsive spectral range could be extended by increasing the Sn content to extend the photodetection range so that it covers the entire 2 μm wavelength band or beyond.

3. Conclusion

In summary, we successfully demonstrated a high-performance GeSn WGPD with a vertical $p$–$i$–$n$ heterostructure for EPICs that operate in the 2 μm wavelength band. Incorporating 5.28% Sn into the active region resulted in the shrinkage of the bandgap, thereby extending the photodetection range to 2090 nm. This covered the entire telecommunications band region and almost the entire 2 μm wavelength band. The waveguide structure enhanced the photon-absorbing length and proper optical confinement significantly as well, thereby enhancing the responsivity substantially. Therefore, we achieved a room-temperature detectivity of up to $1.5 \times 10^7$ cm$^2$Hz$^{-1/2}$ W$^{-1}$ in the 2 μm wavelength band, demonstrating superior performance when compared with the commercially available PbSe or InSb PDs in the 2 μm spectral range as well as the reported GeSn PDs. This study presents a practical pathway for high-performance GeSn WGPDs that can be integrated with EPICs to endow a wide range of applications in the 2 μm wavelength band.

4. Experimental Section

Material Growth: The sample used in this study was grown on an SOI substrate using solid-source MBE. The thickness of the top Si and BOX layer were 2.5 and 1 μm, respectively. To overcome the large lattice mismatch between the GeSn active layer and the SOI substrate, a strain-relaxed Ge VS was first grown using a two-step growth technique.[25] A $\pi$-type B-doped Ge layer was grown at 550°C. Thereafter, to suppress the Sn segregation, the growth temperature was reduced to 450°C to grow the intrinsic GeSn active layer, followed by an $n$-type Sb-doped Ge layer, and was finally capped by a 3 nm thick Si layer. The nominal doping concentration in the $n$- and $p$-Ge layers was $1 \times 10^{19}$ cm$^{-3}$.

UV Raman Experiments: The Raman scattering experiments were performed using a 325 nm He–Cd laser in backscattering configuration. The absorption coefficient in Ge at $\lambda = 325$ nm was $\alpha = 1149962$ cm$^{-1}$, corresponding a penetration depth of $8.7$ nm from $d = 1/\alpha$, which was much smaller than the thickness of the top $n$-Ge layer (110 nm). Thus, it was ensured that the Raman signal came from the top $n$-Ge layer only. The peaks in the Raman spectra were fitted using modified Gaussian function to determine the peak position.

Device Fabrication: The sample was fabricated into $p$–$i$–$n$ diodes using CMOS-compatable processes. A stripe mesa with a width of $W = 10$ μm was created using standard optical lithography and a CF$_4$-based dry etching with reactive ion etching (RIE). Subsequently, a 200 nm thick SiO$_2$ passivation layer was deposited using plasma-enhanced chemical vapor deposition (PECVD); it served as the electric isolator for the $n$- and $p$-Ge regions. Thereafter, contact windows were introduced using wet etching techniques with buffered oxide etch (BOE) solutions to uncover the surface of the $n$- and $p$-Ge regions. For electrical contact, metal pads were patterned using liftoff techniques along with the deposition of an Au/Cr (200/20 nm) bilayer using an electron-beam evaporator. Finally, the samples were cleaved into devices of different lengths.

Responsivity Measurement: For optical characterization, a Fourier transform infrared (FTIR) spectrometer was used along with a built-in near-infrared light source with an aperture size of 2 mm as the light source. The emitted light was reflected by a mirror to the focusing lens and then incident on the active region of the device via a 50x objective. This process ensured that the spot size of the incident light beam would be smaller than that of the device (≈10 μm). The resulting photocurrent was received by the capture card and transmitted to the FTIR software of the computer to convert it into an intensity spectrum. The optical power incident on the devices was measured using a commercially available extended-InGaAs PD (Thorlabs, DET101D2).

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.
Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

GeSn alloy, integrated photonics, photodetectors, waveguide, 2 µm wavelength band

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