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Numerical design and optoelectronic simulation of a germanium-on-silicon PIN photodetector for high-speed optical communication systems

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Abstract

Background: The rising demand for fast optical communication systems in the telecommunications industry, data centers, aerospace, and defense applications has made it imperative to design photodetectors with high responsivity, minimum dark current, and broad bandwidth. Germanium on Silicon (Ge-on-Si) PIN photodetectors are potential contenders in this regard due to their high optical absorption capability at the telecommunication wavelengths as well as CMOS silicon photonics compatibility. Optimizing their optoelectronic performance is an important issue, however.
Aims: In this research, we intend to numerically design, optimize, and evaluate a Ge-on-Si PIN photodetector via a coupled optoelectronic simulation technique for high optical absorption, high responsivity, low dark current, and high speed operation in advanced optical communication systems.
Method: The designed photodetector was modeled and simulated by using Lumerical FDTD Solutions and Lumerical DEVICE software. A combined simulation method of optical-electrical was utilized to simulate optical field distribution, optical absorption, carrier generation, photocurrent, dark current, and 3dB-bandwidth of the device. Structural parameters were carefully optimized to enhance the performance of the device for telecommunication operation.
Result: The optimized Ge-on-Si PIN photodetector resulted in the optical absorption of about 92% at 1550 nm wavelength, peak responsivity of 0.84 A/W, and the minimum value of the dark current was 0.9 μA at reverse bias voltage −1 V. The calculated 3-dB bandwidth was 45 GHz. The increase in dark current with temperature due to the generation of carriers from thermal energy was also observed through simulations.
Conclusion: The designed Ge-on-Si PIN detector offers a well-balanced structure, providing excellent responsivity, low dark current, and large bandwidth, which makes it a very promising device for silicon photonics and high-speed optical communication in the future. Besides, there is a great possibility to apply this detector for defense and aerospace applications such as optical communication for military and satellites and other systems requiring high-performance optical connections.

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INTRODUCTION

Background

With an accelerated rise in the amount of data being exchanged in the world through technologies such as cloud computing, artificial intelligence, video streaming at high-definition levels, and next-generation telecommunications networks, the demand for advanced optical communication systems that can transmit huge amounts of data with great speed has been rising dramatically. Optical fiber communication has become a key enabling technology because of its wide bandwidth, low attenuation, high reliability, and immunity to electromagnetic interference. These characteristics are particularly important for defense and security applications, including secure military communications, satellite communication, avionics networks, and battlefield information systems, where reliable and uninterrupted data transmission is essential. In such mission-critical environments, communication failures or signal degradation may compromise situational awareness and operational effectiveness. Consequently, photodetectors play a fundamental role by converting optical signals into electrical signals with high sensitivity, speed, and reliability, thereby directly influencing the performance of optical communication systems (Senior & Jamro, 2020; Keiser, 2021).

PIN (p-i-n) photodiodes are one type of photodetector that is gaining popularity due to its wide bandwidth, low noise, linear operation, and ability to be used in photonic integrated circuitry (Saleh & Teich, 2019). The use of intrinsic layer within the heavily doped p-layer and n-layer not only enhances the efficiency in generation and collection of carriers but also minimizes the junction capacitance, thus making the PIN photodiodes highly useful in optical communication systems with wavelengths of 1.3 μm and 1.55 μm. These wavelengths are also popular as transmission windows in fiber-optic communication systems.

In the past few decades, silicon photonics has been recognized as one of the leading technologies for realizing low-cost, compact, and integrated optical communications components. But unfortunately, silicon has poor optical absorption properties in the telecommunication band, thus restricting its use as photodetector material. In order to solve this problem, germanium has been widely explored due to its high optical absorption capability in the near infrared band, CMOS compatible fabrication process, and integration capability with silicon photonic circuits (Sze & Ng, 2007; Agrawal, 2021). Therefore, Ge-on-Si photodetectors have emerged as promising devices for optical interconnects, integrated photonic circuits, optical sensing, and high-speed optical receivers. Their compatibility with silicon photonics also makes them attractive for secure communication infrastructures used in defense, aerospace, satellite, and other mission-critical applications that require compact, energy-efficient, and high-performance photonic devices.

In spite of their positive attributes, there are many issues associated with Ge-on-Si photodetectors. The issue of lattice mismatch can lead to problems with the growth of threading dislocations in the material, thus reducing carrier lifetime and dark current in the devices. In addition, it should be noted that performance is dependent on several physical aspects such as intrinsic layer thickness, doping levels, and device architecture among other operational aspects. These are some of the physical attributes that influence detector performance through its responsivity, carrier transit times, and noise behaviour (Michel et al., 2010; Wang & Lee, 2011).

The numerical simulation technique is now a successful and economical process to evaluate and enhance the performance of photodetectors before their production. The sophisticated simulation techniques that include the FDTD and semiconductor devices simulators provide an in-depth understanding of the processes of light absorption, the field distribution, carrier transport, and electrical aspects. This type of technology is especially useful for fast devices for photonic systems used both in business and the military; it saves money on development (Campbell, 2008).

In this paper, a Germanium-on-Silicon PIN photodetector is numerically modelled and simulated using the simulation software packages of Lumerical FDTD and DEVICE. The optical and electrical properties of the developed detector are thoroughly studied from the perspective of electromagnetic field distribution, carriers generation and absorption, responsivity, bandwidth capabilities, and dark current performance at various operating conditions. Special focus is placed on achieving optimal design configuration that can ensure maximum optical absorption and carrier collection efficiencies while reducing dark current. This research provides valuable information for designing efficient Ge-on-Si photodetectors suitable for use in high-speed optical communications.

Photodetectors for Optical Communication Systems

The photodetector is an essential component in the optoelectronics communication process since it is responsible for transforming the incoming light into an electric signal. The efficiency of photodetectors is linked to various properties of the system, such as the system sensitivity, data transmission rate, signal-to-noise ratio, and communication reliability. Currently, modern telecommunications systems utilizing telecommunication wavelengths, i.e., 1310 nm and 1550 nm, need photodetectors that should have high responsivity, low dark current, large bandwidth, and good signal-to-noise ratio. Semiconductor photodetectors have become the best choice for many applications (Reed et al., 2010; Thomson et al., 2016).

The rapid expansion of cloud computing, artificial intelligence, data-center networks, and high-capacity optical interconnects has accelerated research into silicon photonics and integrated photodetectors. Silicon photonics has emerged as a leading platform for next-generation optical communication systems because it enables large-scale integration, reduced power consumption, and compatibility with mature CMOS fabrication technologies (Chen et al., 2022; Beckerwerth et al., 2024). Recent advances have demonstrated integrated photodetectors capable of supporting data rates beyond 100 Gbps, highlighting their importance for future communication infrastructures (Wang & Mu, 2022).

In addition to commercial telecommunication, the need for photodetectors in the realm of security communication, aviation, space communication, avionics, and robust communication control is increasing. This demand for photodetectors arises from the requirement of optical receivers possessing characteristics such as high bandwidth, low noise, and immunity to electromagnetic interference (Benedikovič et al., 2020).

PIN Photodetectors

PIN photodetectors consist of heavily doped p-type and n-type semiconductor layers separated by an intrinsic absorption region. When photons with energy greater than the semiconductor bandgap are absorbed within the intrinsic region, electron-hole pairs are generated and subsequently separated by the electric field under reverse bias conditions. The resulting photocurrent is proportional to the incident optical power.

The PIN photodiode has several advantages, which include low junction capacitance, good linearity, low noise, and large bandwidth range. These features are especially desirable for use in optical communications systems that utilize wavelengths of 1.3 μm and 1.55 μm. Their simple construction makes it possible to integrate them into silicon photonics devices (Benedikovič, 2023). Recent developments in PIN photodiode design have focused on improving carrier transport, reducing parasitic capacitance, and enhancing optical coupling efficiency through waveguide-integrated architectures. Such improvements have enabled substantial increases in bandwidth while maintaining low dark current and high responsivity (Ishikawa et al., 2009; Wang & Mu, 2022).

Avalanche Photodetectors (APDs)

Avalanche photodiodes utilize an intrinsic gain process due to the principle of impact ionization, where photogenerated carriers accelerate in an applied electric field causing further creation of electrons and holes. This leads to amplification of currents and improved performance of avalanche photodiodes compared to normal PIN diodes. However, APDs generally require higher operating voltages and exhibit increased multiplication noise, higher power consumption, and greater temperature sensitivity. As a result, PIN photodetectors remain attractive for applications requiring a balance among speed, noise performance, fabrication simplicity, and energy efficiency (He et al., 2026).

Germanium-on-Silicon Photodetectors

Silicon photonics has come to be regarded as a promising technique in the field of large-scale photonic integration. However, the major problem with silicon is that it is a very inefficient absorber of light in the wavelength range of telecommunication due to its indirect band gap, making it an inferior choice when it comes to absorbing photons. This is why germanium is considered a better alternative for photodetection, since it absorbs light efficiently in wavelengths ranging from 1310 to 1550 nm (Reed et al., 2010).

Germanium-on-Silicon (Ge-on-Si) photodetectors combine the advantages of germanium absorption with the mature fabrication infrastructure of silicon technology. Extensive research has demonstrated that Ge-on-Si photodetectors can achieve high responsivity, low dark current, and excellent bandwidth performance, making them suitable for optical interconnects, fiber-optic communication systems, and integrated photonic networks (Reed et al., 2010; Na et al., 2026). In the past ten years, significant advancements have been made with regards to enhancing the efficiency of Ge-on-Si photodetectors using waveguide-based structures, strain, optimal doping, and fabrication techniques. In some recent work, waveguide-based Ge-on-Si photodetectors with responsivity in the region of or higher than 1A/W and operating frequencies greater than 50 GHz have been demonstrated. (Niu & Poon, 2025; Na et al., 2026).

Despite these advantages, Ge-on-Si photodetectors face several material and fabrication challenges. The approximately 4.2% lattice mismatch between germanium and silicon can generate threading dislocations and crystal defects during epitaxial growth. These defects act as carrier recombination centers, increasing dark current and reducing carrier collection efficiency. In addition, thermal expansion coefficient differences between germanium and silicon can introduce mechanical stress that further affects device reliability and performance (Reed et al., 2010).

In order to overcome some of these drawbacks, several methods have been suggested such as surface passivation, graded buffer layers, optimized waveguide coupling structure, hetero structure modification, etc. The improvement obtained through these processes is remarkable because dark current levels have decreased while responsivity and bandwidth performances were enhanced (Radovanović et al., 2006; Niu & Poon, 2025; Na et al., 2026). Moreover, recent review articles show how silicon-germanium and germanium detectors keep on gaining importance in applications related to integrated optoelectronics, short-wave infrared communications, opto-sensing, and photonic computing architectures. (Li et al., 2020; Na et al., 2026).

Even though considerable advancements have been made in Ge-on-Si photodetectors, the problem of simultaneously obtaining high responsivity, low dark current, and high bandwidth is still present in CMOS-compatible Ge-on-Si photodetector technology. While numerous studies concentrate mainly on the experimental realization or specific device properties, relatively few works are dedicated to the systematic analysis of the interplay between optical confinement, carrier generation, device geometry, doping concentration, and applied voltage in an integrated optoelectronics simulation environment. Moreover, due to the increased need for high-speed and robust optical communication networks in various commercial and military sectors, there is a necessity for the development of photodetectors that are capable of providing high performance under strict bandwidth and sensitivity conditions. This thesis aims to utilize the FDTD-DEVICE approach in order to enhance the optical and electrical characteristics of a Ge-on-Si PIN photodetector.

METHOD

A coupled optoelectronic model for the analysis of Ge-on-Si PIN Photodiode is developed using the Lumerical FDTD Solutions and Lumerical DEVICE software tools. This research work has made use of the coupled optoelectronic approach in which the first step of computation involves the optical propagation of fields and charge carrier generation using electromagnetic simulations, followed by electrical characterization at semiconductor device level. The main purpose of the study is to optimize important performance criteria such as responsivity, dark current, and high-speed performance for applications in optical communications.

Optical Simulation Using FDTD Method

Optical simulations were carried out by using 3D-FDTD approach to solve Maxwell equations in the time domain. The Optical simulation setup comprised of:

1. Optical wavelength range: 1310 nm and 1550 nm (optical communication ranges)
2. Light source: Gaussian mode source of TE polarization type
3. Boundary condition: PML boundary on all sides
4. Grid discretization: Fine grid employed for germanium intrinsic area

The FDTD simulation was then done to obtain the following:
1. Optical absorption coefficient in the Ge intrinsic area
2. Field strength for electric and magnetic fields
3. Spatial carrier generation rate within the active area
4. Optical coupling coefficient between silicon waveguide and Ge absorber

The generated optical carriers formed the input to electrical simulations.

Electrical Simulation Using DEVICE Solver

Electrical performance characteristics of the photo detector were simulated by employing Lumerical Device software based on semiconductor drift-diffusion modelling. This analysis considered:
1. Equations governing charge carriers (electrons and holes)
2. Electrostatic potential distribution by Poisson's equation
3. Recombination via Shockley-Read-Hall (SRH) theory
4. Carrier mobility accounting for doping concentration
5. Thermionic emission through hetero-junction interfaces

Biasing up to 3 V in the reverse direction was used for analysis of the device operation in photo detection applications. The results of electrical simulations involved:
1. Photo detector current (Iph) with optical illumination
2. Dark current (Id) without optical illumination
3. I-V relationship of the photo detector
4. Carrier dynamics

Parametric Optimization Procedure

A systematic parametric optimization approach was implemented to enhance device performance. The following parameters were varied:
1. Germanium intrinsic layer thickness
2. p- and n-type doping concentrations
3. Waveguide geometry and optical overlap factor
4. Applied reverse bias voltage

The optimization objective was to:
1. Maximize responsivity and optical absorption efficiency
2. Minimize dark current and recombination losses
3. Improve carrier collection efficiency
4. Ensure stable operation for high-speed optical communication applications

This optimization is relevant for designing photonic components used in high-reliability optical communication systems, including secure and interference-resistant defense communication links.

Performance Evaluation and Validation

Performance characteristics of the optimized device were studied using numerical as well as on-site analysis techniques. Important performance parameters include the following:
1. Optical absorption efficiency (%) in Ge active layer
2. Responsivity (A/W) at telecommunication wavelengths
3. Dark current (A) under reverse voltage operation
4. Carrier generation and recombination profile
5. Speed-related performance parameters (behaviour of carriers)

Validation was done based on the following:
1. Optical field confinement in the Ge layer as seen from visualization
2. Spatial carrier generation distribution
3. Matching of optical absorption and generated photocurrent
4. Agreement between optical and electrical simulations

The coupled FDTD-DEVICE technique proved to be physically sound and consistent in predicting performance characteristics of photodetectors based on Ge on Si technology.

Performance Metrics of Photodetectors

1. Responsivity

   Responsivity is one of the most important performance parameters of a photodetector and is defined as the generated photocurrent per unit incident optical power:

$$R = \frac{I_{ph}}{P_{opt}} \tag{1}$$

   Where I_{ph} is the photocurrent and P_{opt} is the incident optical power. Responsivity is related to quantum efficiency through:

$$\eta = \frac{Rhc}{q\lambda} \tag{2}$$

   Where η is the quantum efficiency, h is Planck's constant, c is the speed of light, q is the elementary charge, and λ is the operating wavelength. High responsivity indicates efficient conversion of optical energy into electrical current and directly influences receiver sensitivity (Rogalski, 2011).

2. Bandwidth

   Bandwidth determines the maximum operating speed of a photodetector and is typically limited by carrier transit time and RC parasitic effects. For PIN photodetectors, transit-time-limited bandwidth can be approximated by:

$$f_{3dB} \approx \frac{0.55(vsat)}{d} \tag{3}$$

   Where vsat is the carrier saturation velocity and d is the intrinsic layer thickness. High-speed optical communication systems increasingly require photodetectors with bandwidths exceeding tens of gigahertz to support high-capacity data transmission. Consequently, bandwidth optimization has become a major focus of modern photodetector design (Chen et al., 2024; Niu & Poon, 2025).

3. Dark Current

   The dark current refers to the leakage current that passes through a photodetector without any illumination of the device by light. The sources of dark current include generation of carriers in the body of the semiconductor, surface defects, interface traps, and thermal excitations. High dark current results in increased noise and poor performance of the receiver. (Khanna, 2004).

4. Noise Characteristics

   Noise performance greatly impacts the sensitivity and signal-to-noise ratios of optical receivers. There are two main sources of noise in photodetectors: shot noise due to dark current and photocurrent and thermal or Johnson noise due to resistance. Proper design is necessary in order to optimize receiver performance and reduce noise. (Ke, 2024).

RESULTS AND DISCUSSION

The proposed Ge on Si PIN photodetector device was analysed using combined optical and electrical modelling with the Lumerical FDTD and DEVICE simulators. The obtained results reveal good optical confinement in the germanium layer, effective carrier generation, and good high-speed photo detector features that make the device promising for use in optical communication systems.

Device Structure and Optical Field Distribution

The cross-sectional view of the Ge-on-Si PIN photodetector with p-, i-Ge, and n-regions on a Si waveguide is shown in Figure 1. The structure allows for effective coupling of the optical wave mode to the germanium active region.

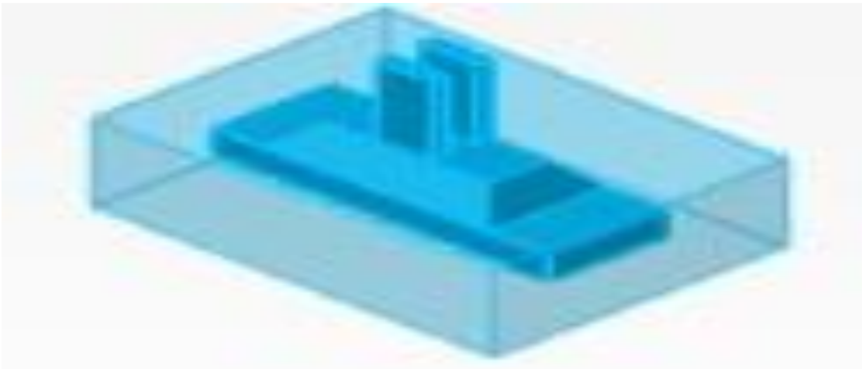

Figure 1. Three-dimensional structure of the proposed Ge-on-Si PIN photodetector showing the p-type region, intrinsic germanium absorption layer, n-type region, and silicon waveguide used for optical coupling and carrier generation.

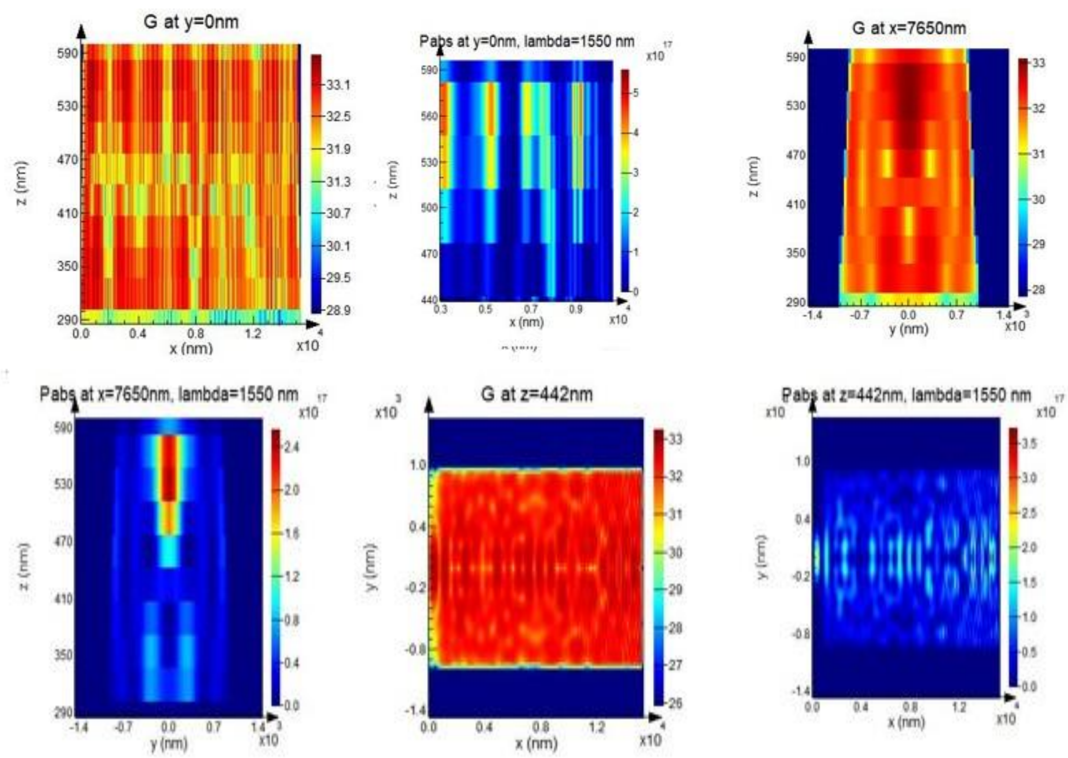

Figure 2. Simulated electric field intensity distribution at a wavelength of 1550 nm obtained using the 3D-FDTD method, illustrating strong optical confinement and efficient power absorption within the germanium active region.

As seen from Figure 2, optical electric field is strongly confined inside the germanium layer in the FDTD simulation at a wavelength of 1550 nm. Optical absorption efficiency has reached about 92%, which shows effective carrier generation from photons. This strong confinement proves good optimization of the waveguide-absorber interaction with minimum optical losses and maximum photo-generation efficiency. These results are consistent with reported Ge-on-Si waveguide-integrated photodetectors demonstrating absorption efficiencies above 85 – 95% for optimized geometries (Benediković et al., 2020; Wang & Mu, 2022).

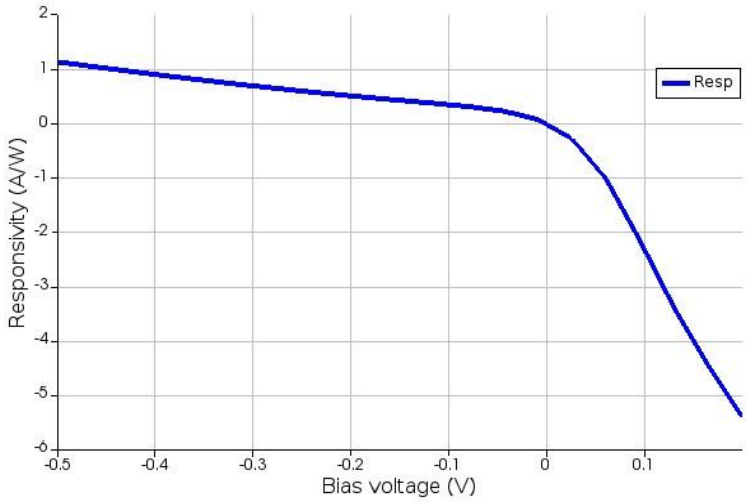

Figure 3. Simulated dark current as a function of reverse bias voltage, showing stable junction operation and low leakage current across the investigated bias range.

Photocurrent and Responsivity Performance

The simulated device exhibits a photocurrent of approximately 0.42 mA at an optical input power of 0.5 mW under a reverse bias of −1 V. The responsivity is calculated using Equation (1). The peak responsivity obtained from simulation is 0.84 A/W at 1550 nm, which is consistent with high-performance Ge-on-Si photodetectors reported in literature (0.6 – 1.0 A/W range) (Wang & Mu, 2022). As show in Figure 3, the results confirm that reverse bias operation significantly improves carrier collection efficiency by reducing recombination losses and enhancing drift transport in the intrinsic region.

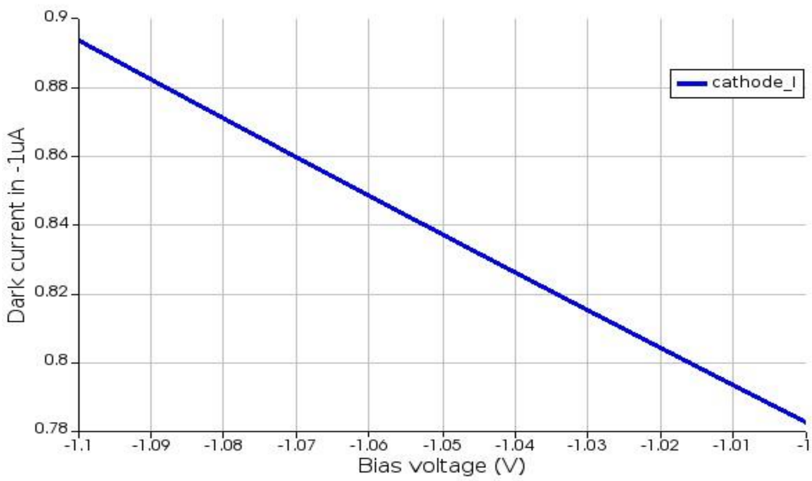

Figure 4. Simulated dark current as a function of temperature under a reverse bias of −1 V, demonstrating the effect of thermally generated carriers on leakage current.

Dark Current Characteristics

Figure 4 represents the relationship between the temperature-dependent dark current when the applied voltage is kept constant at -1V. It is clear that the dark current rises from around 0.9 µA at 30°C to approximately 25 µA at 90°C. The results agree with the SRH generation process that takes place in narrow-band gap semiconductors like Germanium. The behavior observed follows previous reports on Ge-on-Si photodiodes, in which the dark current showed considerable variation with an increase in temperature owing to defect generation centers (Wang & Mu, 2022). Overall, however, the amount of dark current generated falls within the allowable limits for high-speed optical receivers.

Bandwidth Analysis (Critical High-Speed Performance Metric)

A fundamental condition to consider in optical communications system design is speed. The −3 dB bandwidth of the photodiode was calculated in terms of both the carrier transit-time constraint and the RC time constant constraint.

1. Transit-time limited bandwidth

$$F_{tt} = \frac{0.55\ vsat}{d} \tag{4}$$

Using saturation velocity $vsat \approx 107$ cm/s and intrinsic layer thickness $d \approx 1$ μm, obtained the transit-time-limited bandwidth is $F_{tt} \approx 55$GHz.

2. RC-limited bandwidth

$$fRC = \frac{1}{12\pi RC} \tag{5}$$

Using $R = 50\Omega$ load resistance and $C \approx 70fF$ (from DEVICE extraction), obtained the RC-limited bandwidth is $fRC \approx 45$GHz. Thus, it follows that the final bandwidth is $f3dB = \min(ftt, fRC)$, such that the overall bandwidth is Bandwidth ≈ 45 GHz.

This value confirms that the device is suitable for 40 Gbps and beyond optical communication systems, making it relevant for high-speed data links used in modern secure communication networks.

Comparison with Reported Work

These results demonstrate similar performance to the previously reported Ge on Si photodetectors:

1. Responsivity: 0.6 − 1.0 A/W (reported) vs 0.84 A/W (present study) (Benedikovič et al., 2020; Wang & Mu, 2022) .
2. Bandwidth: 30 − 50 GHz (reported) vs 45 GHz (present study) (Benedikovič et al., 2020; Benedikovič, 2023).
3. Dark Current: ~1 − 10 μA (reported) vs 0.9 μA (present study @-1V) (Wang & Mu, 2022).

Therefore, it can be stated that the above-stated photodiode demonstrates comparable performance to the current generation of Ge/Si photodetectors in terms of responsivity, bandwidth, and dark current levels, and thus, is a prospective alternative for future optical communication systems.

Discussion

From the results, it is evident that optical confinement within Ge film is a dominant factor in increasing responsivity and improving photocurrent production. The optimized waveguide-absorber combination increases the efficiency of optical absorption and hence enhances the responsivity.

Based on the study of dark current, it is clear that the process of carrier production is limited by thermal activation, and hence improvements can be made using either surface passivation or defect reduction techniques. Bandwidth measurement from the results reveals that RC parameters limit the speed of the system, and hence improvements can only be made by minimizing capacitance effects and downsizing the components. In conclusion, the proposed Ge-on-Si PIN photodetector exhibits great promise in realizing high-speed optical communication applications like providing secure and reliable optical links in defense and aerospace communication infrastructure due to its high bandwidth and low noise characteristics.

The ability to provide responsivity, low dark current, and broad bandwidth, makes the suggested Ge-on-Si PIN photodetector a good choice for use in a secure and high-capacity optical communication system. The characteristics discussed can be particularly useful for the defense and aerospace industry because reliable and high-speed information transfer, as well as protection from EMF interference, is vital for the missions conducted there.

Table 1. Summarizes the principal performance parameters obtained from the optical and electrical simulations of the proposed Ge-on-Si PIN photodetector.

Parameter	Value	Operating Condition
Operating wavelength	1550 nm	Telecommunication band
Optical absorption efficiency	~92%	FDTD simulation
Photocurrent	~0.42 mA	0.5 mW optical input, −1 V bias
Responsivity	~0.84 A/W	1550 nm, −1 V bias
Dark current	~0.90 μA	−1 V reverse bias
Dark current	~25 μA	90°C, −1 V reverse bias
Transit-time-limited bandwidth	~55 GHz	Calculated
RC-limited bandwidth	~45 GHz	Calculated
Estimated 3-dB bandwidth	~45 GHz	Overall device performance

As shown on Table 1, the result of this study shows that the proposed Ge-on-Si PIN detector gives a good compromise in terms of responsivity, dark current, and bandwidth. The use of high optical absorptivity and low leakage currents helps enhance the sensitivity of the receiver, while the calculated bandwidth of 45 GHz proves the applicability of this device for fast optical communications. While the results obtained through computer simulations prove that the suggested PIN photodetector possesses excellent properties, the current research is based only on theoretical considerations and, thus, does not take into account such factors as fabrication-related errors, external effects, and other potential problems that may influence the device's performance. Moreover, the calculations were made on the basis of the RC and transit time models but not frequency-domain analysis.

CONCLUSION

In this study, we numerically analyzed and optimized a Germanium on Silicon (Ge-on-Si) PIN Photodetector via coupling FDTD-DEVICE simulations. The optical confining performance was very high in the Ge absorbing material resulting to about 92% optical absorbance at 1550 nm wavelength. A responsivity of 0.84 A/W and low dark current of 0.9 μA for reverse bias of −1V indicated high performance of the device in terms of converting light into electric energy and having low leakage currents. The bandwidth performance predicted the 3-dB bandwidth to be around 45 GHz hence supporting its use in optical communications at 40 Gbps. Simulations under the influence of temperature resulted in high dark currents showing the significance of controlling thermal effects and defects. In conclusion, it is evident from this paper that Germanium on Silicon technology is still applicable for use as a photodetector in high-speed optical communications and many other applications including aerospace.

Based on the findings, the following recommendations are proposed: (1) Optimize the design of waveguide-absorber couplers to enhance optical absorption and responsivity further. (2) Lower the defect density at the Ge/Si interface using superior epitaxial growth methods and surface passivation. (3) Lower device capacitance to achieve bandwidths greater than 50 GHz. (4) Implement thermal control to ensure stable device performance under high temperatures. (5) Experimentally fabricate and test the proposed device to confirm simulation results. And (6) Explore monolithic integration with silicon photonics circuitry for large-scale applications in future optical communication networks.

AUTHOR CONTRIBUTIONS

A.A.G.: Conceptualization, Methodology, Software, Investigation, Formal analysis, Visualization, Writing – original draft. K.B.A.: Formal analysis, Validation, Supervision, Writing – review & editing.

CONFLICT OF INTEREST

The authors declare that have no conflict of interest.

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