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Mini Review

Germanium-on-Insulator: A Pathway to Monolithically Integrated SWIR Imaging for Future Satellite Constellations

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Abstract

Short-wave infrared (SWIR) imaging has become an indispensable capability in modern Earth observation, enabling quantitative sensing of vegetation water content, mineral composition, and a range of dynamic environmental processes. As space-based observation paradigms evolve toward proliferated satellite constellations, sensor technologies are increasingly constrained not only by performance, but also by scalability, cost, size-weight-power (SWaP), and manufacturability. Conventional SWIR focal plane arrays (FPAs), predominantly based on InGaAs photodetectors hybrid-integrated with Si readout integrated circuits (ROICs), provide mature and high-performance solutions but face intrinsic trade-offs related to heterogeneous integration and III-V material economics. This work examines Germanium-on-Insulator (GeOI) photodetector technology as an emerging and complementary pathway aligned with the system-level requirements of future distributed satellite missions. We summarize recent progress in GeOI material development and device performance in China and critically assess its current technological status. While most state-of-the-art GeOI FPAs remain hybrid-integrated at present, advances in high-quality Ge heteroepitaxy on Si establish a credible long-term route toward monolithic CMOS integration. Rather than positioning GeOI as a universal replacement for existing technologies, this summary highlights its potential role in enabling low-SWaP, cost-sensitive, and highly integrated SWIR imaging payloads, particularly suited for large-scale satellite constellations and intelligent on-board processing architectures.

Keywords: Germanium-on-insulator (GeOI); short-wave infrared (SWIR); satellite remote sensing; focal plane array; monolithic integration

Introduction

The short-wave infrared (SWIR; ~1.5-3.0 μm) spectral band occupies a unique position in remote sensing, offering sensitivity to molecular vibrational absorption features that are inaccessible in the visible and thermal infrared regimes. This spectral capability underpins a wide range of Earth observation applications, including vegetation water stress monitoring, mineralogical mapping, atmospheric constituent analysis, biomedical, and environmental change detection [1-4]. Historically, high-performance SWIR imaging from space has been dominated by InGaAs-based FPAs, which combine excellent sensitivity, low dark current, and proven reliability. These detectors are typically integrated with Si ROICs via flip-chip bonding, forming hybrid architectures that have demonstrated extensive flight heritage in both scientific and commercial missions. However, the rapid emergence of large-scale satellite constellations-often comprising hundreds or thousands of small satellites-has introduced new system-level constraints. In these scenarios, cost per unit, manufacturability, payload SWaP, and scalability across large production volumes become as critical as ultimate detector performance. Within this evolving landscape, alternative material and integration strategies are being explored to complement established SWIR technologies. Among them, GeOI has attracted growing interest due to its compatibility with Si processing infrastructure and its potential for tighter integration with CMOS electronics [5-12]. This work focuses on the GeOI platform, evaluating its current capabilities, development trajectory, and potential role within future satellite constellation architectures.

The GeOI Paradigm: Material Platform and System-Level Alignment

GeOI technology is based on the integration of a crystalline germanium absorption layer on an insulator substrate, typically consisting of a Si wafer, a buried oxide (BOX) layer, and a thin Ge device layer. From a system perspective, this architecture aligns SWIR photodetection with the Si microelectronics ecosystem, offering a pathway toward wafer-scale manufacturing and tighter integration with on-chip electronics. It is important to distinguish between the current implementation state of GeOI FPAs and their longer-term vision. At present, most reported GeOI imaging demonstrations employ hybrid integration with ROICs, similar to conventional InGaAs FPAs. The fundamental distinction lies in the material platform itself: high-quality heteroepitaxial growth of germanium on Si has matured to a level where device-grade Ge layers can be produced using CMOS-compatible processes. This progress effectively shifts the remaining challenges from fundamental material incompatibility toward process optimization, device engineering, and system integration. From a satellite system standpoint, GeOI is therefore best viewed not as a disruptive replacement technology, but as an enabling platform that may address specific mission profiles where integration density, cost scaling, and SWaP constraints dominate design considerations (Figure 1).

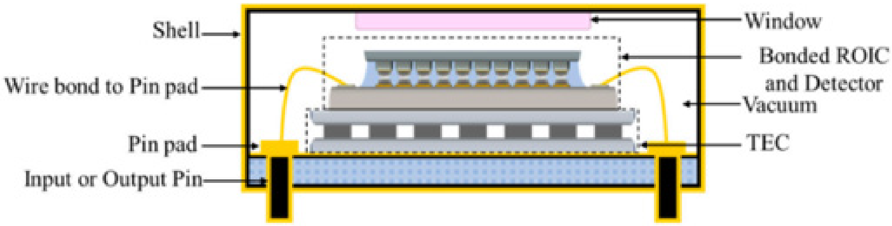

Figure 1: Conceptual schematic of a packaged GeOI SWIR image sensor (reproduced from [13], which is also our previous work, open access by MDPI, 2025).

Foundational Merit: CMOS Compatibility as a System-Level Enabler

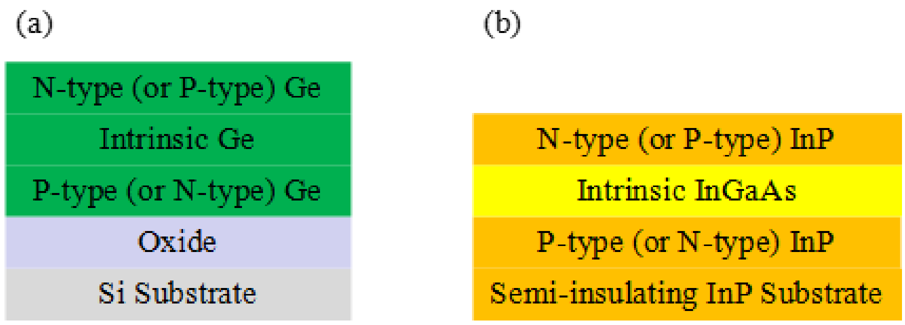

Figure 2: Representative device structures of (a) GeOI and (b) InGaAs photodetector technologies, highlighting the differences in material platforms and integration approaches commonly adopted in SWIR focal plane arrays for satellite imaging applications [15,16].

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The primary advantage of the GeOI platform lies less in a singular detector performance metric and more in its alignment with CMOS manufacturing and integration paradigms. The presence of the BOX layer provides effective electrical isolation from the Si substrate, suppressing parasitic leakage paths and supporting low-noise operation. More strategically, the use of Si-compatible substrates and process flows opens a route toward co-fabrication of photodetectors and electronics within a unified technological framework. Such compatibility has important implications for future satellite payloads. Monolithic or near-monolithic integration can reduce interconnect parasitics, lower assembly complexity, and potentially improve robustness in vibration- and radiation-prone environments. At the same time, it is essential to recognize that mature InGaAs technologies continue to evolve and will remain indispensable for missions requiring maximum sensitivity and proven heritage. In this context, GeOI should be regarded as complementary, addressing application spaces where manufacturability and integration outweigh the need for absolute performance optimization (Figure 2). The Ge/GOI technology has been demonstrated in laboratory-scale SWIR imaging and small-format array prototypes [14].

Device-Level Progress and Development Trajectory

Over the past decade, GeOI photodetector research has progressed from proof-of-concept devices to increasingly application-relevant demonstrations. Key advances include:

a) Responsivity enhancement: Resonant-cavity-enhanced and waveguide-integrated GeOI photodiodes have achieved responsivities exceeding 0.8 A/W at 1.55 µm, in resonant or waveguide-enhanced configurations, approaching those of established SWIR detectors despite thinner absorption layers.

b) Spectral range extension: The incorporation of GeSn alloys has enabled cutoff wavelength extension beyond ~2.0 µm, at the expense of increased material complexity, broadening access to longer-wavelength SWIR features relevant to geological and environmental sensing [17-19].

c) Functional integration: Demonstrations of Ge avalanche photodiodes (APDs) and waveguide-coupled devices indicate the platform's suitability for more complex photonic and optoelectronic integration [20,21].

These developments collectively enhance the credibility of GeOI as a SWIR detector platform. Nevertheless, most demonstrations remain at the component or small-array level, and further work is required to translate these advances into large-format FPAs with uniform performance and space-grade reliability. In the foreseeable future, hybrid-integrated GeOI FPAs are likely to precede fully monolithic implementations, which represent a longer-term engineering objective. A comparative analysis of key characteristics is summarized in Table 1.

Alternative SWIR Detector Technologies for Satellite Applications

The maturation of monolithic GeOI technology could enable shifts in satellite system design aligned with the trends of constellation proliferation and intelligent payloads. The cost structure implied by wafer-scale CMOS integration may lower the barrier to incorporating SWIR sensing on small satellites, facilitating large-scale constellations for high-temporal-resolution monitoring. Beyond economics, the intimate co-location of detectors and Si electronics is transformative, paving the way for embedded on-chip processing (e.g., real-time feature extraction, compression, or decision-making) and enabling intelligent sensors that perform analysis at the edge. The reduced SWaP footprint also invites novel instrument concepts, such as compact multi-spectral imagers or SWIR-based inter-satellite links. Realizing this potential requires overcoming significant, non-trivial challenges. Material optimization for wafer-scale, low-defect Ge layers is ongoing, with the ~4% lattice mismatch between Ge and Si requiring sophisticated strain engineering to minimize threading dislocations that degrade performance [22,23]. The co-optimization of photonic and electronic process modules within a unified CMOS flow is a complex task requiring specialized PDKs. Furthermore, key detector metrics such as dark current density and quantum efficiency, particularly at wavelengths beyond 1.8 µm, still require further improvement to match the benchmark set by mature InGaAs technology. Novel technologies, such as, quantum wells, quantum dots, etc, should be well explored [24,25]. Finally, as with any new space technology, a rigorous qualification phase for radiation hardness and long-term reliability remains an essential and demanding step towards flight readiness.

Conclusion

Germanium-on-Insulator technology represents a promising and complementary pathway within the broader SWIR detector landscape, particularly aligned with the integration, scalability, and SWaP constraints of future satellite constellations. While current GeOI FPAs largely rely on hybrid integration, ongoing progress in material growth and device engineering establishes a credible roadmap toward tighter CMOS integration over the longer term. Rather than supplanting mature technologies such as InGaAs, GeOI expands the design space available to system architects by addressing application scenarios where cost scaling, integration density, and manufacturability are dominant considerations. Continued advances in materials, process integration, and space qualification will ultimately determine the extent to which GeOI-based SWIR sensors contribute to next-generation Earth observation and satellite communication systems.

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