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Integrating environmental and resilience metrics for sustainable material substitution in compound semiconductor laser manufacturing

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ABSTRACT

Compound semiconductor manufacturing faces growing challenges from critical raw material dependence and environmental burdens. This study develops a physics-informed multi-criteria life cycle framework integrating environmental and resilience metrics to evaluate sustainable material substitution. The framework combines life cycle assessment (LCA), material circularity indicators (MCI), and a supply risk index (SRI) within a multi-criteria decision analysis (MCDA) structure. The approach is demonstrated through a 'case study' comparing gallium arsenide (GaAs) and germanium (Ge) substrates in vertical-cavity surface-emitting laser (VCSEL) production. Results show that Ge exhibits 11.4% lower cumulative energy demand, a 0.54 vs. 0.33 MCI, and a 0.18 vs. 0.39 SRI, resulting in a 4.2-fold higher composite sustainability score (0.822 vs. 0.194). These advantages are driven by Ge's diversified supply base, higher recyclability, and absence of arsenic-related toxicity. Although GaAs currently benefits from greater process maturity, its environmental and geopolitical vulnerabilities highlight the long-term advantages of Ge substitution, while also indicating trade-offs in terms of short-term economic implications related to yield, process maturity, and manufacturing transition. The proposed framework offers a transferable decision-support tool for integrating environmental sustainability and supply-chain resilience into material selection and manufacturing strategies for advanced-technology industries.

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Compound semiconductor supply chain; sustainability; resilience; circular economy; life cycle assessment

SUBJECT CLASSIFICATIONS
Advanced manufacturing processes; semiconductor industry; semiconductor manufacture

1. Introduction

Compound semiconductors (CSs) have become the foundational infrastructure of the global digital economy, underpinning a wide range of modern technologies. Materials such as gallium arsenide (GaAs), indium phosphide (InP), and gallium nitride (GaN) occupy a critical position, offering superior optoelectronic, high-frequency, and power-handling properties (Mönch et al. 2018). In parallel, elemental germanium (Ge) is increasingly considered as a substrate material due to its high thermal conductivity, larger wafer availability, and compatibility with III–V epitaxy. From 5G and datacentres to autonomous vehicles, renewable energy, and space applications, CS devices have become indispensable for both industrial innovation and national competitiveness (Xiong, Wu, and Yeung 2024). As such, the resilience and sustainability of the compound semiconductor supply chain (CSSC) is now a matter of global strategic importance (Xiong, Wu, and Yeung 2024). Figure 1 shows the applications of CS in critical areas.

However, the compound semiconductor supply chain (CSSC) is increasingly under strain. CS manufacturing depends on a narrow set of critical minerals such as gallium, indium, arsenic, and germanium. These elements are geologically scarce, often produced as by-products of other mining industries, and heavily concentrated in a few countries. This creates structural fragility: more than 95% of global gallium supply, for example, has historically been concentrated in China, while germanium and indium production are dominated by a small number of producers in East Asia and Central Asia (Gov.uk 2023; Ueberschaar, Otto, and Rotter 2017). Such concentration exposes the CSSC to geopolitical tensions, export restrictions, and trade disputes, which can rapidly cascade across global manufacturing networks. In addition to geopolitical risks, the CSSC is also vulnerable to natural disasters and localised supply disruptions (Moktadir and Jingzheng 2024). Earthquakes, floods, and pandemics can halt operations in upstream mining or downstream fabrication facilities, triggering shortages that reverberate

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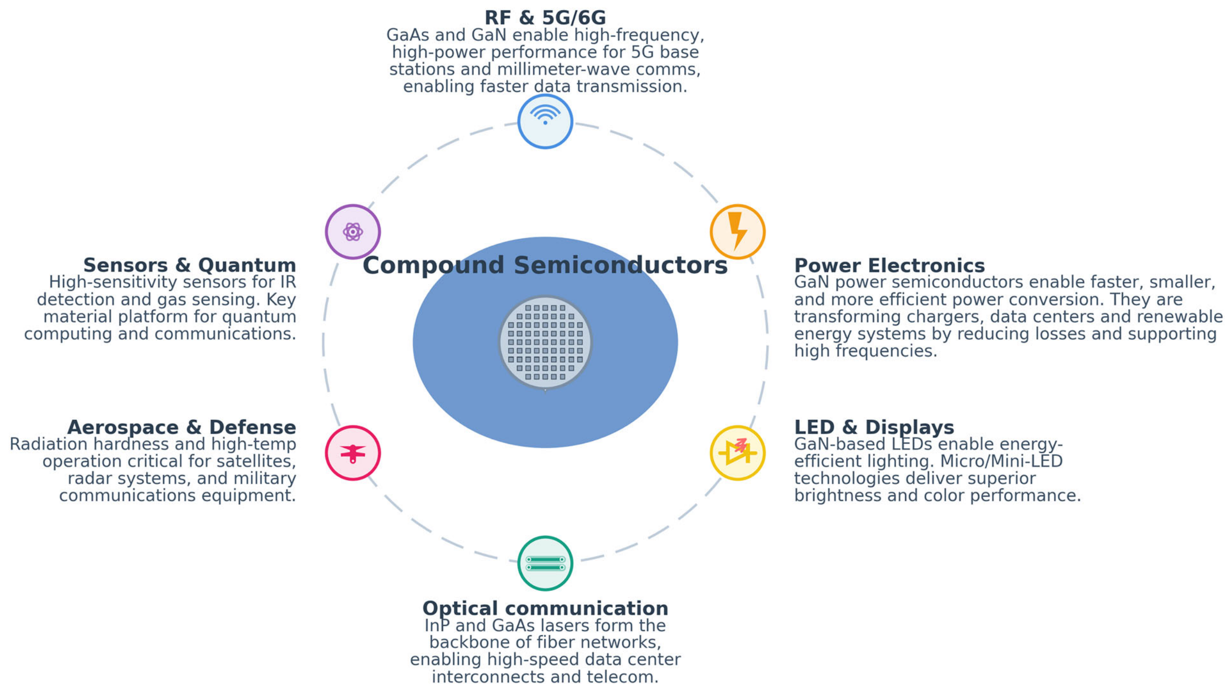


Figure 1. Major application areas of compound semiconductors, demonstrating their central role in advanced communication, power, sensing, and defence technologies (adapted from Gov.uk 2023).

through global industries dependent on CS technologies (Leslie 2021; Ou, Yang, and Liu 2024).

Beyond supply risk, the environmental footprint of CS manufacturing is a growing concern. The extraction and processing of Ga and related elements are highly energy- and water-intensive, generating toxic by-products and hazardous waste streams. Yet these upstream environmental burdens are often underreported or excluded from life cycle assessment (LCA) models, leading to blind spots in sustainability evaluation (Kuo, Kuo, and Chen 2022; Xiong, Wu, and Yeung 2024). At the same time, the linear manufacturing paradigm of 'take–make–dispose' dominates CS production, with recycling and recovery of critical elements still at an early stage of maturity (Awasthi et al. 2019; Gov.UK 2024). This raises concerns about long-term resource security, environmental degradation, and the alignment of CS manufacturing with global sustainability goals. In response, policy frameworks in the China, EU, UK, and US increasingly emphasise resilience, sustainability, and circular economy (CE) strategies for semiconductor supply chains. The US CHIPS and Science Act, the EU Chips Act, and the UK National Semiconductor Strategy all highlight the importance of embedding material security, recycling, and environmental considerations into future manufacturing roadmaps. In addition, other research has shown that supply-chain structure and multi-criteria evaluation have an impact on sustainability results. For example, Shamoushaki and Koh (2024) investigated how diverse sourcing paths affect heat-pump LCA findings, whereas their subsequent study (2025) employed structured scoring to measure hydrogen-economy development across G20 nations. These findings offer valuable similarities for understanding sustainability evaluation in high-tech sectors. Within this context, there is a pressing need to investigate how material substitution and design choices in CS devices can contribute not only to performance and yield but also to supply chain resilience and environmental sustainability. VCSELs, as a high-volume and strategically significant device platform, provide an ideal case study for exploring this intersection.

VCSELs are a class of compound semiconductor lasers widely used in high-speed optical interconnects, LiDAR for autonomous vehicles, and three-dimensional imaging in consumer electronics, with emerging roles in AI hardware accelerators (Baker et al. 2021; Srinivasan et al. 2023). Their unique features such as low power consumption, wafer-level testability, and scalability into dense arrays have made them the dominant light source in short-reach optical communication and sensing markets (Johnson et al. 2012). However, VCSEL manufacturing remains highly dependent on gallium arsenide (GaAs) substrates, which are difficult to recycle and recognised as highly critical in supply chain assessments (Baker et al. 2025). As demand for high-performance optoelectronics grows, sourcing strategies must balance performance

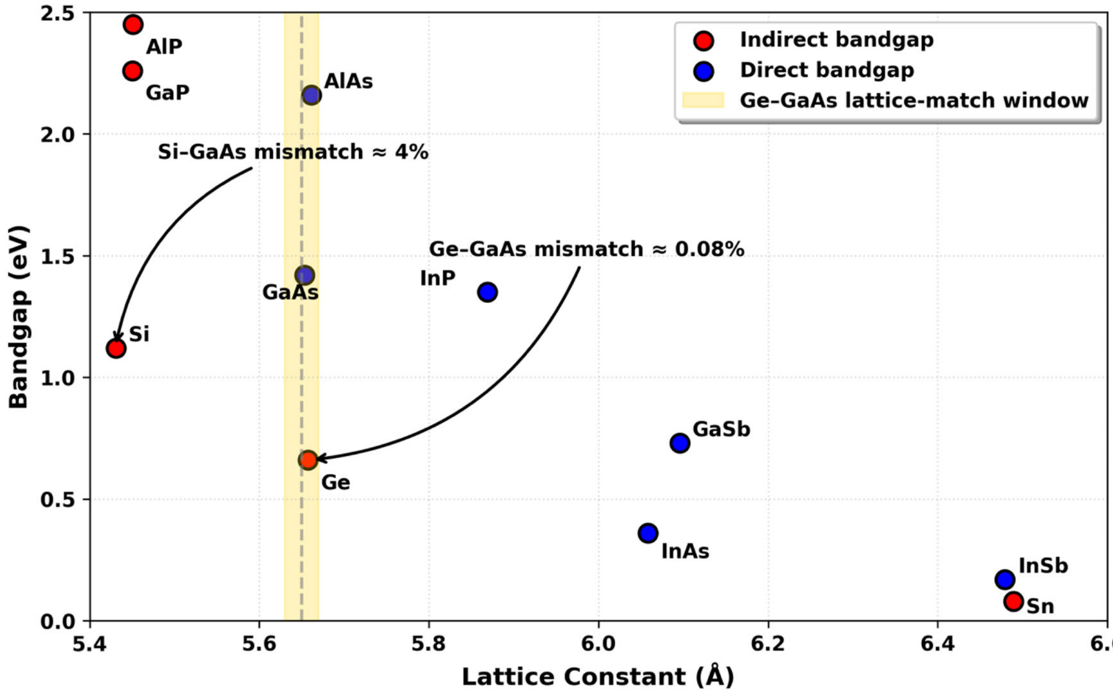


Figure 2. Bandgap energy versus lattice constant for selected semiconductor materials. Direct bandgap materials are marked in blue, while indirect bandgap materials are shown in red. The lattice constant of Ge (∼ 5.658 Å) closely matches that of GaAs (∼ 5.65 Å), enabling high-quality epitaxial growth without significant lattice mismatch. In contrast, the ∼ 4% mismatch between Si and GaAs prevents defect-free growth. This lattice compatibility, combined with Ge's lower supply risk and recyclability as a single-element substrate, highlights its potential as a sustainable alternative for VCSEL manufacturing. Figure reproduced based on data from Paul, D.J. (1995), 'SiGe Lattice Constants and Bandgap,' University of Glasgow. Available at: https://userweb.eng.gla.ac.uk/douglas.paul/SiGe/lattice.html[Accessed 7 Oct 2025].

with resilience and sustainability. This reliance underscores the need to investigate alternative substrate materials, with elemental germanium (Ge) offering a promising pathway due to its close lattice match with GaAs, process compatibility, and relatively lower supply risk (Gillgrass et al. 2025).

As shown in Figure 2, germanium offers an almost identical lattice constant to GaAs (∼ 0.08% mismatch), which ensures compatibility with GaAs and AlGaAs epitaxial layers such as the distributed Bragg reflectors (DBRs) used in VCSEL structures thus enabling high-quality epitaxial growth without significant lattice mismatch. This compatibility contrasts sharply with silicon, whose lattice constant differs by ∼ 4%, leading to dislocation formation and degraded material quality. In addition, elemental Ge is considered ecologically friendly, whereas GaAs requires careful handling because arsenic-containing compounds and arsine precursors are used in its manufacturing supply chain, resulting in a higher toxicity potential over the life cycle. This distinction makes Ge a more sustainable substrate option, with lower environmental risk and greater recyclability potential compared to GaAs.

Despite the growing body of literature on supply chain resilience and sustainable manufacturing, existing studies remain largely fragmented across separate streams of research. Resilience-oriented studies and sustainability-oriented analytical frameworks (such as life cycle assessment) are often developed in parallel, with limited integration into unified decision-making approaches. Recent systematic reviews have explicitly highlighted the lack of integration between supply chain resilience and sustainability perspectives, and have called for incorporating product lifecycle analysis into resilience assessment (Hosseini Shekarabi, Kiani Mavi, and Romero Macau 2025; Mönch et al. 2018; Shishodia et al. 2023).

Furthermore, while LCA, circularity metrics, and supply risk analysis have each been widely applied in isolation, there remains a lack of physics-informed decision frameworks that integrate these dimensions to support material substitution decisions in advanced manufacturing systems. This gap is particularly pronounced in compound semiconductor manufacturing, where material choice simultaneously affects device performance, environmental burden, and supply chain resilience.

Building on this context, the present study makes three specific contributions. First, it develops an integrated decision-support framework that combines life cycle assessment (LCA), material circularity metrics, and supply risk indicators within a unified MCDA structure, directly addressing the lack of integrated approaches identified in the supply chain resilience literature.

Second, the framework is physics-informed, incorporating empirical VCSEL wafer fabrication data to bridge the gap between materials engineering and production-oriented decision analysis. This enables the translation of device-level material characteristics into system-level sustainability and resilience outcomes.

Third, it shows how the framework can be applied in compound semiconductor manufacturing, which is largely absent from existing supply chain resilience literature. This provides a transferable template for material substitution decisions in advanced technology industries, with broader economic implications assessed through yield-adjusted cost and end-of-life recovery analysis.

The paper is structured as follows. Section 2 reviews the background and related literature on compound semiconductor supply chain risks and sustainability challenges. Section 3 describes the methodology, including VCSEL yield and hotspot data analysis, together with modelling approaches for LCA, supply risk, and circularity. Section 4 presents the main results integrating experimental and modelling evidence. Section 5 discusses the implications, highlighting the proposed material substitution decision framework across economic, environmental, and resilience dimensions. Finally, Section 6 concludes the paper and outlines policy recommendations for industry and supply chain stakeholders.

2. State of the art

2.1. Compound semiconductors and VCSEL fundamentals

Compound semiconductors (CSs) are crystalline materials composed of two or more elements, typically from groups III and V of the periodic table. Representative examples include gallium arsenide (GaAs), indium phosphide (InP), and gallium nitride (GaN). Compared with elemental semiconductors such as silicon, CSs exhibit direct bandgaps, higher electron and hole mobilities, and tunable lattice parameters (Kuech 2016). These unique electronic and optical properties make CSs the foundation of modern optoelectronic and microwave technologies, including photodetectors, high-electron-mobility transistors, and semiconductor lasers (Kuech 2016).

Among III–V materials, gallium arsenide (GaAs) has become the dominant substrate and epitaxial platform for short-wavelength optoelectronic devices such as light-emitting diodes, laser diodes, and photodetectors, owing to its direct bandgap (1.42 eV), excellent crystalline quality, and mature epitaxial growth technology (Kuech 2016). Indium phosphide (InP) is typically used for longer-wavelength telecommunication applications, while gallium nitride (GaN) offers superior power-handling capability and thermal stability for high-power and high frequency electronics (Kuech 2016; Monemar 1999).

Recently, an elemental semiconductor germanium (Ge) with a lattice constant nearly identical to that of GaAs (mismatch $\approx$ 0.08%) and high carrier mobility, has attracted renewed attention as an alternative substrate material for AlGaAs-based vertical-cavity surface-emitting lasers (Johnson et al. 2021). Ge has been applied as a growth substrate for GaAs-based photovoltaic systems, with multiple studies demonstrating high-quality GaAs epitaxy and device performance on Ge substrates (Derluyn et al. 2002; Winter et al. 2022). Its compatibility with both silicon and III–V systems enables heterogeneous integration, while its greater material availability and recyclability present potential advantages for sustainable semiconductor manufacturing.

A vertical-cavity surface-emitting laser (VCSEL) is a representative III–V optoelectronic device that emits light perpendicular to the wafer surface rather than from its edge (Michalzik 2012). Its structure consists of an active multiple-quantum-well region sandwiched between two distributed Bragg reflector (DBR) mirrors, which provide optical feedback and vertical confinement. The upper DBR is partially transmissive to allow light emission, while a current-confining oxide aperture ensures efficient carrier injection and stable single-mode operation (Michalzik 2012). The compact vertical geometry enables low threshold current, high modulation bandwidth, and straightforward integration into arrays, making VCSELs the backbone of modern data communication, sensing, and LiDAR systems (Michalzik 2012). GaAs-based VCSELs commonly use AlGaAs-based DBRs and quantum wells, offering high reflectivity and manufacturability through mature epitaxial techniques such as molecular-beam epitaxy (MBE) or metal–organic chemical vapour deposition (MOCVD) (Michalzik 2012). However, the fabrication of GaAs-based VCSELs relies on critical elements such as gallium and arsenic, whose supply chains are geographically concentrated and environmentally intensiveGov.uk 2023 (Gov.uk, 2023). Exploring alternative substrates such as germanium (Ge), which offers chemical stability, recyclability, and a lower criticality level, could reduce both environmental burden and supply-chain vulnerability without compromising optical performance (Figure 3).

The following sections examine the vulnerability of these critical materials and assess how material substitution strategies, for example, replacing GaAs with Ge to

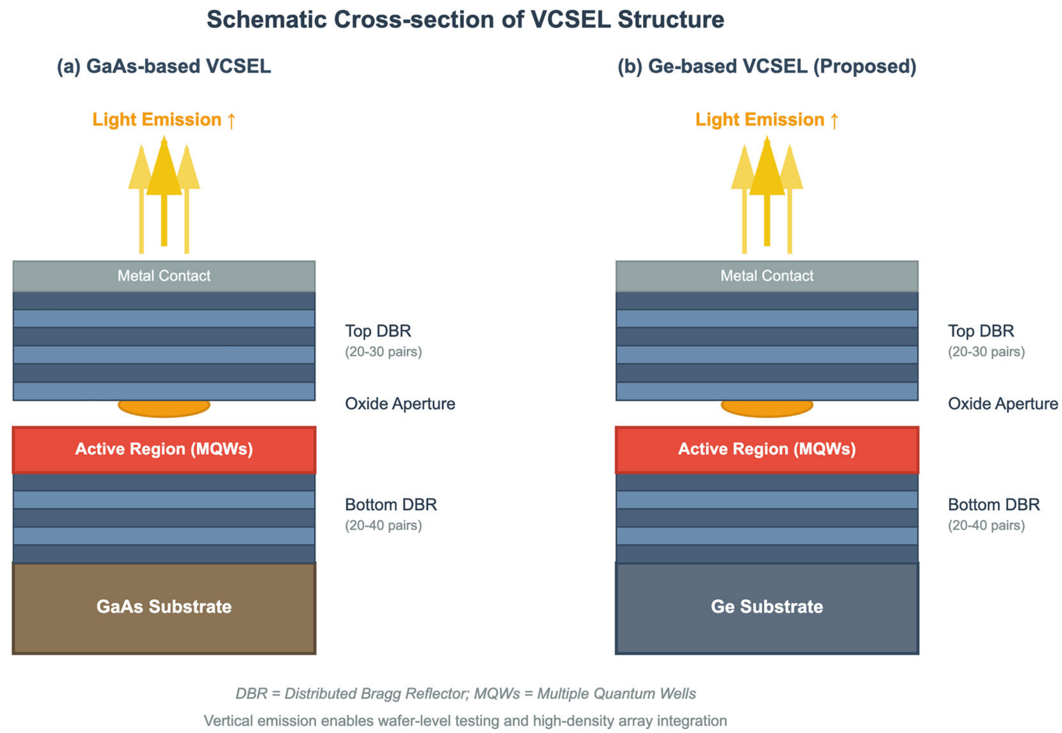


Figure 3. Schematic cross-section of VCSEL structures. (a) Conventional GaAs-based VCSEL and (b) proposed Ge-based VCSEL. Both devices comprise a multiple-quantum-well (MQW) active region sandwiched between distributed Bragg reflector (DBR) mirrors, with light emission occurring perpendicular to the wafer surface. The Ge-based structure maintains identical optical design while substituting the GaAs substrate with Ge to improve material availability and sustainability.

contribute to more sustainable and resilient compound-semiconductor manufacturing.

2.2. Supply chain vulnerability of critical minerals

The compound semiconductor industry forms one of the most complex and globally interdependent manufacturing systems. The supply of critical minerals for these devices is increasingly exposed to intertwined geopolitical, environmental, and economic risks. A defining feature of these supply chains is their structural fragility: a few upstream countries dominate the mining and processing stages, while downstream semiconductor fabrication is distributed globally. For instance, gallium, arsenic, and indium are key elements for GaAs and InP-based optoelectronics that are primarily produced as by-products of aluminium, copper, or zinc extraction, leading to volatile availability. Over 95% of refined gallium and a majority of high-purity germanium originate from China and a small group of secondary refiners in East Asia, exposing the value chain to geopolitical and trade disruptions (Khan 2021; Woods and Gajjar 2024).

Several studies have emphasised how cascading disruptions such as COVID-19 lockdowns, port closures, or trade disputes can propagate through multi-tiered supply chains, delaying the availability of materials critical to wafer-level manufacturing (Gov.uk 2023; Ou, Yang, and Liu 2024). The reliance on just-in-time inventory practices further amplifies the vulnerability of foundries and packaging facilities, particularly in regions without domestic access to refined critical minerals (Gov.uk 2023).

Additionally, the environmental burden associated with critical mineral extraction presents long-term sustainability concerns. The mining of gallium, indium and arsenic is often energy- and water-intensive, generates hazardous waste, and contributes to ecosystem degradation. These environmental externalities are rarely priced into the final cost of semiconductor devices, leading to underestimation of their full ecological impact (Awasthi et al. 2019).

In summary, section 2.2 highlighted the structural fragility of critical mineral supply chains; the degree of criticality varies considerably across specific elements. These differences motivate the exploration of Ge as a potential alternative substrate material, as discussed in Section 2.3.

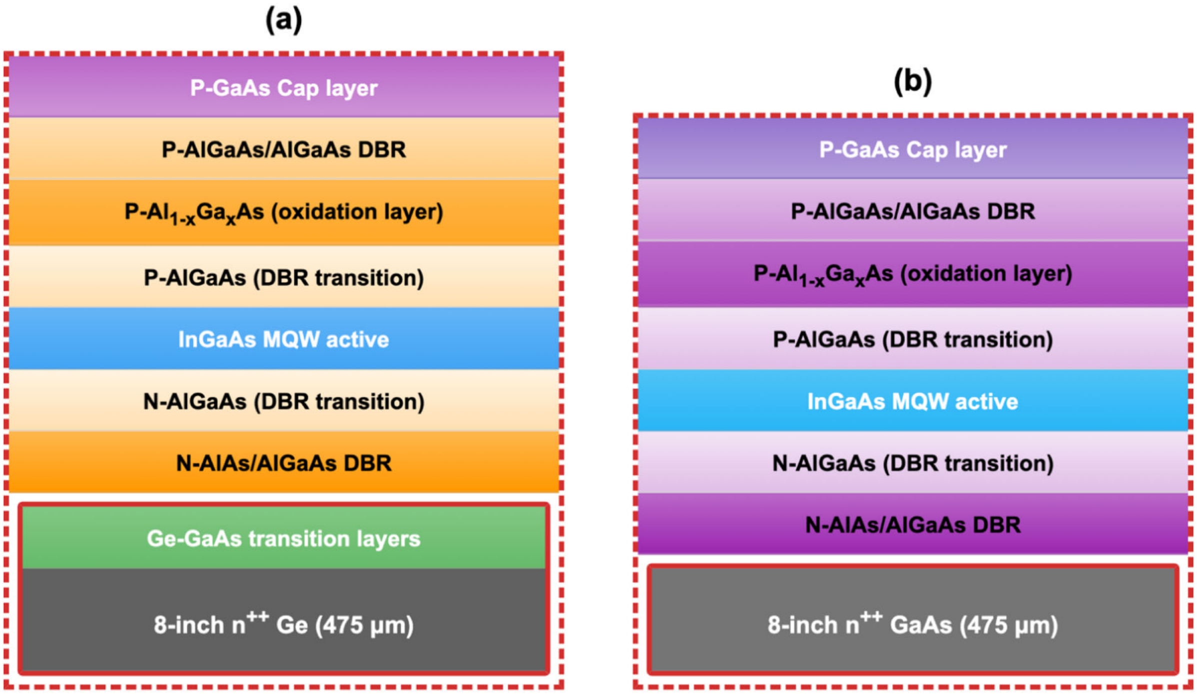


Figure 4. Comparison of epitaxial structures for 940 nm emitting (a) Ge-based and (b) GaAs-based VCSELs.

2.3. Material substitution and manufacturing constraints

Material substitution has been recognised as an effective strategy to mitigate supply risk and environmental impact in critical-material–intensive industries (Baker et al. 2025; Wan et al. 2024). Rather than pursuing complete supply-chain decoupling, substitution aims to maintain technological functionality while reducing dependence on high-risk resources. In compound-semiconductor manufacturing, gallium arsenide (GaAs) faces two challenges: its production depends on geographically concentrated, by-product supply chains, and its processing requires control measures and careful handling to prevent environmental or health issues (Kumar, Thorbole, and Gupta 2024). These factors make GaAs both strategically sensitive and environmentally intensive. Consequently, exploring germanium (Ge) as an alternative substrate offers a promising approach to improve both resilience and sustainability (Kumar, Thorbole, and Gupta 2024).

The choice of substrate strongly impacts VCSEL performance, yield, and long-term manufacturability (Wan et al. 2024). Figure 4 compares representative epitaxial structures of 940 nm-emitting VCSELs grown on Ge and GaAs substrates. The key difference in the epitaxial structure occurs in the nucleation and transition layers required when using Ge. These layers are added to stabilise the GaAs/Ge interface and to avoid the creation of new defects. They also maintain the performance comparable to VCSEL devices produced on GaAs substrates.

The GaAs substrates provide good lattice matching for AlGaAs DBRs and benefit from decades of process optimisation. However, GaAs is brittle, prone to wafer bow during thick DBR growth due to the small lattice mismatch, and its raw materials (Ga, As) are geopolitically sensitive. Ge substrates offer better lattice match and lower bow during growth for large area substrates, higher thermal conductivity, larger wafer diameters, and potential reuse via epitaxial lift-off. Nevertheless, Ge-based VCSELs grown on 200 mm substrates have exhibited non-uniformities and hotspot formation (Gillgrass et al. 2024) and require further development to reach the manufacturing maturity and performance already achieved for VCSELs on 150 mm Ge substrates. We note that in this paper, the term hotspot is not related to temperature but refers specifically to randomly distributed high-threshold current devices; it is not related to temperature.

GaAs-based VCSELs yield low defect densities and mature, high-yield growth processes. By contrast, Ge-based VCSELs require a nucleation layer and buffer layers to bridge the transition from a polar to non-polar semiconductor and the avoidance of growth issues associated with antiphase domains. While these layers are included to enable epitaxial growth on Ge, there is the possibility that the defect density (e.g. threading dislocations, antiphase domain boundaries) is higher than that of AlGaAs on GaAs growth, which potentially seeds hotspots. On the other hand, Ge offers higher thermal conductivity

Table 1. Compares the criticality attributes of Ge and GaAs across multiple dimensions (Kumar, Thorbole, and Gupta 2024; Nassar and Fortier 2021; Swart et al. 2011).

Dimension	Germanium (Ge)	Gallium arsenide (GaAs)
Chemical composition	Elemental semiconductor	Compound semiconductor (III–V: Ga + As)
Critical-material status	Listed as a *Critical Raw Material* (CRM) in EU and US frameworks	Composed of two *Critical Elements* (Ga and As)
Main applications	Infrared optics, fibre optics, solar-cell substrates, military optics	High-frequency and optoelectronic devices (5G, radar, VCSEL, LEDs)
Major producing countries	China (≈ 60%), Russia, Belgium, Canada, Japan	Ga is refined mainly as a by-product of bauxite; As is a by-product of copper/lead smelting; > 95% Ga refined in China
Abundance in crust	Extremely low (≈ 1.6 ppm)	Ga ≈ 19 ppm (low); As ≈ 1.8 ppm (moderate)
Supply risk	High – production concentrated in China/Russia; few refining sites	Very high – > 95% Ga refining in China; GaAs wafers rely almost entirely on Asian supply chain
Recycling rate	Around 2% end-of-life recycling input rate (European Commission 2023)	Around 0% for both Ga and As; gallium is recycled only within primary production and does not re-enter substrate manufacture (European Commission 2023; Ueberschaar, Otto, and Rotter 2017)
Environmental burden	Derived from coal combustion or zinc-slag residues; acidic and CO2 emissions	Involves toxic arsenides; requires sealed manufacturing systems
Substitutability	Moderate can be partly replaced by Si or InP in optics applications	Very low; no direct substitute for high-frequency or VCSEL devices
Strategic applications	Infrared imaging, space solar cells, optical communication	5G RF chips, radar, VCSELs, quantum communication
EU criticality rating (2023)	High risk but partially substitutable	Very high risk, low substitutability
Overall assessment	High criticality	Very high criticality

and larger wafer diameters, making it attractive for thermal management and scaling to 200 mm wafer platforms.

From a sustainability perspective, Ge supports thinner wafer designs, reduced breakage losses, and partial compatibility with silicon manufacturing infrastructure (Dong et al. 2025; Gillgrass et al. 2025). Although Ge substrates remain costlier and require further interface optimisation, their recyclability and established recovery routes make them strong candidates for sustainable material substitution in future III–V manufacturing. Table 1 summarises the comparative criticality and sustainability attributes of GaAs and Ge.

2.4. *Environmental assessment and circular economy*

While material substitution can mitigate specific supply-chain and toxicity risks, genuine sustainability in compound-semiconductor (CS) manufacturing requires a system-level understanding of energy and resource flows. Circular-economy (CE) and life-cycle assessment (LCA) approaches provide complementary perspectives for this purpose (Kuo et al. 2020). LCA quantitatively evaluates environmental burdens across a product's life, whereas CE aims to maintain material value through closed-loop resource circulation. Aguilar Esteva et al. (2020) demonstrated how these two frameworks can be combined by integrating energy and material loops within a unified life-cycle boundary, thereby quantifying renewable-energy use and recycled-material content as circularity metrics. Their automotive case study offers a transferable template for other manufacturing sectors seeking to operationalise CE strategies through LCA-based indicators.

Building on this framework, LCA provides a structured approach to quantify the environmental impacts of semiconductor processes from raw-material extraction to device end-of-life. For CS technologies, epitaxy and photolithography dominate the overall footprint due to energy-intensive growth conditions and the use of toxic precursors such as arsine (AsH3) and phosphine (PH3) (Luo et al. 2025). Recent studies (Kuo, Kuo, and Chen 2022; Luo et al. 2025) confirm that III–V materials such as gallium and indium possess among the highest per-gram impact scores because of their low natural abundance and complex separation procedures. Despite growing attention, LCA applications in CS manufacturing remain limited by non-standardised inventory data, incomplete process transparency, and weak integration with early-stage design. Addressing these gaps requires coupling LCA with real-time manufacturing data and design-for-sustainability frameworks to ensure that substitution or process modifications yield measurable reductions in environmental burden.

CE provides a complementary lens that emphasises closing material and energy loops in production systems (Pan et al. 2024; Paul et al. 2025). In the CS context, this involves material reuse, design-for-disassembly, and recycling of high-value elements such as Ga, In, and Ge through routes including hydrometallurgical processing and chemical delamination. While industrial examples such as TSMC's acid-recovery systems demonstrate feasibility in vertically integrated chains, scaling such initiatives across global multi-tier networks remains challenging for small-volume specialty materials (Awasthi et al. 2019; Dumée 2021).

Bridging LCA and CE perspectives enables decision-makers to balance environmental performance with supply-chain resilience. Embedding circularity into LCA-based decision models can reduce dependence on critical raw materials, lower environmental footprints, and support data-driven design of resilient, low-impact III–V technologies, providing the unified analytical foundation developed in Section 2.5.

2.5. Integrated sustainability perspective and research gaps

The present study draws on three complementary theoretical perspectives that together provide the conceptual foundation for the proposed integrated framework. First, Industrial Ecology and Circular Economy theory inform the assessment of material flows, end-of-life recovery, and environmental burdens across the product lifecycle, grounding the use of life cycle assessment and the Material Circularity Indicator as analytical tools (Ellen MacArthur Foundation, 2015 ; Kusiak 2020). Second, Supply Chain Resilience theory provides the conceptual basis for evaluating vulnerability, disruption risk, and material criticality, informing the construction of the Supply Risk Index and its integration into sustainability-oriented decision-making (Hosseini Shekarabi, Kiani Mavi, and Romero Macau 2025; Shishodia et al. 2023). Third, Multi-Criteria Decision Analysis serves as the decision-making framework for integrating heterogeneous sustainability dimensions into a structured and transparent evaluation process. Together, these perspectives position the proposed framework within established theoretical traditions and provide a conceptual basis for integrating environmental, circularity, and supply risk considerations in material substitution decisions.

Studies in other sectors show that supply-chain configuration can strongly influence environmental performance. For instance, Shamoushaki and Koh (2023) demonstrated this for the UK heat-pump supply chain. However, similar supply-chain-aware environmental analysis is rarely applied to compound semiconductors. The growing complexity of compound semiconductor (CS) manufacturing requires a unified sustainability perspective that integrates environmental and supply-chain dimensions (de Lima, Seuring, and Sauer 2021). While life-cycle assessment (LCA) provides quantitative insights into environmental burdens, it rarely captures the geopolitical and systemic risks associated with critical-mineral supply. Conversely, studies on supply-chain resilience focus on access, disruption, and cost but often overlook circularity or environmental performance (Wang, Tong, and Zhuang 2024). Bridging these analytical domains is essential for developing CS manufacturing pathways that are both environmentally sustainable and strategically resilient.

Recent literature further confirms that supply chain resilience research remains fragmented across multiple analytical streams, including optimisation modelling, digital technologies, and risk management approaches, with limited integration between these perspectives. These studies highlight that existing research often treats resilience and sustainability as separate domains, with insufficient attention to their joint role in supporting decision-making in complex manufacturing systems (Hosseini Shekarabi, Kiani Mavi, and Romero Macau 2025; Mönch, Uzsoy, and Fowler 2018; Shishodia et al. 2023).

Despite these advances, a clear gap remains. LCA studies of III–V materials seldom include upstream extraction data for gallium, indium, or arsenic, and often rely on generic proxies that fail to capture regional variations in energy intensity and emissions. Similarly, supply-chain assessments rarely quantify how substitution or recycling decisions influence life-cycle impacts. Few comparative frameworks incorporate supply-risk indices or circularity metrics into environmental models, leaving environmental and geopolitical dimensions disconnected. Moreover, most sustainability analyses stop at device performance, overlooking end-of-life recovery or design-for-disassembly principles that could substantially improve circularity (Kusiak 2020). Limited interdisciplinary collaboration between materials scientists, LCA analysts, and policy researchers further constrains the development of coherent data sets and decision tools.

Existing studies can be broadly categorised into two largely disconnected streams. On the resilience side, Mönch et al. (2018) surveyed semiconductor supply chain models encompassing network design and simulation, while Shishodia et al. (2023) and Hosseini Shekarabi, Kiani Mavi, and Romero Macau (2025) systematically reviewed supply chain resilience frameworks across multiple industries. However, none of these studies incorporate environmental impact assessment, circularity metrics, or material substitution decision support. On the sustainability side, Shamoushaki and Koh (2023) and Shamoushaki and Koh (2024b) demonstrated how supply chain configuration and background energy mix influence LCA outcomes, and a recent industrial-scale LCA of primary gallium production identified key emission hotspots relevant to compound semiconductor manufacturing (Luo et al. 2025). Notably, Luo et al. (2025) apply the same ReCiPe 2016 Midpoint methodology adopted in this study, confirming the methodological consistency of the approach while highlighting the absence of supply-risk and circularity dimensions in upstream material assessments. Most recently, Shamoushaki et al. (2026) conducted a geo-spatial prospective LCA of InGaN and InGaP compound semiconductors across 80 international supply chain scenarios, identifying epitaxial growth and substrate preparation as persistent environmental hotspots across all configurations. However, these LCA-focused studies do not extend to supply risk quantification or circularity indicators, nor do they provide a decision framework for material substitution. Alexopoulos et al. (2022) proposed a quantitative resilience measure for manufacturing systems but similarly omit environmental and circularity dimensions. Beyond compound semiconductor manufacturing, similar integration attempts remain incomplete elsewhere. One method combines criticality assessment with LCA (Hackenhaar et al. 2025). It frames criticality assessment as an 'outside-in' evaluation of external supply disruption risk. This contrasts with LCA's 'inside-out' quantification of a system's own environmental impacts. The two approaches differ in scope and data structure. Direct integration between them remains methodologically challenging. Within the production research literature, a data-driven model has also been developed for sustainable-resilient supplier selection (Gholami, Delorme, and Dolgui 2025). It does not incorporate a life-cycle environmental dimension. Separately, the concept of supply chain resilience itself has recently been shown to remain theoretically fragmented (Ruel, Zsidisin, and Blackhurst 2026). This taxonomy also omits any environmental or circularity dimension. Conceptual pathways toward sustainability and circularity in compound semiconductor manufacturing have also been outlined at a broader level (Yu et al. 2026). This work identified structural limits to circularity. It did not translate these ideas into a quantitative decision-support tool.In conclusion, no existing study integrates LCA, circularity metrics, supply risk assessment, and physics-informed device data within a unified decision framework applied to compound semiconductor manufacturing. This study addresses this precise gap.

In conclusion, this is the first study to integrate life cycle assessment, the Material Circularity Indicator, and a supply-risk index within a single quantitative decision framework, and to apply it to a device-level material substitution decision using measured production data. This differs from existing sustainability–resilience research, which has largely remained conceptual, addressed supplier selection rather than material selection, or assessed these dimensions separately rather than within a unified decision structure. By linking experimental device-level data with system-level sustainability and resilience metrics, the framework enables quantitative trade-off analysis for material substitution in compound semiconductor manufacturing.

3. Study design and scope

The objective of this study is to compare the performance and manufacturability of vertical-cavity surface-emitting lasers (VCSELs) fabricated on gallium arsenide (GaAs) and germanium (Ge) substrates, with particular emphasis on hotspot behaviour on the 200 mm substrate platform defined here as random, localised high-threshold current devices and wafer-scale yield. The broader motivation is to evaluate whether substrate substitution can contribute to more resilient and sustainable compound semiconductor manufacturing.

Two representative 940 nm VCSEL epitaxial wafers were investigated: a GaAs-substrate wafer and a Ge-substrate wafer. Both wafers were 200 mm (8-inch) substrates and subsequently processed using a quick VCSEL fabrication (QuickSEL) method, which enables rapid assessment of epitaxial quality and wafer-scale uniformity without full device processing (Baker et al. 2022). We note that the 200 mm Ge substrate growth is part of an optimisation study. This provides a controlled platform to isolate the influence of substrate choice on device metrics while keeping the epitaxial design and nominal fabrication process consistent.

The experimental scope is limited to post-fabrication characterisation and analysis. Wafer-scale electro-optical testing was carried out to extract the threshold current I_{th}, differential efficiency η_d, and spatial uniformity across the wafers. Hotspots were identified as localised devices exhibiting abnormally high I_{th} and degraded η_d, often corresponding to underlying crystal imperfections. Statistical hotspot mapping and yield analysis were used to quantify process efficiency and identify substrate-dependent behaviour.

Physically, we attribute these variations to material-related mechanisms including dislocation propagation, threading defect density, nucleation layer quality, surface morphology, and strain relaxation effects. However, a full determination of the underlying drivers of hotspot devices requires robust experimental measurements which are beyond the scope of this paper. Their combined influence is to increase the optical loss within a device, affecting both the threshold current and external differential efficiency. By linking these physical observations with yield-based process efficiency metrics, this study establishes an empirical foundation for integrating experimental data into sustainability analysis. The findings serve as a bridge between material-level phenomena and system-level evaluation, enabling subsequent life-cycle assessment (LCA) and circularity-risk modelling of GaAs and Ge substrates.

3.1. Empirical data acquisition and process efficiency metrics

Wafer-scale electro-optical measurements were performed on VCSELs fabricated using GaAs and Ge substrates to obtain empirical data for process efficiency analysis. Each wafer was tested under continuous-wave (CW) operation, and the threshold current (I_{th}) and differential efficiency (η_d) were extracted for every device using a dual-criterion algorithm combining power-threshold and curvature detection. The resulting I-V-L datasets were mapped across 16 wafer tiles to visualise spatial non-uniformities.

Hotspots were defined as devices exhibiting threshold currents above either $\mu + 2\sigma$ (where μ is the wafer-level mean and σ is the standard deviation; z-score outlier criterion) or above Q3 + 1.5×IQR (where Q3 is the third quartile and IQR is the interquartile range; Tukey outlier rule), alongside an observable drop in η_d. Yield was determined as the proportion of devices meeting both optical and electrical performance criteria within each tile.

These metrics quantify the material-related process efficiency of GaAs and Ge wafers. Yield and hotspot statistics serve as empirical inputs to the life-cycle inventory (LCI) model, linking device-level variability with system-level sustainability performance. By embedding these measured efficiency parameters into the functional unit of the LCA, the physical data obtained here provide the foundation for subsequent environmental and decision-modelling analyses.

3.2. Life cycle assessment framework

3.2.1. Goal and scope

The life cycle assessment (LCA) aims to quantify the environmental implications of substituting gallium arsenide (GaAs) with germanium (Ge) as the substrate material for vertical-cavity surface-emitting laser (VCSEL) manufacturing. The analysis supports the development of a material-substitution decision framework that integrates device performance, environmental sustainability, and supply-chain resilience within compound semiconductor manufacturing.

An attributional LCA was conducted to represent current industrial practice and evaluate the average environmental burdens of both substrate routes. The functional unit (FU) is defined as 1 cm⊐2 of functional VCSEL tile produced at wafer level (pre-packaging), meeting the baseline electrical and optical performance specifications. This area-based FU explicitly incorporates wafer yield, aligning with manufacturing throughput rather than device count.

3.2.2. System boundary

The study follows a cradle-to-gate scope encompassing all stages from raw material extraction and substrate fabrication to epitaxial growth and wafer-level device processing (Figure 5). Epitaxy for both GaAs and Ge wafers is modelled under consistent process assumptions to ensure comparability between the two substrate routes. The downstream packaging, use, and disposal phases are excluded, as the focus is on upstream manufacturing efficiency. Both routes share almost identical processing beyond the epitaxial stack, with the key difference being the substrate type and the N-contact metallisation scheme (AuGe/Ni/Au for GaAs versus Ni/Au for Ge). The Ge route introduces an additional end-of-life substrate reclaim scenario, reflecting 50–80% reclaim credit depending on recovery efficiency, whereas GaAs waste is treated as hazardous landfill without recycling. This boundary definition allows quantification of environmental trade-offs directly attributable to substrate choice.

3.2.3. Geographical and temporal scope

The model represents UK-based VCSEL manufacturing in 2024–2025, using primary data provided by Cardiff Lab and supplementary secondary data from the Ecoinvent v3.11 database for upstream processes and utilities. The UK electricity grid mix is applied in the base case, and alternative mixes are tested in sensitivity analyses to capture variations in renewable and fossil energy contributions.

3.2.4. Cut-off and allocation procedures

The life cycle inventory adopts a cradle-to-gate system boundary. Upstream processes, including electricity generation and the production of gases, chemicals and water, are taken from the Ecoinvent v3.11 database, which provides cradle-level data with embedded allocation rules. These are used without modification. The VCSEL fabrication sequence comprises single-output manufacturing steps, therefore no allocation procedures or system expansion approaches are required in the foreground model. All upstream and process-level environmental burdens are assigned directly to the functional unit.

3.2.5. Impact categories and methods

Environmental impacts are evaluated at the midpoint level using the ReCiPe 2016 (H) method. The analysis covers a set of indicators that capture climate impacts,

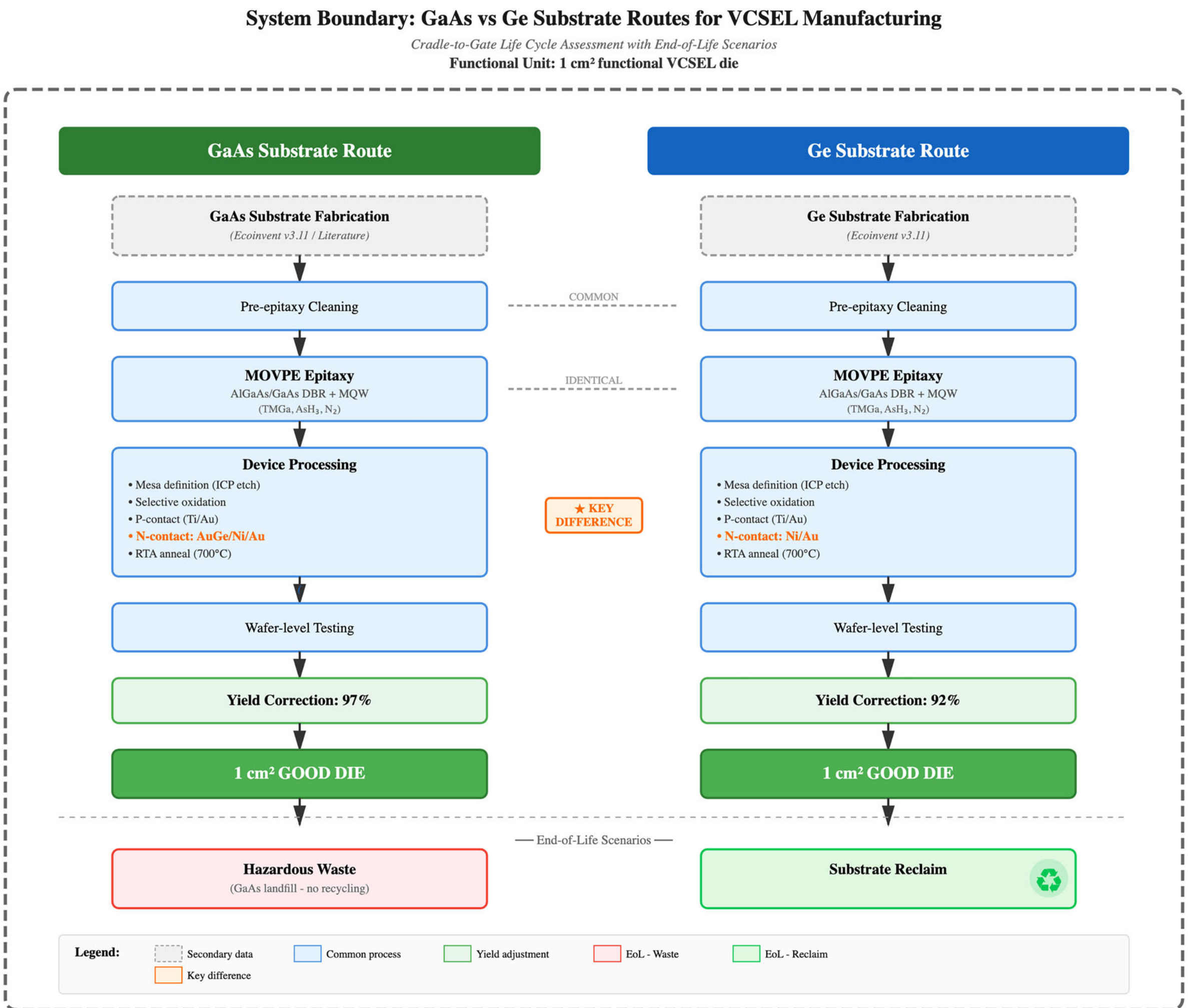


Figure 5. System Boundary: This cradle-to-gate LCA encompasses the full VCSEL manufacturing supply chain from substrate material production through epitaxial growth to device fabrication. The substrate production and epitaxial growth are upstream processes and included in the system boundary to enable comparative assessment of GaAs versus Ge substrate routes. The functional unit is defined as 1 cm⊃2 of processed VCSEL die ready for packaging.

resource use and toxicity-related burdens. These indicators include global warming potential (GWP, expressed in kilograms of CO_2 equivalent), cumulative energy demand (CED, expressed in megajoules), water use, human toxicity and ecotoxicity (both expressed in kilograms of 1,4-DB equivalent), and mineral resource scarcity (expressed in kilograms of copper equivalent). These midpoint indicators provide a comprehensive profile of the environmental differences associated with GaAs and Ge substrate routes.

3.2.6. Modelling assumptions

The device structures are assumed to be identical for both routes except for the substrate material and associated buffer layers. Material consumption, energy use and process waste are normalised by wafer yield, using yield values of 97 per cent for GaAs and 92 per cent for Ge. End-of-life differences are represented through a simplified scenario approach. Ge substrates are assigned a reclaim credit reflecting reported wafer-recovery efficiencies of fifty to eighty per cent, while GaAs substrates are treated as non-recyclable and sent to hazardous landfill. These assumptions allow the analysis to capture the circularity implications of substrate choice without modelling full waste-processing inventories.

This LCA framework provides a quantitative foundation for evaluating substrate substitution through both environmental and resource-efficiency lenses. It serves as the environmental dimension within the broader multi-criteria decision framework described in Section 3.5.

3.3. Circularity and supply-risk indicators

While the life-cycle assessment (LCA) quantifies environmental burdens, two complementary indicators were introduced to capture resource circularity and supply-chain vulnerability: the Material Circularity Indicator (MCI) and the Supply-Risk Index (SRI). Together, these extend the sustainability assessment beyond process emissions to encompass end-of-life recovery potential and raw-material criticality.

Material Circularity Indicator (MCI). The MCI app lied here is adapted from the Material Circularity Indicator framework of the Ellen MacArthur Foundation (2015), which quantifies how effectively materials remain within the industrial loop through recycling and reuse. The indicator compares actual material flows with an ideal circular system by combining the fraction of recycled content (F_r), end-of-life recycling rate (F_{eol}), and utility loss due to degradation (F_u):

$$MCI = \frac{1}{1 + \alpha(1 - F_r) + \beta(1 - F_{eol}) + \gamma F_u} \quad (1)$$

where α, β and γ are weighting factors (default $= 1$). For Ge, Fr was set at 0.50 based on reported recycled feedstock shares in commercial germanium refining, with F_eol varied across the reported wafer-recovery range of 0.50–0.80. GaAs was assigned Fr $=$ F_eol $= 0$, consistent with its reported zero end-of-life recycling input rate. This reflects the absence of commercial post-use recovery routes for arsenic-containing substrates, which are classified as hazardous waste; any in-process scrap recovery occurs before the substrate enters service and is therefore outside the end-of-life boundary. Fu was set to zero for both routes, as reclaimed substrates re-enter the same application without downgrading. Full derivation is provided in Supplementary Material S1. A higher MCI indicates a more circular material flow. In this study, Ge substrates are expected to show higher MCI values owing to their chemical delamination and reuse potential, while doped GaAs substrates exhibit lower recyclability due to contaminant retention and hazardous waste classification.

The SRI follows the composite approach of the European Commission's Critical Raw Materials methodology (European Commission 2023) and the USGS criticality framework (Nassar and Fortier 2021). It integrates four key parameters: (i) the Herfindahl–Hirschman Index of global production weighted by the World Governance Indicator (HHI_{wgi}); (ii) import reliance (IR); (iii) end-of-life recycling input rate ($EOL - RIR$); and (iv) the substitution index ($SI(SR)$) describing technical replaceability (Kuo et al. 2020). The composite formulation is:

$$SRI = HHI_{wgi} \times IR \times (1 - EOL - RIR) \times SI(SR) \quad (2)$$

normalised to a 0–1 scale, where higher values indicate greater supply vulnerability.

Key methodological point. These four parameters are not an ad-hoc selection. They are exactly the four parameters that the European Commission's own official Supply Risk (SR) score is built from. The EU CRM 2023 report states this explicitly in its description of the overall criticality methodology structure (see Figure 1 of that report, 'Overall structure of the criticality methodology'), which shows the Supply Risk parameter as a function of global supply concentration and EU sourcing concentration, each weighted by country governance (the World Governance Indicator), combined with import reliance, end-of-life recycling input rate, and the substitution index for supply risk.

As this study focuses on applying an integrated sustainability–resilience framework to a substrate-selection decision, rather than on developing or validating supply-risk methodology itself, we adopt the official SR scores already published in the EU CRM 2023 assessment as direct inputs to Eq. (2), rather than independently sourcing the four sub-parameters from scattered annexes and manually recombining them. Manual reconstruction would risk introducing our own aggregation error, not validated by any external body. Using the Commission's own already-computed score instead is methodologically more defensible, since it inherits a parameterisation that has been peer-reviewed and stakeholder-validated by DG GROW, rather than relying on our own assumptions about relative sub-weights.

Because GaAs requires both Ga and As, averaging their elemental supply-risk (SR) scores could dilute the contribution of the more supply-critical constituent. It would also be inconsistent with the system-failure logic in which disruption of any required input can constrain substrate production. (Rousseau et al. 2026) identify the maximum rule as the limiting case for strongly dependent elemental risks. Accordingly, the maximum rule is adopted here as a conservative aggregation approach, giving SR_GaAs $= \max(3.9, 1.9) = 3.9$. For Ge, the processing-stage SR score of 1.8 is used directly.

The SR scores are then divided by 10 to express them on a 0–1 scale. This gives SRI values of 0.39 for GaAs and 0.18 for Ge. These values are normalised using the same buffered min–max transformation (Eq. 3) applied elsewhere in the MCDA. As supply risk is a lower-is-better criterion, the resulting supply-resilience scores are 0.146 for GaAs and 0.933 for Ge. Higher values therefore indicate greater supply resilience.

As a check on the robustness of this input across methodologies, rather than as an independent derivation, we compared the resulting rankings against the USGS criticality framework (Nassar and Fortier 2021), which reports overall supply-risk scores (0–1 scale) of 0.67 for Gallium (rank 1 of 54), 0.49 for Germanium

Table 2. Data provenance for the Supply-Risk Index (SRI) parameters used in this study.

Parameter	Value	Source	Location
Gallium import reliance	98%	European Commission (2023)	Annex 1, "Critical Raw Materials overview"
Arsenic import reliance	39%	European Commission (2023)	Annex 1, 'Critical Raw Materials overview"
Germanium import reliance	42%	European Commission (2023)	Annex 1, 'Critical Raw Materials overview"
Gallium EoL-RIR	0%	European Commission (2023)	Annex 1, 'Critical Raw Materials overview"
Arsenic EoL-RIR	0%	European Commission (2023)	Annex 1, 'Critical Raw Materials overview"
Germanium EoL-RIR	2%	European Commission (2023)	Annex 1, 'Critical Raw Materials overview"
Gallium official Supply Risk (SR) score	3.9	European Commission (2023)	Annex 2, 'Overview of the Assessment Results'
Arsenic official Supply Risk (SR) score	1.9	European Commission (2023)	Annex 2, 'Overview of the assessment results"
Germanium official Supply Risk (SR) score	1.8	European Commission (2023)	Annex 2, 'Overview of the assessment results"
Gallium overall supply-risk score (cross-validation)	0.67 (rank 1 of 54)	Nassar and Fortier (2021)	USGS Open-File Report 2021-1045, Figure 3
Germanium overall supply-risk score (cross-validation)	0.49 (rank 24 of 54)	Nassar and Fortier (2021)	USGS Open-File Report 2021-1045, Figure 3
Arsenic overall supply-risk score (cross-validation)	0.45 (rank 30 of 54)	Nassar and Fortier (2021)	USGS Open-File Report 2021-1045, Figure 3

All values are cited directly from the referenced sources; derived quantities (e.g. the GaAs aggregate score, normalised supply-resilience scores, and their propagation through the MCDA composite score) are calculated from these inputs, with full derivation steps provided in Supplementary Material S1.

(rank 24), and 0.45 for Arsenic (rank 30). Both frameworks agree that Gallium carries substantially higher supply risk than either Arsenic or Germanium, corroborating the ranking obtained from the EU CRM-derived SRI used in this study. We note a minor reversal in the relative ordering of Arsenic and Germanium between the two frameworks (EU CRM: As slightly above Ge; USGS: Ge slightly above As), which is attributable to the two methodologies weighting EU-specific versus U.S.-specific trade exposure differently. This reversal does not affect the substrate-level comparison, since Gallium's risk dominates the GaAs aggregate in both frameworks. Full derivation details are provided in Supplementary Material S1 (Table 2).

The MCI and SRI together form the circular-economy and resilience dimensions of this study, complementing the environmental dimension captured by the LCA and enabling multi-criteria comparison of substrate options in Section 3.5.

3.4. Integrated multi-criteria decision framework (MCDA)

The multi-criteria decision analysis (MCDA) integrates the environmental (LCA), circularity (MCI), and risk (SRI) dimensions into a single evaluation framework. Each metric is normalised (0–1 scale) using a min–max transformation:

$$N_i = \begin{cases} 1 - \frac{X_i - X_{min}}{X_{max} - X_{min}}, & \textit{if lower is better} \\ \frac{X_i - X_{min}}{X_{max} - X_{min}}, & \textit{if higher is better} \end{cases} \quad (3)$$

where X_i denotes the original value, and N_i the normalised score.

The overall sustainability score is computed as: $S = w_E N_E + w_C N_C + w_R N_R$, where w_E, w_C and w_R represent the weights assigned to the environmental (LCA), circularity (MCI), and risk (SRI) dimensions respectively, with equal weights (1/3 each) applied in the baseline case.

To enable decision-oriented comparison across inherently heterogeneous sustainability dimensions, the framework operationalises environmental performance, material circularity, and supply-chain resilience into measurable indicators through life cycle assessment (LCA), the Material Circularity Indicator (MCI), and the Supply Risk Index (SRI), respectively. This transformation allows abstract concepts such as environmental impact, circularity, and resilience to be captured in quantifiable terms and incorporated into a structured decision-making process.

The selection of GWP, MCI, and SRI as the operationalising metrics reflects both data availability and policy relevance. GWP is adopted as the primary environmental indicator because it is the most widely regulated and policy-relevant environmental metric globally, directly linked to legally binding targets under the UK Climate Change Act, the EU Green Deal, and the Paris Agreement. Carbon performance is also increasingly associated with financial risk through corporate reporting frameworks such as Scope 3 emissions disclosure and the Task Force on Climate-related Financial Disclosures (TCFD), making it a highly decision-relevant indicator for manufacturing firms. MCI captures the circularity dimension by quantifying how effectively substrate materials remain within the industrial loop, directly reflecting the end-of-life recyclability asymmetry between Ge and GaAs that is central to this study. SRI captures supply-chain resilience by integrating production concentration, import reliance, recycling input rate, and substitutability into a composite score, translating complex geopolitical and structural risks into a quantifiable decision input.

To ensure comparability, all indicators are normalised to a common scale and directionally aligned, enabling them to be treated as commensurable criteria within the MCDA structure. The trade-off between these dimensions is resolved using a Simple Additive Weighting (SAW) approach with equal weights (1/3 each), which serves as a neutral baseline assumption rather than an assertion of equal real-world importance. This approach avoids introducing subjective preference bias in the absence of stakeholder-specific priorities and is consistent with established MCDA practice in sustainability assessment, where no universally accepted weighting scheme exists across heterogeneous criteria.

The framework is inherently flexible and allows weighting schemes to be adjusted to reflect different industrial priorities, regulatory contexts, or decision-maker preferences. In this study, equal weighting is adopted to provide a transparent and generalisable reference case for comparative assessment, without imposing predefined value judgements across dimensions.

Regarding economic viability, this dimension is not incorporated as a fourth MCDA criterion due to the absence of commercially comparable cost data at the 200 mm wafer scale. Instead, economic considerations are addressed through a qualitative feasibility analysis in Section 5.3.

Supplementary Material S1 provides the full computational basis for the framework, including the raw indicator values, normalisation bounds, and derivation of the MCI and SRI inputs. It also reports three sensitivity analyses, covering the weighting scheme, the reported range of germanium reclaim efficiencies, and wafer yield, together with a pedigree-matrix assessment of foreground data quality. The ranking is unchanged across all scenarios tested, with the composite score ratio remaining between 2.21 and 7.22 across weighting scenarios and between 4.06 and 4.38 across the reclaim range.

4. Results

4.1. Experimental analysis: process efficiency and hotspot behaviour

Building on the material-level compatibility established in Section 1, this section compares the manufacturing performance of 200 mm GaAs- and Ge-based VCSEL wafers to evaluate their practical substitution feasibility. Wafer-scale threshold-current measurements

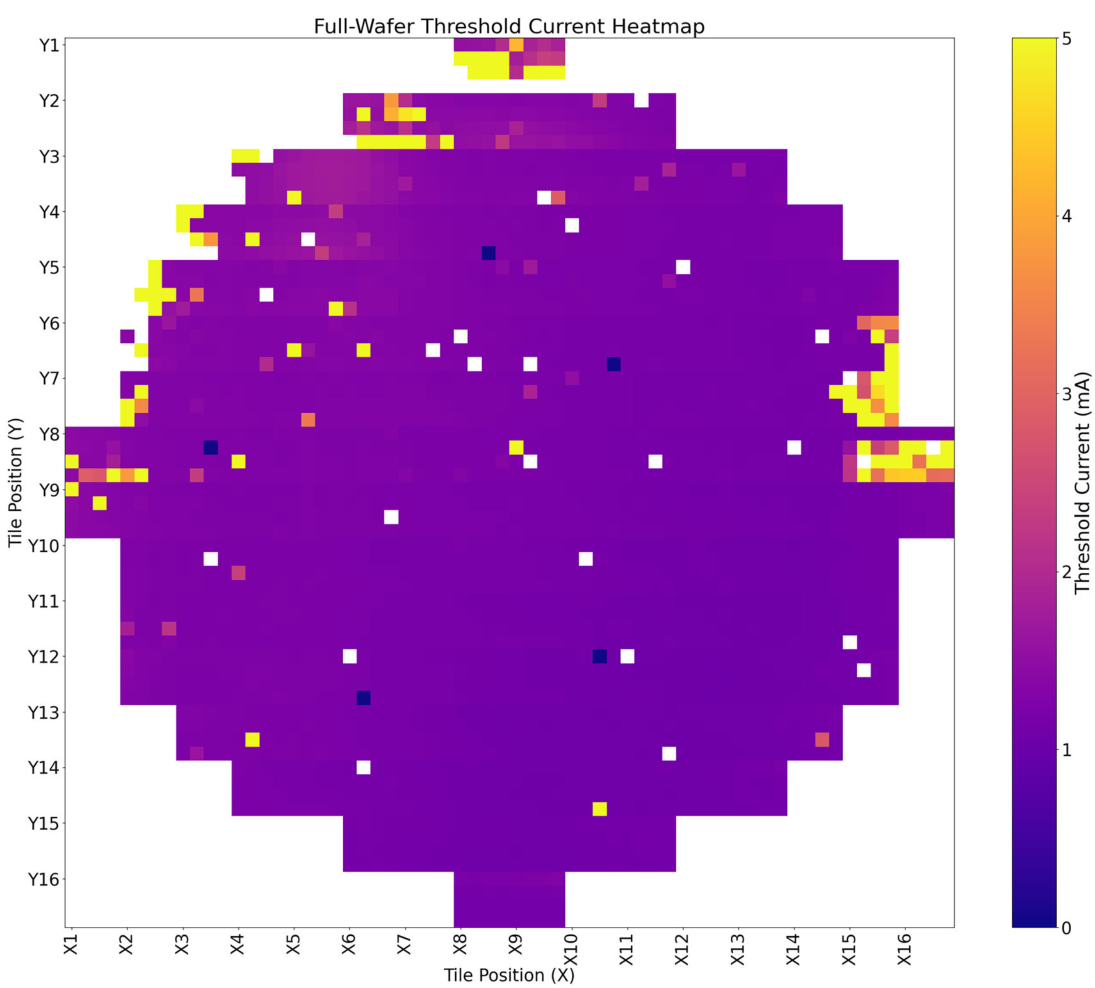


Figure 6. Full-wafer threshold current heatmap of the GaAs-substrate wafer.

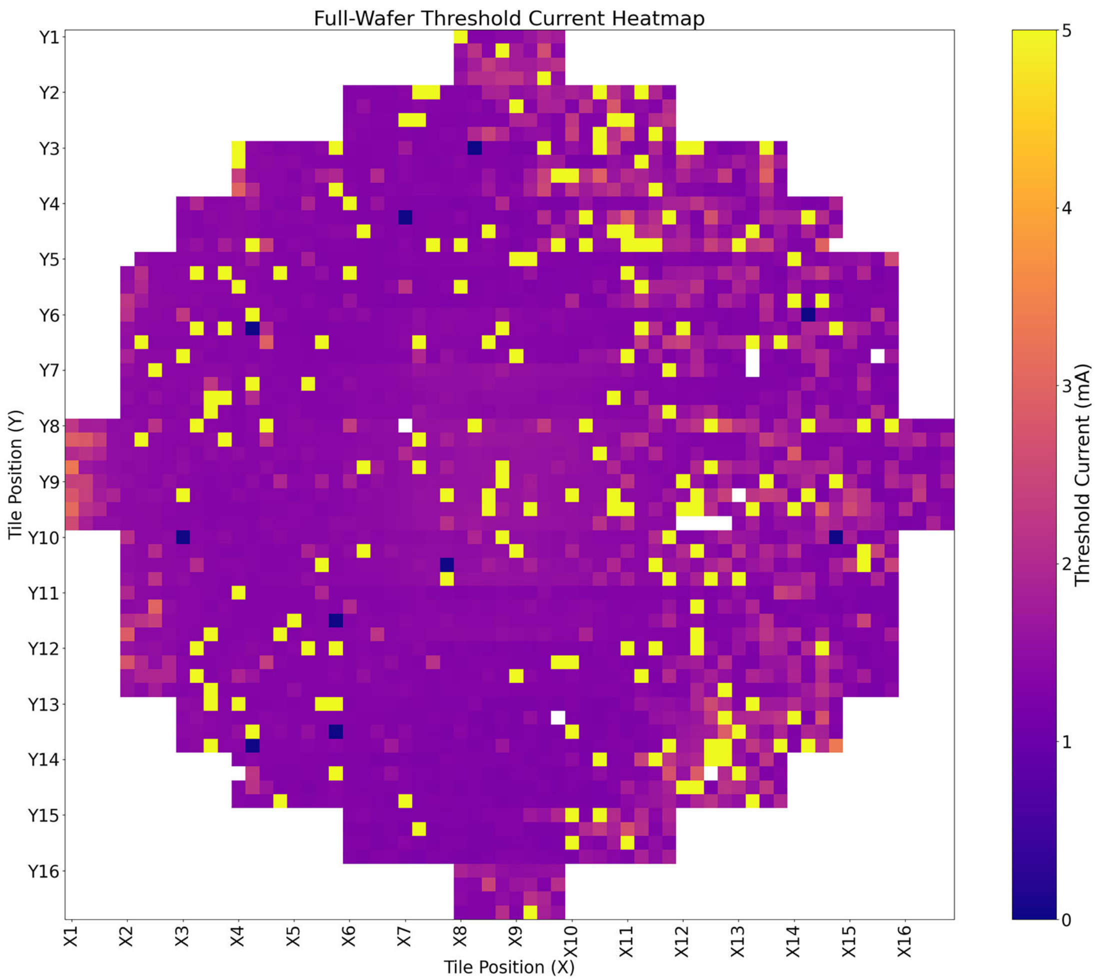


Figure 7. Full-wafer threshold current heatmap of the Ge-substrate wafer.

were performed under identical fabrication and testing conditions.

Figures 6 and 7 present full-wafer threshold current I_{th}maps for the Ge-substrate and GaAs-substrate wafers, respectively. Each pixel corresponds to a single device, colour-coded according to its extracted threshold current.

The Ge wafer (Figure 7) exhibits a noticeably larger population of elevated-threshold devices distributed across both central and peripheral regions. A small number of extreme outliers attributable to threshold-extraction instability were excluded, as described below. The remaining high-thresholdI_{th} devices represent true electro-optical degradation, contributing to the long-tailed threshold distribution observed across the Ge wafer.

To verify the reliability of the threshold-extraction method and to demonstrate the physical validity of the identified hotspots, we examined the raw electro-optical characteristics of all devices measured at a representative wafer position (D59) (Figure 8). The raw P-I curves show that most devices have consistent lasing turn-on and comparable slope behaviour, whereas a few have particularly delayed threshold changes. The corresponding V-I curves remain tightly grouped, showing that these variances are not due to electrical artifacts or measurement noise. Differential-efficiency analysis suggests that the high-threshold devices also have a lower maximum slope efficiency. The inverse correlation between I_{th} and $\eta_{d,max}$, as shown in the threshold-versus-efficiency scatter graph, shows that hotspot devices are likely caused by localised performance deterioration. Importantly, this pattern differs qualitatively from the characteristics of threshold-extraction failure; such algorithmic faults were recognised and addressed prior to analysis.

Complementary histogram analysis (Figure 9) shows that both wafers exhibit long-tailed Ith distributions, but with distinct signatures. The Ge wafer retains a minority of devices in a high-current tail despite most devices clustering near the nominal operating point, reflecting randomised hotspot formation. In contrast, the GaAs wafer exhibits a broader overall spread with a

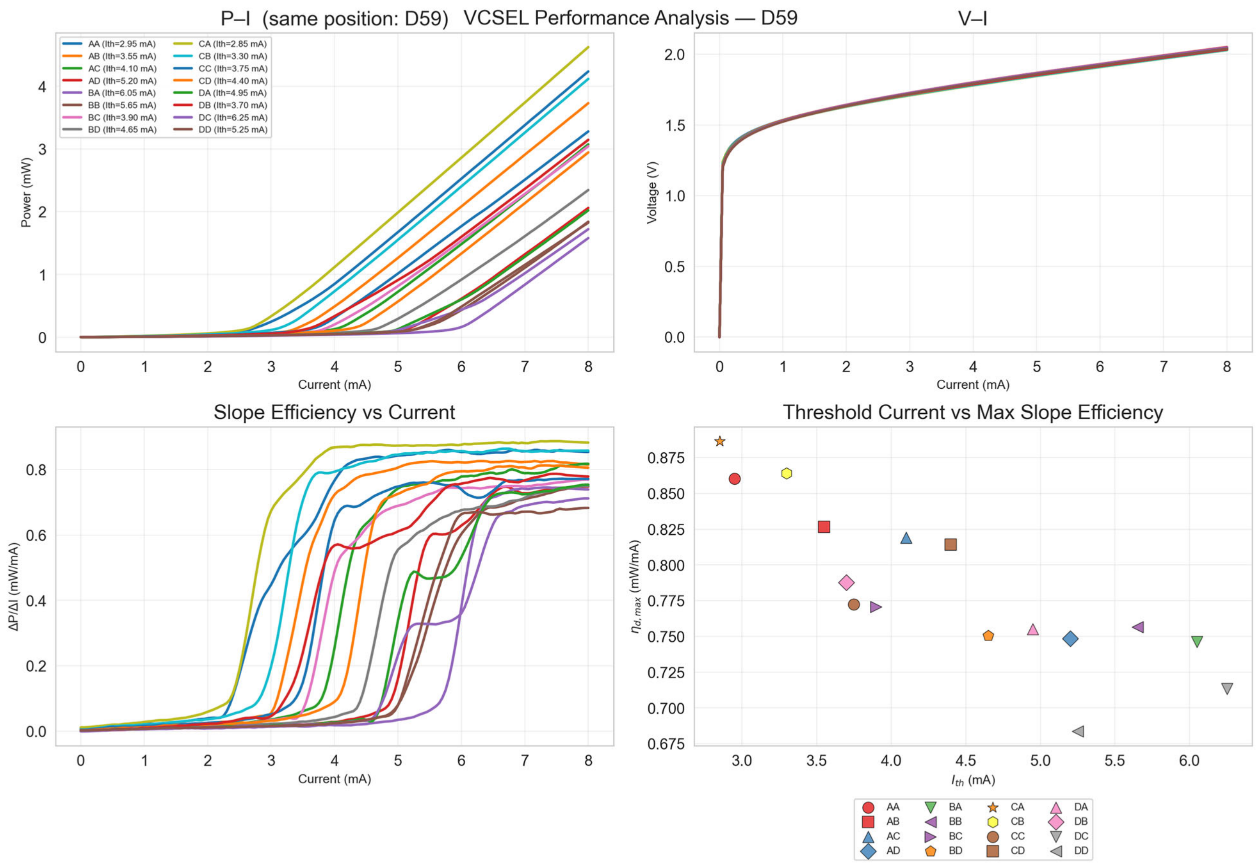


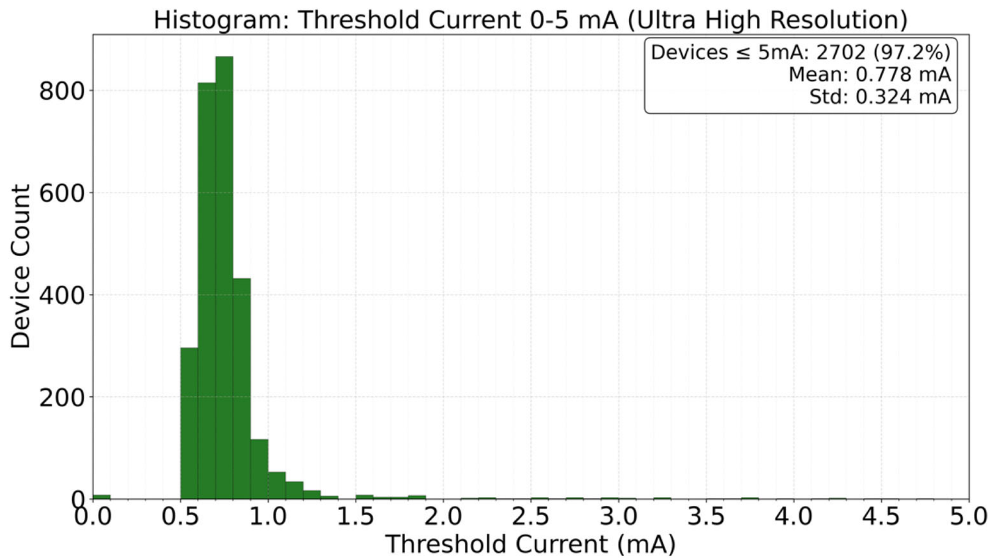
Figure 8. Raw P–I, V–I, slope-efficiency and I_{th}–$\eta_{d,max}$ characteristics for devices at wafer position D59, showing consistent nominal behaviour and a clear correlation between elevated threshold current and reduced differential efficiency.

pronounced edge-driven tail, consistent with large-scale non-uniformity from epitaxial growth.

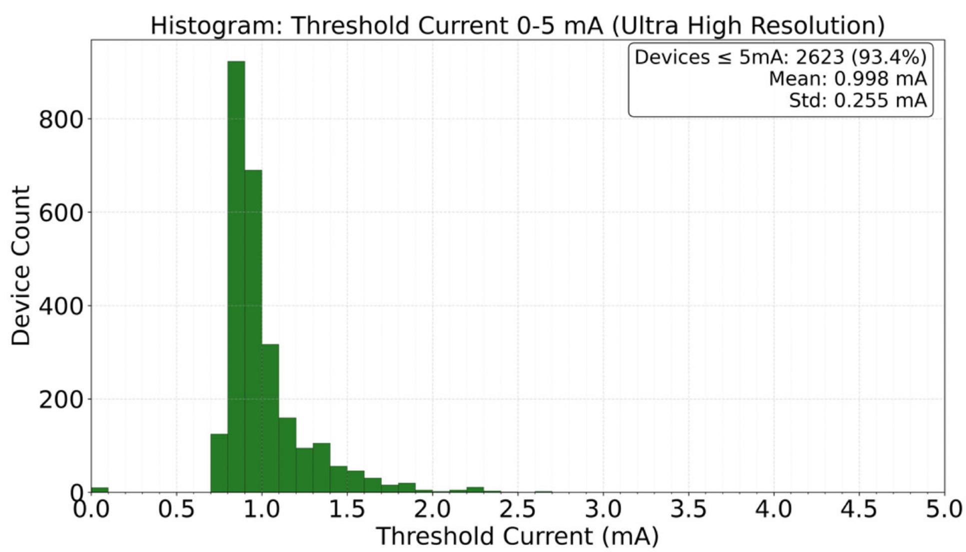
Taken together, these results indicate that Ge wafers are characterised by randomised high-threshold outliers (hotspots), while GaAs wafers show greater overall uniformity but systematic edge degradation. These trade-offs directly impact wafer-scale yield and highlight the need for further optimisation.

To further investigate the origin of non-uniformities, we conducted a high-resolution analysis of the tile from the Ge-based wafer (Figure 10). Unlike earlier sections, where only one representative device per group was sampled, here all 16 groups (AA–DD) with 100 devices each were measured, yielding a dataset of more than 1,100 devices. This allows a comprehensive evaluation of spatial variations, statistical distributions, and structural dependencies within a single tile.

Using this dataset, additional diagnostic checks were carried out to further narrow down the physical origin of these hotspots. Optical microscopy inspection of representative devices revealed no visible fabrication defects, such as damaged mesas or broken contacts, ruling out gross process errors as the primary cause. Threshold current was found to scale systematically with mesa size, as expected from device geometry; however, a substantial spread in threshold current remained among devices of the same mesa size, indicating that geometry alone cannot account for hotspot formation. Combined with the inverse correlation between threshold current and differential efficiency noted above, this pattern is consistent, under the standard threshold-gain condition for semiconductor lasers, with increased internal optical loss, potentially involving material-related defects such as threading dislocations or anti-phase domains, which are known to form at the Ge/III-V heterointerface due to lattice and polarity mismatch, rather than with mirror-reflectivity-related loss. To further test this hypothesis, reverse-bias leakage measurements were performed on the same devices. A weak but statistically significant positive correlation was found between threshold current and reverse leakage current, indicating that leakage-related mechanisms alone are insufficient to explain the observed hotspot behaviour. Taken together, these diagnostic results are consistent with a material-related internal-loss mechanism as a candidate cause of hotspot formation; however, direct microstructural confirmation was beyond the scope of the present study.



(a)



(b)

Figure 9. Histograms of threshold current distributions for all devices measured on (a) the GaAs-substrate wafer and (b) the Ge-substrate wafer.

Overall, the results indicate that Ge can reproduce GaAs-level device performance but currently suffers from more pronounced local non-uniformities. These observations highlight both the physical feasibility and the process maturity challenges of Ge substitution, forming the empirical foundation for the life-cycle assessment in section 4.2.

4.2. Environmental assessment (LCA baseline comparison)

Building on the experimental comparison in Section 4.1, a cradle-to-gate life-cycle assessment (LCA) was conducted to quantify the environmental implications of substrate substitution from GaAs to Ge in VCSEL manufacturing. The analysis aims to evaluate whether the potential sustainability benefits of Ge with lower resource criticality and higher reclaim potential can outweigh the additional process variability observed experimentally. We note that further epitaxial growth development is expected to reduce this variability.

The functional unit was defined as 1 cm⊃2 of good VCSEL tile produced at wafer level, incorporating the yield correction derived from Section 4.1. The system boundary covers substrate fabrication, epitaxial growth, and wafer-level device processing up to the finished die. Impact categories include global warming potential (GWP), cumulative energy demand (CED), water use,

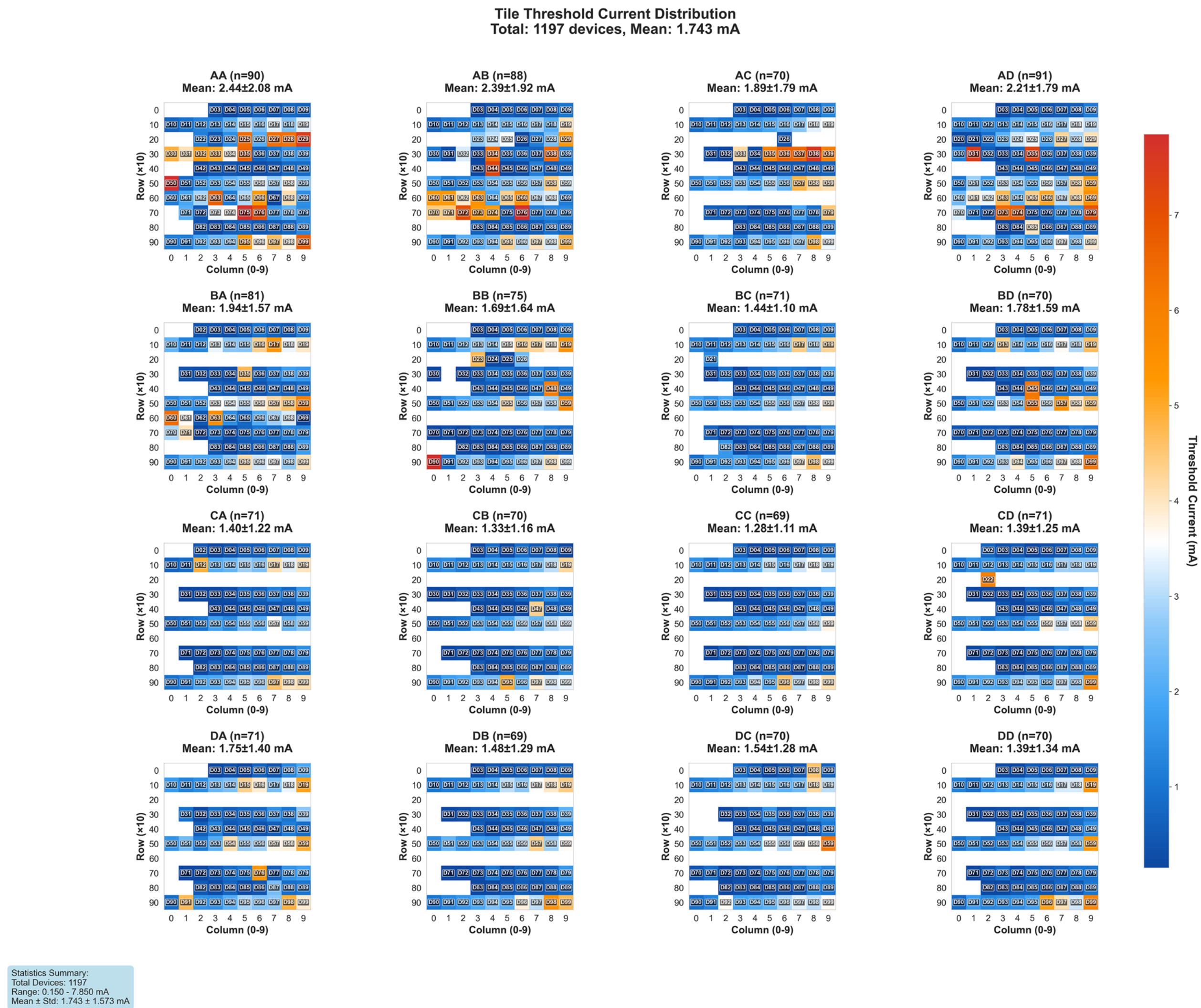


Figure 10. Full-tile threshold current distribution. The majority of devices exhibit I_{th} around 1.6 mA, though isolated high-current hotspots are visible. No clear spatial trend across the 4 × 4 groups can be identified, suggesting that randomised defects rather than systematic process gradients dominate intra-tile variation.

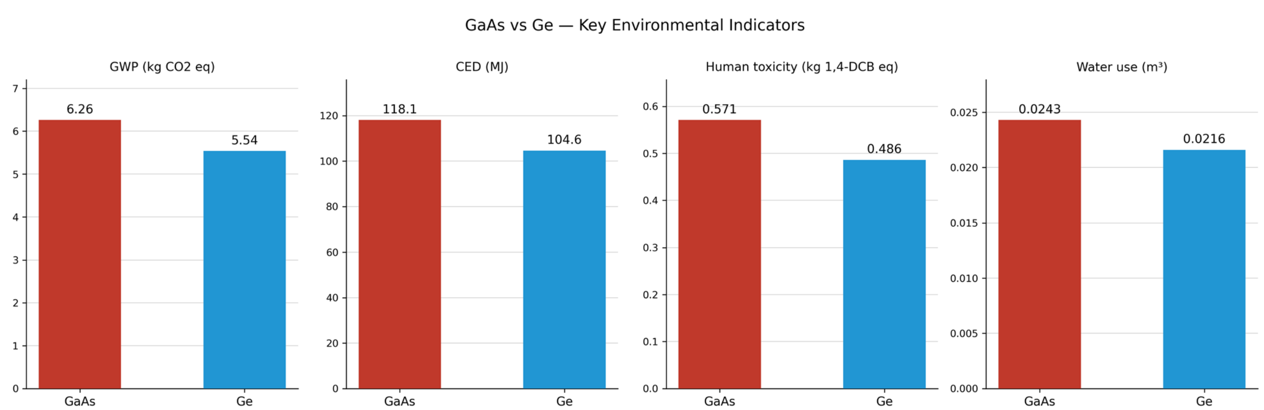


Figure 11. Comparison of four major midpoint impact categories obtained from the cradle-to-gate LCA of VCSEL wafer fabrication: Global Warming Potential (GWP), Cumulative Energy Demand (CED), Human Toxicity (carcinogenic, kg 1,4-DCB eq), and Water Use (m^3). Each bar represents the impact per functional unit (1 cm⊃2 processed wafer area). Red indicates GaAs and blue indicates Ge. Across all four categories, GaAs shows slightly higher environmental burdens compared with Ge.

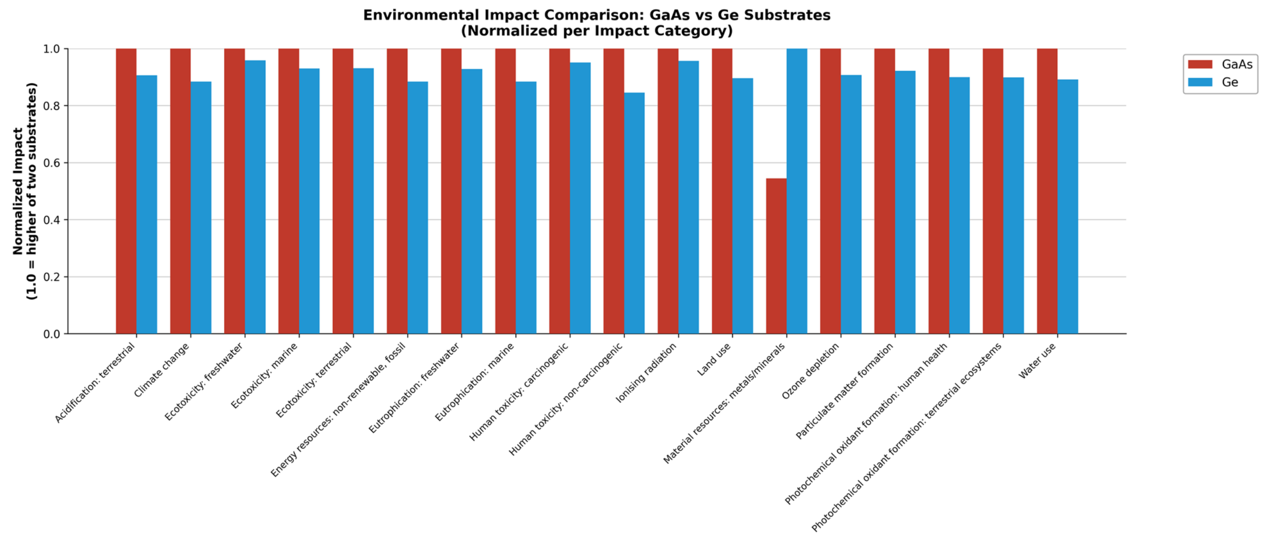


Figure 12. Normalised life-cycle environmental impacts of GaAs and Ge substrates across all 18 ReCiPe midpoint categories. Each midpoint indicator is independently normalised so that 1.0 represents the higher-impact substrate. Red indicates GaAs and blue indicates Ge. Ge consistently shows lower normalised impacts across all categories, except in material resources. The most pronounced differences were observed in land use, ionising radiation, and human toxicity indicators.

human toxicity, and mineral resource scarcity. Figure 11 shows four major environmental indicators that are most relevant to policy and industrial practice: global warming potential, cumulative energy consumption, human toxicity, and water usage. These metrics were chosen because they reflect the primary sources of environmental impact in compound semiconductor fabrication and are often utilised in regulatory and sustainability assessments. Across all four measures, the findings demonstrate that Ge consistently has lesser effects, with reductions ranging from approximately 11 to 15 per cent. These savings are due to the elimination of arsenic from the material system, decreased cumulative energy consumption during substrate manufacturing, and the possibility of partial substrate recovery. Using a normalised grouped bar chart, Figure 12 broadens the study to include all ReCiPe midpoint indicators. The analysis demonstrates that Ge outperforms GaAs across the majority of midpoint categories, with the single exception of material resources (metals and minerals). These variations result from differences in upstream material processing, with GaAs constrained by arsenic toxicity and a more energy-intensive epitaxy chain. Taken together, the two figures demonstrate that Ge provides significant benefits in important impact areas while also presenting particular trade-offs that must be addressed when assessing material substitution in semiconductor manufacture.

The extended analysis across all 18 ReCiPe midpoint indicators (Figure 12) confirms that Ge consistently outperforms GaAs across the full impact profile, with Ge showing lower environmental burdens across most impact categories, except in material resources. Reductions range from approximately 11% in water use and ecotoxicity-related indicators to over 45% in land use, reflecting the combined effect of differences in upstream refining chains, process chemistry, and end-of-life treatment for Ge. The most policy-relevant improvements are observed in climate change, human toxicity, and energy resource consumption, where the elimination of arsenic-based chemistry and lower cumulative energy demand in the Ge route contribute to meaningful reductions. The exception is material resources (metals/minerals), where GaAs outperforms Ge; this reflects the fact that gallium and arsenic are recovered as by-products of aluminium and zinc smelting, resulting in a lower allocated mineral resource burden compared with germanium, which requires dedicated extraction and refining from coal fly ash or zinc ores. These results confirm that the environmental advantages of Ge substitution are broad-based rather than limited to specific impact categories, strengthening the case for Ge as a more sustainable substrate material across multiple dimensions of environmental performance. Section 4.3 extends this analysis by incorporating circularity metrics and supply-risk indicators, thereby providing a complete multi-criteria evaluation of the two substrate options.

Table 3. Comparative sustainability indicators for GaAs and Ge substrate routes.

Indicator	Definition	Unit / Scale	GaAs	Ge	Relative interpretation
MCI (Material Circularity Indicator)	Based on recycled content, EoL recycling rate, and utility loss (Ellen MacArthur Foundation 2015)	0–1	0.33	0.54	Ge shows higher circularity due to reclaimable substrates and lower contamination
SRI (Supply Risk Index)	Weighted composite of production concentration, governance, import reliance, recycling input, and substitution index (European Commission 2023; USGS 2021)	0–1	0.39	0.18	Ga has 98% import reliance and negligible recycling input; As has moderate import reliance (39%) but negligible recycling input; Ge has lower import reliance (42%) and modest recycling input (2%), resulting in a lower composite supply-risk score. Cross-validated against USGS criticality rankings.
Environmental Score (LCA composite)	Normalised mean of GWP, CED, toxicity, water use	0–1	0.32	0.72	Ge route scores ~55% higher on the normalised environmental composite

4.3. Framework synthesis and implications

The environmental comparison presented in Section 4.2 forms the first dimension of the proposed sustainability–resilience framework. Beyond environmental performance, the framework integrates circularity and supply-chain risk dimensions to provide a more comprehensive assessment of material substitution (Table 3).

The Material Circularity Indicator (MCI) represents the resource-efficiency perspective, quantifying how effectively materials are retained within industrial cycles through recycling and reuse. The Supply-Risk Index (SRI) captures vulnerability to raw-material supply disruption by combining production concentration, geopolitical stability, and end-of-life recycling input rates. Together, these two indicators extend the LCA beyond environmental metrics to system-level sustainability.

Qualitatively, Ge substrates are expected to exhibit higher circularity due to their reclaimable nature and lower contamination levels, whereas GaAs involves arsenic-containing compounds that hinder recycling. Conversely, Ga and As are classified as critical raw materials with high production concentration and low end-of-life recycling input rates, leading to higher supply-risk scores.

These indicators are integrated through a Simple Additive Weighting (SAW), a widely applied multi-criteria decision analysis (MCDA) approach to generate an overall sustainability–resilience score. Each dimensions (environmental, circularity, and risk) are normalised to a 0–1 scale using a buffered min–max transformation (±10% bounds) to reduce outlier sensitivity. Equal weights are then assigned to the three dimensions, reflecting a balanced sustainability perspective. The final sustainability–resilience score is obtained through a linear additive aggregation of the weighted normalised indicators. This SAW-based evaluation provides a transparent and interpretable basis for comparing GaAs and Ge substrate routes.

Figure 13 shows the results comparing GaAs and Ge substrates using the buffered normalisation method (±10%). Three sustainability dimensions environmental performance (GWP), circularity (MCI), and supply resilience (1-SRI) were normalised on a 0–1 scale with equal weighting. Ge exhibits consistently higher normalised scores across all criteria, resulting in a 4.2× higher composite sustainability score ($S = 0.822$) relative to GaAs ($S = 0.194$). Buffered normalisation prevents endpoint saturation while preserving the relative performance distances between indicators. These results suggest that although Ge manufacturing currently shows slightly lower yield and higher process variation (Section 4.1), its advantages in environmental impact, circularity, and supply security could collectively result in a more sustainable substrate pathway, particularly as maturity improves. To examine whether the conclusion is sensitive to the weighting assumption, a weighting sensitivity analysis was conducted, including scenarios with increased emphasis on individual dimensions and limiting cases where the entire weight is assigned to a single dimension. Detailed results are provided in Supplementary Material S1. Ge achieves higher normalised scores than GaAs across all three dimensions individually. As the composite score is calculated as a weighted combination of these dimension-level scores, the ranking remains consistent across the evaluated weighting scenarios. The magnitude of the relative advantage varies depending on the assigned priorities. Across the evaluated scenarios, the Ge-to-GaAs score ratio ranges from 2.21 to 7.22, while the equal-weight case adopted in this study results in a ratio of 4.2.

The quantitative implementation of the full framework including the MCI, SRI, and MCDA results are discussed in the next stage of the analysis. The outcomes of this integration serve as the foundation for the broader discussion of trade-offs and policy implications in Section 5.

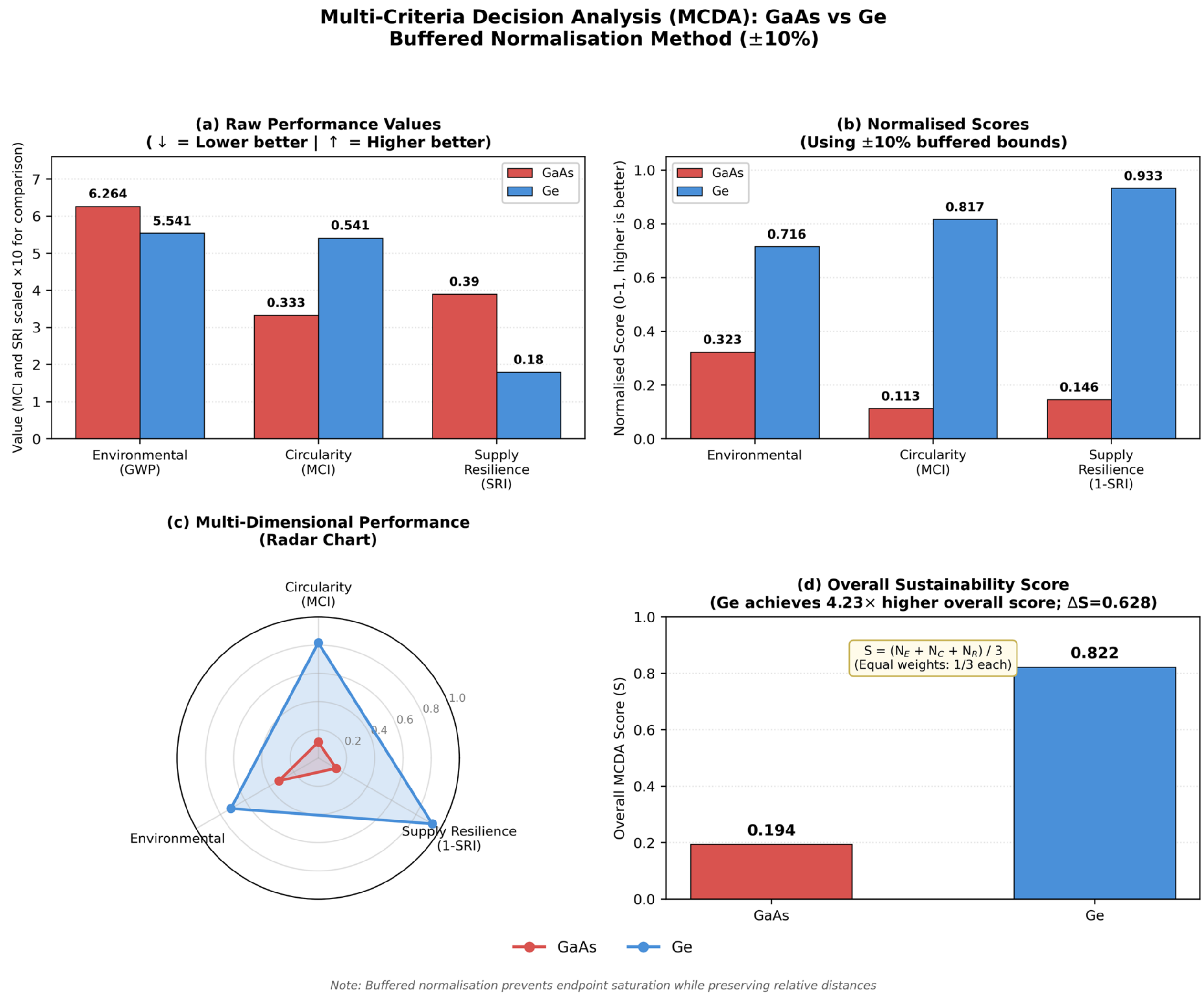


Figure 13. Multi-Criteria Decision Analysis (MCDA) results for comparing GaAs and Ge substrate.

5. Discussion

5.1. Interpretation of key findings

The results presented in Section 4 collectively demonstrate the dual nature of germanium (Ge) substitution in compound semiconductor manufacturing: while technical maturity remains a limiting factor, the potential sustainability gains are substantial. The experimental comparison in Section 4.1 confirmed that Ge-based VCSELs can achieve comparable threshold-current distributions and optical performance to their GaAs counterparts, however with higher local non-uniformities. These hotspots are defined as randomised high-threshold outliers which indicate defect propagation in Ge-based epitaxy, requiring further optimisation. Nevertheless, the overall yield and process reproducibility achieved in this study confirm the physical feasibility of Ge as a substrate material for large-diameter VCSEL wafers.

From a sustainability perspective, the cradle-to-gate LCA (Section 4.2) shows that Ge has lower environmental burdens across multiple midpoint categories, including global warming potential (GWP), cumulative energy demand (CED), and human toxicity. This advantage primarily arises from the elimination of arsenic-containing compounds and the higher recyclability of Ge wafers. The results are present in the radar comparison in Figure 13, where Ge outperforms GaAs in several environmental dimensions. In parallel, the multi-criteria indicators introduced in Section 4.3—the Material Circularity Indicator (MCI) and the Supply Risk Index (SRI)—together show that Ge achieves a higher circularity score (0.54 vs 0.33) and a much lower supply-risk score (0.18 vs 0.39). When integrated through the multi-criteria decision analysis (MCDA), Ge has a composite sustainability–resilience score approximately 4.2 times higher than that of GaAs.

Taken together, these findings show that while Ge substitution currently introduces greater process variability, its advantages in environmental performance, recyclability, and material security substantially outweigh the drawbacks associated with manufacturing immaturity. These results suggest that targeted improvements in epitaxial quality and wafer uniformity could unlock the full sustainability potential of Ge-based VCSEL production at industrial scale.

From a decision-making perspective, this indicates that material selection in compound semiconductor manufacturing should not be evaluated solely based on process maturity, but rather through a multi-dimensional framework that incorporates environmental impact, circularity, and supply chain resilience as core criteria.

5.2. Trade-offs between performance, environment, and resilience

The comparison between GaAs and Ge highlights a critical trade-off between short-term process efficiency and long-term system sustainability (Ivanov 2023). GaAs remains a technologically mature platform with high yield and well-established epitaxial recipes. However, this maturity is offset by intrinsic material constraints that are toxicity, poor recyclability, and extreme supply concentration. By contrast, Ge offers a single-element, non-toxic alternative with a diversified supply base and potential established recovery routes, but currently suffers from limited process maturity.

Previous research (Gillgrass et al. 2023 ; Johnson et al. 2021; Dong et al. 2025 ; Gillgrass et al. 2025) on 150-mm Ge-substrate VCSELs demonstrated that Ge devices could achieve performance equivalent to GaAs, including threshold current and efficiency. This demonstrates that the material has no fundamental performance limitations. The differences found in the current 200-mm wafers represent regular early-stage optimisation, and there is no fundamental reason comparable performance cannot be achieved as the 200-mm platform matures.

At present, the measured hotspot formation in 200 mm Ge-based wafers implies that yield losses may reach approximately 5% under current process conditions. On the other hand, the environmental and strategic gains quantified in this study show approximately 11-15% lower normalised environmental impact and an approximately 4.2-fold increase in the composite sustainability score. These suggest that even before the current process immaturities are resolved, such yield penalties are acceptable within a broader sustainability–resilience framework. As manufacturing processes evolve, improvements in buffer-layer design, dislocation management, and oxidation uniformity are expected to close the yield gap without sacrificing environmental advantages.

In terms of supply-chain resilience, the substitution of GaAs with Ge also mitigates systemic concentration risks. Gallium refining is highly concentrated in China (import reliance 98%), while arsenic shows moderate import reliance (39%); both show negligible end-of-life recycling input, exposing global supply to geopolitical tensions and export restrictions. In contrast, germanium production is distributed across multiple regions, including China, Russia, and the EU, with a modest end-of-life recycling input rate (2%) that nonetheless exceeds that of gallium and arsenic. These structural differences translate into an approximately 54% reduction in the composite SRI value for Ge, confirming its strategic advantage in a resilience-oriented material strategy.

Overall, the findings reinforce the need to transition from purely performance-centric design to a balanced framework that considers environmental, circular, and resilience dimensions. The moderate yield trade-offs associated with Ge substitution are an investment in long-term sustainability and supply security, not a technical retreat. This indicates that material substitution decisions should shift from short-term yield optimisation towards long-term system-level sustainability and resilience consideration.

5.3. Economic implications of substrate substitution

In addition to environmental and resilience considerations, the results also have important economic implications for material substitution decisions. While economic cost is not explicitly modelled as a standalone criterion, several aspects of the analysis inherently reflect cost-related factors. It is generally recognised that Ge substrates tend to have a higher upfront acquisition cost compared to GaAs on a per-wafer basis, reflecting differences in material availability, production scale, and supply-chain constraints. However, the effective economic performance of a substrate material in manufacturing is not determined solely by its initial price, but by a combination of factors including yield performance, process compatibility, and end-of-life recovery potential.

Because device performance is only assessed at wafer-level test, a yield loss discards the full value accumulated from substrate preparation through epitaxial growth and cleanroom fabrication, rather than the substrate cost alone. The 5 percentage-point yield differential therefore corresponds to an additional manufacturing expenditure of approximately 5% of the total cost accumulated up to test, of which the substrate is only one component. For the Ge route to be economically neutral at current yields, the combined benefit of any substrate price advantage and end-of-life reclaim value would need to offset this additional expenditure. As substrate procurement typically represents a minority of total processing cost in compound semiconductor manufacturing, this condition may not be achievable through substrate pricing alone. In the absence of validated cost data for either substrate or for the subsequent processing steps, no absolute monetary threshold is proposed here. The realisable benefit of reclaim is likewise governed by reclaim processing costs and substrate requalification requirements rather than recovery efficiency alone (Ward et al. 2016). Taken together, these considerations indicate that the economic case for Ge substitution rests principally on closing the yield gap through process maturation rather than on substrate procurement terms.

Second, process compatibility with existing fabrication infrastructure can substantially reduce the transition cost associated with Ge adoption. As discussed in Sections 3 and 4, the epitaxial growth and device fabrication steps for Ge-based VCSELs are largely comparable to those used for GaAs, with the primary differences arising from the substrate material and the N-contact metallisation scheme. This level of compatibility suggests that Ge substrates could be integrated into existing manufacturing lines with limited additional capital investment, thereby lowering the economic barrier to substitution relative to more disruptive material transitions, particularly in the short term.

Third, the circularity advantage of Ge substrates introduces a potential cost recovery dimension that may partially offset higher substrate acquisition costs. The end-of-life reclaim credit considered in this study reflects reported wafer recovery efficiencies in the range of 50–80%, indicating that a significant proportion of the substrate material value could be retained through reuse or recycling pathways. In contrast, GaAs substrates are typically associated with more complex handling and disposal requirements due to arsenic-related considerations, which may limit opportunities for material recovery. Over the lifecycle of production, this asymmetry in end-of-life treatment may help to partially offset the higher upfront acquisition cost of Ge substrates.

5.4. Policy and industrial implications

5.4.1. Implications for industrial decision-makers

The quantitative results of this study offer direct guidance for industrial decision-makers. The 4.2-fold difference in composite sustainability score between Ge (0.822) and GaAs (0.194), combined with a 54% reduction in supply risk exposure, provides a clear evidence base for foundries and integrated device manufacturers to initiate substrate transition roadmaps. In the short term, manufacturers should prioritise investment in Ge epitaxial process optimisation, particularly in nucleation layer engineering and defect management. This is because the current 5% yield gap represents the primary economic barrier to substitution and is not a fundamental material constraint. The replacement of GaAs with Ge is furthermore consistent with the broader industry trend toward low-toxicity and high-recovery materials and establishing dedicated Ge wafer reclaim channels would improve circularity while reducing dependence on primary extraction.

Additionally, the study provides a feasible analytical template for assessing alternative materials in the larger semiconductor system. By integrating experimental yield data, environmental evaluations, and supply-risk criteria, the methodology allows for quantitative trade-off analysis that informs material selection and investment choices. Also, in practice, the MCDA framework will enable companies to compare candidate substrate materials transparently and select the option that best balances performance, cost, environmental impact, and supply-chain risk.

5.4.2. Policy implications

From a policy perspective, the findings directly support the strategic objectives of recent industrial frameworks such as the EU Chips Act and the UK National Semiconductor Strategy. These policies emphasise circularity, resource security, and supply diversification as pillars of semiconductor resilience. The strategic relevance of these findings has been further highlighted by trade restrictions on gallium and germanium, which created immediate supply disruptions and reinforced the case for supply chain diversification through material substitution. The integration of LCA and supply-risk indicators demonstrated in this study could inform future policy tools for evaluating material substitution and recycling initiatives. Furthermore, by quantifying the resilience advantages of Ge substitution, this study adds to current attempts to operationalise 'resilience metrics' in industrial sustainability evaluations, which are still mostly conceptual in policy discourse.

The findings also highlight the value of cross-sector collaboration among materials scientists, physicists, LCA experts, and policy analysts. To translate laboratory-scale substitution into system-level effect, industry suppliers, research laboratories, and politicians must all work together to share data. The methodology proposed here might serve as a starting point for such multi-stakeholder engagement, allowing evidence-based initiatives for resilient and sustainable compound semiconductor production.

5.4.3. Transferability of the framework

Beyond the specific case of GaAs-to-Ge substitution in VCSEL manufacturing, the proposed framework is transferable to other material substitution decisions in advanced manufacturing where environmental, circularity, and supply risk dimensions are simultaneously relevant. Candidate applications include indium phosphide versus silicon for integrated photonics substrates, cobalt versus manganese cathode materials in battery supply chains, and rare earth element substitution in permanent magnets. The framework's modular structure combining LCA, circularity metrics, supply risk indices, and MCDA allows adaptation to different system boundaries, functional units, and indicator sets, making it applicable across a range of high-technology manufacturing contexts where critical material dependencies intersect with sustainability objectives.

Adapting the framework to a new material substitution context involves retaining its core structure, namely the integration of environmental, circularity, and supply-risk dimensions through buffered normalisation and equal-weight aggregation, while re-specifying several context-dependent elements.

Within compound semiconductor manufacturing itself, the same analytical structure applies directly to substrate and material choices beyond VCSELs, such as GaAs- versus Ge-based photodetectors, high-electron-mobility transistors (HEMTs), or other III-V optoelectronic devices that rely on comparable substrate and epitaxial material systems. In these cases, the functional unit and process-efficiency metrics would need to be redefined around the relevant device architecture, but the underlying LCA, MCI, and SRI data structures, and their aggregation through MCDA, remain unchanged.

The framework is robust and adaptable to single-element or bulk commodity materials, such as silicon or copper, which are extensively traded and for which officially published criticality and trade data are readily available. For such materials, the SRI calculation is in fact simpler than for GaAs, since it requires no elemental aggregation step of the kind used here to combine gallium and arsenic into a compound-level score; the relevant criticality and import-reliance figures can be applied directly. Compound or composite materials, by contrast, require an explicit aggregation rule reflecting their stoichiometry, as demonstrated in this study for GaAs, and this step becomes more complex for multi-element compounds with more than two constituent elements.

Extending the framework beyond compound semiconductors to other advanced manufacturing sectors requires re-specifying a larger set of context-dependent elements. First, the functional unit and system boundary must reflect the relevant production stage and output metric of the new sector (e.g. energy stored per kWh for battery cathode materials, rather than a unit wafer area). Second, the supply-risk component requires an equivalent officially published criticality assessment for the materials in question; where such an assessment does not decompose cleanly into elemental scores as for GaAs, an analogous aggregation logic would need to be established. Third, circularity data (recycled content, end-of-life recycling rate, and utility loss) must be collected for the specific material system, since established methodologies such as the Ellen MacArthur Foundation's framework do not yet provide sector-specific parameters for all candidate materials. Finally, the equal weighting applied here reflects the absence of a dominant stakeholder preference in this study; in sectors with established regulatory priorities or supply-chain constraints, the framework's weighting scheme could instead be informed by stakeholder elicitation or policy targets, without altering its underlying structure.

6. Conclusions

This work evaluated GaAs-to-Ge substrate substitution by integrating empirical wafer-scale measurements with life-cycle, circularity, and supply-risk modelling. The research establishes an integrated framework that links device-level physics to system-level policy outcomes. The results show that Ge-based VCSELs can achieve comparable threshold current and optical efficiency to GaAs devices, although higher hotspot density led to a modest yield reduction ($\approx$ 92% for Ge versus $\approx$ 97% for GaAs). These variations highlight the need for further optimisation of nucleation, transition layers, and defect management to reach GaAs-level uniformity.

On an environmental basis, the cradle-to-gate LCA indicates that Ge substrates reduce global warming potential and cumulative energy demand by approximately 11%, eliminate arsenic-related toxicity, and enable partial substrate reclamation. These improvements raise Ge's circularity score (MCI = 0.54 vs. 0.33 for GaAs) and reduce supply-risk exposure (SRI = 0.18 vs. 0.39). When integrated through the multi-criteria decision analysis (MCDA), Ge achieves a composite sustainability-resilience score of 0.822, approximately 4.2 times higher than GaAs (0.194), driven by strong gains in environmental performance, recyclability, and supply security.

The novelty of this research lies in its methodological, conceptual, and practical contributions. Methodologically, it introduces a physics-informed multi-criteria decision analysis (MCDA) framework that integrates empirical semiconductor performance data with life-cycle and risk metrics, achieving a rare cross-scale linkage from wafer-level measurements to policy-relevant sustainability indicators. Conceptually, it advances the operationalisation of 'resilience metrics' by transforming supply-chain resilience from a qualitative policy notion into quantifiable indicators through the Supply-Risk Index (SRI), thereby providing a measurable and comparable dimension within industrial LCA where resilience has traditionally remained abstract. Practically, the study provides a replicable decision-support tool for material substitution. It uses buffered normalisation and equal-weighted aggregation to combine environmental, circularity, and risk metrics, offering a transparent approach that industry and policymakers can readily adopt.

Overall, the findings highlight how material-level engineering decisions may induce systemic sustainability changes in high-tech manufacturing supply chains. The suggested methodology provides a practical foundation for assessing compound semiconductor materials based on trade-offs between performance, circularity, and supply security. Future studies should extend the framework to cradle-to-cradle boundaries and incorporate economic factors such as cost and yield weighting. They should also validate precursor and process data through broader industry collaboration. Finally, the transition from GaAs to Ge epitaxy is more than just a material change; it signifies a shift toward a new design paradigm that prioritises technical innovation, sustainability, and supply-chain resilience simultaneously.

7. Limitations and future work

Several limitations must be acknowledged. First, the life-cycle inventory (LCI) for the metal–organic chemical vapour deposition (MOCVD) epitaxy process (P6) relied on elemental metal proxies for organometallic precursors such as trimethylgallium (TMGa) and arsine (AsH_3), as these compounds are absent from standard LCA databases. While this proxy approach captures approximately 60–80% of the environmental burden associated with metal extraction and refining, it may underestimate the impacts of organometallic synthesis and purification by 20–30%.

Second, the system boundary was set to cradle-to-gate. The exclusion of packing, usage, and end-of-life phases means that downstream implications, particularly those related to device energy use and recycling logistics, were not evaluated. Future research might take a cradle-to-cradle approach, encompassing both production and recovery loops, to completely quantify circularity advantages.

Third, the empirical dataset was based on single-wafer analysis for each substrate type. Although the measurement density exceeded 1000 devices per wafer, a multi-wafer dataset would improve statistical confidence and allow examination of process variability across production batches. Further experiments should directly examine the candidate defect mechanisms identified in Section 4.1 through targeted microstructural characterisation. In particular, focused ion beam and transmission electron microscopy (FIB-SEM/TEM) analysis of representative hotspot devices, performed at the specific wafer locations identified by wafer-scale mapping, would allow direct confirmation of the underlying defect structures. Extending this analysis across multiple wafers and process batches would also help establish whether the observed hotspot behaviour reflects a consistent substrate-related phenomenon rather than a batch-specific artefact.

Finally, the multi-criteria framework assigned equal weight (1/3) to the environmental, circularity, and risk aspects. While this neutral weighing promotes comparability, real-world decision-making might require context-specific weighting that takes into account stakeholder preferences such as environmental compliance, cost structure, or national security. Future study might use the analytic hierarchy process (AHP) or interactive weighing methodologies to improve the decision framework.

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Author contributions

CRediT: **Xin Aria Yu:** Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft; **Moein Shamoushaki:** Supervision, Writing – review & editing; **Jack Baker:** Resources, Supervision, Writing – review & editing; **Sara-Jayne Gillgrass:** Resources; **Peter M. Smowton:** Supervision, Writing – review & editing; **S. C. Lenny Koh:** Supervision, Writing – review & editing

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Data availability statement

The data for this study are confidential.

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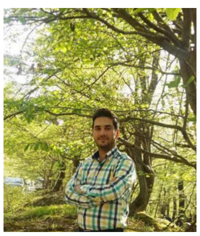

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