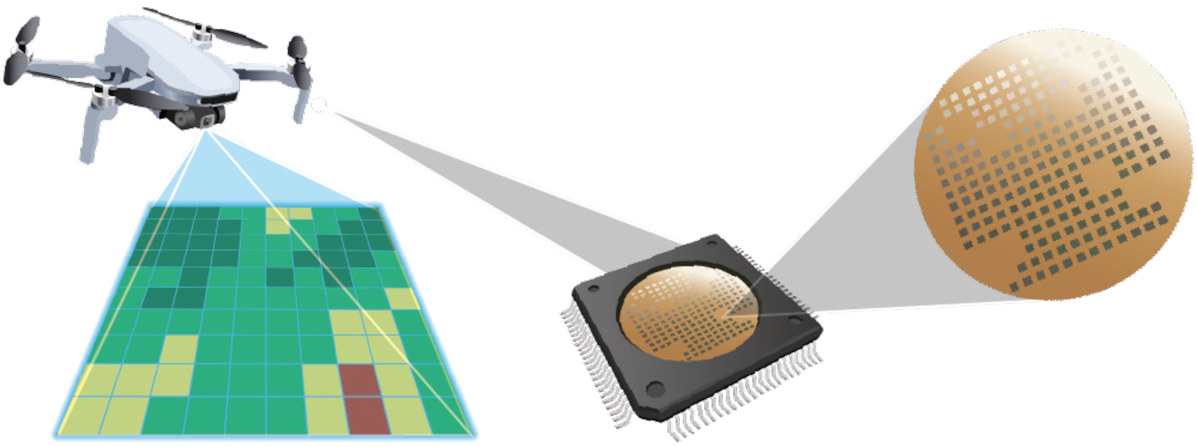
Hi-ACTS
Helmholtz Innovation Platform
for Accelerator-based
Technologies and Solutions

**IMPACT STUDY OF THE SOCIO-ECONOMIC BENEFITS FROM THE HI-ACTS USE CASE INITIATIVE**

# Wafer-scale CMOS technology for room-temperature extended short-wave infrared GeSn photodetectors based on ion implantation and flash lamp annealing



**FINAL REPORT**

know.space

August 2025

## INFRARED PHOTODETECTORS ARE VALUABLE FOR MANY DOMAINS OF MODERN TECHNOLOGY...

Infrared imaging plays a crucial role across many sectors, including healthcare, transportation, and environmental monitoring - ultimately enhancing the safety, efficiency, and security of modern life. Short-wave infrared (SWIR) photodetectors are an important technology that enable infrared imaging in the SWIR wavebands. For example, SWIR imagery enhances visibility in poor conditions such as fog, making it a valuable component for Light Detection and Ranging (LiDAR) for vehicle safety.[i] It can also be leveraged for remote sensing and soil monitoring, supporting valuable applications in agriculture and more general environmental and sustainability efforts.

Complementary Metal-Oxide-Semiconductor (CMOS) is the standard technology used to manufacture microchips, forming the foundation of nearly all modern electronics. Due to this, well-established, large-scale manufacturing processes and infrastructure already exist to produce CMOS-compatible devices. Today, SWIR photodetectors[1] are often made from semiconductors such as indium gallium arsenide (InGaAs) and indium antimonide (InSb) as they can be tuned to detect specific wavelengths with high sensitivity. These, however, are *not* CMOS-compatible. As a result, their production cannot take advantage of the standard CMOS manufacturing infrastructure and instead relies on expensive, specialised processes. Therefore, CMOS-compatible SWIR photodetectors, made from materials that align with the silicon-based components used in CMOS technologies are advantageous, as they can be manufactured using standard CMOS processes and facilities. The compatibility also enables the integration of photodetectors and the electronics (like amplifiers or processors) on the same chip.

## ... AND HI-ACTS FUNDING HAS ENABLED THEIR DEVELOPMENT TO INDUSTRY STANDARD SIZE

Helmholtz-Zentrum Dresden Rossendorf (HZDR) is a Dresden-based research facility focused on health, energy and matter. Under the Hi-Acts Use Case Initiative, HZDR’s Semiconductor Materials department received €89,000 in funding to scale-up its in-house CMOS-compatible technology.

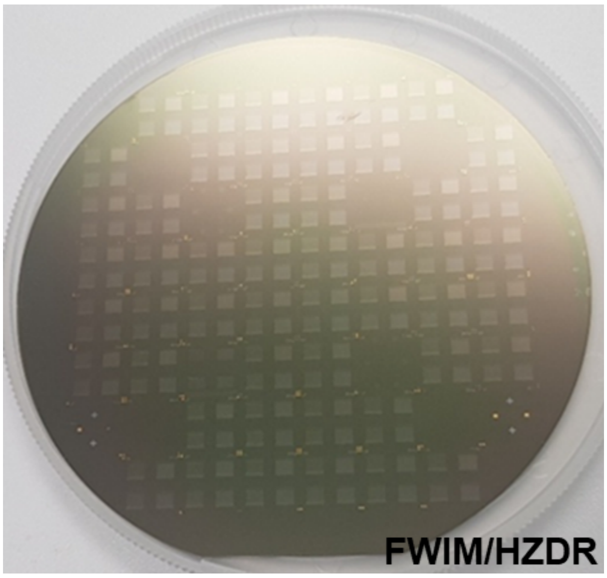
This project built on HZDR’s pre-existing in-house CMOS-compatible photodetector technology. The institution’s approach, which was a first-of-a-kind innovation, used ion implantation and flash lamp annealing[2] to alloy Germanium-Tin (GeSn), creating a 10mm x 10mm CMOS GeSn photodetector (the standard size for research purposes).

The aim of the 8-month long Hi-Acts project was to scale 10mmx10mm single photodetector fabrication process to a lateral array of photodetectors on 3-inch commercial wafers. This scaling enables cost-effective mass-produced GeSn SWIR photodetectors for industry, supporting manufacturing efficiency and affordability across the wider semiconductor value chain - from sensor manufacturers to end users.

**Figure 1: 3-inch GeSn wafer with array of SWIR sensors**

[1] Hereafter referred to as ‘photodetectors’.

[2] Ion implantation combined flash lamp annealing is a non-equilibrium technique used to introduce impurities into semiconductors at concentrations higher than their natural solubility limit.




**Source: HZDR**

## TECHNOLOGICAL INNOVATION

*High-acts funding has enabled technological innovation, raising the technology maturity from Technological Readiness Level (TRL) 3 to TRL 4, by further refining highly innovative processes for wafer development.*

Over the course of the project, HZDR progressed the GeSn wafers from TRL 3 to TRL 4. This indicates a shift from proof-of-concept to laboratory testing to validate the feasibility of a 3-inch GeSn wafer. This progress involved scaling up HZDR's novel ion implantation and flash lamp annealing process for GeSn alloying, from a 10mm x 10mm photodetector to a 3-inch wafer, pushing the limits of the already innovative technique.

This success helps position HZDR as a pioneer in the integration of photonics and CMOS technology. Demonstrating scalability is a key step toward commercialising the CMOS technology, proving that a lab-scale innovation can be adapted to industry-standard sizes and brought to market. In doing so, it also enables industry to unlock the benefits of efficient production and lower energy usage associated with CMOS-compatible photodetectors, while also supporting the European Chips Act, which aims to bolster Europe's strength in semiconductors by increasing resilience and reducing reliance on external suppliers.[ii] These benefits are discussed in further detail below.

## DRIVING EFFICIENCY IN SENSOR MANUFACTURING

*By showcasing the scalability of GeSn photodetectors to an industry standard 3-inch wafer, the project has supported efforts towards lower costs, reduced energy demand, and improved efficiency across the photodetector supply chain.*

The advancements in HZDR's wafer-scale CMOS technology present an opportunity for increased efficiency in commercial photodetector manufacturing, as photodetectors can be manufactured using standard CMOS manufacturing and facilities. This compatibility allows industry actors to integrate photonic components into existing semiconductor manufacturing lines, increasing production efficiency, lowering costs, and reducing the need for highly specialised and costly techniques associated with conventional photodetectors (based on InGaAs and InSb).[3] This has the potential to

[3] Indium Gallium Arsenide (InGaAs) and Indium Antimonide (InSb) are both semiconductor compounds.

accelerate the prototyping and development of sensors, which could reduce the time to market for photodetector products. Moreover, it enables manufacturers to respond more quickly to emerging demand and increase production capacity.

The project is also progressing towards a competitively priced wafer with high-temperature resilience for industry. Unlike the InGaAs SWIR sensors commonly used for comparable applications, the GeSn sensors function without the need for cooling. This means that end-user applications, especially those in agriculture and biomedical products, could benefit from operation under high temperatures with reduced energy consumption and without the need for active cooling systems, leading to simpler designs and lower operational costs. While research is underway to understand the exact energy cost savings, stakeholders currently estimate 40-50% in energy savings between the GeSn sensor and those like the InGaAs SWIR sensors. Through a reduced need for cooling, HZDR's wafers could aid industry in the deployment of durable and cost-effective photodetectors for a broad range of applications.

In addition to this, HZDR shared that the 3-inch GeSn wafer is currently estimated to cost around €1 per sensor, with an estimated market price for the encapsulated photodetector at around €10. This is a significantly reduced cost compared to market-available alternatives, which HZDR stakeholders noted were typically priced at €500 per sensor, meaning a potential cost saving of 98%. As various technologies may have multiple sensors (e.g. 10 sensors for one product), this could result in significant cost savings within the supply chain (e.g. 10 sensors at €10 would be €100, compared to 10 sensors at €500, totalling €5,000). In recent conversations with potential customers, an HZDR stakeholder was told that the price of sensors is a key inhibitor to the scaling of technologies supporting tomography[4] for the public healthcare system. Offering a cost-effective alternative not only strengthens the industrial supply chain but also delivers broader societal benefits by reducing the overall cost of equipment used in healthcare and other sectors, such as agriculture. At the same time, it positions HZDR as a competitive supplier of wafers in the commercial market.

## CONTRIBUTING TO EUROPEAN CIRCULARITY

*By developing a photodetector using non-toxic elements, the project supports wider European Union and Commission goals towards circularity, strategic autonomy and climate neutrality.*

The GeSn SWIR photodetectors offer a more sustainable option to current alternatives, as they are composed of non-hazardous elements. This is particularly relevant in Europe, where regulations increasingly restrict hazardous substances in electronic equipment.[5,iii,iv] Notably, current sensors on the market may contain toxic elements like Indium and Gallium, which are not only hazardous but also challenging to recycle.

In contrast, GeSn sensors offer potential advantages in addressing recycling challenges, as they are made from materials that are more commonly recycled. Recycling infrastructure - particularly for Germanium - is actively being developed, driven by increasing interest and investment from various industries, including the space sector, with support from organisations such as the European Space Agency (ESA).[6v]

By comparison, elements and compounds such as indium and gallium arsenide have extremely limited capacity for recycling in Europe and, due to regulatory constraints, including their listing under

[4] A method used to create an image of a cross-sectional slice of the human body or another solid object by employing X-rays or ultrasound.

[5] This includes the REACH (registration, evaluation, authorisation, and restriction of chemicals) Regulation (2007), as well as the Restriction of Hazardous Substances in Electrical and Electronic Equipment (RoHS) (2002), and ROHS2 (2011) and its 2017 amendment.

[6] Notably, there are initiatives for recycle germanium include the Belgian-based Umicore germanium recycling programme.

REACH (registration, evaluation, authorisation, and restriction of chemicals) as restricted substances, may require complex processes in order to comply with the regulation.[vi][vii] When such materials are not recycled, they often end up in general waste streams, where they may be added to landfills or incinerated, releasing toxic substances into the environment that can negatively impact human health and the broader ecosystem.[viii] For example, studies have shown that prolonged exposure to indium has been linked to elevated levels of the element in the bloodstream,[ix] and that gallium-based compounds may pose health risks, including skin irritation and reduced blood cell production.[x]

In line with this, initiatives aimed at reducing environmental impact in the semiconductor manufacturing process are a key priority under the EU Chips Act.[xi] By supporting a more efficient and cleaner product, the UCI funding supports wider EU initiatives aimed at promoting European autonomy and environmental protection.

Although precise recycling costs for hazardous materials are hard to quantify, the European Commission is increasingly placing requirements on electronics to be recyclable. One stakeholder even reported that an international supplier for sensors faced export challenges due to these restrictions. As such, GeSn SWIR photodetectors present a compliant and forward-looking solution focusing on circularity, which may become increasingly important in the European market should international suppliers face continued constraints.

## SUPPORTING END USER APPLICATIONS

*Follow-on activities, such as early market engagement, are helping ensure that the technology is leveraged effectively by end users to support safety and sustainability applications.*

While commercialisation was beyond the scope of this specific Hi-Acts project, HZDR's focus on industry-standard CMOS technology has laid the foundations for early exploration of target markets. Since the project's conclusion, the team at HZDR has conducted market research and engaged with end users to identify where their wafer-scale CMOS technology can deliver the greatest value. These insights are helping to pinpoint the most promising opportunities for adoption, guiding the development of a business model and a strategic path to commercialisation.

The shortwave infrared market was valued at €147m ($167m) in 2021, with an expected compound growth rate of 8.7% until 2030.[xii] HZDR's advancements of their wafer-scale CMOS technology has the potential to provide value in several application fields within this market. LiDAR and agriculture were identified as particularly suitable due to the strong match between HZDR's technology and the applications' key requirements, including spectral range, bandwidth and sensitivity.[7] LiDAR, often used in autonomous vehicles and environment mapping, presents an enhanced form of imaging that can enable safer systems. However, the GeSn wafer, as noted by stakeholders, would still require additional technical development to prove its compatibility.

Alternatively, infrared photonics in agriculture can offer increased precision for monitoring crop health, soil moisture or other activity supporting efficient farming and food security, demonstrating the diverse range of user-applications. This market research, which took place as a follow-on from the Hi-Acts project, indicates the potential to drive progress towards low-cost and energy-efficient technologies that can, in turn, support safer systems and sustainability efforts. However, as the technology is in the early stages of development, it is difficult to predict the extent of industry uptake, and thus materiality of this impact.

[7] Several other applications were identified during market research activities, including biomedical sensors, chemical spectroscopy for food and pharmaceuticals, and motion and proximity sensors. Other potential applications are still being investigated, such as consumer electronics and monitoring of industrial processes.

## FOLLOW-ON COMMERCIAL OPPORTUNITIES

*The project's success is paving the way for commercialisation, backed by plans for a spin-out company, and improved business know-how.*

The project's advancements under Hi-Acts UCI have enabled a path to commercialisation for HZDR's wafer-scale CMOS technology. HZDR representatives noted that plans are underway to establish a spin-out company for the GeSn wafer, as well as another sensor developed by the team (developed separately from the Hi-Acts project). While the spin-out will focus on two technologies, a stakeholder noted that it would not be possible without the GeSn wafer. This could provide the opportunity to capture commercial value from the infrared photodetector market through product sales. The nascent spin-out intends to operate as a fabless company,[8] enabling resources and time to be focused on technology design while outsourcing manufacturing. This presents an opportunity for continued research, development, and innovation beyond the Hi-Acts project, while also supporting the creation of a spin-out company with a novel product positioned to enter the photodetector market.

Alongside the development of these commercial opportunities, a HZDR scientist noted that the project played a significant role in supporting their understanding of the sensor market, as well as their skill set related to business and commercialisation. In shifting focus toward a commercially viable product rather than one intended for a scientific audience, the scientist gained valuable insight into the sensor market and commercialisation processes that would have otherwise remained outside their typical scope.

These developments represent important progress towards commercialisation and demonstrate the strong potential for bringing a CMOS-compatible photodetector to the industrial market - progress that is highly attributable to the work supported by Hi-Acts UCI funding.

## SUPPORTING THE LOCAL ECONOMY

*The project is supporting Dresden's semiconductor ecosystem with potential for leveraging local expertise, enhancing the region's reputation, and catalysing work for a local research services company.*

Stakeholders noted that HZDR's work under Hi-Acts aligns with and supports the local industry's strengths in semiconductors. Dresden, where HZDR is based, has a growing semiconductor ecosystem, with a concentration of organisations involved across the supply chain.[xiii] By advancing CMOS compatible photodetector technology, the project added to this regional expertise in semiconductor innovation and manufacturing.

Furthermore, if the spin-out achieves its goal of becoming a fabless company by leveraging local facilities and manufacturers, the innovation developed through the Hi-Acts programme could continue to enhance regional expertise. This would help position the region as a specialist in this unique technology, while also securing contracts for local industry.

Follow-on work from the Hi-Acts project also stimulated a market study and technical evaluation undertaken by local Dresden-based research services companies, KETmarket and Finnoval. The €4,500 contract was funded outside of the Hi-Acts project by the Free State of Saxony. As part of this work, the team delivered a report assessing the TRL of the technology, identifying the applications, exploring the interest of the potential users, and supporting meetings with potential users and

[8] Fabless describes a company that designs and sells semiconductors but outsources the manufacturing (fabrication) to a third party.

planning the next steps of commercialisation. The study identified pulse oximetry[9] as one of the potential applications for the wafer-scale CMOS technology, due to the alignment in bandwidth required and low-cost potential. In doing so, the Hi-Acts project was able to catalyse an additional contract, contributing to the local economy. At the same time, this contract offered value to the HZDR team in supporting their knowledge of the potential market applications for the novel sensor.

## ATTRIBUTABILITY OF THESE BENEFITS TO HI ACTS FUNDING

The Hi-Acts UCI funding was regarded as crucial for HZDR's success in demonstrating the scalability of CMOS technology for infrared photodetectors, as well as the follow-on activities and the associated socio-economic impacts. Stakeholders noted that there were no other funding opportunities to progress the project, and thus, Hi-Acts funding was an instrumental enabler. UCI funding has directly contributed to progress in developing an innovative and increasingly efficient infrared photodetector, as well as a clear route to commercialisation. The broader socio-economic impacts, such as improved industrial efficiency across the supply chain and a range of potential environmental and societal benefits, are promising and expected to grow as industry uptake and manufacturing capabilities continue to advance.

Attributing the ultimate success of the 3-inch GeSn wafer solely to the Hi-Acts UCI funding will become increasingly difficult over time, as many factors may influence successful commercialisation and the uptake of the product. However, it is important to recognise that without this initial funding support, the project may never have been pursued, potentially preventing the development of the wafer-scale CMOS technology as well as any path to commercialisation from emerging at all.

While the UCI-funded hardware represents an essential enabling step, realising its full impact will depend on several additional technological, funding and policy factors.

[9] Pulse oximetry is a biomedical technology that measures blood oxygen levels.

# IMPACT SUMMARY

**Wafer-scale CMOS technology for room-temperature extended short-wave infrared GeSn photodetectors**

| HZDR | Industry | Society |
|---|---|---|
| **Jobs and Skills:**<br>• Commercial skills: Business know-how developed/increased for scientists<br>• Market knowledge: Sensor-market knowledge and commercial application developed through follow-on work<br><br>**Technical:**<br>• TRL progression: TRL 3 to TRL 4 (laboratory validation and testing)<br>• Development of a solution that is better for the environment (in terms of toxicity and recycling potential)<br>• Addressable industries: agriculture, biomedicine<br><br>**Commercial:**<br>• Cost savings: ability to leverage CMOS cost effective manufacturing processes and infrastructure, leading to energy savings estimated at 40-50% and cost savings of ~98% for GeSn sensors.<br>• Revenue: significant commercial potential, with potential to break into a €147m (valued in 2021) shortwave infrared market<br>• Spin-out: possible creation of a new organisation to support commercialisation endeavours | Potential strengthening of regional expertise, capability, and reputation.<br>Relevant for:<br>• Economy<br>• Knowledge & Technology<br>• German / European Competitiveness, sovereignty & resilience<br>• Improved attractiveness of the local area / Germany / Europe for investment<br>• Innovation | Sustainable, low-cost sensor alternatives aligned with EU standards and circular economy goals.<br>Relevant for:<br>• Scientific knowledge<br>• Environment & sustainability<br>• Health & wellbeing<br>• National security & safety<br>• Governance |

Granularity of evidence

Attribution to UCI support

[i] Cao, F., Liu, L. and Li, L. (2023). 'Short-wave infrared photodetector', *Materials Today*, 62, pp.327-359. DOI: https://doi.org/10.1016/j.mattod.2022.11.003

[ii] European Commission (n.d.). *European Chips Acts.* Available at: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/europe-fit-digital-age/european-chips-act_en

[iii] European Commission (n.d.). *REACH Regulation.* Available at: https://environment.ec.europa.eu/topics/chemicals/reach-regulation_en

[iv] European Union (2017). *Directive of the European Parliament an of the Council amending Directive 2011/65/EU of the restriction of the use of certain hazardous substances in electrical and electronic equipment.* Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1485526057244&uri=CELEX:52017PC0038

[v] European Space Agency (2022). *Effective recycling for Germanium.* Available at: esa.int/Enabling_Support/Space_Engineering_Technology/Shaping_the_Future/Effective_recycling_for_Germanium

[vi] European Chemicals Agency (n.d.). *Substances restricted under REACH.* Available at: https://www.echa.europa.eu/substances-restricted-under-reach

[vii] De Tandt, Ellen, Cody Demuytere, Elke Van Asbroeck, Hiram Moerman, Nicolas Mys, Gianni Vyncke, Laurens Delva et al. (2021) "A recycler's perspective on the implications of REACH and food contact material (FCM) regulations for the mechanical recycling of FCM plastics." *Waste Management* 119: 315-329. Available at: https://doi.org/10.1016/j.wasman.2020.10.012

[viii] Haiying, Zhang, Zhao Youcai, and Qi Jingyu (2010). "Characterization of heavy metals in fly ash from municipal solid waste incinerators in Shanghai." *Process Safety and Environmental Protection* 88, no. 2:114-124 Available at: https://doi.org/10.1016/j.psep.2010.01.001

[ix] Nakano, Makiko, Kazuyuki Omae, Akiyo Tanaka, Miyuki Hirata, Takehiro Michikawa, Yuriko Kikuchi, Noriyuki Yoshioka, Yuji Nishiwaki, and Tatsuya Chonan (2009). "Causal relationship between indium compound inhalation and effects on the lungs." *Journal of occupational health* 51,6: 513-521. Available at: https://doi.org/10.1539/joh.L9077

[x] Zhan, Lu, Fafa Xia, Qiuyu Ye, Xishu Xiang, and Bing Xie (2015). "Novel recycle technology for recovering rare metals (Ga, In) from waste light-emitting diodes." *Journal of Hazardous Materials* 299:388-394. Available at: https://doi.org/10.1016/j.jhazmat.2015.06.029

[xi] European Union (2023). *Regulation (EU) 2023/1781 of the European Parliament and of the Council of 13 September 2023 establishing a framework of measures for strengthening Europe's semiconductor ecosystem and amending Regulation (EU) 2021/694 (Chips Act).* Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2023.229.01.0001.01.ENG

[xii] Polaris Market Research. (2022). *Shortwave Infrared (SWIR) Market Share, Size, Trends, Industry Analysis Report, By Type; By Technology (Cooled Infrared Imaging, Uncooled Infrared Imaging); By End-User; By Region; Segment Forecast, 2022 – 2030.* Available at: https://www.polarismarketresearch.com/industry-analysis/shortwave-infrared-swir-market/toc

[xiii] McKinsey & Company. (2024). *Exploring new regions: The greenfield opportunity in semiconductors*. Available at: https://www.mckinsey.com/industries/semiconductors/our-insights/exploring-new-regions-the-greenfield-opportunity-in-semiconductors