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materials for a better life

Germanium substrates:
New production possibilities through CMOS integration, Ge recycling & security of supply

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Integrated Photonics - SEMICON Europa

Nov 14th, 2023

Contents

- Intro to Umicore and Electro-Optic Materials.
- Germanium into photonics:
  - Ge properties and photonic applications.
  - III-V industry and CMOS.
  - Ge wafer recycling & cost advantages.
- Ge sourcing and security of supply.
- Next steps in reducing primary sourcing dependency.
- Conclusions.

Umicore and Electro-Optic Materials Unit

Umicore structure

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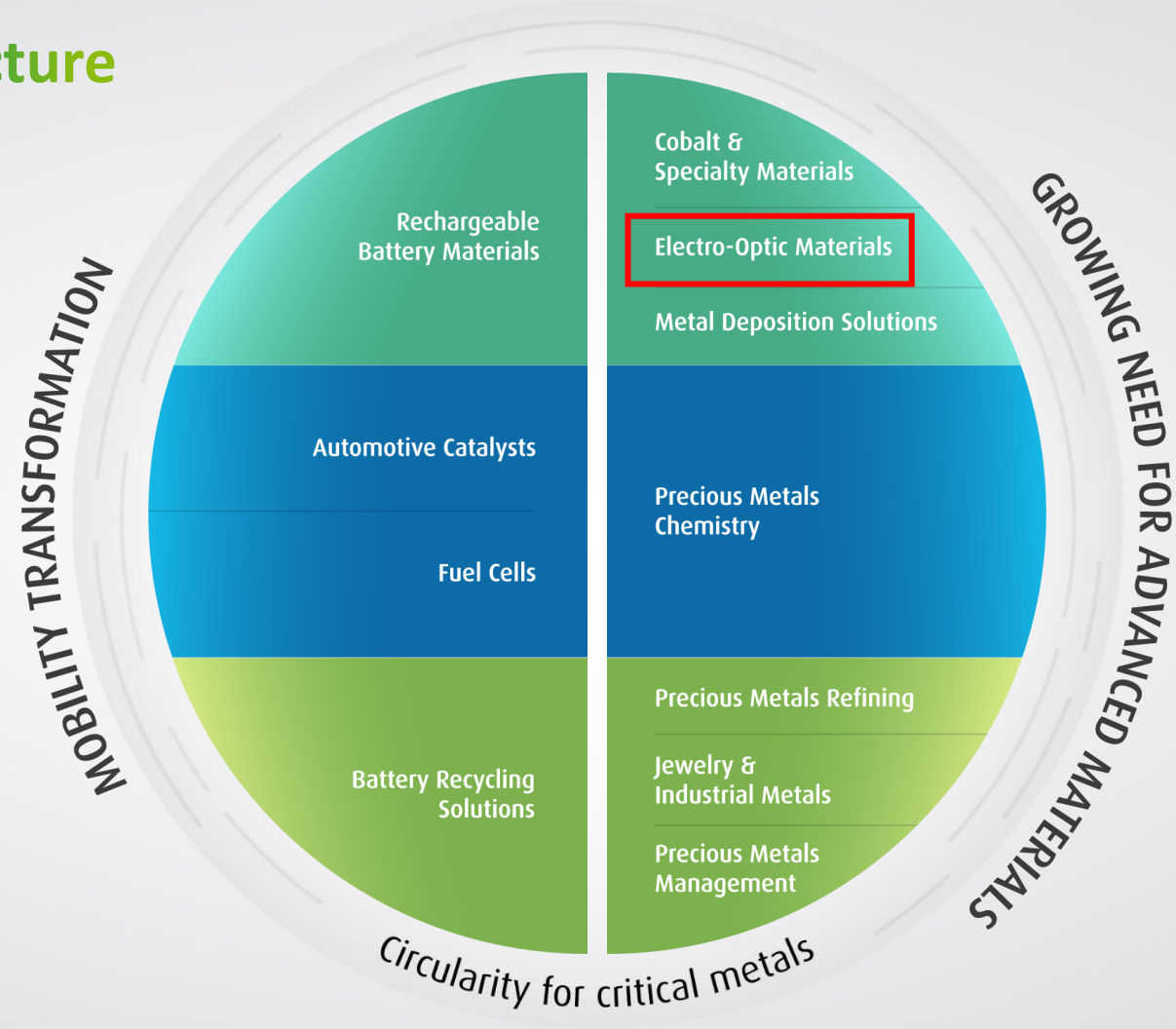
Colleagues
11 565

Revenues
€ 4.2 bn

Adjusted EBIT
€ 1.2 bn

R&D spend
€ 316 m

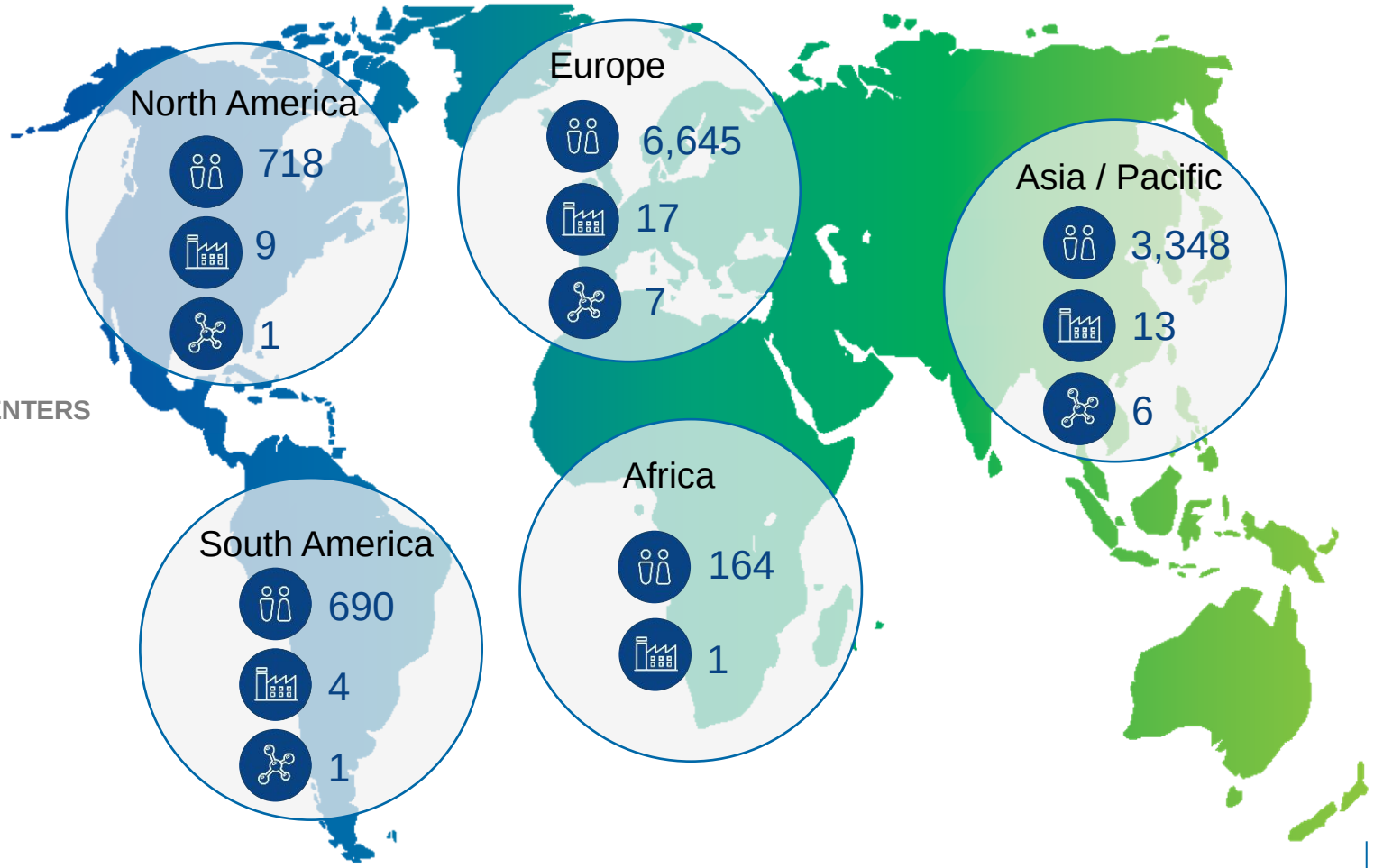


Your global supplier, locally

COLLEAGUES
11,565

PRODUCTION SITES
44

R&D | TECHNICAL CENTERS
15



Net Zero GHG emissions by 2035

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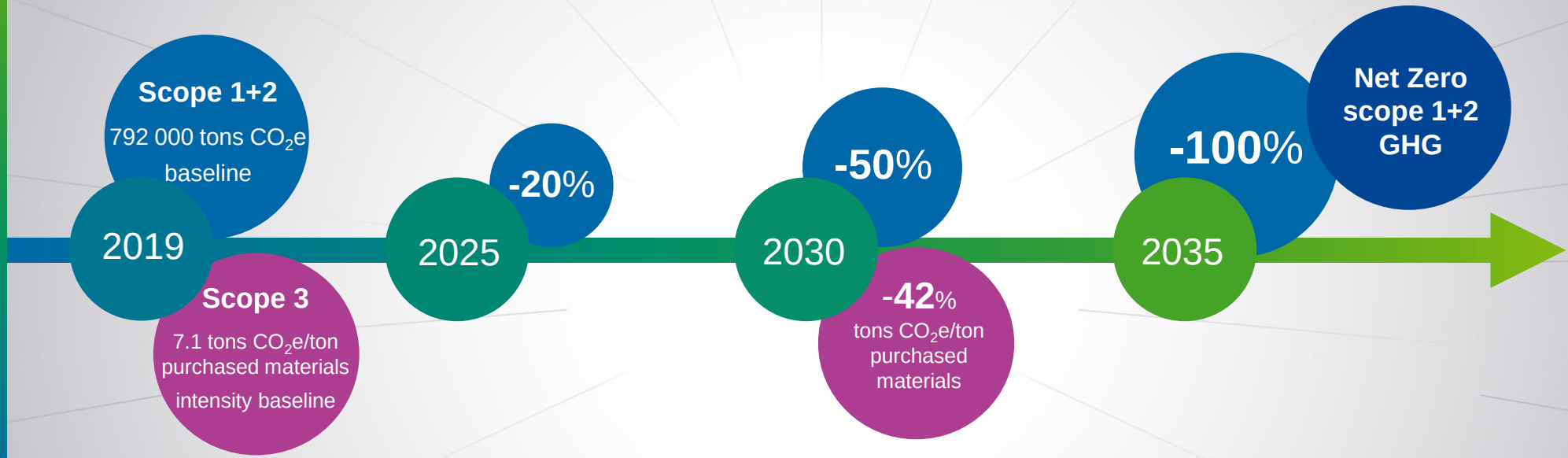


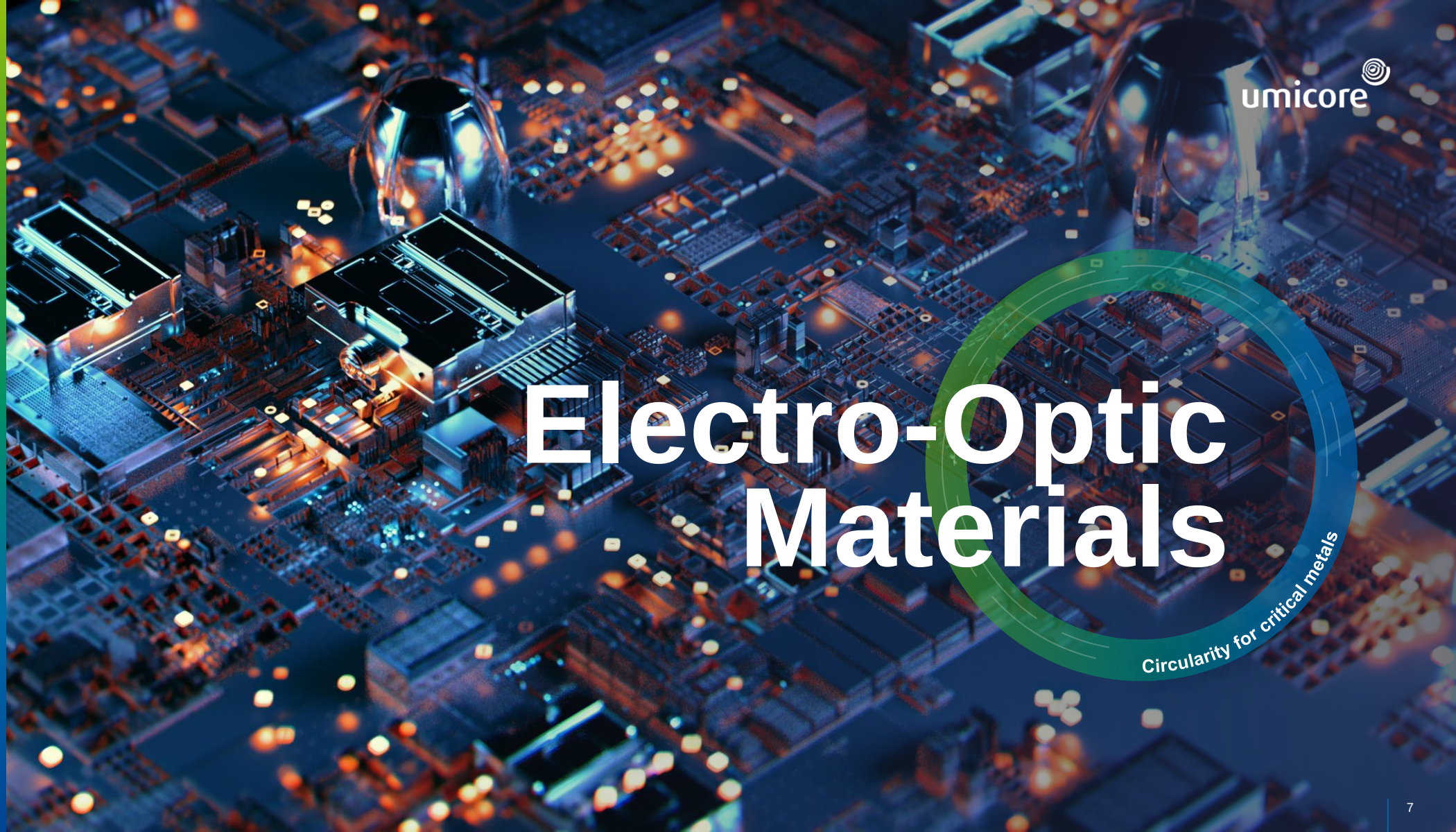
Let's go for zero

Net Zero GHG. Zero regrets.
Endless possibilities.

TCFD TASK FORCE ON CLIMATE-RELATED FINANCIAL DISCLOSURES

SCIENCE BASED TARGETS
DRIVING AMBITIOUS CORPORATE CLIMATE ACTION
committed

Belgian Alliance for Climate Action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Electro-Optic Materials
Circularity for critical metals

Electro-Optic Materials

2 Business Lines

Germanium Solutions

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$GeCl_4$

- **$GeCl_4$ as precursor** for telecom fiber
- **Closed loop recycling** of Germanium from telecom fiber waste streams

Germanium Substrates

- **4”- 6”** in volume production
- **8” - 12”** on request
- **9 Million Ge wafers sold** in 20 years

High Purity Germanium

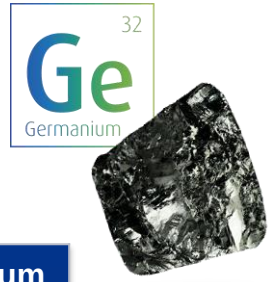
- Ge crystals for **gamma-ray detection**
- World’s purest metallic element with 13N purity **(99.99999999999%)**

Sustainable Sourcing and Recycling

- **Security of Ge supply** with access to global Ge sources.
- Guarantee of **Sustainable** sources and availability of **100% recycled** sources.
- Recovery of both Germanium and other metals of interest from **solid and liquid sources**.
- Our **Pyro- and hydrometallurgy plants** process **several thousand tones** of recycling streams **annually**.

Germanium properties and photonic applications

Basic Germanium properties



Property	Silicon	GaAs	Germanium
Crystal structure	Diamond	Zincblende	Diamond
Density (g/cm³)	2.33	5.32	5.33
Lattice constant (Å)	5.430	5.653	5.658
Bandgap energy at 300K (eV)	1.12	1.42	0.66
Cut-off wavelength (µm)	1,06	0,87	1,6
Electron mobility (cm²/V-s)	1350	8500	3900
Hole mobility (cm²/V-s)	480	400	1900
Melting point (°C)	1415	1238	937
Thermal expansion (1/°C)	2.6 10^{-6}	5.7 10^{-6}	5.9 10^{-6}
Thermal conductivity (W/cm°C)	1.3	0.55	0.58
Fracture toughness (MPa.m$^{1/2}$)	0.8	0.3	0.7
Young's modulus (GPa)	130-188	85-130	103-153

Si and Ge are elemental indirect semiconductors with similar up to 12” diameter 0 EPD* crystal processes

Ge and GaAs are lattice matched

Ge cut-off wavelength enables SWIR photodiodes

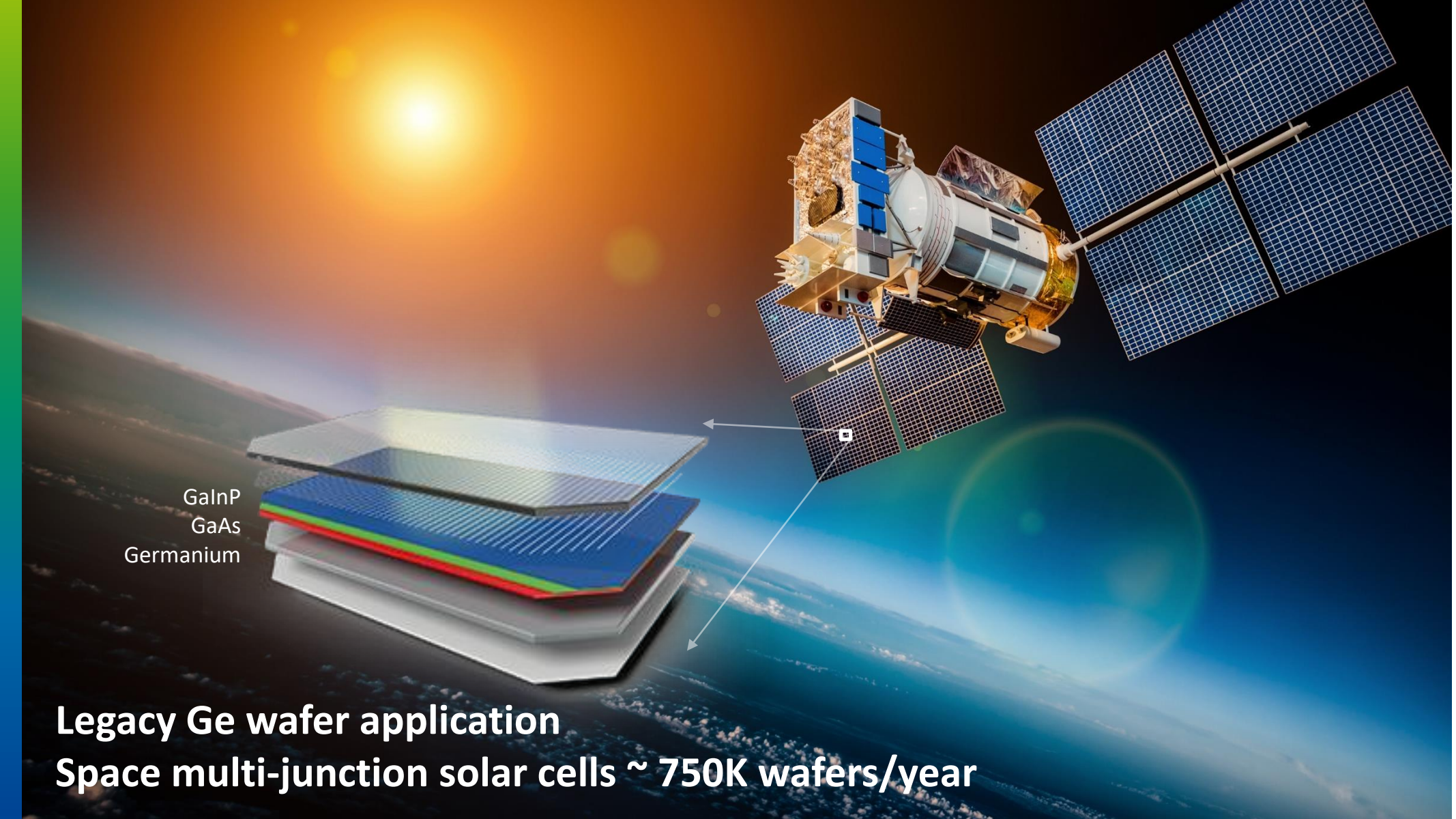
Ge has high electron and high hole mobility vs Si

Ge and GaAs have similar thermal expansion & conductivity

Ge is twice as tough as GaAs

Ge [100] is 18% less prompt to deformation vs GaAs

** EPD: Etch pitch density, dislocation density*



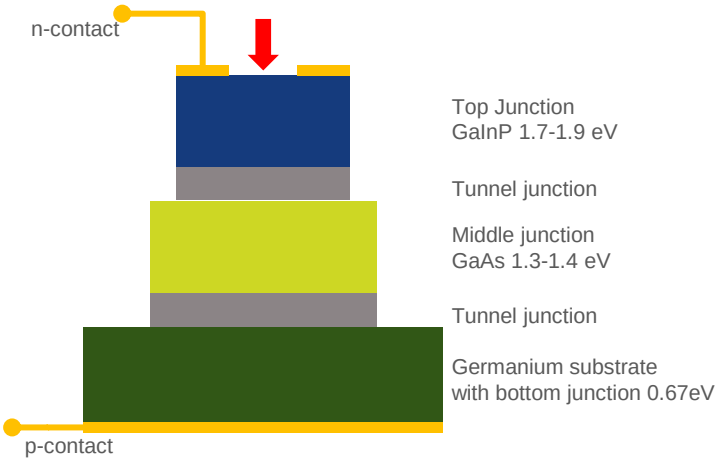
Legacy Ge wafer application
Space multi-junction solar cells ~ 750K wafers/year

Photonic applications

MJ Solar cells and VCSEL, µ-LED lattice match with GaAs

Germanium is the platform for MJ solar cells as it is stronger and thinner (lighter) weight than GaAs, and it also provides bottom junction.

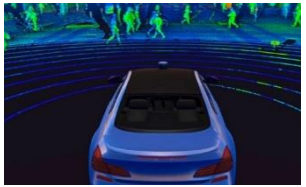
This makes Germanium wafers a candidate for other opto-electronic devices based on GaAs epilayers, such as VCSEL's, µ-LED that need affordable large diameter wafers.



Triple-junction solar cell structure

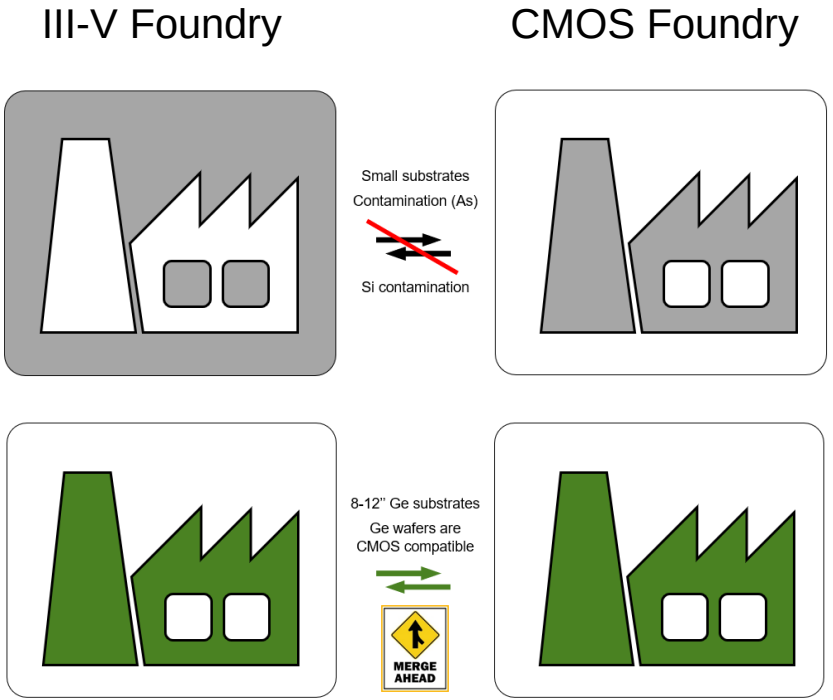
VCSELs for 3D sensing (consumer & automotive)

Micro-LEDs for VR/MR applications



SWIR sensors

Two worlds: III-V and CMOS



CMOS offers a set of very advanced processing steps and low production cost in high volumes.

Ge substrate is compatible with CMOS production, while other III-V substrates are not (GaAs, InP, etc.)

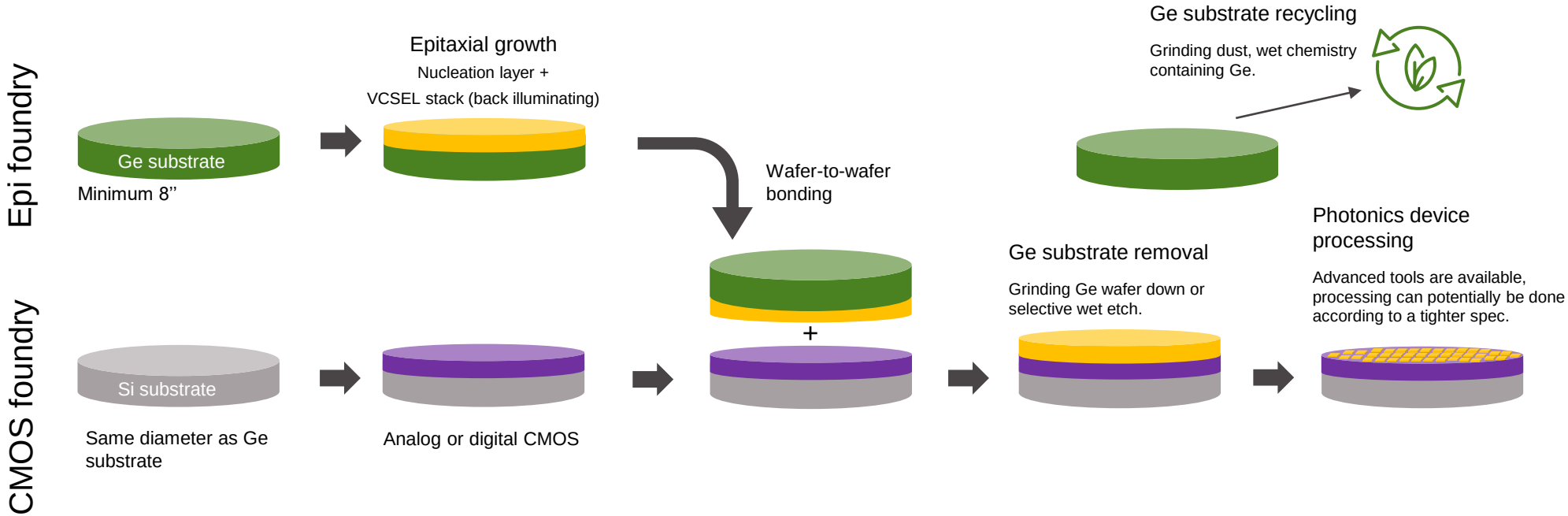
Number of applications benefit from the integration between CMOS and III-V.

Ge substrate can be selectively removed and Ge metal can be recycled to recuperate a part of the substrate cost.

Ge wafers allow III-V device manufacturing through CMOS fabs – new device concepts, high performance, low cost.

Potential avenue: CMOS drivers & VCSELs fusion

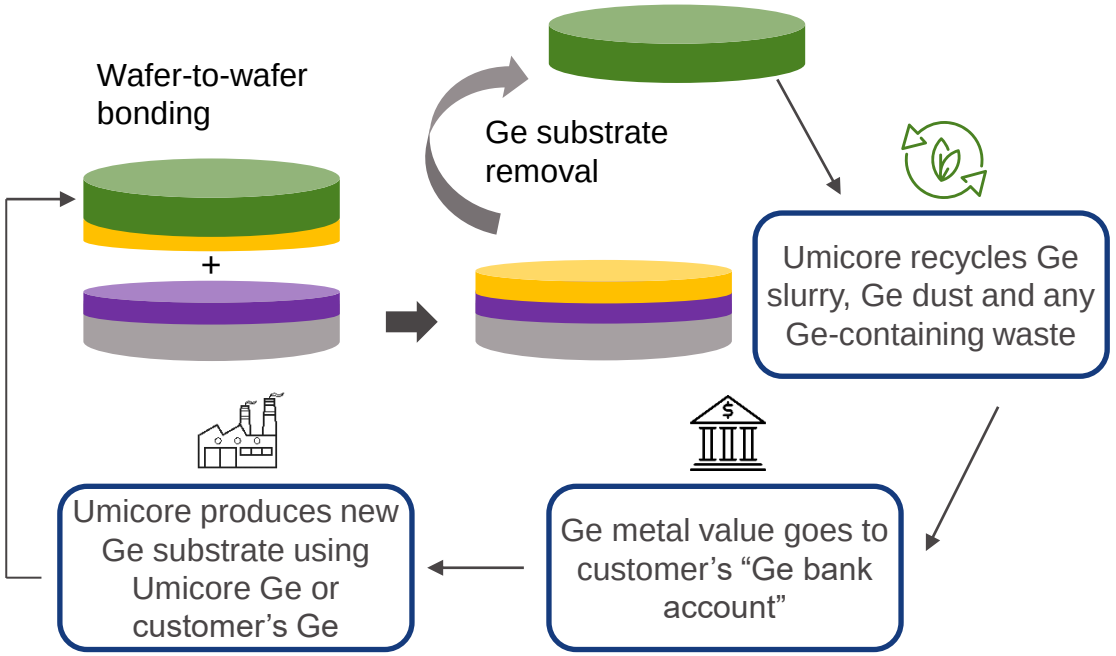
Ge substrate can be selectively removed and recycled



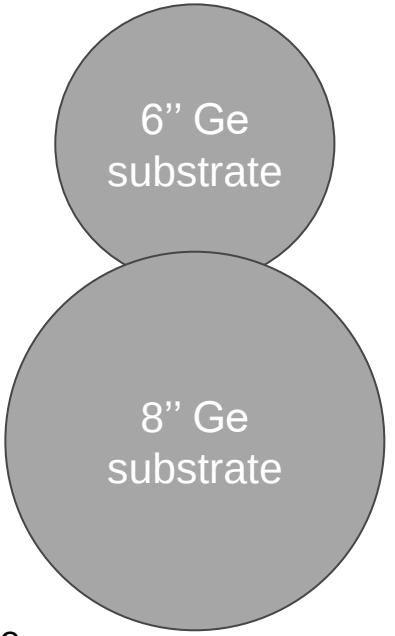
- Ge wafers allow for VCSEL device processing performed at CMOS foundries.
- In addition, integration of Si CMOS drivers with VCSELs is possible via wafer-to-wafer bonding.
- Wafer-to-wafer integration enables higher throughput = lower cost. Ge substrate removal avoids unnecessary waste generation and provides extra cost benefits.

Ge wafer recycling - advantages

Ge recycling – technically and financially beneficial



More than half of Ge metal value can be returned back to a customer.



Typical thickness 675 um
(min 225 um for epi wafers)
~ 85 $ Ge metal value *

Typical thickness 725 um
(min 425 um for epi wafers)
~ 175 $ Ge metal value*

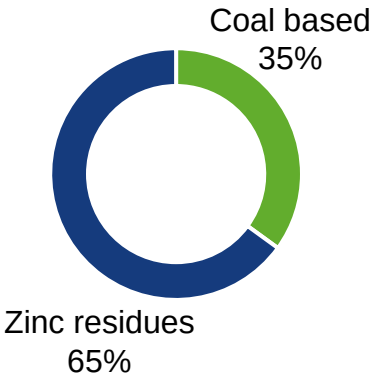
- While laser grade Ge and GaAs price is on par in high volumes, Ge recycling allows to recuperate significant part of Ge wafer cost.
- "Ge bank account" concept helps to hedge Ge metal price fluctuations.

*Assuming current Ge price 1400 $/kg

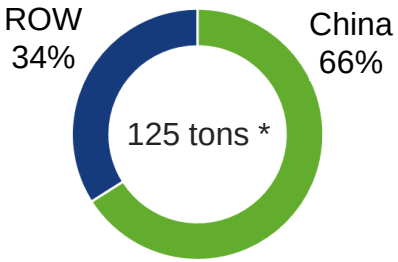
Germanium primary sourcing

Relatively small market with a potential to grow its global supply

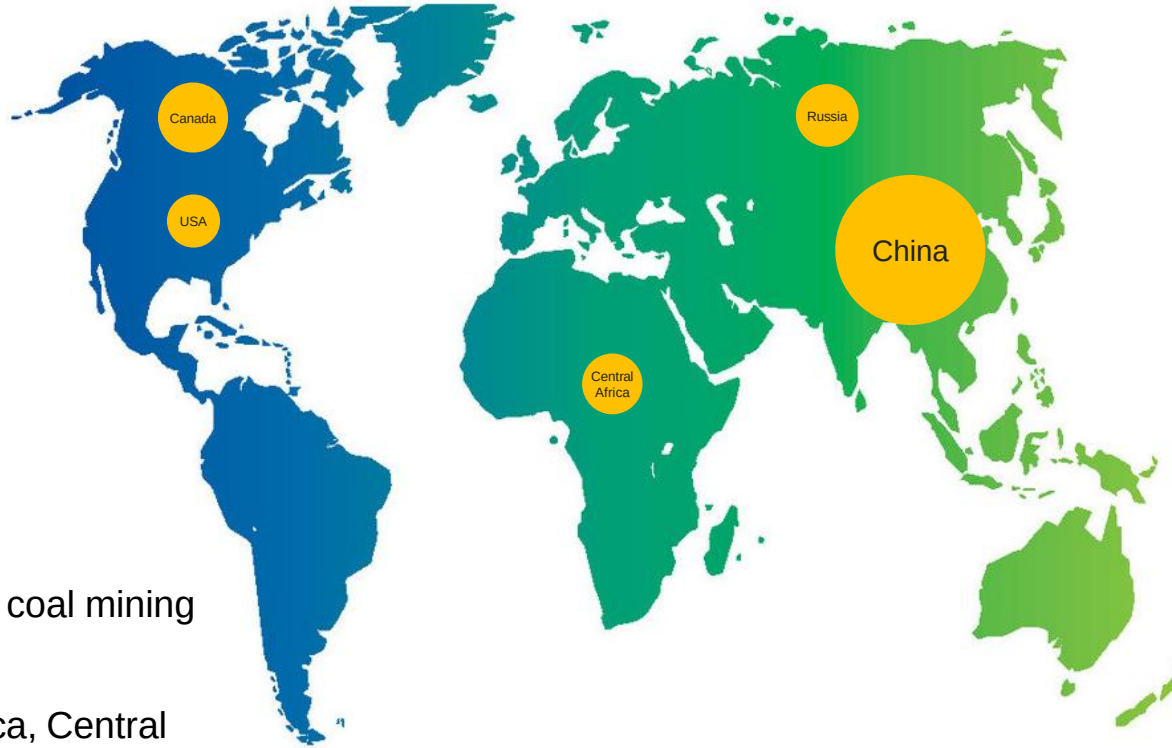
Type of global primary Ge supply



Origin of global primary Ge supply



* Annual fluctuations are in the order of ± 15%



- Germanium is extracted out of feed from zinc and coal mining
- Ge deposits across the globe
- Active sources are located in China, North-America, Central Africa and Russia
- New primary sources under development

Germanium – security of supply

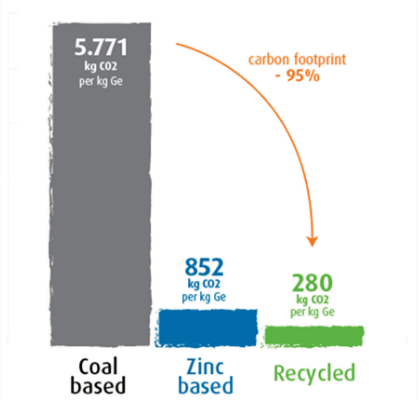
Umicore has well diversified Ge supply chain with above 50% coming from recycling

Beijing imposed export control on Ga and Ge

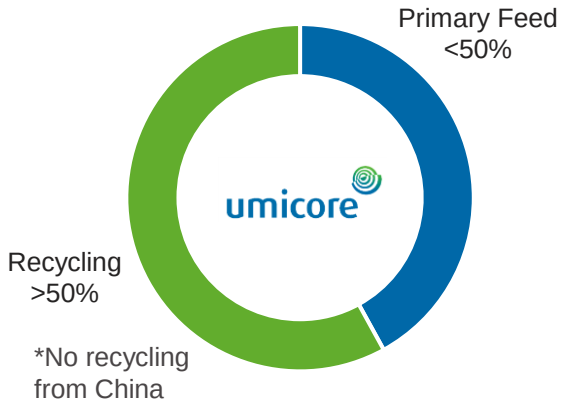
London/Paris (CNN) — Beijing will impose export controls on two rare elements essential for manufacturing semiconductors, in apparent retaliation after the United States and Europe restricted chip exports to China.

Gallium and germanium will be subject to export controls starting August 1 "to protect national security and interests," China's Ministry of Commerce said in a statement Monday.

Environmental impact of Ge sources



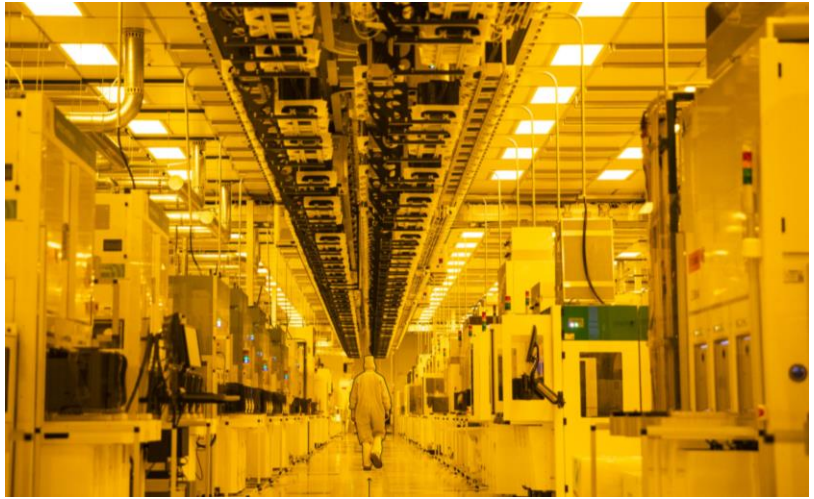
Umicore Primary vs Secondary Sourcing (2022)



- No coal-based Ge in Umicore supply chain.
- Years-long focus on closing the loop via germanium recycling.
- Recycling feed from all major Ge industries (fiber optics, solar, IR optics, LED, micro-electronics).
- Over 50% of our needs met through recycling; none from China.
- Global supply diversification strategy active.
- Continual investment in innovations to reduce dependency upon primary sourcing

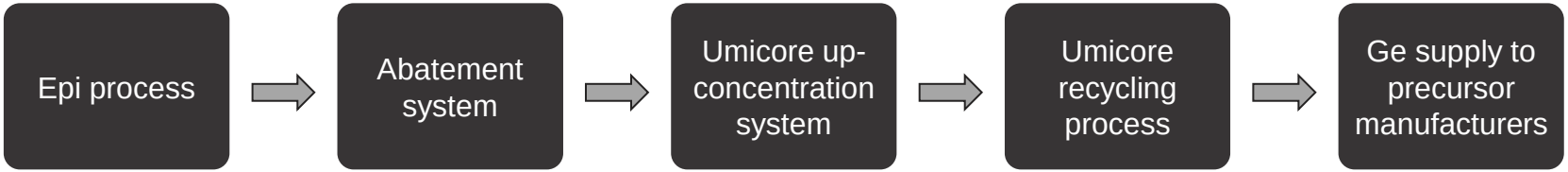
Establishing Ge Recycling from the CMOS Industry

Recycling GeH_4 waste from epi processes



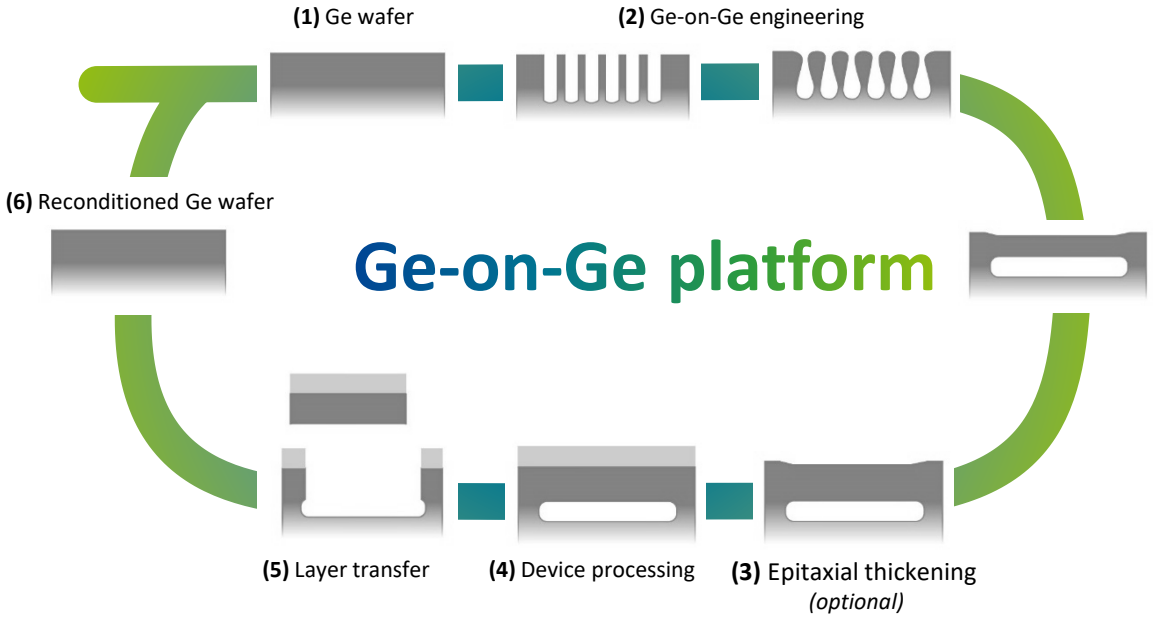
Photographer: Adam Glanzman/Bloomberg
https://www.bloomberg.com/graphics/2021-chip-production-why-hard-to-make-semiconductors

- More than 15 ton of Ge metal is consumed by CMOS industry annually (DRAM & Logic).
- No Ge recovery is implemented at the moment.
- With the epi process efficiency reaching maximum 30-40%, more than 9 ton of Ge goes to waste. This is > 7 % of the global annual primary Ge supply.
- Umicore collaborates with abatement system stakeholders to devise cost-effective Ge recycling solutions.



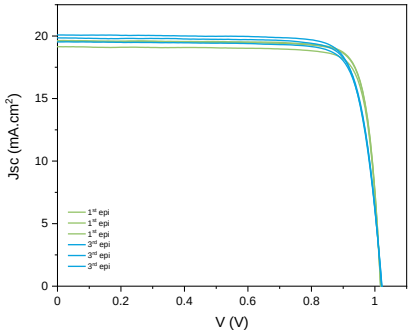
Next step in reducing primary sourcing dependency

Ge-on-Ge platform: high performance & wafer re-use



Demonstration of Ge thin-film

Free-standing Ge membrane



JV-characteristics of thin-film GaAs solar cells grown on a new Ge wafer (1st epi) and on a reused Ge wafer (3rd epi). 1 cm^2 without ARC.

- Ge-on-Ge platform allows for thin Ge layer removal in a III-V / CMOS-compatible process flow.
- The quality of the transferred Ge thin film results in similar JV characteristics for solar cells, whether grown on new or reused Ge wafers.

Conclusions

Ge is a high-quality epi substrate with zero EPD, allowing to manufacture new photonics devices such as long/short wavelength VCSELs and SWIR sensors.

Ge is a CMOS compatible material enabling integration between CMOS and III-V materials. Ge wafers can be removed selectively with respect to the III-V stack.

While primary Ge supply chain is dominated by China, Umicore gets more than 50% of it's raw materials from recycling non of which is of Chinese origin.

Umicore develops new Ge recycling sources as well as technical solutions for Ge substrate re-use.

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Connecting Life