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EFFECTIVE USE OF GERMANIUM

ESA-EUOG

EXECUTIVE SUMMARY

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Motivation

In previous Life Cycle Assessment (LCA) studies, Germanium (Ge) has been identified as one of the major environmental hotspots of ESA's space missions. Ge is one of the critical raw materials and the use of it (mainly driven by the solar cells) is the major contributor for the impact of the spacecraft in mineral resource depletion. Today, Ge is used as a growth template for III-V based solar cells and serves as the lowest active junction in state-of-the-art multi-junction solar cells. While the thickness of the Ge on solar cell level is around 140µm for a 100mm wafer, actually only 10-20µm are active, i.e. required for providing the requested electrical performance. Therefore, for cells to become thinner and lighter, solar cell manufacturers start to thin down the Ge wafers after cell processing by grinding or etching. However, the Ge waste that is produced during this thinning step is not recovered today since no economical process exists. Therefore, one idea to improve the use of Germanium is to effectively recover this Ge and establish a cost-effective recycling stream.

Another possibility to become lighter and reduce the amount of Ge is to start from a different growth template. The contrast between the active Ge thickness and the standard substrate thickness, makes it clear that current versions of multi-junction solar cells mainly used in space have a certain amount of superfluous germanium. From a cost, weight and a material criticality point of view, an alternative growth template in the form of an engineered or virtual substrate with only 10-30 µm of germanium would be an interesting product to have.

Objectives

The main objectives of this activity are as follows:

- Develop and implement a recycling process for Germanium for process steps in the wafer/solar cell productions of today's solar cells for which this is currently not done (e.g. the thinning process of the Ge backside).
- Develop a process for manufacturing high efficient III-V solar cells using alternative growth templates that allow for a significant reduction of Germanium. Thereby, nowadays state-of-the-art III-V multi-junction solar cell efficiencies shall be maintained
- A Life Cycle Assessment (LCA) of the two options ("recycling" and "alternative growth template") shall be performed. This shall be benchmarked against current technology and manufacturing processes.

Results

- Recycling

In the current project, the challenge is to recycle Germanium from the thinning process after deposition of the III-V layers. At Azur Space, the backgrinding process is done with a very fine grinding wheel creating a Ge sludge containing ~100 mg/L Ge. The challenge is to increase this concentration at Azur Space to at least 1 g/L with a high Ge yield (> 90%) so that further concentration increases, and recycling can be performed at the Germanium refinery site (Umicore).

Figure 1 shows the main development phases that the project went through and the main results from each of the phases. The first phase (lab trials at Umicore) was executed prior to the start of this ESA activity and helped further define the approach and the scope of this activity. The first lab trials at Azur demonstrated an excellent retention and recovery of 82-90% of the germanium in 1 process step. Further processing with different techniques could increase the total retention to 99.4% but this approach didn't pass the economic screening exercise and wasn't withheld for further piloting trials.
The pilot trials consisted of a series of tests with the objective to both confirm the positive germanium recovery results obtained in the bench-scale set-up and to reach the minimum concentration limit of 1 g/L germanium in the concentrate stream, in a stable process. In this phase a significant volume reduction of 98% was demonstrated. We demonstrated the high concentration of at least 1 g/L and obtained stable operation of the pilot equipment.
Finally, the process performance was tested during a longer period. A stable operation was demonstrated.
In the project a more complex recycling flow with higher Ge yield was also demonstrated to work. Despite the higher Ge yield, the simple recycling operation that was at the core of the project, is the more interesting investment from an operational and economic point of view.

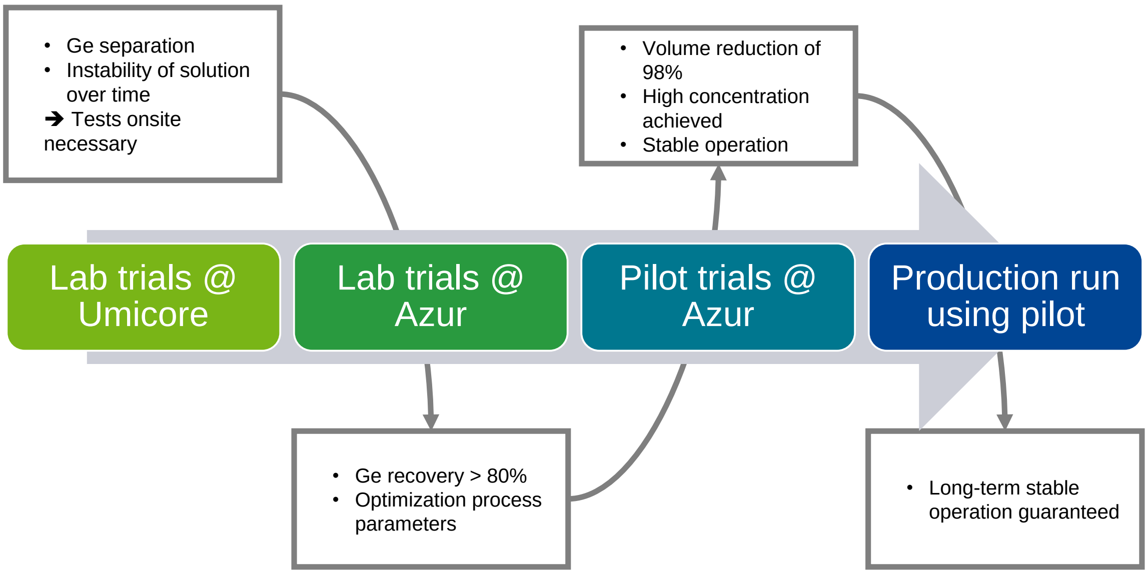

Figure 1: Main development phases and results for the germanium recycling work.

The overall conclusion from the LCA study on the recycling work is that introducing the germanium recycling process in solar cell backgrinding would reduce environmental impacts to mineral resource depletion, climate change and acidification. This is due to the lower primary germanium consumption, leading to a lower energy and mineral consumption, thus reducing impacts overall. However, impacts to marine eutrophication and freshwater ecotoxicity increase slightly due to the additional wastewater generated in the recycling process. Primary germanium production is by far the most significant contributor to all minerals and metals resource depletion indicators, which is understandable as this study concerns manufacturing of germanium wafers.

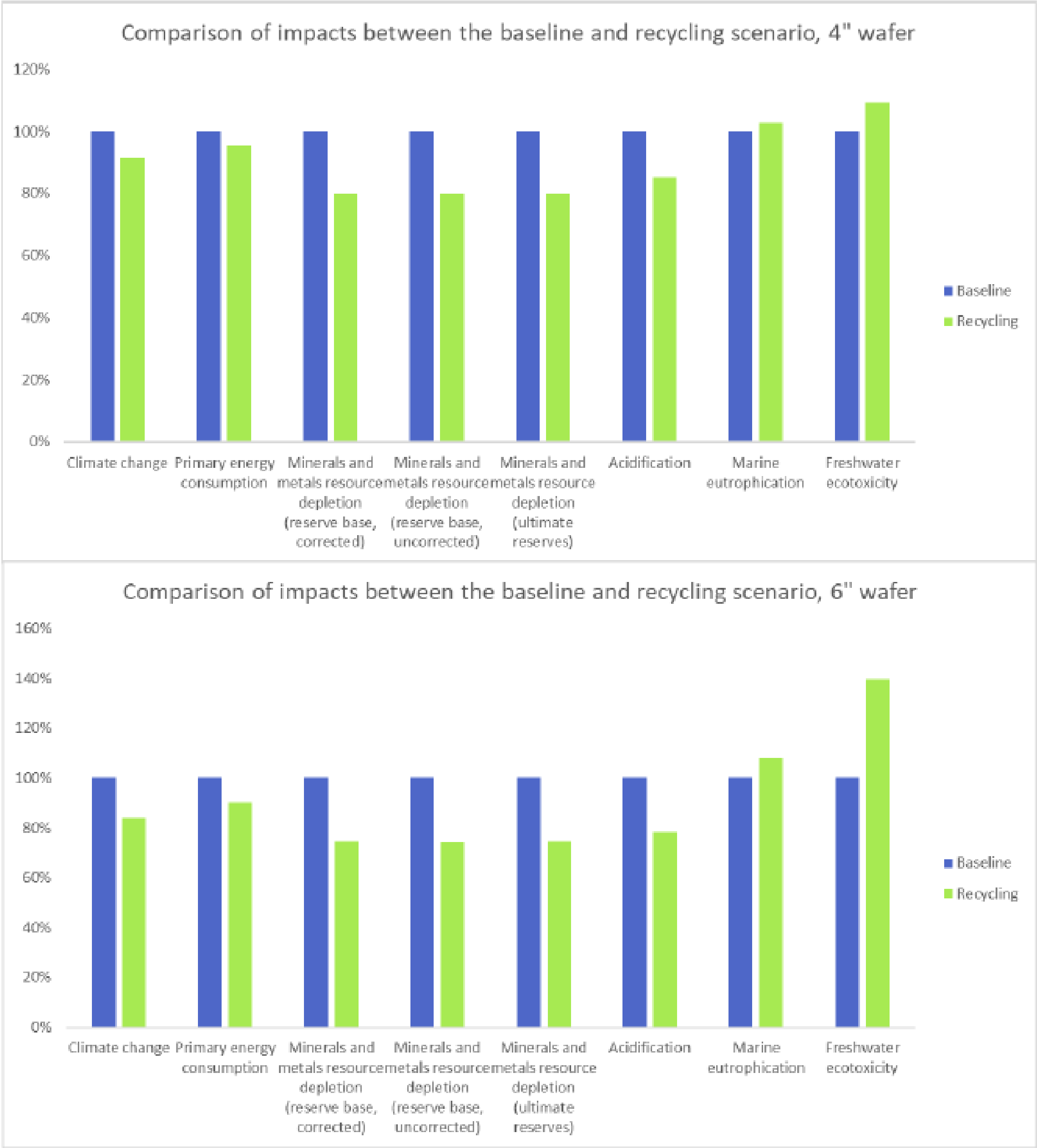

Figure 2: Comparison of the baseline and recycling scenario. Manufacturing of one output 4"/6" germanium wafer with backgrinding (78.5 cm² / 181.5 cm² surface area, 105µm / 147µm thickness).

- Alternative growth substrate

The second work package studied how Ge-on-Ge engineered substrates could substitute standard Ge substrates as alternative growth template for III-V multi-junctions. Ge-on-Ge engineered substrates are being developed in a parallel activity (ESA ELLA, Contract n°4000129924/20/NL/FE). The key focus of the work in the current activity is the integration with the III-V heteroepitaxy and basic cell processing steps.

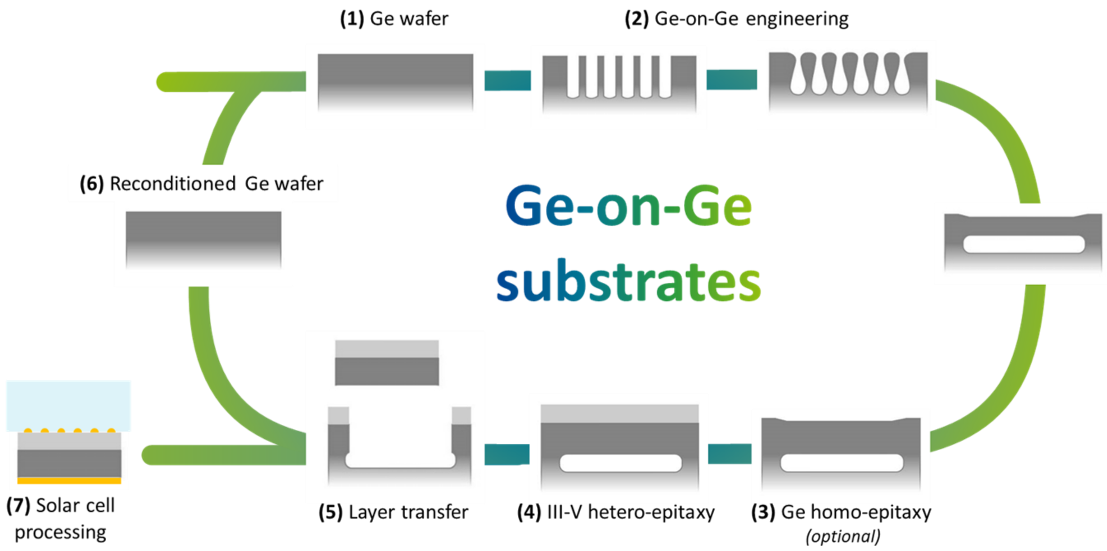

Figure 3: Key building blocks along the Ge-on-Ge engineered substrate cycle.

High quality III-V heteroepitaxy was demonstrated and validated through material characterization and solar cell characterization. Through 4 iterations of Ge-on-Ge samples, the prototypes gradually improved. The first iteration consisted of 200 mm substrates that couldn't be processed easily at Azur Space. This iteration was used to demonstrate double heterostructures that could be used for photoluminescence mapping. In this way, the bandgap and minority carrier lifetime were shown to be similar to layers grown on standard wafers. In the second iteration we shifted to resizing the substrates to 150mm prior to shipping them to Azur. This allowed the wafers to be used for the first demonstration of 3G30 cells. The cell processing had some unexpected complications which resulted in a loss in fill factor. The third iteration brought a substantial improvement in the surface quality and the epi-readiness of the Ge-on-Ge engineered substrates. Standard 3G30 structures were grown on n-type substrates, resulting in 2x2 cm^2 dual junction devices with a performance closely matching that of reference cells. The fill factor was recovered thanks to some improvements in cell processing. Concluding, the Ge-on-Ge surfaces provided by Umicore are suitable for epitaxial growth of the 3G30 cell structure. The fourth iteration was used to try and demonstrate lift-off as well. Unfortunately, the structure delaminated prematurely during the III-V heteroepitaxy of 3G30 structures.

The overall conclusion from the LCA study on the alternative growth template, is that introducing an alternative growth template in III-V solar cell manufacturing would reduce environmental impacts to mineral resource depletion as between one-tenth and one-fourth only of germanium is needed. However, the annealing and epitaxy step of the alternative template leads to an increase of climate change and primary energy consumption. In the alternative growth template, the mother substrate manufacturing and the annealing and epitaxy steps are the most significant contributors to minerals and metals resource depletion indicators due to the deposition of the germanium foil, which is understandable as this study concerns the use of germanium in III-V solar cell manufacturing.

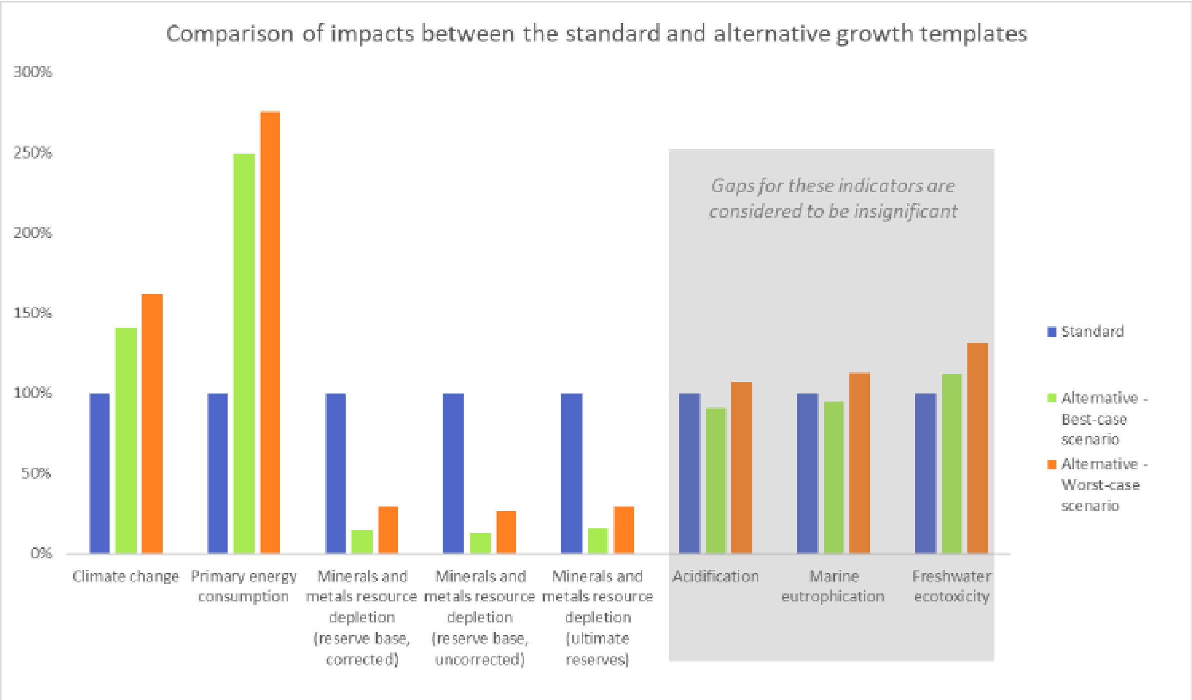

Figure 4: Comparison of the standard and alternative growth templates for the "Manufacturing of one 4" germanium template for III-V solar cell deposition (78.5 cm² surface area)".

Conclusion

This project worked on two different approaches to increase the effective use of germanium in multi-junction solar cells.

The first work package studied how germanium can be recycled from the waste stream of the backgrinding step that is performed by Azur Space to thin down the solar cell. The choice of recycling technique was made by combining technical feasibility, cost assessment and life cycle assessment. Through lab scale and pilot scale experiments, a Ge recovery yield of more than 80% was achieved in combination with a volume reduction of 98%. Azur Space has installed an industrial recycling installation based on the pilot set-up, of which the end-stream is currently recycled at Umicore.

The second work package studied how Ge-on-Ge engineered substrates could substitute standard Ge substrates as alternative growth template for III-V multi-junctions. High quality III-V heteroepitaxy was demonstrated and validated through material characterization and solar cell characterization. Through 4 iterations of Ge-on-Ge samples, the prototypes gradually improved. Standard 3G30 structures were grown on n-type substrates, resulting in 2x2 cm² dual junction devices with a performance closely matching that of reference cells. Concluding, the Ge-on-Ge surfaces provided by Umicore are suitable for epitaxial growth of the 3G30 cell structure.