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EPITAXIAL LAYER AND LIFT-OFF APPROACH

ESA-ELLA

EXECUTIVE SUMMARY

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Contents

1. Introduction 1
2. Aims of the project 2
3. Project highlights 3
  3.1 GeON 3
    3.1.1 Ge foil formation, Ge epitaxy and foil transfer 3
    3.1.2 Solar cell demonstration 5
  3.2 PGe 5
    3.2.1 Full-area electrochemical porosification tool development 6
4. Concluding remarks 7
5. References 7

1. Introduction

Today, Ge wafers are the substrate of choice for multi-junction, high-efficiency III-V solar cells for applications in space. In such cells, Ge functions as an epitaxy template for the growth of III-V (Al, Ga, In, P, As, Sb) compound semiconductor layers and also as the bottom junction of the solar cell. Commonly, 100 mm and 150 mm diameter Ge wafers with a thickness of 140 µm and 225 µm, respectively, are used, while merely 5-10 µm thick Ge is enough for the proper (electro-optical) functioning of the solar cell [1]. The remaining Ge thickness only serves as a mechanical support for handling and processing. However, using thick Ge for mechanical support is not ideal as Ge is a major cost element of such solar cells and also accounts for most of the weight.

Thinner Ge substrates would reduce the cost of III-V solar cells, the weight of the solar arrays and the associated launch cost. In addition, an efficiency gain in operation is anticipated through lower heat generation. Unfortunately, these advantages do not compensate for the increased wafer breakage during solar cell fabrication. For that reason, thick commercial wafers are used. The wafer thickness is reduced in the final product to about 80 µm via a back-grinding process [2].

While the incumbent technology can support the general expansion of the legacy space market, new power-hungry space concepts remain out of reach, such as a habitable moon base, data centers in space, or space-based solar power. To meet the corresponding high needs in substrates, a more efficient use of Ge is needed. For this reason, Umicore is developing an engineered Ge substrate based on a novel epitaxial layer and lift-off approach (ELLA) [3]–[8]. An engineered Ge substrate consists of a 1-10 µm thick, detachable Ge foil, supported by a "weak Ge layer", on a Ge wafer. After solar cell processing on an engineered Ge substrate, the foil can be detached and the parent wafer can be reused. This concept is illustrated in Figure 1.

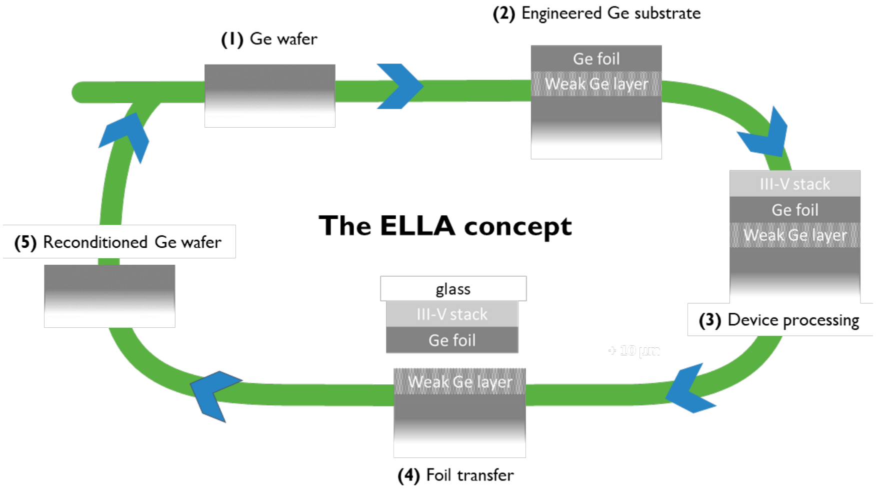


Figure 1: General process flow of the ELLA concept.

2. Aims of the project

In this project, we explored two approaches to make an engineered Ge substrate. The first approach, developed in a collaboration between Umicore and imec (ESA-GeON, 4000126837/19/NL/BJ/va), is based on photo-lithography and is called germanium-on-nothing (GeON), while the second, developed by Umicore in collaboration with Université de Sherbrooke (UdS), employs electrochemical porosification of Ge and is called porous germanium (PGe).

We used the GeON approach to examine the critical features of the engineered Ge substrates, viz., the quality (epi-readiness) of the Ge foil, its suitability for solar cell processing, the performance of the solar cells, the detachability of the Ge foil (including the solar cell) from the parent wafer, and the reconditioning of the parent wafer, and its reuse. III-V solar cell manufacturing companies/ institutes were involved in this study and their feedback was utilized in improving the design of the engineered Ge substrates.

From a commercial perspective, the PGe approach is more suitable. However, a commercial tool for single-side, full-wafer porosification of Ge was not available on the market at the time of this project. Therefore, a main part of the project was the development of a single-wafer electro-chemical porosification tool for 100 mm diameter Ge wafers, with the potential to be scaled-up for 150 mm and 200 mm wafers. This was done by our partner UdS, the pioneer in bipolar electrochemical porosification of Ge. The tool and the electrochemical porosification process know-how was later transferred to Umicore. We critically examined the design of the tool and the porosification process through a structured risk analysis methodology. The outcomes of the study were used to design the specifications and the to be tested features in the next-generation α prototype tool.

3. Project highlights

This highlights of the project are presented in this section. In the first part, the results of the GeON approach are covered while, the work on the PGe approach is presented afterwards.

3.1 GeON

The GeON approach for the engineered Ge substrates is schematically shown in Figure 2. It consists of pore formation on the parent wafer surface by photolithography and dry etching. The macro-pores re-structure themselves during a subsequent high-temperature annealing step to form a closed Ge layer on top of the Ge wafer.

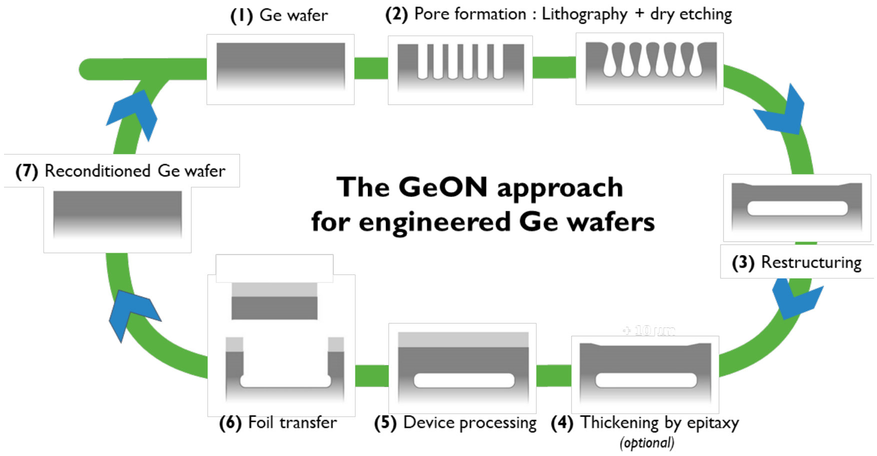


Figure 2: Process flow of engineered Ge substrates from the GeON approach.

This work focused on demonstrating that engineered Ge substrates from the GeON approach can fulfill the threefold functions of Ge substrates for space solar cells: (i) epi-ready foil surface for high-quality III–V growth, (ii) carrier for solar cell processing, and (iii) full-area detachment and transfer to a carrier, such as glass.

3.1.1 Ge foil formation, Ge epitaxy and foil transfer

The feasibility of the GeON approach to form an engineered Ge substrate had been demonstrated in an earlier project (ESA-GeON, 4000126837/19/NL/BJ/va). In this project, the ultimate target was to implement the process on a 200 mm diameter wafer. The crystalline quality and orientation of the parent wafer as well as the doping concentration and surface roughness have to be replicated in the Ge foil for growing good quality III-V layers.

With the GeON process we could successfully and repeatably obtain a perfectly closed Ge foil on a 200 mm monocrystalline wafer of 700 µm thickness and a 6° offcut towards (111). Moreover, the foil was free of crystallographic defects and retained the crystalline orientation of the parent wafer.

In the ideal GeON approach the Ge foil is attached/supported to/by the Ge wafer only by the edge. Such a foil, especially on full wafers, tends to flake very easily during subsequent solar cell processing. Moreover, the foil sags under its own weight and may come in contact with the Ge wafer below. Contact of the foil with the wafer leads to re-bonding of the foil to the wafer during subsequent high-temperature III-V growth. To overcome this issue on large wafers (200 mm diameter), support structures, called pillars, were incorporated, during the pore formation process (Figure 3 (a)). With the optimum pillar design the foil was able to resist delamination during solar cell processing and was still easily detachable afterwards (Figure 3 (b)).

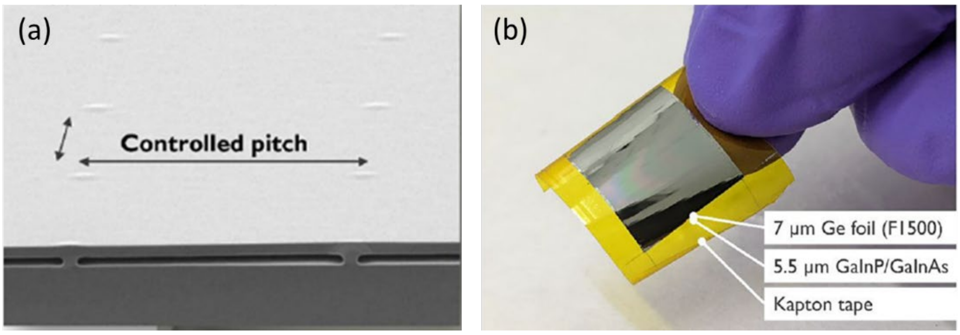
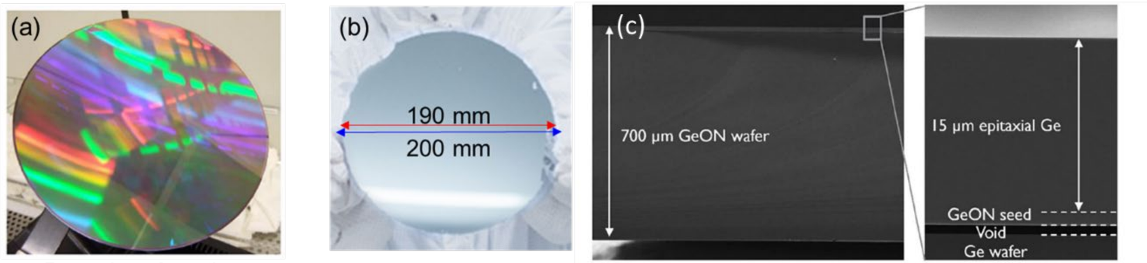


Figure 3: (a) A robust Ge foil formation using support pillars, and (b) a detachment result after III-V layer growth.

Epitaxial thicknening of the foil to up to 30 µm, with the possiblilty to be pushed further for growing free-standing layers, was demonstrated. Impressive growth rates of up to 190 nm/min for Ge homo-epitaxy were achieved by using a novel Ge precursor - $GeCl_4$ from Umicore. Moreover, very high B doping ($3x10^{17}$ to $1.3x10^{19}$ cm^{-3}) of the Ge foil during epitaxial thickening was achieved. Also, the electrical quality of the foil was found to be very good (minority-carrier lifetime > 25 µs for a 16 µm thick Ge foil [5]). These properties makes the Ge foil an excellent candidate for growing high-quality 3J III-V solar cells.

As mentioned earlier, foil detachability and wafer reuse are the unique features of engineered Ge substrates. A 190 mm diameter Ge foil on a 200 mm diameter Ge wafer was transferred to a glass substrate by adhesive bonding (Figure 4 (b)). The Ge wafer was reused 2 times to grow the Ge foil.



Porous layer formation entire surface

Large area foil detachment

Ge epitaxy on a Ge foil

Figure 4: Images of a 200 mm Ge wafer processed into an engineered Ge substrate via the GeON approach: (a) 12 areas were defined by lithography and dry etching; (b) a successful formation of a 190 mm diameter foil and its transfer to a glass substrate, and (c) cross-section SEM of a GeON wafer

3.1.2 Solar cell demonstration

3J InGaP/InGaAs/Ge solar cells with 0.1 cm^2 active area were grown by Universidad Politécnica de Madrid on a few defined areas of an engineered Ge substrate with a 7 µm thick foil and compared with those on standard wafers [4]. The usual processing for 3J solar cell structures on standard Ge was used. The foil was not detached from the wafer. It should be noted that the engineered Ge substrates did not show any issues, such as cracking or delamination, during the growth of the 3J solar cell structures or metallization. The results of the solar cells are shown in Figure 5.

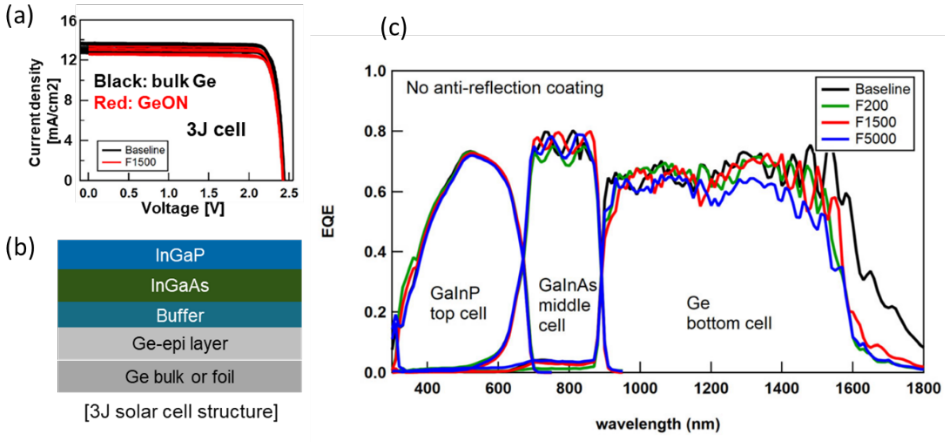


Figure 5: Performance of solar cells fabricated on a 7 µm thick Ge foil and bulk Ge wafers. (a) current-voltage comparison between cells on foil and on bulk Ge, (b) a schematic solar cell structure, and (c) external quantum efficiency of the fabricated triple junction solar cells.

Solar cells fabricated on the foil showed very similar performance as the ones on the standard wafer. This proves that the Ge foil is perfectly suitable for growing III-V layer with the same quality as on a standard Ge wafer. Additionally, the 7 µm thick Ge bottom junction is adequate to generate enough current for proper solar cell functioning.

In summary, by using the highly precise GeON approach we could qualify the engineered Ge substrate (parts of it, to be precise) on all the critical aspects required for high-quality III-V solar cells.

3.2 PGe

In parallel to the GeON approach, the PGe approach for engineered Ge substrates was also explored in this project. In the PGe approach, the weak layer is formed by bipolar electrochemical etching (BEE), which yields a meso-porous (pore size: 2-5 nm) layer. The detachable Ge foil is grown by homo-epitaxy on the porosified Ge surface. Even though the PGe approach is much less precise than the GeON approach, in terms of the geometry of the weak layer, and is challenging to reproduce consistently, it has the potential to be inexpensive and easily scalable for large-volume production. The project dealt with developing the BEE porosification process to achieve uniform porosification over 100 mm diameter wafers. For this purpose a tool was also developed.

3.2.1 Full-area electrochemical porosification tool development

For the PGe approach, Umicore, with its partner UDS, developed a tool for single-side electrochemical porosification of 100 mm Ge wafers. A schematic of the tool are shown in Figure 6.

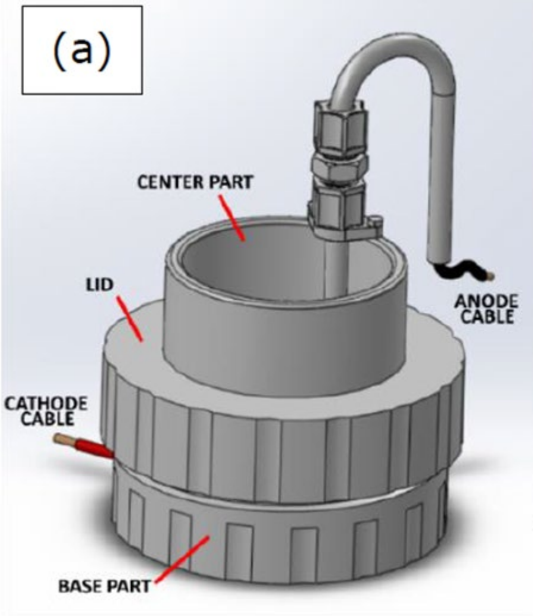


Figure 6: Illustration of the BEE porosification tool developed in this project by UdS.

Thanks to the unique tool design – dry back contact and full front electrolyte coverage – 100 mm wafers can be porosified selectively on one side and without any edge exclusion. Through continuous process improvement uniformly porosified wafers are now repeatedly achieved.

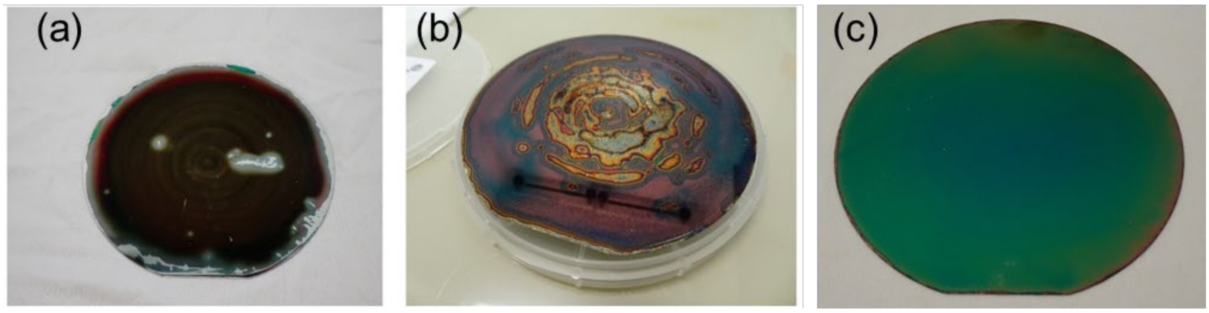


Figure 7: Images of electrochemically porosified wafers illustrating the improvements made in the process over the course of this project. (a) and (b) are images of non-uniformly porosified wafers that were seen at the beginning of the process development. (c) an image of a uniformly porosified wafer after implementing many process improvements. Notice that the entire wafer surface is porosified.

Moreover, failure mode and effect analyses of the tool design and of the BEE process were conducted with a view to identify the failure modes – safety-wise, or of the product – and improve the designs of the tool and the process. The findings of this study will be implemented in the next generation of tool and process.

Much work still needs to be done to realize cost-effective engineered Ge substrates via the PGe approach. In particular, epitaxial growth of the Ge foil on porosified wafers, foil detachment and its qualification for III-V solar cells are the key areas that require extensive study. In addition, much effort will be needed to develop a first prototype of a tool that eventually allows for consistent, high-throuhgput, high yield, reproducible full wafer porosification.

4. Concluding remarks

The ESA-ELLA project has been a great success in the development of engineered Ge substrates for efficient use of germanium. Through collaboration with its partners (imec and UdS), Umicore has been able to understand and overcome the technical challenges of the engineered Ge substrate concept. This concept, particularly with the PGe approach, has the potential to revolutionize the III-V solar cell manufacturing ecosystem. The sustainability and reusability aspects of the engineered Ge substrate ensure that the Ge-based III-V solar cell industry can be ready for multifold expansion in the coming years. However, the technology is not yet fully mature and further developmental work, in close collaboration with all the stakeholders, needs to be done to bring it up to production-ready level. The results achieved in this project are a great stepping stone for the next phase of the engineered Ge substrate development.

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