Improvements in ultra-light and flexible epitaxial lift-off GaInP/GaAs/GaInAs solar cells for space applications

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Abstract
A thin, lightweight, flexible solar cell is developed that maximizes the power-to-mass ratio under AM0 illumination and has a competitive efficiency after typical high energy electron irradiation. The inverted metamorphic triple junction (IMM3J) solar cells with Ga0.51In0.49P/GaAs/Ga0.73In0.27As subcells are grown on GaAs substrates and have a total epitaxy thickness of about 10 μm. After epitaxial growth, the inverted layer stack is metallized, with the metal serving as back-contact, back reflector and support layer for the ultra-thin solar cells before the GaAs substrate is separated by an epitaxial lift-off (ELO) process. The nondestructive nature of the ELO process makes multiple reuses of the GaAs substrate possible. The solar cell structure is optimized for maximum EOL efficiency, that is, after 1-MeV electron irradiation with a fluence of $1 \times 10^{15}$ cm$^{-2}$, by means of simulations that include the irradiation induced defects in the various semiconductor alloys. Assuming realistic charge carrier lifetime in the materials, we predict a near-term efficiency potential for the IMM3J ELO of 30.9% under AM0 illumination before and 26.7% after irradiation. Several IMM3J ELO solar cells with an area of approximately 20 cm$^2$ from different development stages were tested under AM0 illumination. The newest solar cells (generation III) with a mass density of only 13.2 mg/cm$^2$ reach conversion efficiencies of 30.2% at 25°C. The resulting power-to-mass ratio of 3.0 W/g for the bare solar cell is one of the highest published ratios. After irradiation, a conversion efficiency of 25.4% was measured for “generation II” devices under AM0 illumination, which corresponds to a power-to-mass ratio of 2.6 W/g. IMM3J ELO solar cells from “generation I” were also tested for mechanical stability as “de-risking” test of this new cell technology. No degradation of the cell performance was found after dipping the cell in liquid N2 and then heating up to 25°C for five times, despite of strong deformation of the flexible cell during the temperature cycle.

Keywords
multijunction solar cell, solar cell characterization, space solar cells
1 | INTRODUCTION

Solar cells used in space applications are operated in an atmosphere of high energy particles that decrease the cell performance during their operation. Therefore, III-V multijunction solar cells with high efficiencies after particle irradiation are used in space missions. These space solar cells (e.g., previous works\(^1\)–\(^6\)) reach efficiencies of 25%–29% after typical irradiation conditions with \(10^{15} \text{cm}^{-2}\) electrons of 1-MeV energy. Besides the end-of-life (EOL) efficiency, the power-to-mass ratio of the solar cell modules is one of the most important criteria for the assessment of new cell designs. Ever more space missions require an increasing power demand as there is a trend for satellites toward electrical propulsion. Options to meet these demands are thin, ultra-lightweight solar cells that reduce the mass and volume per solar cell and reach comparable EOL efficiencies. The reduced mass decreases the cost for the initial transport to the release orbit. Another advantage of thin solar cells is their flexibility that gives additional opportunities for possible stowage in a rolled configuration of a deployable solar generator or to conform to curved surfaces as often needed in mobile applications. Efficient thin and lightweight solar cells may also find applications in avionics and high-altitude pseudo satellites (HAPS).

Thin, flexible multi-junction solar cells with high efficiencies without irradiation, that is, Begin-of-Life (BOL), were already demonstrated by different research groups (e.g., Geisz et al.\(^7\) and Kim et al.\(^8\)). Cardwell et al. from Micro-Link Devices presented a triple junction GaInP/GaAs/GaInAs solar cell with a BOL power-to-mass ratio >3 W/g under AM0 spectrum.\(^9\) Inverted metamorphic triple-junction solar cells from Sharp\(^3,\(^10,\(^11\)) reached efficiencies above 26% after electron irradiation with \(1 \times 10^{15} \text{cm}^{-2}\) (1 MeV) electrons. These thin solar cells were grown inverted on a substrate that was removed afterwards.

The development of lightweight, flexible and foldable solar arrays is the goal of the EU-project ALFAMA.\(^12\) A key factor for a high power to mass ratio of the fabricated modules is the development of thin and thus flexible solar cells by retaining high EOL efficiencies under AM0 illumination. The route to achieve this goal within the project is an inverted metamorphic triple junction (IMM3J) cell with Ga\(_{0.51}\)In\(_{0.49}\)P/GaAs/Ga\(_{0.73}\)In\(_{0.27}\)As subcells in combination with an Epitaxial Lift-Off (ELO) process. The focus of the development is a device structure with optimized efficiency after 1-MeV electron irradiation with a fluence of \(1 \times 10^{15} \text{cm}^{-2}\). The technological development is supported by measurements of the subcell voltage and quantum efficiency. The full optoelectronic simulation of the triple junction cell predicts the efficiency potential before and after irradiation. In combination with the cell characterization, it allows an efficient and target-oriented optimization of the solar cell.

2 | CELL GROWTH AND SIMULATION METHOD

All layers of our metamorphic Ga\(_{0.51}\)In\(_{0.49}\)P/GaAs/Ga\(_{0.73}\)In\(_{0.27}\)As triple junction (IMM3J) solar cell (see Figure 1A) are deposited on a GaAs substrate by metal organic vapor phase epitaxy in an AIX2800G4-TM reactor. Between the GaAs middle cell (J2) and the GaInAs (J3) subcell a step-graded metamorphic buffer is grown to overcome the lattice mismatch. Figure 1B shows a cathodoluminescence measurement at a double hetero structure with the step-graded GaInP buffer as used in the triple junction device. The extracted average threading dislocation density of \(1.5 \times 10^6 \text{cm}^{-2}\) is small enough to allow charge carrier lifetimes above the nanosecond range. The grown cells have a total epitaxy thickness of about 10 \(\mu\)m. Before the actual IMM3J structure, the AlAs release layer stack is grown on top of the GaAs nucleation layer. The inverted epitaxial structure is metallized, with the metal serving as back-contact, back reflector and support layer for the ultra-thin solar cells. The epitaxial structure is nondestructively separated from the substrate by an epitaxial lift-off (ELO) process, whereby a HF solution selectively etches the AlAs release layer whilst the resulting crevice is bent open to avoid mass transfer limitations and thus maintain a constant high etch rate.\(^13,\(^14\)\) In this way, full 4” films are released.
from the wafer. This leads to an ultra-lightweight solar cell of approximately 13.2 mg/cm². The front metal fingers are processed by standard lithography. Finally, a double layer ZnS/MgF₂ anti-reflective coating (ARC) with a thickness of 150 nm is deposited on top of the solar cells by thermal evaporation. The solar cells produced are highly flexible and have an aperture area of about 20 cm². The non-destructive nature of the ELO process makes multiple reuses of the GaAs substrate possible. The solar cells have no further support. However, similar processed solar cells have been laminated in a flexible lightweight module within the ALFAMA project.²

The design of the absorber layers is chosen to reach current matching of the GaInP subcell (J1) and GaAs subcell (J2) after irradiation with 1 MeV electron (10¹⁵ cm⁻²): For the optimization a two-dimensional numerical solar cell model of half a finger pitch is elaborated in Sentaurus TCAD.¹⁶ The optical simulation uses the transfer-matrix method, while the different recombination and tunnel processes are considered in the electrical part. Material properties and models for GaInP, GaAs, and Ga ₀.₄₇In₀.₅₃As including bandgaps, density of states, effective masses and electron affinities for band alignment, carrier mobilities, recombination coefficients and sensitivities are taken from previous studies. The optical material parameters for GaInAs are generated from GaAs and Ga ₀.₄₇In₀.₅₃As parameters by using a morphing algorithm presented in Schygulla et al.¹⁹

For an estimate of the realistic near-term BOL efficiency potential of the solar cell structure, we use Shockley–Read–Hall (SRH) lifetimes τSRH for the different materials that we extracted from former measurements on inverted grown samples. Electron irradiation mainly causes point defects by collisions with atoms of the crystal lattice and the following creation of vacancy-interstitial pairs.¹⁵ In the simulation, these point defects can be described with the Shockley–Read–Hall (SRH) formalism and a corresponding minority carrier lifetime limitation due to irradiation induced defects τID at low injection.²⁰ The EOL SRH lifetimes τEOL is calculated by combining the BOL SRH lifetime and τID from previous experiments²⁰,²¹ and irradiation experiments at single junction solar cells by

\[ \tau_{EOL} = \left( \tau_{SRH} + \tau_{ID} \right)^{-1}. \]

Table 1 summarizes the crucial parameters of the electrical simulation: the minority carrier lifetimes for the three p-type absorbers. The used electron lifetime for GaAs at low injection τID (e⁻) lies between the values from Grunginskie et al.²² and Lang et al.²⁰ For GaInAs with increasing In fraction, we observed a slightly stronger degradation. The GaInP subcell is the radiation hardest subcell due to the high photon absorption rate in GaInP and relatively small irradiation damage. We determined a τID (e⁻) of 0.4 ns after irradiation with an electron fluence Φe = 10¹⁵ cm⁻² (1 MeV) and subsequent annealing at 60°C. Our τID (e⁻) for GaInP is a factor of ~4 higher than before annealing and close to the values in Khan et al.²³ and Yamaguchi.²⁴ We assume that only the charge carrier lifetimes in the absorber changes during electron irradiation. With these parameters, we can simulate the realistic near-term EOL efficiency potential and optimize the structure in terms of EOL efficiency. The comparison of measurements and these simulations allows a successive adjustment of the solar cell structure and processing routines during the development process. In this paper solar cells from three development status (Gen I-III) are discussed. Gen I solar cells were also used for the temperature cycling tests (Section 3.3). Gen II solar cells for the irradiation tests (Section 3.2), whereas Gen III solar cells were measured only BOL yet. The simulated near-term potentials used for comparison reveal the necessary improvement steps of solar cells of different generations.

3 | RESULTS

3.1 | BOL cell characterization

In Figure 2, the IV characteristics under AM0 of the solar cells from Gen I–III are shown. The solar cell from Gen I suffers from a high series resistance that limits the FF to 76.8% (green squares). For the Gen II solar cell an efficiency of 28.9%, with a fill factor of 84.6%, JSC of 15.8 mA/cm² and a Voc of 2.95 V was measured (blue dots in Figure 2). In Gen II solar cells, the doping concentrations in the contact layers were increased, an improved back surface field for the GaInP subcell was integrated and the thickness of the GaInP subcell decreased for the purpose of an improved EOL current matching. The increased doping concentration in the contact layers significantly reduces the series resistance in comparison with Gen I solar cells. However, the FF of the solar cell from Gen II still suffers from a too high series resistance Rs: To match the IV measurement a lumped series resistance of 3 Ω cm² for the contact and finger resistance must be assumed in the simulations, which results in an FF loss of ~1%abs compared with a contact and finger resistance <1 Ω cm². In addition, a too small parallel resistance reduces the FF of the Gen II solar cell.

The external quantum efficiency (EQE) is measured for the three subcells separately and calibrated with the IV measurement. The measured subcell EQEs and the extracted subcell current densities are
The thicknesses of the absorber layers were chosen that $J_1$ and $J_2$ have the same simulated current density after irradiation and that $J_3$ has a 1 mA/cm$^2$ higher current density. Due to the different degrees of degradation of the subcells, this inevitably leads to strongly different subcell currents before irradiation. The comparison of measured and simulated EQEs in Figure 3 reveals only small deviations to the near-term potential (black lines) in all three subcell EQEs of Gen II (blue symbols). As a result, the sum of the measured EQEs (open blue symbols) is quite constant over a wide wavelength range besides few dips due to reflections. However, the EQE sum at wavelengths that were mainly absorbed at the front side of $J_1$ and $J_2$ subcells is lower than the simulated EQEs (see arrows in Figure 3).

We performed electroluminescence (EL) measurements in spectral mode with varying current density at a Gen II solar cell. The subcell open circuit voltages are determined with the EL signal close to the bandgap of the subcells according to the “reciprocity principle.” Finally, pairs of $J_{SC}/V_{OC}$ measured at the same current densities are used for the calibration of the subcell voltages.

For the comparison of the $V_{OC}$ losses in the three subcells, the $W_{OC} = \frac{E_g}{e} - V_{OC}$ is shown in Figure 4 as blue filled symbol. The slight increase of $W_{OC}$ from GaInAs to GaAs can be explained with the higher bandgap of GaAs. However, the GaInP subcell has a significantly higher $W_{OC}$ due to the thermal load during the inverted growth and the resulting dopant diffusion. Comparison with the simulated $W_{OC}$ (black bars in Figure 4) shows that subcell $J_1$ and $J_2$ are of lower quality than expected from simulations based on previous experimental results.

In Gen III solar cells, the thickness of both ARC layers was reduced by 8 nm to decrease reflection for small wavelengths and thus increase the generated photo current in $J_1$. As a drawback the generated photo current in $J_3$ is lower. Furthermore, the thickness of the $J_1$ emitter was reduced by 10 nm and the flux of the doping source during the bottom p-type contact layer growth in Gen III is further increased compared with Gen II.
The IV characteristic of the best Gen III solar cell is shown in Figure 2 (red symbols). An efficiency of 30.19% ± 0.91% under AM0 illumination was measured with a $J_{SC}$ of 16.05 mA/cm$^2$, a $V_{OC}$ of 3.043 V and an FF of 84.5%. Besides a remaining high series resistance, the solar cells of Gen III are in good agreement with the simulated near-term efficiency potential of 30.9% (black line in Figure 2). Despite the higher dopant flux during contact layer growth in Gen III solar cells the $R_S$ does not improve. We therefore assume that the high $R_S$ in Gen II and Gen III solar cells cannot be attributed to the contact resistance. The measured $V_{OC}$ in Gen III fulfill the expectations from the simulations and, in the shown solar cell, even exceed the simulated $V_{OC}$ by 10 mV. The unexpectedly high $V_{OC}$ can be explained by the high GaAs quality in Gen III solar cells, which is reflected in the low subcell $W_{OC}$ (see Figure 4). From Gen II to Gen III, the $W_{OC}$ of J1 and J2 was significantly reduced, whereas the $W_{OC}$ of J3 is the same in both generations. The comparison with the parallel shifted line of the radiative limit reveals that the BOL quality of GaInP and GaInAs in Gen III solar cells is significantly lower than for GaAs. This indicates further potential for $V_{OC}$ improvements in subcell J1 and J3, although the overall $V_{OC}$ is already satisfactorily high for an IMM solar cell. The $W_{OC}$ differences between Gen II to Gen III can neither be explained by the small differences in the epitaxial growth of J1 nor by the ARC adaption. Thus, we focus on differences in processing and analyze two Gen III solar cells before and after small adaptions in the mesa etch procedure.

The IV curve of the best Gen III solar cell, which was processed after the adaptions, is parallel to the simulated curve. In contrast, the low FF and the slope of the IV curve from the Gen III solar cell before the adaptions indicates a parallel resistance problem similar to Gen II solar cells (see Figure 5) that could be caused by local shunts in the current limiting subcell. To test the shunt hypothesis, we perform electroluminescence imaging of J1, with filters in front of the detector for luminescence to select either signal from J1, J2, or J3 at both Gen III solar cells (Figure 5). A large dark spot in the vicinity of the contact pad in J1 (Figure 5, right: lower right corner of the low FF cell), can be identified as a shunt since the introduced excess charge carriers can flow away in this region via a locally low parallel resistance. Consequently, no radiative recombination is seen in this region of the subcell under consideration. In contrast, the increased current flow through a shunt in one subcell leads to an even stronger excess carrier density in the surrounding, non-shunted subcells, that is, to an increased radiative recombination, which can be identified as bright areas in J2 of the low FF cell from Gen III. In analogy, the small white spots in J1 are caused by shunts in J2, where they appear as black spots. Only one smaller dark spot in J2 is visible in the best solar cell. Adaptations to the thin-film processing resulted in a reduced shunt probability for later Gen III solar cells. Gen III solar cells before the adaptions have a lower $V_{OC}$, besides the lower FF. The large shunts found in older solar cells might partially explain the lower $V_{OC}$ of Gen II and Gen III solar cells before the process adjustments.

In addition to shunts, we observe defects generated during post-process handling of the thin cells like the crack indicated with the green arrow in Figure 5 (right) that was not visible directly after processing. In Figure 3, the subcell EQEs of the Gen III solar cell is compared with the Gen II solar cell and the simulation of the near-term potential. Due to the improvements in J1 and the ARC adjustments, the EQEs of the Gen III solar cell get closer to the near-term potential. The subcell currents of J1 and J2 increased by 0.2 mA/cm$^2$ in Gen III (red numbers within the EQEs) compared with the Gen II solar cell (blue numbers). Before irradiation the radiation hard GaInP (J1) subcells limit the overall current to 15.8 mA/cm$^2$ (Gen II) and 16.0 mA/cm$^2$ (Gen III), whereas the GaAs (J2) subcells becomes current limiting after irradiation with more than $10^{15}$ (1 MeV) electrons per cm$^2$ as will be discussed in the next section.

**FIGURE 5** EL images of J1 and J2 of two Gen III solar cells. The luminescence of J2 and J3 or J1 and J3 is blocked by using optical filters in front of the camera sensor. A large shunt close to the contact pad (black spot) in J1 and shunts in J2 (white spots) are visible on the right cell (red arrows). The green arrow indicates a crack that was not visible in an EL image directly after processing and thus introduced during handling. On the left solar cell only one smaller shunt in J2 is visible. In the IV curve in the middle the low parallel resistance of the shunted solar cell results in a steeper decrease of the current at lower voltage.
3.2 | EOL cell characterization

The Gen II IMM3J ELO solar cell shown in Figure 2 before irradiation was irradiated with 1 MeV electrons at DELFT with an $e^-$/C0-fluence of $10^{15}$ cm$^{-2}$. After irradiation the solar cell was annealed according to the European Cooperation for Space Standardization (ECSS). In Figure 6, the measured IV characteristic under AM0 illumination of the irradiated Gen II solar cell (blue symbols) is compared with the near-term EOL potential (black line). In Gen II, an efficiency of 25.4% is reached, which is 1.3% below the simulated near-term EOL potential of 26.7%. The FF of 81.1% suffers from the high series and low parallel resistance already found before irradiation. The $V_{OC}$ (2.741 mV) is 40 mV below the simulated EOL $V_{OC}$.

In Figure 4, the $W_{OC}$ of the subcells of the Gen II IMM3J ELO after irradiation is shown. The $W_{OC}$ of the GaInP subcell (J1), which had the highest $W_{OC}$ before irradiation, increases by only 16 mV. For the other two subcells we measured a 121 mV (J2) and 100 mV (J3) higher $W_{OC}$ in comparison to BOL. GaInP is a relative radiation hard material, that is, $\tau_{id}$ is higher compared with the other materials (see Table 1), and thus has the lowest $W_{OC}$ after irradiation when the performance of the subcells is limited by the radiation damage. The $W_{OC}$ analysis implies that GaInP is the only subcell after irradiation that is affected by the non-radiative lifetime BOL $\tau_{BOL}$ (SRH) and further improvements of the BOL bulk quality increases the EOL $V_{OC}$ only in the GaInP subcell. For the best Gen III solar cell, we expect an efficiency of 25.8% based on the device simulation, i.e. an efficiency between Gen II and near-term potential of 26.7%.

3.3 | Temperature cycling tests

Some Gen I IMM3J ELO solar cells were tested for mechanical stability under extreme temperature cycling as “de-risking” test of this new cell technology. In this project a very aggressive thermal cycling was chosen. The solar cells were dipped in liquid N2 and then heated up to 25°C for five times. The different thermal expansion coefficients resulted in a total rolling of the thin solar cells (see Figure 8A). After the five liquid nitrogen dips a quick visual examination was conducted. By eye, no contact finger delamination or other structural defects were visible (see Figure 8A bottom). The measured efficiencies under AM0 illumination at 25°C before immersion in liquid N2 and the
measurements in between and after the thermal cycles are similar within measurement uncertainty (see Figure 8B). Thus, no degradation was observed due to the thermal stress and the extreme mechanical deformation. Further temperatures cycle test also including higher temperatures are already in planning.

4 | DISCUSSION

The goal of the new IMM3J ELO solar cell is the optimization of the power-to-mass ratio without significant EOL efficiency losses compared with conventional space solar cells. Thus, comparisons of the efficiency and the power-to-weight ratio of the IMM3J ELO and state-of-the-art space solar cells are shown in Figure 9. We concentrate on thin-film and thinned Ge substrate-based space triple junction solar cells with published efficiency and weight. The Gen III IMM3J ELO solar cell reaches almost the BOL efficiency of the 3-junction ELO solar cell from MicroLink Devices with a BOL design and exceeds the efficiencies of the Azur 3G30 advanced and SolAero ZTJ space solar cells (Figure 9A). After irradiation with an electron fluence of $10^{15}$ cm$^{-2}$ the Gen II IMM3J ELO solar cell is $\sim2$%$_{abs}$ below the 3-junction space solar cell with the highest efficiency. The remaining factor of the Gen II IMM3J ELO (88%) is smaller compared with the Azur 3G30 advanced but exceeds all others plotted space solar cells. However, higher BOL efficiency caused by material improvements have only a small impact on the EOL performance and thus, the remaining factor usually decreases with increasing BOL efficiency. This effect partially explains the stronger degradation at lower electron fluence for solar cells with high BOL efficiency. Note that not all space solar cells are optimized for an electron fluence of up to $10^{15}$ cm$^{-2}$, which might explain differences in degradation curves.

The $V_{OC}$ of the Gen II solar cell after an electron fluence of $10^{15}$ cm$^{-2}$ is higher than the $V_{OC}$ of the Sharp solar cell and an even higher $V_{OC}$ is expected for Gen III and future generations (see Figure 6). The back reflector of the new IMM3J ELO increases the $J_{SC}$ and $V_{OC}$ remaining factor of the GaInAs subcell compared with the space solar cell from Sharp. The simulation of the near-term potential of our IMM3J ELO solar cell (orange line) is shown as an estimate for Gen III solar cells and future runs after irradiation. With the expected EOL efficiency of $>26$% after $10^{15}$ cm$^{-2}$ e$^{-}$irradiation the IMM3J ELO solar cell would be in the range of the of the Azur 3G30 advanced and the space solar cell from Sharp. The $V_{OC}$ of the Gen II solar cell after an electron fluence of $10^{15}$ cm$^{-2}$ is higher than the $V_{OC}$ of the Sharp solar cell and an even higher $V_{OC}$ is expected for Gen III and future generations (see Figure 6). The back reflector of the new IMM3J ELO increases the $J_{SC}$ and $V_{OC}$ remaining factor of the GaInAs subcell compared with the space solar cell from Sharp. The simulation of the near-term potential of our IMM3J ELO solar cell (orange line) is shown as an estimate for Gen III solar cells and future runs after irradiation. With the expected EOL efficiency of $>26$% after $10^{15}$ cm$^{-2}$ e$^{-}$irradiation the IMM3J ELO solar cell would be in the range of the of the Azur 3G30 advanced and the space solar cell from Sharp.
The BOL power-to-mass ratio of the bare IMM3J ELO solar cell is 3.0 W/g under AM0 illumination. As expected for an ultralight solar cell, this is more than three times higher than for conventional space solar cells even on thinned substrates\(^1\textsuperscript{,}4\textsuperscript{–}6,3\textsuperscript{1}\) (see Figure 9B). However, the IMM solar cells from MicroLink Devices,\(^3\) which to our knowledge has not been tested after irradiation, and the solar cell from Sharp\(^3\) have a slightly higher power-to-mass ratio BOL of the bare solar cell. After electron irradiation the power-to-mass-ratio of the Gen II IMM3J ELO reaches 2.6 W/g (see Figure 9B), which is already the 2nd highest EOL power-to-mass ratio reported to our knowledge.

## 5 \hspace{1cm} CONCLUSIONS

For our new lightweight IMM3J ELO solar cells from Gen III, we measured a BOL efficiency of 30.1\% under AM0 illumination. The higher efficiency compared with solar cells from Gen II (28.9\%) were achieved by an improved ARC adaption to the device and a reduction of the shunt probability due to small adaptions in thin film processing. Handling of the extremely thin solar cells can easily cause cracks, shunts and other defects to form or enlarge. After electron irradiation (\(10^{15}\) cm\(^{-2}\)) solar cells from Gen II reaches a \(V_{\text{OC}}\) of 2.74 V and an efficiency of 25.4\% which corresponds to a remaining factor of 88\%. The power-to-mass-ratios of the presented solar cells of 3.0 W/g (BOL) and 2.6 W/g (EOL) are already three to four times higher compared with space solar cells on thin germanium substrates and can compete with best published values for thin film solar cells.\(^3\textsuperscript{,}9\)

The combination of the solar cell development process with opto-electrical simulations of the whole device and detailed characterization enables us to distinguish between avoidable and unavoidable (e.g., reflection or irradiation damage) losses in the different subcells. According to our simulation further (BOL) material improvements increase the EOL efficiency only by 0.2\%\textsubscript{Max}. In contrast, with a perfect current matching and realistic series resistance reduction, we expect solar cell efficiencies of 30.9\% (BOL) and 26.7\% (EOL) already with the material quality of Gen III. The nondestructive nature of the applied ELO process makes multiple reuses of the GaAs substrate possible, which opens opportunities for cost reduction.

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## DATA AVAILABILITY STATEMENT

Research data are not shared.

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