Ultrathin GaAs solar cells with a high surface roughness GaP layer for light-trapping application

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Abstract

By reducing the thickness of the absorber layers, ultrathin GaAs solar cells can be fabricated in a more cost-effective manner using less source material and shorter deposition times. In this work, ultrathin GaAs solar cells are presented with a diffuse scattering layer based on wide bandgap GaP grown directly on the device layers of the cells with MOCVD. The roughness and surface morphology are quantified using atomic force microscopy and the resulting diffuse scattering capability is assessed using wavelength-dependent reflectance measurements. Ohmic rear contacts are made using contact points etched through the GaP layer, for which an etching procedure using I2:KI was developed and optimized. The performance of the GaP textured ultrathin GaAs cells are compared with equivalent planar cells using current density-voltage measurements and external quantum efficiency measurements, where the GaP textured cells demonstrate an increase of 6.7% in the short-circuit current density ($J_{SC}$), which was found to be as high as 21.9 mA cm$^{-2}$ as a result of increased photon absorption by light-trapping.

KEYWORDS

GaP, III-V thin-film PV, light-trapping, ultrathin GaAs

1 | INTRODUCTION

III-V solar cells offer high efficiencies and tolerance for harsh environmental conditions. However, high cost prevents wide-scale implementations outside of niche markets like space applications and concentrator photovoltaics (CPV). Generally being made out of direct-bandgap semiconductors, the active layer structure of these cells can be thin (3–10 μm) compared to indirect-bandgap semiconductor-based cells like silicon. By further reducing the thickness, ultrathin GaAs solar cells with an absorber thickness of only 300 nm can be obtained. These cells can be fabricated in a more cost-effective manner using less source material and shorter deposition times. Lowering the thickness can also offer better performance in cells that are grown in ways that do not necessarily ensure high crystalline quality, such as hydride vapor phase epitaxy (HVPE) or III-V on silicon (III-V/Si), which both have the potential to reduce costs of III-V cells even further. Ultrathin cells are also less affected by proton and electron radiation induced defects and can potentially achieve a higher open-circuit voltage ($V_{OC}$) than thicker structures.

With a suitable light-trapping scheme increasing the path length through the solar cell, the ultrathin structures can be made optically thick and achieve current-densities matching those of conventional thin film (2–3 μm) GaAs cells. Light-managing structures in GaAs solar cells include front side nano-structures like plasmonic scattering...
particles, textured window layers, and dielectrics, as well as rear side scattering layers with metallic mirrors, like transferred textured substrates, dielectric nanostructures, gratings, (anisotropically) etched III-V layers, and as-grown surfaces. However, none of these methods meet all the important criteria for light-trapping structures that can be applied in large-scale production, namely, simplicity, reproducibility, cost-effectiveness, and close-to-zero parasitic absorption of high-energy photons above the GaAs bandgap.

Our group has reported a simple wet-chemical etching method to texture the AlGaAs back contact prior to deposition of the silver mirror to create a diffusive back-scattering structure in ultrathin GaAs solar cells with a 300 nm thick absorber. However, the high aluminum content of the textured layer makes it difficult to combine this approach with HF-based epitaxial lift-off (ELO) to separate the content of the textured layer makes it difficult to combine this approach with HF-based epitaxial lift-off (ELO) to separate the ultrathin film devices from their native growth wafer. Therefore, a different method for the creation of light-trapping structures is required. With the proper implementation, gallium phosphide (GaP) might be used to form a textured diffuse scattering structure that can meet all the above-mentioned requirements while still being compatible with ELO. Grown directly on the device layers of the cells with MOCVD, the small lattice constant of 5.45 Å compared to 5.65 Å for GaAs allows quick lead to loss of the planar epitaxial growth inducing a largely increased surface roughness within a relatively thin layer. Virtually no parasitic absorption of light is expected in these thin GaP structures because of the indirect wide bandgap (2.24 eV), while at the same time, the benefit of reduced source material usage and deposition time for ultrathin cells is maintained.

In this work, we present ultrathin GaAs solar cells with a diffuse scattering layer of GaP with increased surface roughness grown directly on the device layers of the cells using MOCVD. Cross-sectional TEM is used to analyze the internal crystallographic structure of the GaP layer, while atomic force microscopy (AFM) is used to characterize the surface morphology and quantify the roughness. The resulting diffuse scattering capability is assessed using in situ reflectance and ex situ wavelength-dependent reflectance measurements. Ohmic contact is made using etched-through contact points in the GaP layer, for which a selective etching procedure using I₂:KI was developed and optimized. The effect of increased diffuse reflectance on the current production and device performance was demonstrated by comparing GaP textured ultrathin GaAs cells with equivalent planar cells using current density-voltage (JV) measurements and external quantum efficiency (EQE) measurements. The GaP textured cells demonstrate significant improvements in the short-circuit current density \( J_{SC} \) as a result of increased photon absorption from light-trapping.

2 | EXPERIMENTAL

2.1 | MOCVD growth of device layers and mismatched GaP

The GaP textured ultrathin GaAs homojunction solar cell structures and equivalent planar cells without GaP, as shown in Figure 1, were grown using an Aixtron 200 MOCVD reactor at 20 mbar on 2” (100) GaAs substrates, 2” offset to the (110) orientation. Note that the cell structures were grown in an inverted order (i.e., finishing with the GaP layer or rear contact layer for textured and planar cells, respectively) to avoid that defects induced in the lattice mismatched GaP can extend into the active layers of the cell. Trimethylgallium (TMGa), trimethylaluminum (TMA), and trimethylindium (TMI) were used as element III precursor source gasses and arsine (AsH3) and phosphine (PH3) as sources for element V. Disilane (Si2H₆) and diethyl telluride (DETe) were used for the silicon and tellurium n-type dopants, where the tellurium was only used in the GaAs layer at the interface with the gold front contact. Diethylzinc (DEZn) was used as a precursor for the Zn p-type dopant, except for the final Al0.1GaAs layer at the interface with the silver back contact, which was intrinsically doped with carbon at a growth temperature of 570 °C. Doping levels and layer thicknesses can be found in the supporting information. The GaP layer, of which the rough surface is shown in the inset of Figure 1, was grown at 700 °C at a TMG flow rate of 1.8 standard cubic centimeters per minute (SCCM), while the PH3 source flow was kept at an excess of 120 SCCM. This resulted in a V/III ratio of about 66. The growth was monitored using a Laytec EpiTT layer monitoring system, including 405 and 950 nm in situ LED reflectance.

2.2 | Device processing

The ohmic contact points with a center-to-center spacing of 500 μm, radius of 62.5 μm, and total surface coverage of 9.8% were defined using standard photolithography and subsequently etched using a solution of 0.15 M I₂ and 0.3 M KI in a pH 13 0.132 M NaOH and 0.05 M KCl solution at 25 °C as elaborated further in Section 3. The InGaP etch stop layer was removed using HCl (37%) prior to e-beam evaporation of the 3 μm thick silver mirror/back contact, which was capped with 50 nm of gold to prevent oxidation. As only a thin coating is necessary for ohmic contact and the mirror, the silver can be thinned substantially and complimented with an alternative support structure to achieve greater cost-reduction in future works.

After evaporation, the structure was flipped and bonded to a glass substrate using a heat activated adhesive for substrate etching in a 1:3 solution of NH₄OH (32%) and H₂O₂ (30%). The substrate etch-stop layer was removed using HCl (37%), and the front contact grid with a surface coverage of 16.6% (to allow easy processing and contacting of the first series of cells) as well as 6.8% (as a first optimization step for a second batch of cells) was defined with photolithography. A total of 200 nm gold contacts were applied using e-beam evaporation, and metal lift-off was performed in acetone. The GaAs n-contact layer was removed in between the grid fingers using a 1:2:10 solution of NH₄OH (32%), H₂O₂ (30%), and H₂O. An array of 5 x 5 mm² solar cells was defined using photolithography and subsequently a mesa etch through the window layer, and emitter was performed using HCl (37%) and a 1:2:10 solution of NH₄OH (32%), H₂O₂ (30%), and H₂O, respectively. Finally, an antireflection coating (ARC) of 44 nm ZnS and 94 nm MgF₂ was applied by thermal evaporation.
Omitting the contact point definition and etching of the InGaP etch stop layer, processing of the planar cells proceeded similar to the GaP textured cells.

2.3 | Device characterization

Optical microscopy images were obtained using a Reichert-Jung Polyvar MET microscope equipped with a Zeiss Axiocam. AFM images were made using a Dimension 3100 system, operated using a Nanoscope (v6.12r1) control unit (Digital Instruments) and Gwyddion 2.59 visualization software. NT-MDT NSG30 tips with a nominal curvature radius of 10 nm were used in tapping mode. A Dektak 6 M programmable surface profiler was used to measure step heights after the etching experiments. Transmission electron microscopy (TEM) samples were prepared using a Thermo Fischer Helios NanoLab 650 focused ion beam (FIB). Scanning transmission electron microscopy (STEM) was conducted on the TEM samples in a JEOL JSM-IT800 in bright field mode, with a STEM conversion holder. TEM imaging and electron diffraction was performed with a JEOL 2100F.

JV characteristics of the solar cells were measured with an ABET Technologies Sun 2000 Class AAA solar simulator, which simulates the AM1.5G spectrum with a power density of 1,000 W m$^{-2}$, a Keithley 2601B source meter, and ReRa Tracer 3.0 software. The solar cells were kept at 25°C during measurement using a custom water cooling/heating setup with Pt100 temperature sensing. The system was calibrated before each measurement series using a calibrated GaAs reference cell. External quantum efficiency spectra were measured using a ReRa SpeQuest system with ReRa Photor 3.1 software using a step size of 5 nm. This system was also used to measure the wavelength-dependent reflectance spectra by employing an integrating sphere (Bentham DTR6).

3 | WET-CHEMICAL ETCHING OF GAP WITH I$_2$:KI

The removal of GaP with wet-chemical etchants can be achieved using hot phosphoric acid, Br$_2$/methanol, HCl:CH$_3$COOH:H$_2$O$_2$, aqua regia, KOH:K$_3$Fe(CN)$_6$, and aqueous solutions of Cl$_2$. However, the use of these solutions in device fabrication is not preferred because of the non-selective behavior towards (Al)GaAs and InGaP or because of hazardous compositions. Therefore, in this study, the use of I$_2$:KI was investigated to remove the GaP for the creation of the rear contact points, which reportedly has an excellent selectivity towards InGaP at alkaline (pH > 9) reaction conditions.

To ensure strong alkaline conditions, the I$_2$ and KI were added to a solution of 0.132 M NaOH and 0.05 M KCl with a starting pH of 13. It was found that upon dissolution of the I$_2$, the pH can drop up to 2.5 points depending on the I$_2$ concentration and continues to decrease even when the iodine appears to be fully dissolved. Because of this, a study was performed to optimize the vertical etch rate so it could fully remove the GaP in a solar cell before the pH would drop to a point where the etch rate of GaP was slowed down too much, and the selectivity would be lost due to increased InGaP/AlGaAs etch rates.

The vertical etch rate was studied using samples that include the GaP layer on top of 50 nm InGaP, 30 nm Al$_{0.1}$GaAs, and 100 nm Al$_{0.3}$GaAs to simulate the backside of a solar cell. Areas of the GaP surface were masked with photoresist, and the samples were submerged in the etching solution at 25°C. Subsequently, the photoresist was removed, and the step height was measured between the etched and unaffected area. Table I shows the vertical etch rates for I$_2$ concentrations of 0.08, 0.1, 0.15, and 0.2 M. A maximum of 32 nm/min was found using 0.15 M I$_2$, doubling the etch rate with respect to the 0.08 M I$_2$ solution. For higher concentrations of I$_2$ (0.2 M), the etch rate decreases. This is likely caused by the resulting lower starting pH.
of this etching solution, as it is observed that the etch rate significantly decreases when lower pH values are reached.

Using the etching solution with a maximum vertical etch rate of 32 nm/min means that the bulk of the 500 nm thick GaP layer can be fully removed in about 15 min. However, due to the surface roughness, the complete removal time can be significantly longer than this. Therefore, during processing of the solar cells, the structure is over-etched for an additional 15 min to ensure the layer has been fully removed. Generally, the pH of the etching solution was found to be around 9.8, which is high enough so that no etching of the InGaP etch stop layer is observed.

Due to the extended etching time, some underetching can be observed, as is shown in the differential interference contrast microscopic (DICM) image in Figure 2. As a result of this underetching, the contact point diameter increases from 125 to 140 μm, resulting in a back contact coverage of 12.4%. As a future improvement, lower coverage contact points can be used at the back side to maximize the amount of diffuse scattering at the rear. Coverages as low as 3% have been used in GaAs solar cells that do not introduce any significant drop in performance.38

4 | TEXTURED SURFACE MORPHOLOGY AND REFLECTANCE

Figure 3 shows the in situ reflectance during the growth of a solar cell structure as illustrated in Figure 1. The short wavelength 405 nm light is quickly absorbed and therefore mainly provides information on the status of the surface of the growing layer. The 950 nm light is not absorbed in the structure and provides more information on layer thickness by interpreting the constructive and destructive interference. The constant signal of the 405 nm reflection during layer growth and sharp transitions at the interfaces result from 2D epitaxial Frank-van der Merwe (FvdM) growth39 for the device layers prior to GaP deposition. However, during the growth of GaP (between 3,500 and 4,100 s in Figure 3), this 2D growth mode can only be maintained for a very short period due to the large difference in lattice constant. The critical layer thickness, calculated to be in the order of 1–2 nm,40,41 is reached within the first few seconds of GaP growth. After this, the deposition starts to take place according to the 3D Stranski-Krastanov (SK) growth mode,42 yielding surface roughening due to island formation and lattice strain relief. The signal of the 950 nm reflection shows oscillations from interference during the entire GaP layer growth. This is a strong indication that, despite the surface roughening, the bulk of the layer is grown with a high crystallinity.

Figure 4 shows a 10×10 μm² AFM height (left) and amplitude (right) map of the rough GaP layer grown on a solar cell structure at the center of the wafer. The average root-mean-squared roughness (Sₐ), calculated from the AFM images taken at the center of five different samples, was found to be around 90 nm, with a maximum recorded feature height (Sₘ) of around 500 nm. The image shown here is representative of the morphology among all samples, with main features that appear to be individual growth hillocks with a lateral size

| Table I | Vertical etch rate, starting pH, and final pH of I₂:KI based GaP etchants with varying concentrations of I₂ at 25°C |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Vertical etch rate [nm/min] | 0.08 M I₂, 0.3 M KI | 0.1 M I₂, 0.3 M KI | 0.15 M I₂, 0.3 M KI | 0.2 M I₂, 0.3 M KI |
| Starting pH [-] | 17.3 | 25.5 | 32.1 | 30.0 |
| End pH [-] | 11.1 | 10.8 | 10.4 | 10.4 |

Note: The concentration of KI was kept constant to ensure good solubility of the I₂.
ranging from 0.2 up to 4 μm in diameter. The hillocks typically cover the entire surface, but depending on the fraction of larger or smaller hillock appearing in each 10×10 μm² area sample, S_q locally varies between 70 and 125 nm for different locations at each sample. Figure 5A,B shows, respectively, the cross-sectional TEM and STEM images of the solar cell structure after MOCVD growth. As intended by the inverted growth approach, the active layers of the cell up to and including the InGaP etch stop show a virtually perfect crystalline structure without any signs of dislocations or other irregularities. Then, in the area corresponding to the transition to and initial stage of GaP SK growth, a dense network of misfit and threading dislocations is formed. However, already after about 100 nm of GaP growth, the dislocation density is strongly reduced again, as was also observed in the in situ reflection signal of the 950 nm light. This indicates that a smooth coalescence of the islands formed in the SK growth mode has taken place with a minimum incorporation of defects. The fact that this process is already completed during the first 100 nm of GaP growth indicates that the 500 nm thickness of the GaP layer used in this study is actually thicker than required. In the subsequent part of the layer, high crystallinity is maintained through the remaining of the layer and into the surface features, the inclination of which is clearly visible in Figure 5B. The crystalline imperfections that do occur are mainly identified as stacking faults and threading dislocations, as shown in Figure 5C,D, respectively. In some occasions, also some areas that appear as antiphase domains are observed (see Figure 5A).

Figure 6 shows the total and diffuse reflection of the GaP at the center of the wafer. It is evident that a large portion of the total reflection is indeed diffusely scattered from the surface. This ratio is commonly referred to as the “haze” in reflection and is also shown. For short wavelengths, the haze reaches a maximum value of about 85% at 350 nm but gradually drops to around 60% near the GaAs bandgap. The oscillations in both the reflections and the haze are caused by constructive and destructive interference of the back-reflected light with the incoming wavefront.

5 | DEVICE PERFORMANCE

Figure 7 shows the JV and EQE characteristics of the best performing cells in terms of power conversion efficiency (PCE) of the cells applied
with diffuse scattering layer compared to that of cells with a planar back mirror. Table II shows the $J_{SC}$, $V_{OC}$, fill factor (FF), and efficiency (PCE) averaged over 11 cells for both the GaP textured and planar solar cells with 16.6% front coverage, as well as the values for the best performing cell for either category indicated by the values in brackets.

The fact that the textured and planar cells have comparable FF and $V_{OC}$ shows that the GaP texturing approach introduced in this study does not lead to increased series resistance or internal energy barriers. As anticipated, the textured GaP layers yield an increased photocurrent following from the increased optical path length through the solar cell as a result of diffuse scattering at the rear mirror and subsequent total internal reflection. Textured cells applied with an ARC and a front contact coverage of 16.6% yield a $J_{SC}$ up to 20.3 mA cm$^{-2}$ and PCE of 17.5%, compared to the maximum $J_{SC}$ of 19.0 mA cm$^{-2}$ and PCE of 16.5% for cells equipped with a planar back mirror. This corresponds to a relative increase of 6.7% in current-density. The 16.6% front coverage is primarily used because it allows for easier processing during the development of new cell structures and they are easy to probe during characterization. Therefore, a second set of similar cells with 6.8% coverage instead of 16.6% were fabricated to demonstrate that higher current densities and efficiencies are easily possible by optimizing the cell architecture. The performance parameters of GaP textured solar cells with this lower front coverage were averaged over four cells, with the best performing cell reaching a $J_{SC}$ of 21.9 mA cm$^{-2}$ and PCE of 18.7%. The fact that the average maximum active area current density of the cells with 16.6% and 6.8% front grid coverage is virtually equal (23.4 mA cm$^{-2}$ vs. 23.5 mA cm$^{-2}$, respectively) confirms that the epi-layers are of

**FIGURE 5** Cross-sectional TEM (A) and STEM (B) images of the solar cells structure and high-resolution images of a stacking fault (C) and a treading dislocation (D) in 111 GaP with electron diffraction insert. The GaP layer shows misfit and treading dislocations, stacking faults and occasionally some areas that appear as antiphase domains (APD).

**FIGURE 6** Haze in reflection and the total and diffuse reflection of the bare GaP surface after MOCVD growth.
high quality and that the developed processing does not lead to parasitic resistances at higher currents. As a result, further optimization to cells with a grid coverage as low as 2% is feasible.

The external quantum efficiency (EQE) spectra shown in Figure 7 clearly demonstrate that the origin of the increase in current production is the enhanced absorption of lower energy photons with wavelengths starting from 675 nm up to the GaAs bandgap. The additional GaP layer with a bandgap of 2.24 eV in the textured cells could have resulted in parasitic absorption of photons with wavelengths up to 550 nm. The fact that up to this wavelength, the EQE signals of the planar and textured cells almost completely overlap indicates that most of these photons actually do not reach the GaP layer. The maximum of 0.92 around 500 nm shows that the vast majority of these photons are absorbed during their first pass through the absorber layer. Note that an EQE of 1.0 cannot be obtained due to reflection and absorption in the layers of the ARC and AlInP window layer. From 500 to 675 nm, both curves still largely overlap but start to decline to about 0.8 at 675 nm, indicating parasitic absorption in the 110 nm InGaP BSF and the 100/30 nm AlGaAs contact layers of both cells. A first-order simulation indicates that the 8% absorption in this region is mainly inflicted in the AlGaAs layer. The textured cell has an additional thin 50 nm InGaP etch stop layer that might explain the slightly higher absorption of the textured cell between 450 and 625 nm, even though up to 525 nm, this difference is hard to distinguish (the maxima of the two curves differ 0.5%). Above 550 nm, the escape of light at the front side of the cell also starts to play a role. First-order simulations of a planar structure without InGaP BSF and AlGaAs contact layers indicate that this loss increases from virtually zero at 550 nm to about 15% at 700 nm. As already stated above, beyond the 675 nm cut-off wavelength of InGaP, the textured cells start to benefit from the increased average path length through the absorber layer of the more diffusively reflected photons. Compared to the planar cell, the absorption in the textured cells is also extended to larger wavelengths because photons above the GaAs bandgap that have been scattered multiple times have a higher chance to be absorbed in the Urbach absorption tail.

The EQE analysis clarifies that there is substantial parasitic absorption loss in the BSF, contact, and etch stop layers at the rear side of the cell which for this proof-of-concept study were simply taken the same as previously developed for cells of regular thickness. Therefore, in future work, these should be optimized for the specific geometry of the ultrathin film cell. In the present study, these layers obstruct a clear analysis of the potential absorption loss in the GaP scattering structure. However, in a first-order approximation (simulating a planar cell structure with only a 500 nm thick GaP layer with perfect reflector at the rear side) shows that in this case, there will only be noticeable parasitic absorption in the wavelength range between the 475 and 550 nm cut-off wavelength of the GaP layer.

### Table II

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<th>Device parameters of GaP textured and equivalent planar 300 nm absorber ultrathin GaAs solar cells with 16.6% and 6.8% front grid coverage</th>
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<tr>
<td>Planar (16.6%)</td>
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<td>GaP textured (16.6%)</td>
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<td>GaP textured (6.8%)</td>
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Note: Values are averaged over 11 and 4 cells for the 16.6% front coverage cells and 6.8% coverage cells, respectively.
This absorption would yield a maximum loss in $J_{SC}$ of only 0.2 mA cm$^{-2}$ with the current non-ideal Lambertian scattering, with a negligible difference in the perfect Lambertian limit.

6 | DISCUSSION

The generated photocurrent showed a relative increase of 6.7% by the application of the textured GaP layer, but a bigger increase was anticipated from the measured haze (ranging from 60% up to 85%) of the GaP surface. To assess the full contribution of the roughness to the light-trapping inside the solar cells, a thorough, wave-optics based approach is necessary\textsuperscript{46–48} that is beyond the scope of this work. However, with an average correlation length of 1.74 μm (the distance at which the extrapolated Gaussian autocorrelation function of the surface decays to 1/e), combined with an $S_{0}$ around 90 nm, a simple geometric evaluation of the surface morphology can be made for normal incident light\textsuperscript{69} as a first-order approximation of the light-trapping induced by the rough GaP layers.

To facilitate total internal reflection, light reflected at the rear mirror of the solar cell needs to arrive at the front surface again under an angle larger than 16° with the front surface normal. Ignoring the refraction at different III–V hetero-interfaces for this first order approximation, and assuming normal incident light, this means that the GaP surface features should have an inclination angle of at least 8° to induce multiple internal reflections. To investigate to what extend this requirement is met in the GaP textured cells, the inclination of the GaP surface features is examined in detail using AFM. Using Gwyddion 2.59 software, a slope distribution (relative to a horizontal plane) was generated by first calculating the first derivative, followed by the angle calculation. Figure 8 shows the normalized distribution of the slope of the GaP surface features, extracted from AFM measurements on the center of five different samples. A similar variation in angle distribution is found for different areas sampled at the same epi-structure. They all show the same signature of a more or less Gaussian distribution around a mean inclination angle of 6° to 9° depending on the particular image. On average, the majority of the surface is inclined at an angle between 3° and 12°, with a significant portion of about half the surface having an inclination less than 8°. This distribution explains why the high haze determined from the reflection at the GaP surface does not yield a higher increase in photocurrent of the textured cells. In the applied integrating sphere set-up (see Section 2), light reflected at an angle larger than 1.5° contributes to the haze, but an angle larger than 8° is required to facilitate light-trapping by multiple internal reflections. It is expected that the diffuse scattering capabilities and cell performance can be increased by optimizing the surface morphology of the GaP layer by tuning the growth parameters, starting with the growth temperature. Preliminary investigations have shown that the surface feature morphology and size, and thereby also the inclination angle, varies substantially with temperature. Parameters like III–V ratio and growth time (i.e., layer thickness) are also expected to influence the feature inclination. These parameters can easily be altered without interfering with the performance of the solar cell structure underneath and can change the surface morphology substantially. If the growth conditions can be optimized in such a way that the whole surface of the GaP layer rather than half of it is made up of features inclined at angles higher than 8°, a relative increase of 13.4% in photocurrent compared to the planar cell structure can be anticipated. It should be noted that a similar increase in photocurrent can be obtained by increasing the thickness of the planar cell from 300 nm to about 475 nm. In the present study, the added GaP layer to induce the light scattering surface is actually significantly thicker than that. However, TEM analysis demonstrated that under the currently applied process conditions the epitaxial layer break-up and coalescence occurs within the first 100 nm of GaP growth, indicating that there are good opportunities to develop an effective light scattering surface formed from GaP layers with an initial thickness around 100 nm.

Previous studies on ultrathin GaAs cells with an equal (300 nm) absorber thickness reported active area $J_{SC}$ values beyond 26 mA cm$^{-2}$.\textsuperscript{19,22} In the present proof-of-concept study for the use of a GaP layer to induce diffusive reflection, an active area $J_{SC}$ of 23.5 mA cm$^{-2}$ was demonstrated. First-order simulation of the textured cell structure, neglecting loss mechanisms like resistances and recombination, shows that the upper limit active area $J_{SC}$ can reach about 26 mA cm$^{-2}$ with the non-ideal level of Lambertian scattering as obtained in this work. For perfect Lambertian scattering at the rear, with the rest of the cell structure remaining the same, this value can increase to about 27.5 mA cm$^{-2}$. However, as demonstrated by the EQE, the cell structure used in the present work suffers from significant parasitic absorption in the contact layers and BSF at the rear side. Optimizing their thicknesses will provide further improvements towards the 29 mA cm$^{-2}$ current densities that are typically obtained with regular optically thick GaAs solar cells.
Finally, it should be noted that in contrast to previously reported Al-based scattering layers,\textsuperscript{19,23} preliminary experiments demonstrated that textured GaP layers produced in the current study are sufficiently resistant to HF to further evaluate their application in devices produced utilizing an HF-based ELO process. Although the introduced misfit dislocations have largely released the strain resulting from the lattice mismatch of the GaP layer, the solar cell epi-structure will have some residual stress. This, however, should not be a problem during ELO processing as the same process is already successfully applied for the production of strained structures like triple junction inverted metamorphic (IMM) solar cells.\textsuperscript{50}

7 | CONCLUSION

In this study, an easy and reliable light-trapping scheme for ultrathin GaAs solar cells is presented based on lattice mismatched GaP grown directly on the device layers with MOCVD. The large lattice mismatch results in a combination of high surface roughness with a still relatively thin layer, maintaining the benefits of reduced source material usage and deposition time. TEM analysis demonstrated that the process of epitaxial layer breakup and coalescence of islands formed during SK growth is already completed during the first 100 nm of GaP growth. To ensure perfect crystalline quality of the active layers in the device, GaP is grown as the last layer on top of an inverted grown GaAs cell structure. A selective wet chemical etching procedure using I\textsubscript{2}:KI was developed to locally etch the GaP surface morphology towards a higher average inclination and absorption in the cell. The GaP based light-trapping scheme is successfully demonstrated in ultrathin GaAs homojunction solar cells with a 300 nm thick absorber. EQE analysis clarified that there is substantial parasitic absorption loss in the BSF, contact layer, and etch stop layer at the rear side of the cell. In forthcoming studies, these should be optimized for the specific geometry of the ultrathin film cell. Nevertheless, already with no-optimized layers of the present study, 6.7% increase in $J_{SC}$ of the textured cells compared to equivalent planar cells is achieved, with a maximum demonstrated current of up to 21.9 mA cm\textsuperscript{-2}. The increased quantum efficiency for photons of 675 nm and beyond shows that the GaP based light-trapping scheme is a promising approach towards high efficiency III–V solar cells with reduced layer thicknesses. Detailed analysis of the obtained increase in cell performance related to the GaP induced surface roughness shows that the current density can be further improved by tuning the GaP surface morphology towards a higher average inclination and reducing the rear contact coverage.

ACKNOWLEDGEMENTS

The research was financially supported by Shell Global Solutions International B.V. under contract number CWS-149392. The authors would also like to thank J. van Gastel from Radboud University for his support in quantifying the parasitic absorption and theoretical limit of the solar cell structure.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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