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Multijunction Solar Cell Mesa Isolation: A Comparative Study

Mathieu de Lafontaine^{1,2}, Farah Ayari¹, Erwine Pargon², Guillaume Gay², Camille Petit-Etienne², Artur Turala¹, Abdelatif Jaouad^{1, a)}, Maïté Volatier¹, Simon Fafard¹, Vincent Aimez¹, and Maxime Darnon¹

¹Laboratoire Nanotechnologies Nanosystèmes (LN2) – CNRS IRL-3463 Institut Interdisciplinaire d’Innovation Technologique (3IT), Université de Sherbrooke, 3000 Boulevard Université, Sherbrooke, J1K 0A5 Québec, Canada

²Université Grenoble Alpes, CNRS, CEA/LETI-Minatec, Grenoble INP, LTM, 17 rue des Martyrs, F-38054 Grenoble, France

^{a)} abdelatif.jaouad@usherbrooke.ca

Abstract. At the end of the fabrication process, multijunction solar cells must be electrically isolated from one to another; a step commonly known as mesa isolation. In this paper, three different techniques are assessed to perform this step: saw-dicing, wet etching and plasma etching. Triple junction solar cells were fabricated with each process and the open-circuit voltages were measured in order to compare the impact of each technique on the device performance. An optional wet treatment is also proposed to clean the sidewalls after the mesa isolation process. The process throughput and the wafer area yield are also assessed for all techniques in order to determine which one is the most suitable from the industrial standpoint. This study indicates that a plasma etching process followed by a wet clean is the process that maximizes the solar cell performance, the process throughput and the wafer area yield.

INTRODUCTION

The mesa isolation step is a process that occurs at the end of the multijunction solar cell microfabrication cycle. Its goal is to isolate electrically all the solar cells from one to another. This step will alter the cell performance as it will affect the perimeter recombination [1, 2]. Unlike silicon, III-V materials do not have a passivating native oxide. Therefore, limiting the sidewall damage during this step is mandatory in order to reduce the losses. Furthermore, perimeter recombination effects become dominant as the device size is reduced. Developing and optimizing a damage-free process for mesa isolation is a priority considering the keen interest for micro-solar cells and micro-concentrator photovoltaics (Micro-CPV) [2, 3]. The miniaturization of solar cells also increases the expensive semiconductor epitaxy and substrate losses associated to mesa isolation [2]. Consequently, micro-solar cells require a mesa isolation process that can pattern narrow trenches ($<10\ \mu\text{m}$) to maximize the used wafer area. Lastly, the process must enable a high throughput for industrial purposes.

Three techniques are generally used to perform mesa isolation: saw dicing, wet etching and plasma etching. Several studies reported successful wet mesa isolation processes using $\text{K}_2\text{Cr}_2\text{O}_7/\text{HBr}$ and $\text{KOH}/\text{glycerol}$ solutions [4], $\text{Br}_2/\text{CH}_2\text{OH}$ and H_2O_2 [5], $\text{HBr}/\text{Br}/\text{H}_2\text{O}$ [6] and $\text{H}_3\text{PO}_4/\text{H}_2\text{O}_2/\text{H}_2\text{O}$ and $\text{HBr}/\text{H}_3\text{PO}_4$ [7]. For plasma etching, the chemistries used are generally BCl_3/Cl_2 [8,9], $\text{SiCl}_4/\text{Cl}_2$ [9] and SiCl_4/H_2 [10]. In this paper, we present a comparative study between saw-dicing, wet etching and plasma etching to perform the mesa isolation. The techniques are assessed based on the solar cell performance, the process throughput and the epiwafer area yield.

EXPERIMENTS

Multijunction solar cells were fabricated using the process presented in fig 1. The starting epiwafers (fig 1a) are quantum dot-enhanced III-V/Ge triple junction heterostructure with an InGaP top cell, an (In)GaAs middle and a Ge

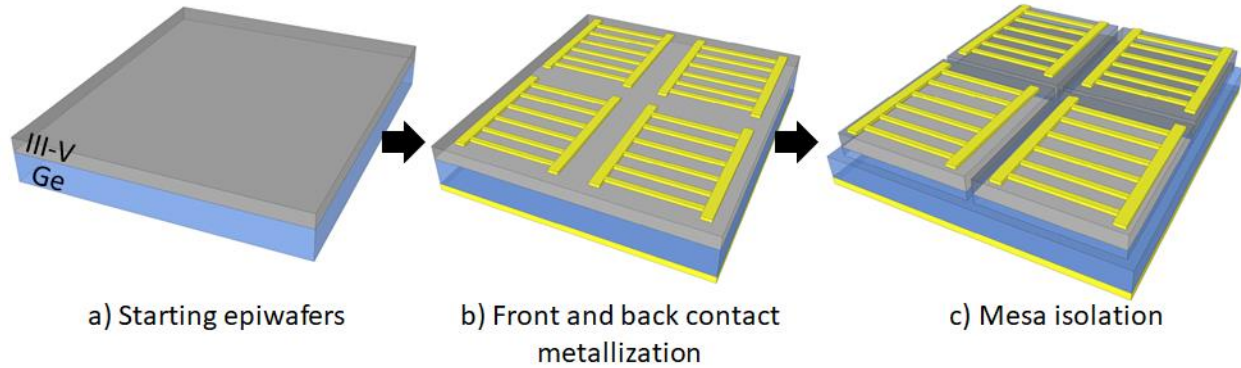


FIGURE 1. Schematics of the microfabrication process consisting in a) the starting III-V/Ge epiwafers, b) the front and back metallization and c) the mesa isolation step performed by saw dicing, wet etching or plasma etching.

bottom cell [11]. Front and back contacts are patterned by contact photolithography, evaporation and lift-off (fig 1b). In order to rigorously compare the cell performance, the devices must have the same perimeter-to-area ratio (P/A). All fabricated cells had a $5.5 \times 5.5 \text{ mm}^2$ format. Despite the fact that P/A effects will be more important on micro solar cells, they are still observable on millimeter-size cells. The last step is the mesa isolation and it is performed by saw dicing, wet etching and plasma etching. Saw dicing was performed with a standard $100 \mu\text{m}$ -thick diamond blade. Samples were coated with a protecting photoresist film prior to dicing. In order to keep the same P/A , $100 \mu\text{m}$ -wide trenches were patterned by photolithography, using a thick ($\sim 10 \mu\text{m}$) photoresist film to perform either wet or plasma mesa isolation. The wet etching process consists in a succession of $\text{H}_3\text{PO}_4/\text{H}_2\text{O}$, $\text{HCl}/\text{H}_3\text{PO}_4$, $\text{H}_2\text{SO}_4/\text{H}_2\text{O}_2/\text{H}_2\text{O}$ solutions at room temperature to etch the III-V epitaxy. HCl and H_3PO_4 was used to etch III-P materials, whereas H_2SO_4 was used to etch III-As materials. H_2O_2 heated to 50°C was used to etch the Ge bottom cell. As for the plasma etching process, a SiCl_4/H_2 plasma at room temperature was used to etch all three junctions in a single step. Different hydrogen dilutions were investigated (from 0 % up to 67 % of the total gas flow). After mesa isolation, the samples were cleaned. An optional $\text{NH}_4\text{OH}/\text{H}_2\text{O}_2/\text{H}_2\text{O}$ wet clean was performed on the saw-diced and plasma-etched samples. No antireflection coating was deposited on the solar cells. Finally, the open-circuit voltage (V_{oc}) of the solar cells were measured under 1-sun AM1.5D illumination as it is a parameter that is sensitive to perimeter recombination.

RESULTS AND DISCUSSION

Solar Cell Performance

Figure 2 presents the average 1-sun open-circuit voltage of the devices. Before the wet clean, both the saw-diced and plasma-etched samples present quite low open-circuit voltages, when compared to the wet-etched solar cells. The addition of the wet clean after saw dicing and plasma etching seems mandatory to obtain good performance, as it increases the V_{oc} by 12 % and 2 % respectively. This enhancement makes the V_{oc} similar for all three techniques. The improvement can be explained by a sidewall roughness reduction. Saw-dicing is mechanically harsh and it can severely damage the sidewalls. Plasma etching uses a combination of chemical reactions and ion bombardment. The ion bombardment is a physical mechanism that can also roughen up the sidewall. In the case of wet etching, it solely relies on chemical reactions. The wet clean enables to reduce the roughness created by the physical mechanisms. Therefore, minimizing the sidewall roughness is the key to maximize the device performance during the mesa isolation step.

Figure 2 also demonstrates that the combination of plasma etching and wet clean produces the highest V_{oc} , making it the best technique from the performance standpoint. It can be explained by the morphology of the etched trenches. The wet etching process is isotropic and results in lateral etching. The sidewalls are slanted, which enhances the total perimeter surface and therefore recombination. Plasma etching offers a synergy between the ions and the reactive species that creates steep sidewalls [10]. Therefore, the addition of wet clean after plasma etching combines both best characteristics: steep sidewalls and low sidewall roughness.

Changing the hydrogen fraction of the total gas flow can also alter the device performance, as shown in fig. 3. Increasing the hydrogen flow up to 67 % of the total gas can further increase the V_{oc} . This behavior has been observed

in a previous study and it can be explained by a combination of Cl-based defect reduction and sidewall passivation by hydrogen [10]. In summary, the combination of plasma etching and wet clean presents a new pathway towards multijunction solar cells with higher conversion efficiency thanks to a low roughness, steep sidewalls, reduced Cl-based defects and hydrogen passivation.

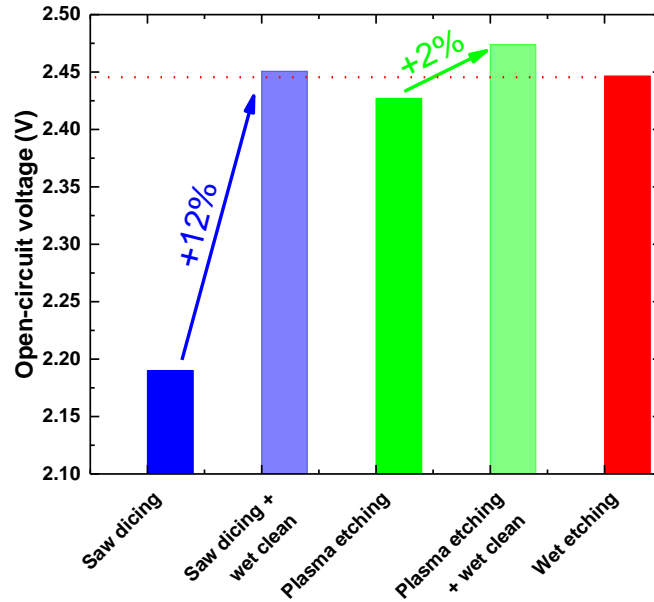


FIGURE 2. 1-sun AM1.5D open circuit voltage of III-V/Ge triple junction solar cell mesa etched with different techniques.

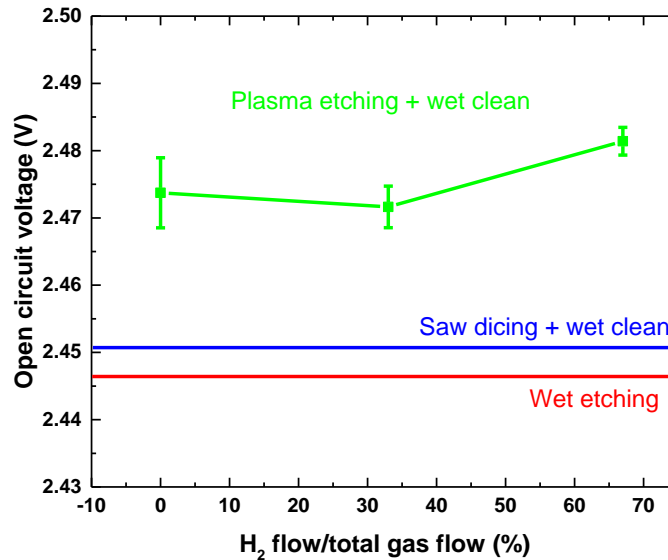


FIGURE 3. 1-sun AM1.5D open circuit voltage of III-V/Ge triple junction solar cell mesa etched with different plasma chemistries, compared to saw dicing + wet clean and wet etching.

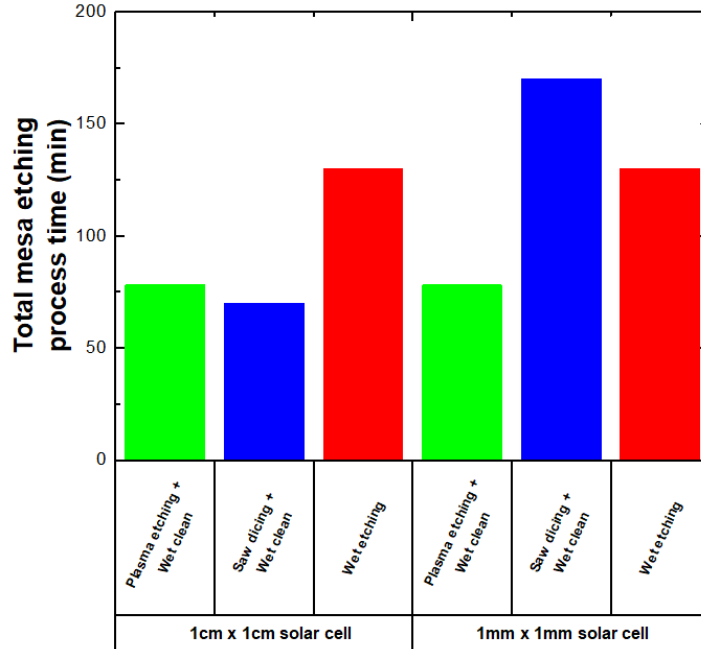


FIGURE 4. Mesa isolation process time required for each technique and for two different cell sizes.

Process Throughput

For each technique, the total process time has been assessed and it is presented in fig. 4. The total process time includes all the required steps to perform mesa isolation (photoresist deposition, optional photolithography, mesa isolation and cleaning) on a 4" wafer and performed in an academic research laboratory setting. For example, we considered that it takes 30 minutes to perform the photolithography and 30 minutes for the post-process cleaning. However, the time required for the optional wet clean (for saw-dicing and plasma etching) was not taken into account as it can be combined to the contact-layer etching step, mandatory to all cells regardless of the mesa isolation technique. The process time remains the same for plasma and wet etching when the cell size is changed since both are parallel processes. Saw dicing is a serial process where rows and columns of cells are isolated one after another. Therefore, the total wafer processing time for this technique increases as the cell dimensions decrease. Figure 4 clearly shows this behaviour since saw dicing presents the best throughput for 1cm x 1cm solar cell but becomes the worst for a 1mm x 1mm cell size. Plasma etching is faster than wet etching, regardless of the cell size. The difference comes from the fact that wet etching requires the samples to swap between several baths whereas plasma etching is performed in a single step. Considering the recent interest for micro solar cells, parallel processing is mandatory for this step. Consequently, plasma etching is the technique that offers the best throughput since, from our results, it reduces the process time by 40 % compared to wet etching and by 54 % compared to saw-dicing for 1x1 mm² solar cells.

Epiwafer Area Yield

Figure 5 presents an estimation of the epiwafer area loss expected from the mesa isolation step for each technique. In this calculation, a standard blade width and its device-free (exclusion) zone (100 μm) determine the area loss from saw dicing [2, 12]. For both plasma and wet etching, the area loss is calculated from a conservative width (10 μm) that enables a good wetting of the patterns (for wet etching) and for which aspect ratio dependent etching (ARDE) is limited (for plasma etching). Since wet etching creates slanted sidewalls, an additional 10 μm lateral etching is also considered. It is important to note that the cell singulation (individual device separation) can be aligned with the mesa isolation trench but additional details must taken into account. For example, a saw-dicing can completely separate the devices while keeping the same wafer area yield. For wet etching, the mesa isolation is also the cell singulation, when it is combined with epitaxial lift-off (ELO) [6]. Without ELO, wet etching will however create an unacceptable lateral under-etch. In this specific case, the values presented in fig. 4 and 5 would be severely underestimated for a wet etch

singulation. For plasma etching, an anisotropic time-multiplexed plasma process (or Bosch process) can completely separate each device [8, 10], regardless of whether ELO is used or not. This plasma singulation could keep the same trench dimensions and the values presented in fig. 5 would remain unchanged. In this latter case, plasma etching could also enable the fabrication of circular solar cells as it is no longer limited to rectilinear patterns. The process time presented in fig. 4 would increase if complete singulation is considered. However, the plasma singulation would remain a parallel process whereas saw-dicing would remain a serial process. This confirms that plasma etching would remain advantageous for micro solar cell processing.

Figure 5 shows that for 10 x 10 mm² solar cell, all three techniques induce a quasi-similar epiwafer area loss (<2 %). As the solar cell size is reduced, it is clear that saw dicing is the worst technique as the area lost increases rapidly up to 75 % for 100 x 100 μm² solar cells since the mesa trench width is identical to the device width. At these dimensions, wet etching is preferable as the loss is reduced to 41 %. However, the best technique is still plasma etching as steep sidewalls limit the loss to 17 % for 100 x 100 μm² solar cells. In this latter case, it is important to note that the minimal area lost is determined by ARDE limitations. If the plasma etching process is further optimized, with a time-multiplexed process for example, isolation trenches could even be narrower, which will lead to smaller semiconductor material losses. These characteristics are especially relevant considering the fact that the substrate and the epitaxy represent over 70 % of the cost of the solar cell [13]. In summary, plasma etching offers a pathway towards micro solar cell manufacture without wasting the majority of the product of the most expensive steps.

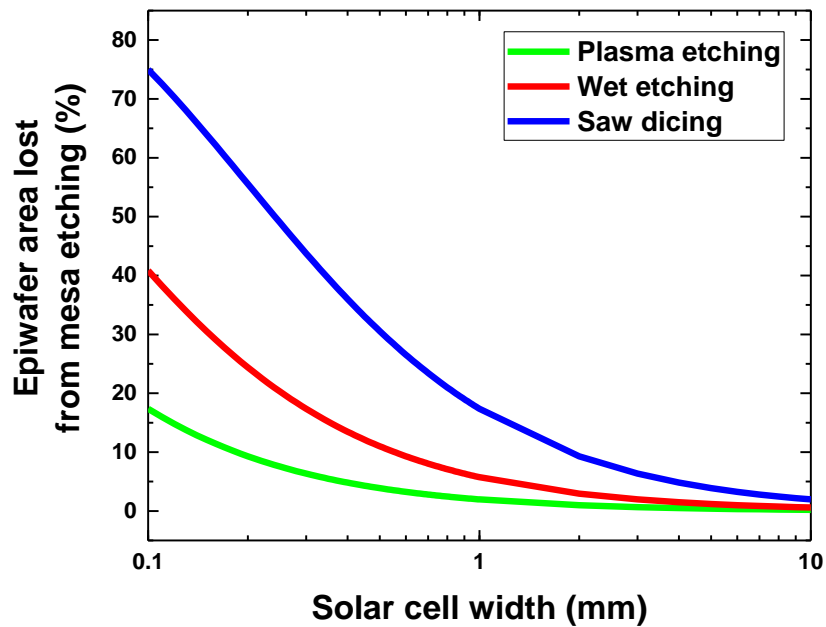


FIGURE 5. Epiwafer area lost from mesa isolation as a function of a square solar cell width.

CONCLUSION

In conclusion, this paper presented a comparative study of three mesa isolation techniques for multijunction solar cells considering three criteria: (1) cell performance, (2) process throughput and (3) epiwafer area yield. The cost associated to each technique could not accurately be assessed since the study was performed in an academic laboratory, which is quite different from the industrial framework. The study was performed on III-V/Ge triple junction solar cell, but the processes are readily transferable to other heterostructures. Saw dicing is appealing by its simplicity, but it rapidly becomes irrelevant when the cell dimension is reduced. Wet etching presents good performance, and it is suitable for micro solar cell. However, the lateral etching and the lack of sidewall passivation indicate that improvements are required to unlock the full potential of the device. In view of these considerations, plasma etching is the most suitable technique. It allows to combine a sidewall passivation with the mesa isolation step. The steep

sidewalls and the high throughput are very promising for micro solar cell manufacture. Further improvements are also possible for plasma etching. A time-multiplexed process could reduce even more the epiwafer area loss. Furthermore, complete cell singulation could also be performed by plasma etching [8].

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