Thinned Germanium Substrates for III-V Multijunction Solar Cells

Ivan Lombardero¹, Naoya Miyashita², Mario Ochoa¹,³, Yoshitaka Okada², Carlos Algora¹

¹Instituto de Energía Solar, Universidad Politécnica de Madrid, 28040 Madrid, Spain
²Research Center for Advanced Science and Technology (RCAST), The University of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo 153-8904, Japan
³Laboratory for Thin Films and Photovoltaics, Empa-Swiss Federal Laboratories for Materials Science and Technology, Ueberlandstrasse 129, 8600 Dübendorf, Switzerland

Abstract—Multijunction solar cells are usually grown on Ge substrates. This implies several disadvantages that hinder the performance of the whole multijunction and limit their possible applications. The drawbacks caused by the substrate are: heavier devices, higher operation temperatures, lower performance and lack of photon confinement. In this work we propose thinning the substrate as a valid solution to the aforementioned challenges. The influence of the substrate thickness on the Ge subcell performance inside a multijunction is simulated using 2D TCAD tools. Simulation results point to the back surface recombination as the key parameter to enhance the development of thinned Ge subcells. Ge substrates have been thinned down, achieving 115 μm thick samples. Finally, solar cells have been manufactured out of the thinned substrates proving a limited degradation and showing the feasibility of this process to manufacture Ge subcells thinned down up to 115 μm.

Index Terms—thin solar cells, chemical thinning, III-V solar cells, space solar cells, germanium.

I. INTRODUCTION

Semiconductor substrates are used as the solar cell base in certain structures, among we can find germanium solar cells. Mostly used as multijunction’s bottom subcell, Ge solar cells are usually fabricated on p-doped substrates by phosphorous diffusion inside a metal-organic vapor phase epitaxy (MOVPE) reactor. Although most of the efforts trying to improve multijunction solar cells performance focused on increasing the number of junctions [1]–[3], there are several drawbacks caused by the substrate that limits their performance. Among them we can find heavier devices, higher operation temperatures, lower voltage generation and lack of photon confinement. The use of thinned substrates is proposed to solve, or at least mitigate, these detrimental effects. This would allow to improve the current technology without involving any major changes on the semiconductor structure nor the device design either. Therefore, the aim of this study is to point out the advantages of a thinned Ge subcell for multijunction solar cells with special emphasis on triple junction ones.

II. SUBSTRATE INFLUENCE ASSESSMENT

Ge substrates for multijunction solar cells are usually 165-185 μm thick and p-type doped 10¹⁷-10¹⁸ cm⁻³. The optimum doping level is derived from the Ge minority carrier properties (which strongly depends on the doping level[4], [5]) and its resistivity. The thickness is determined by the manufacturing process, which requires a minimum thickness to ensure a high yield. Typical substrates doped 7·10¹⁷ cm⁻³ with a thickness of 175 μm will be assumed in this work.

A. Solar Cell Weight

The solar cell weight is of paramount importance for some applications where the weight dramatically influences the cost, such as in space applications[6]. More than 95% of the total weight of a standard GaInP/Ga(In)As/Ge triple junction is caused by the Ge substrate, which highlights the importance of making it thinner. Fig.1 shows the weight of a triple junction solar cell as a function of the substrate thickness assuming 2 μm and 5 μm for the GaInP and Ga(In)As subcells respectively. These thicknesses are overestimated to take into account other layers apart from the subcells themselves, such as the tunnel junctions or the buffer layers. It can be seen that once the substrate is thinned down to 10 μm the weight reduction starts to saturate, achieving values lower than 10% of the total weight.
Fig. 1. GaInP/Ga(In)As/Ge triple junction solar cell weight reduction as a function of the Ge substrate thickness. 2μm and 5μm thick layers for the GaInP and Ga(In)As are considered to take into account other layers apart from the subcells themselves. The initial substrate thickness considered is 175μm.

B. Heat Absorption

Ge substrates suffer from free carrier absorption (FCA)[7], absorbing wavelengths longer than their bandgap and heating up the solar cell[8]. This kind of absorption becomes noticeable once the photogeneration is dominated by indirect transitions (λ>1600nm). Consequently, most of the light beyond 1600nm will be transformed into heat, degrading the device performance. Fig.2 shows the spectral irradiance for AM0, AM1.5G and AM1.5D spectra, together with their cumulative irradiance (i.e. the irradiance integral from 300nm).

Fig. 2. AM0, AM1.5G and AM1.5D spectral irradiance. The cumulative irradiance (i.e. integral from 300nm) for each spectrum is also shown.

The irradiance beyond 1600nm is around 8% of the total energy for each spectrum. If we consider that the other 90% is transformed into electricity with an efficiency around 40% for the standard triple junction, wavelengths longer than 1600nm accounts for 14% of the total irradiance heating up the solar cell.

Fig. 3. Internal absorption (see equation 1) for a triple junction as a function of the substrate thickness.

In order to assess how thin the substrate should be to avoid being heated up by useless wavelengths, the absorption between 1600 and 2000nm has been simulated for different substrate thicknesses (see Fig.3). The transfer matrix method (TMM) was used to perform the optical calculations using data from [9]. To avoid the influence of optical effects, the internal absorption has been calculated:

\[ A_{\text{internal}}(\lambda) = A(\lambda)/(1 - R(\lambda)) \]  \hspace{1cm} (1)

where \( A \) stands for the Absorptivity and \( R \) for the Reflectivity. Fig.3 shows that the absorption decrease starts to saturate for thicknesses around 10μm. For this thickness the absorption has decreased from 71 to less than 13%, which means that the heat absorption for long wavelengths would decrease by more than 80%.

C. Performance at 1 Sun

Now, we proceed to evaluate the performance of a Ge subcell. To do so, 2D simulations have been carried out with Silvaco Atlas[10], [11]. Neither shadowing nor resistive losses at the contacts have been considered. Optical calculations have been carried out using the Transfer Matrix Method (TMM) assuming no antireflection coating (ARC) and a gold back metal contact. The change in the operation temperature as a result of a lower heat absorption, caused by a thinner substrate, has not been considered.

An n/p Ge single junction with \( 10^{19} \) and \( 6 \cdot 10^{17} cm^{-3} \) constant doping levels for the emitter and the base respectively has been simulated. The emitter is assumed to be 190nm thick, being the rest of the substrate the
base of the solar cell. A standard surface recombination velocity of $2 \cdot 10^5$ cm/s [12] has been considered at the window-emitter interface. To model the back surface recombination the infinite recombination at the back metal contact has been avoided by means of an ideal heterojunction at the back surface with a 1 eV bandgap material. The affinity has been set to be such that there is no barrier for holes (i.e. at the valence band) forming a 375meV barrier at the conduction band. Then, the desired surface recombination velocity for electrons and holes at that interface has been set, considering $10^9$ cm/s as infinite recombination.

Fig. 4 shows the evolution of the power generation of a Ge subcell under AM0 filtered by a GaAs layer for three different scenarios: only standard front surface recombination (Front), only infinite back surface recombination (Back) and combination of standard front and infinite back surface recombination (Front and Back). Thick substrates are dominated by the front surface recombination while thin ones are dominated by the back one. This different behavior is explained as the emitter thickness is constant and it does not change as the substrate is thinned down. Conversely, the thinner the substrate the closer the back surface is to the $pn$ junction increasing its influence on the overall performance. For the optimum thickness pointed out in the previous sections ($\sim 10 \mu$m), it is more important to avoid the back surface recombination than the front one in order to achieve a good performance in the Ge subcell. Moreover, as long as the back surface recombination is avoided, the power loss is limited to only 6% if the substrate is thinned down from 175 to 10$\mu$m.

D. Photon confinement

Typical Ge substrates are not suitable to exploit the benefits of confining photons using a back reflector[13], [14]. First, the FCA will absorb most of the long wavelength photons, which are the ones that would benefit from the back reflector. Second, wavelengths influenced by the back reflector would be mostly absorbed too far away from the $pn$ junction to be collected, given the typical diffusion length of electrons in highly doped germanium substrates ($<100 \mu$m). Therefore, the collection of carriers photogenerated by long wavelengths are hindered by a thick, highly doped substrate. These two effects are avoided as the substrate is thinned down, improving the effectiveness of the back reflector.

III. EXPERIMENTAL

Once the advantages of a thinner substrate for a multijunction solar cell has been evidenced, we proceed to assess how the thinning process could be performed and demonstrate its suitability to manufacture solar cells.

A. Thinning Process

Ge substrates have been thinned down by means of chemical etching processes. This method has been selected due to its scalability and ease of application during the manufacture of a solar cell. Among the options reported to etch Ge substrates [15]–[19], acid-base etchants has been selected to carry out the etching process. In order to measure the etch rate one side of the sample was protected with photoresist. Then, the step was measured with the help of a profilometer. All etching processes were carried out at ambient temperature (23-27 °C) with enough solution in order to avoid its saturation. Standard (100) Ge substrates with a miscut of 6° towards the nearest (111), a thickness of 175$\mu$m and $6 \cdot 10^{17}$ cm$^{-3}$ doping level were used to assess the etch rate evolution with time as depicted in Fig. 5. The etch rate is fairly constant around 10$\mu$m/hour, similar to what has been reported in the literature. Etching processes as long as 6 hours have been carried out achieving substrates thinned down to 115$\mu$m.

![Fig. 4. Maximum power generated by a Ge solar cell under AM0 filtered by a GaAs layer. Three scenarios are plotted regarding the Ge solar cell surface recombinations: only standard window-emitter surface recombination (Front), only infinite back surface recombination (Back) and combination of standard window-emitter and infinite back surface recombination (Front and Back).](image-url)
IV. Conclusions

In this work, the drawbacks caused by the Ge substrate in the solar cell performance have been pointed out. Thinning the substrate has been demonstrated as a solution to decrease the weight of the solar cell, cool down the operating temperature, enhance the performance and allow to benefit from a back reflector. Thinning the substrate down to 10μm would reduce the weight by more than 90% while limiting the heat absorption in useless wavelengths (>1600nm) by more than 80%. In order to achieve a good performance for thinned Ge solar cells it is mandatory to avoid the back surface recombination while the front one will only degrade the performance by a 6% for 10μm thick samples. Ge substrates have been thinned down, achieving thicknesses around 115μm. Thinned Ge solar cells have been manufactured with limited losses, showing the feasibility of this process.

ACKNOWLEDGMENTS

This work has been supported by the Fundacion Iberdrola Espana Research Grants, Spanish MINECO through the project TEC2017-83447-P and by the Comunidad de Madrid through the project MADRID-PV2 (S2018/EMT4308). I. Lombardero acknowledges the financial support from the Spanish Ministerio de Educacion, Cultura y Deporte through the Formacion del Profesorado Universitario grant with reference FPU14/05272.

REFERENCES

[1] N. Miyashita, Y. He, T. Agui, H. Jusko, T. Takamoto, and Y. Okada, “Inverted Lattice-Matched Triple Junction Solar Cells With 1.0 eV GaInNAsSb Subcell by MOCVD/MBE Hybrid Growth,” IEEE Journal of Photovoltaics, vol. PP, pp. 1–7, 2019.

[2] J. F. Geisz, M. A. Steiner, N. Jain, K. L. Schulte, R. M. France, W. E. McMahon, E. E. Perl, and D. J. Friedman, “Building a Six-Junction Inverted Metamorphic Concentrator Solar Cell,” IEEE Journal of Photovoltaics, vol. 8, no. 2, pp. 626–632, 2018.

[3] M. Nederjekovic, R. Soref, and G. Z. Mashanovich, “Predictions of freecarrier electroabsorption and electorefraction in germanium,” IEEE Photonics Journal, vol. 7, no. 3, 2015.

[4] F. Dimroth, T. N. D. Tibbits, M. Niemeyer, F. Predan, P. Beutel, C. Karcher, E. Oliva, G. Sieler, D. Lackner, P. Fus-Kauliweit, A. W. Bett, R. Krause, C. Drazek, E. Guiot, J. Wasselin, A. Tazzin, and T. Sigmanarchez, “Four-junction wafer-bonded concentrator solar cells,” IEEE Journal of Photovoltaics, vol. 6, no. 1, pp. 343–349, 2016.

[5] E. Gaubas and J. Vanhellemont, “Dependence of carrier lifetime in germanium on resistivity and carrier injection level,” Applied Physics Letters, vol. 89, no. 14, pp. 23–26, 2006.

[6] M. B. Prince, “Drift Mobilities in Semiconductors. I. Germanium,” Experimental Techniques, 1953.

[7] A. P. Kirk, “High efficacy thinned four-junction solar cell,” Semiconductor Science and Technology, vol. 26, no. 12, p. 125013, 2011.

[8] D. A. Clogston and P. A. Basore, “Modelling Free-carrier Absorption in Solar Cells,” Tech. Rep., 1997.

Simulations pointed to a degradation of 6% and 2% for the “Back” and “Front and Back” scenarios respectively (see Fig.4). This could point to an overestimated front degradation. However, this is only an hypothesis and a more thorough analysis regarding the difference between simulation and measurement results is required.
[9] M. Seiji and A. Toshihiro, “The Intrinsic Absorption Edge of Heavily Doped N - and P -type Germanium,” p. 269, 1964.
[10] Silvaco Atlas™, “2.26.1.R,” p. 1776, 2018.

[11] Silvaco DeckBuild™, “4.6.2.R.p.221-2017

[12] D. J. Friedman and J. M. Olson, “Analysis of Ge junctions for GaInP/GaAs/Ge three-junction solar cells,” Progress in Photovoltaics: Research and Applications, vol. 9, no. 3, pp. 179–189, 2001.

[13] O. D. Miller, E. Yablonovitch, and S. R. Kurtz, “Intense internal and external fluorescence as solar cell approach the SQ efficiency limit,” Photovoltaics, IEEE Journal of, vol. 2, no. 3, pp. 1–27, 2012. [Online]. Available: http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=6213058

[14] M. A. Steiner, J. F. Geisz, I. Garcia, D. J. Friedman, A. Duda, and S. R. Kurtz, “Optical enhancement of the open-circuit voltage in high quality GaAs solar cells,” Journal of Applied Physics, vol. 113, no. 12, p. 123109, mar 2013. [Online]. Available: http://scitation.aip.org/content/aip/journal/jap/113/12/10.1063/1.4798267

[15] B. Schwartzl and H. Robbins, “Chemical Etching of Germanium in Solutions of HF, HNO3, H2O and HC2H3O2,” pp. 1–6.

[16] M. Inoue, “Etching of Germanium with Water Vapor,” 1972.

[17] K. Ito, D. Yamaura, and T. Ogino, “Chemical wet etching of germanium assisted with catalytic-metal-particles and electrolessmetal-deposition,” Electrochimica Acta, vol. 214, pp. 354–361, 2016. [Online]. Available: http://dx.doi.org/10.1016/j.electacta.2016.08.016

[18] R. Leancu, N. Moldovan, L. Csepregi, and W. Lang, “Anisotropic etching of germanium,” pp. 35–37, 1995.

[19] S. Kagawa, T. Mikawa, and T. Kaneda, “Chemical Etching of Germanium with H3PO4-H2O2-H2O Solution,” Japanese Journal of Applied Physics, pp. 1616–1618, 1982.