Wafer-Bonded AlGaAs//Si Dual-Junction Solar Cells

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Abstract — Monolithic two-terminal III-V on Si dual-junction (2J) solar cells were fabricated by means of Surface-Activated direct wafer Bonding (SAB). $\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}$ single-junction cells are grown on GaAs substrate by Metal-Organic Vapor Phase Epitaxy (MOVPE) and bonded at room temperature to independently fabricated Si solar cells. The $\text{n}^+\text{-GaAs}/\text{n}^+\text{-Si}$ bonding interface is characterized by Transmission Electron Microscopy (TEM) revealing a 2-3 nm thick amorphous interlayer. The performance of the 1 cm^2 tandem cells, designed for low concentration applications, was studied by External Quantum Efficiency (EQE) and J-V measurements showing a power conversion efficiency of 17% under one-sun AM1.5G spectrum. To our knowledge, this is the highest efficiency ever reported for a wafer-bonded 2J III-V on Si solar cell. Limitations to performance have been identified and therefore higher efficiencies are expected.

Index Terms — photovoltaic solar cells, multijunction, III-V on silicon, surface-activated direct wafer bonding.

I. INTRODUCTION

Today, Si based solar cells is the dominant photovoltaic technology with more than 90% of the market share. However, Si cell improvement gradually slows down as the power conversion efficiency record, 26.3% at this time [1], approaches the theoretical efficiency limit for Si of 29.4% [2]. Stacking highly efficient III-V junctions on top of Si solar cells is a promising way to overcome the Si single-junction efficiency limit. In addition, unlike III-V multijunction solar cells (MJSC) grown on expensive GaAs or Ge substrates, III-V cells mechanically stacked or wafer bonded to much cheaper and widely available Si wafers, combined with III-V substrate reuse strategies, could result in a significant cost reduction, thus potentially allowing for a competitive Levelized Cost Of Electricity (LCOE) in one-sun or low-concentration terrestrial solar applications [3].

In the '80s and '90s, much effort was invested in the epitaxial growth of (Al)GaAs on Si. However, mismatches in lattice parameter and in coefficient of thermal expansion, polar/nonpolar materials and AlGaAs minority carrier lifetime sensitivity to oxygen contamination have limited the efficiency to 21.4%, as reported by Soga et al. back in 1997 for a tandem AlGaAs/Si solar cell [4].

An attractive approach to overcome heteroepitaxy issues consists of joining independently processed Si and III-V solar cells by direct wafer bonding or mechanical stack techniques, as recently demonstrated by Cariou et al. with a triple junction GaInP/GaAs//Si solar cell using SAB technique, showing 30.2% one-sun power conversion efficiency [5].

In the case of a III-V on Si 2J solar cell, detailed balance modeling shows a Shockley-Queisser limit conversion efficiency beyond 40% for a top-cell band gap of about 1.7 eV under the AM1.5G spectrum [6]. Therefore, a 2J III-V on Si solar cell has the potential to reach very high efficiencies and it could be more cost competitive compared to the 3J-MJSC due to the high cost of III-V additional epitaxial layers needed [7]. To our knowledge, the best efficiency reported so far for a wafer-bonded 2J III-V on Si solar cell under AM1.5G standard spectrum is 11.1% achieved by Shigekawa et al. with a GaInP//Si cell structure [8].

In this work, the fabrication process of monolithic two-terminal $\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}$ //Si tandem solar cells using SAB is presented along with EQE and current density-voltage (J - V) characteristics under one-sun AM1.5G spectrum.

II. EXPERIMENTAL

A. Sample Preparation

Wafer-bonded $\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}$ //Si 2J solar cells were fabricated according to the process described hereunder and the resulting cell structure is presented in Fig. 1.

1) $\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}$ top cells (1.7 eV) are grown lattice matched with inverted layer configuration on 4-inch GaAs substrates by MOVPE, including a highly doped GaAs tunnel junction and a 500 nm thick bonding layer.

2) The Si bottom cells are manufactured independently by thermal diffusion processes on p-type Czochralski (CZ) c-Si wafers (14-22 $\Omega\cdot\text{cm}$, 525 μm), resulting in the formation of P-doped n^+ emitter and a B-doped p^+ back surface field (BSF).

3) Si and GaAs wafer surfaces are cleaned using wet chemical treatments and planarized by Chemical-Mechanical Polishing (CMP), resulting in a bonding layer thickness of 170 nm.

Fig. 1. AlGaAs/Si 2J solar cell structure scheme (not to scale).

Afterwards, the wafers are loaded into an EVG580 ComBond vacuum chamber and then exposed to an Ar ion beam of few hundreds of eV that removes the native oxide layers via sputtering and leaves very reactive surfaces with dangling bonds. The wafers are then brought into contact and covalent bonds are formed at room temperature without the need of annealing.

4) The GaAs substrate and GaInP etch-stop layer (not represented in Fig. 1) are etched away respectively by $\text{H}_2\text{O}_2 + \text{NH}_4\text{OH}$ and $\text{HCl}/\text{H}_3\text{PO}_4$ solutions, leaving the few-micrometers-thick III-V active layers on the Si bottom cell.

5) Finally, front metal contacts designed for low concentration (~ 20 suns, $\sim 5\%$ shading factor without bus bars [9]) and full sheet back metal contacts are deposited by evaporation. Mesa etching (trenches down to $2\ \mu\text{m}$ inside Si) is performed to partially isolate individual cells of 1 or $2\ \text{cm}^2$ and a $65\ \text{nm}$ Si_3N_4 Anti-Reflection Coating (ARC) is deposited by PECVD.

Single-junction $\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}$ and Si stand-alone solar cells were also manufactured, performing step 1 (in upright configuration) and 5 for the AlGaAs solar cell and 2 and 5 for the Si solar cell.

B. Characterization

Spectral response and reflectivity measurements were performed using a conventional EQE system as previously reported in [10]. J - V measurements were carried out using a Spectra-Nova one-sun AM1.5G class AAA solar simulator. A shadow mask, designated area of $0.68\ \text{cm}^2$, was used to avoid potential contributions from the Si wafer outside the cell area.

III. RESULTS AND DISCUSSION

The implementation of the SAB technique using Ar fast atom beam sputtering results in the formation of a $\sim 3\ \text{nm}$ thick

Fig. 2. TEM image taken under Si orientation showing the $\sim 3\ \text{nm}$ thick amorphous layer between the GaAs-Si bonding interfaces.

amorphous interlayer, as revealed by TEM analysis shown in Fig. 2. No voids or crystal dislocations could be found.

In Fig. 3 and Fig. 4, EQE and J - V measurements of the tandem AlGaAs/Si subcells are presented along with the AlGaAs and Si single-junction stand-alone reference cells. J_{SC} can be calculated from EQE by convolution with the AM1.5G spectrum obtaining 13.5 and $12.7\ \text{mA}/\text{cm}^2$ for top and bottom subcells respectively. This suggests that the Si bottom junction limits the current of the series connected tandem device, although the subcells are not far from being current matched. However, both top and bottom junctions could produce much higher currents as detailed hereunder:

a) Anti-Reflection Coating. The reflectivity curve at normal incidence (black dotted line in Fig. 3) shows that the single-layer Si_3N_4 ARC is adapted for AlGaAs top subcell ($\sim 550\ \text{nm}$) but is not very performant for the Si bottom subcell spectral absorption region (reflectivity from 10 to 20% between 730 to $1200\ \text{nm}$). A more adapted bilayer ARC with optimum materials and layer thicknesses will be used to significantly increase the EQE, especially in the bottom subcell region.

b) Material quality. $\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}$ stand-alone cell suffers from a high band gap-voltage offset $W_{OC} = E_g/q - V_{OC} = 0.51\ \text{V}$, calculated using the V_{OC} shown in the inset table of Fig. 4 and the bandgap energy of $1.7\ \text{eV}$, suggesting low crystal quality probably due to oxygen contamination during epitaxy caused by the strong bond between oxygen and aluminum [11]. Si stand-alone high $W_{OC} = 0.54\ \text{V}$ could be explained by the low crystal quality of the CZ substrate that is not adapted to the $525\ \mu\text{m}$ thickness. PC1D simulations (not shown here) indicate that the use of float-zone (FZ) Si substrates, with higher minority carrier lifetime, coupled with an improved emitter profile and rear surface passivation will allow to improve the Si bottom subcell V_{OC} and J_{SC} .

Fig. 3. EQE and reflectivity of tandem AlGaAs/Si subcells along with the AlGaAs and Si single-junction stand-alone cells used as reference. J_{SC} (mA/cm^2) calculated by convolution with the AM1.5G spectrum is also shown.

Fig. 4. J - V curve at one sun AM1.5G spectrum of tandem AlGaAs/Si subcells along with the AlGaAs and Si single-junction stand-alone cells used as reference.

c) Front contact processing and inverted growth issues.

$\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}$ top subcell shows degraded performance compared to the stand-alone single-junction cell ($J_{SC} = 15.7 \text{ mA}/\text{cm}^2$, dashed blue line from Fig. 3). TEM and Energy-Dispersive X-ray spectroscopy (EDX) analysis shown in Fig. 5) suggest different hypotheses that could explain the lower EQE of the grown inverted top subcell respect to the upright 1J cell. In the inverted growth structure, a $\sim 5 \text{ nm}$ GaAs layer was found at the interface between the GaInP barrier and the AlGaAs window layers. This may be caused by dopant diffusion due to the different growth sequence in the inverted configuration [12]. In addition, TEM analysis also revealed the presence of gold particles in the front surface of the tandem cell, probably

Fig. 5. TEM images and EDX profiles of the 2J and 1J upper cell layers.

due to some difficulties during the tandem cell front contact processing steps. In contrast, gold particles were not found in the stand-alone cell surface and the GaInP barrier layer was $\sim 10 \text{ nm}$ thinner, which could reduce losses due to absorption. Solving these epitaxy and front contact processing issues a J_{SC} greater than $15 \text{ mA}/\text{cm}^2$ should be attainable in the top subcell, as already demonstrated for the stand-alone cell.

d) GaAs absorption. The bottom Si subcell shows low EQE from 730 to 800 nm due to optical absorption in the 170 nm of the GaAs bonding layer and in the 50 nm of the GaAs tunnel junction. These GaAs layers have indeed a 1.4 eV bandgap that is lower than that of the top junction and hence they block part of the light that should be absorbed by the Si bottom subcell. This will be partially mitigated in future work by thickness reduction of the bonding layer to around 50 nm.

As the subcells are connected in series, a small variation in one region of the spectrum may lead to an underestimation or overestimation of one of the subcells current and hence to the J_{SC} of the total device. For this reason, despite of the solar simulator being AAA class, it is not perfectly tuned for MJSC characterization. Therefore, the possible spectral imbalance produced by the solar simulator could be responsible for the increase in the current mismatch between the subcells and hence explain the slight higher fill factor (FF) of the tandem cell [13]. Nonetheless, very little difference could be observed between the J_{SC} calculated from EQE and the one extracted from the J - V curves. Measurements under concentrated light

from 1 to 30 suns are currently being done using a flash solar simulator calibrated for MJSC accurate characterization [14]. Similar cells with the same front metal contact designed, optimized for ~15 suns, have shown a boost of around 3% in efficiency when measured under the same concentrations with respect to the one-sun performance.

IV. CONCLUSIONS AND FUTURE WORK

In conclusion, $\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}/\text{Si}$ tandem solar cells has been demonstrated using SAB showing improved efficiency compared to its AlGaAs and Si stand-alone counterparts. A power conversion efficiency of 17% under one-sun AM1.5G spectrum was measured, which is higher than the present record for a wafer-bonded 2J III-V on Si solar cell [8]. Moreover, this performance level can be further improved by solving the following issues: a) non-optimum ARC, b) Si and AlGaAs material quality, c) front contact processing and inverted growth difficulties and d) over-thick GaAs bonding layer. Ongoing work on these issues is expected to bring large performance improvements.

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