Fabrication of GaInP/GaAs//Si Solar Cells by Surface Activated Direct Wafer Bonding

Karen Derendorf, Stephanie Essig, Eduard Oliva, Vera Klinger, Tobias Roesener, Simon P. Philipps, Jan Benick, Martin Hermle, Michael Schachtner, Gerald Siefer, Wolfgang Jäger, and Frank Dimroth

Abstract—GaInP/GaAs//Si solar cells with three active p-n junctions were fabricated by surface activated direct wafer bonding between GaAs and Si. The direct wafer bond is performed at room temperature and leads to a conductive and transparent interface. This allows the fabrication of high-efficiency monolithic tandem solar cells with active junctions in both Si and the III–V materials. This technology overcomes earlier challenges of III–V and Si integration caused by the large difference in lattice constant and thermal expansion. Transmission electron microscopy revealed a 5-nm thin amorphous interface layer formed by the argon fast atom beam treatment before bonding. No further defects or voids are detected in the photoactive layers. First triple-junction solar cell devices on Si reached an efficiency of 23.6% under concentrated illumination.

Index Terms—Heterojunctions, III–V semiconductor materials, multijunction solar cell, silicon, wafer bonding.
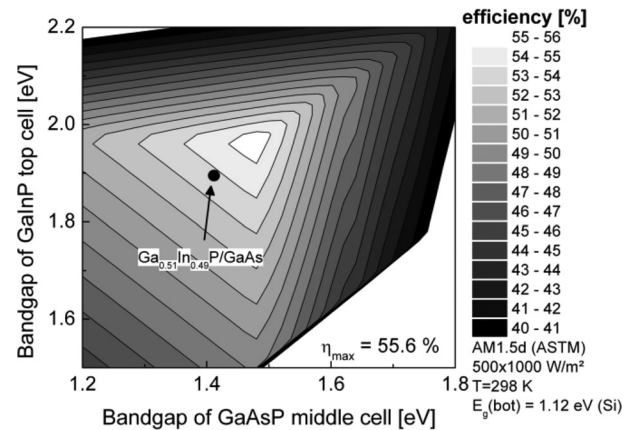

Fig. 1. Theoretical efficiency limit of a triple-junction solar cell with Si fixed as the bottom junction. The graph shows the dependence of the efficiency on the bandgap of the two upper subcells. The calculations were performed using etaOpt [5] for 500-fold concentration of the AM1.5d (ASTM) spectrum.

I. INTRODUCTION

THE conversion efficiency of solar cells in a photovoltaic module has a major impact on electricity generation costs. Therefore, achieving high solar cell efficiencies has always been driving research and development in this field. Silicon is the most widely used semiconductor in photovoltaics and efficiencies up to 25% under 1-sun AM1.5g conditions have been published [1]. Significantly higher efficiencies up to 44% under 947-suns (AM1.5d) conditions [2] are only achieved with multijunction devices made of III–V compound semiconductors. These solar cells are widely used in space and in terrestrial concentrator systems. By concentrating the sunlight by a factor

of 300–1000, the solar cell area can be reduced while keeping the amount of gained power. This leads to a reduction of the required semiconductor material and enables the use of more expensive III–V materials.

State-of-the-art solar cells in this field are made of lattice-matched GaInP/GaInAs/Ge and reach solar electric conversion efficiencies up to 41.6% at 364 suns [3]. The germanium (Ge) acts as a substrate for the growth and forms the bottom p-n junction. This has two disadvantages. Because of the low bandgap energy of 0.66 eV [4], the Ge bottom cell produces a high excess current compared with the two upper subcells. The excess current cannot be used in the series-connected device as the current is limited by one of the upper cells. Another disadvantage is the use of Ge, which is an expensive material with limited availability. In fact, silicon would be a better choice taking into account the cost, availability, and the higher bandgap energy of 1.12 eV [4].

The growth of III–V semiconductors on silicon is a challenging field of research [6]–[9]. The large differences in thermal expansion coefficients and lattice constants between GaAs and Si have prohibited the fabrication of high-efficiency solar cells on silicon so far [10]. We, therefore, developed a new process to realize a triple-junction solar cell on silicon by direct wafer bonding.

Theoretical efficiencies of triple-junction solar cells containing a Si bottom cell were calculated with etaOpt [5] for a concentration of 500 suns under ASTM G173-03 conditions (see Fig. 1). The calculation is based on the detailed balance limit

of Shockley and Queisser [11], which was implemented in the program etaOpt. The model assumes ideal solar cells, which in particular implies a quantum efficiency of 100% for all photons with energies above the bandgap of the semiconductor. In addition, the only recombination channel is radiative recombination. Thus, the calculated currents are to be seen as upper limits. A maximum efficiency of 55.6% requires bandgap energies of 1.96 and 1.48 eV for the top and middle cells, respectively. The realized triple-junction solar cell on Si contains a $Ga_{0.51}In_{0.49}P$ top and GaAs middle cell (see Fig. 1). This bandgap combination leads to a theoretical efficiency of 53.8%. The maximum achievable current densities are 16.6, 14.9, and 12.3 mA/cm^2 for the top, middle, and bottom junctions, respectively. In contrast with the triple-junction solar cell on Ge, this device is limited by the current in the bottom cell. This can be changed by thinning the upper subcells, and thereby, balancing the current throughout the device. Besides the limited availability of Ge another main advantage of the combination of $Ga_{0.51}In_{0.49}P$/GaAs//Si is that the upper two subcells can be grown lattice matched on a GaAs substrate. This lattice-matched growth prevents the formation of dislocations and allows a high minority carrier lifetime. After the substrate removal by selective etching, the GaInP/GaAs stack is bonded to a separately prepared silicon bottom p-n junction, which further serves as a mechanical support of the III–V layers.

Different direct wafer bonding methods can be found in the literature, which are distinguished by the preparation of the wafer surfaces. One approach is to create hydrogen-terminated surfaces by wet-chemical etching. After compression, the hydrophobic surfaces are connected via weak hydrogen-bridge bonds [12]. To achieve high bond strength, the wafer pair has to be annealed at temperatures up to 850 °C to create covalent bonds between the surface atoms [13]. Another technique is the surface activated wafer bonding where the surfaces are treated either with a reactive plasma [14] or with a beam of highly energetic ions or neutral atoms [15] prior bonding. Surface activated Si/GaAs bonds at room temperature after the argon fast atom beam treatment with high mechanical strength have been reported by different groups [16], [17]. Today wafer bonding is an established fabrication method for the integration of optoelectronic devices like lasers or photodetectors on Si integrated circuits and starts being used for the fabrication of high-efficiency solar cells [18], [19]. In most cases, Si is used as a nonactive carrier for the solar cell structure. Zahler *et al.* used hydrogen implantation, wafer bonding, and layer splitting to transfer a thin layer of Ge or InP onto Si. Afterwards, a III–V multijunction solar cell structure was grown epitaxially on this template [20], [21]. Other publications show results of III–V subcells grown separately and joined afterwards by wafer bonding [22], [23].

This paper presents first experimental results of a wafer-bonded GaInP/GaAs//Si triple-junction solar cell with an active Si bottom cell. This cell concept was also suggested in [24]. In the presented experiments, fast atom beam activated bonding was chosen. Because of the high bond strength at room temperature, annealing of the solar cell wafers at temperatures above 200 °C could be avoided which minimizes thermal stress caused by the difference in thermal expansion between GaAs
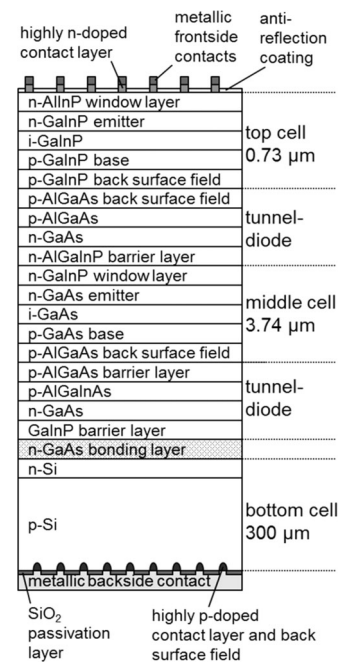

Fig. 2.   Schematic layer structure of the GaInP/GaAs//Si triple-junction solar cell. The thicknesses of the subcells are given.

and Si [17]. The overall structure is illustrated in Fig. 2. It consists of a 730-nm thick GaInP top cell grown on a 3740-nm thick GaAs middle cell and bonded to a separately prepared 300-μm diffused np-Si bottom cell. Tunnel diodes are used for the series connection of the different subcells.

II. EXPERIMENTAL SETUP

A. Sample Preparation

Metal organic vapor phase epitaxy (MOVPE [25]) was used for the growth of the GaInP/GaAs tandem cell on (001) GaAs with a misorientation of 6° toward $\langle 111 \rangle$A. An Aixtron 2600-G3 planetary reactor with 8×4-in wafers was used. Typical precursors were TMGa, TMIn, TMAl, DMZn, DETe, CBr$_4$, AsH$_3$, PH$_3$, and SiH$_4$. Growth conditions varied between pressures of 70–100 mbar and temperature of 560–660 °C. Upright growth started with a degenerately doped n-GaAs bonding layer ($n = 10^{19}$ cm^{-3}), followed by a tunnel diode, the np-GaAs solar cell structure, another tunnel diode, the np-structure of the GaInP solarcell and a highly doped GaAs contact layer. After the growth, the epitaxial layers with an overall thickness of 4.7 μm were stabilized by a sapphire wafer and the GaAs substrate was removed by selective etching.

For the Si bottom cell, a cell design with homogenous emitter and locally diffused back surface fields and contacts was used. The p-doped FZ Si wafer (3E15–1.5E16) was treated with a diffusion process with boron (B) to form point-shaped structures at the backside for the back surface fields. Subsequently, a 200-nm thick SiO$_2$ passivation layer was applied to the rear side. Thereafter, the front-side emitter was formed by diffusion of phosphorus (P) into the 300-μm thick p-type Si wafer, leading to a high surface carrier concentration of $n = 10^{20}$ cm^{-3}. The surface of the emitter also forms the interface for the wafer

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bonding process. Finally, the backside metal contact was applied by locally opening the SiO_2 passivation layer and metal evaporation.

The two parts of the device structure were joined by direct wafer bonding between the degenerately doped n-GaAs bonding layer and the highly n-doped Si emitter layer which forms the top surface of the Si bottom cell.

The bond process was carried out in a SAB-100 system from Ayumi with a low vacuum of 10^{-6} Pa. The bond chamber contains two saddle field fast atom beam (FAB) sources [26], which can simultaneously remove the oxides from both wafers. An acceleration voltage of 1 kV during 1 min was applied. The energetic Ar atoms leave the FAB source through an aperture plate and hit the wafer surfaces under an angle of $45°$. The two surfaces were brought in contact at room temperature and bonding was initiated by applying a force of 5 kN for 1 min.

Afterwards, the temporary sapphire stabilization of the GaInP/GaAs tandem cell was removed and the front side was processed with metal fingers and antireflection coating. No annealing was performed to avoid the formation of stress within the structure. Finally, concentrator solar cell devices with an area of 5.5 mm^2 were defined by mesa etching.

B. Characterization

The bond interface was analyzed by cross-sectional transmission electron microscopy (TEM) at 300 kV using bright-field and high-resolution imaging in a $\langle 110 \rangle$ Si zone axis. The cross-sectional TEM sample was prepared by a focused ion beam technique.

For measurements of the external quantum efficiency (EQE), a grating monochromator setup with spectrally adjusted biaslight was used [27]. The *I–V* characteristics were measured to investigate the cell performance under 1-sun (AM1.5d ASTM G173) conditions [27]. Further measurements were carried out under a flashlight simulator to analyze the performance under concentrated illumination.

III. Results and Discussion

Fig. 3 shows a high-resolution TEM image of the bond interface between GaAs and Si. No voids could be found which supports the high mechanical stability. Despite the large lattice mismatch between GaAs and Si, the crystals remain without dislocations, which is one of the advantages of the room temperature wafer bonding approach. A 4–5-nm-thin amorphous layer is identified at the GaAs/Si interface. It is formed due to displacement damage caused by the Argon fast atom beam treatment of the Si and GaAs surface. The thickness of this damage layer is mainly influenced by the acceleration voltage of the argon ions. The electrical and mechanical properties of fast atom beam activated n-Si/n-GaAs bonds containing an amorphous interface layer have been published elsewhere [28].

The 1-sun *I–V*-characteristics of the GaInP/GaAs//Si solar cell in Fig. 4 show a high open-circuit voltage of 2.78 V. The comparison of the V_{OC} with a typical value of 2.62 V for a GaInP/GaInAs/Ge solar cell under the same conditions [1] shows that a 0.16-V additional voltage could be gained from substituting the Ge bottom cell with Si. The fillfactor is also
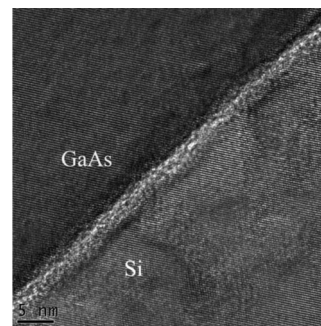

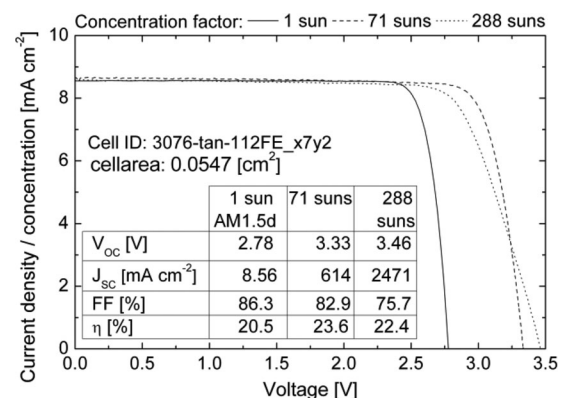Fig. 3. High-resolution TEM image of GaAs/Si interface (bright field, zone axis Si).

Fig. 4. *I–V* characteristics of the GaInP/GaAs//Si solar cell under illumination at 1 sun, 71 suns, and 288 suns. The current density is divided by the concentration factor. The table provides parameters at 1-sun and 71-suns concentration.
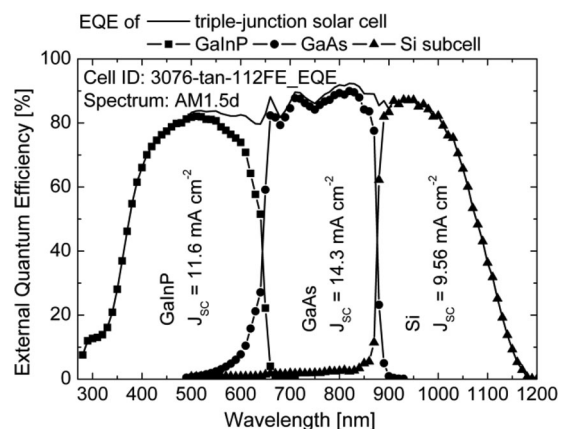
Fig. 5. EQE of the GaInP/GaAs//Si solar cell and the subcells. It was measured on a different cell than the *I–V* characteristics but from the same epitaxy (see text). The current densities of the subcells were calculated for the AM1.5d spectrum (ASTM G173-03).

rather high with 86% and leads to no indication of a high resistance of the bond interface under 1-sun conditions.

Fig. 5 shows the EQE of the entire multijunction solar cell device. It was measured on a cell from the same epitaxy and technology but with larger size and less grid shadowing compared with the cell used for *I–V* characteristics. All three junctions lead to EQE values exceeding 80%, which indicates the high crystal quality of all materials. The photovoltaic activity of the Si subcell proves a high transparency of the bond interface. The EQE

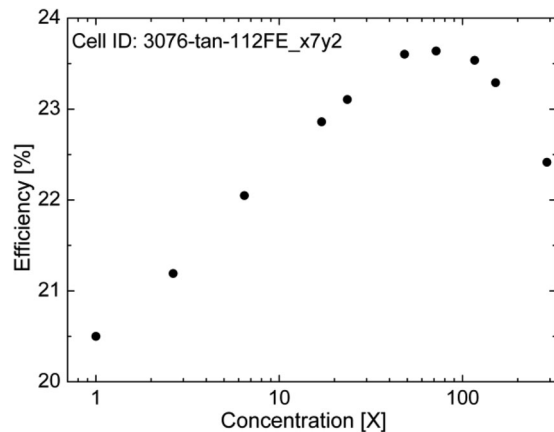Fig. 6. Efficiency of the GaInP/GaAs//Si solar cell as a function of the concentration factor. The maximum efficiency is found at 71suns.

rises sharply at the GaAs/Si interface and the sum of all quantum efficiencies shows no dip for wavelength around 900 nm for light transmitted into the Si bottom cell. This indicates that direct wafer bonding is a viable technology for the fabrication of high-efficiency multijunction solar cells including an active junction in Si.

The efficiency of present GaInP/GaAs//Si triple-junction solar cells is limited by the low overall current generated in the Si bottom cell. This subcell limits the current of the complete device, due to series connection. The EQE in Fig. 5 shows calculated current densities for each of the subcells under the AM1.5d spectrum. The current densities of the top and middle cells are 11.6 and 14.3 mA/cm^2 under AM1.5d conditions, respectively, whereas the Si bottom cell only produces 9.6 mA/cm^2. A comparison with the theoretical values (16.6, 14.9, and 12.3 mA/cm^2) reveals that the top and bottom cells still have to be improved to reach higher efficiencies. The main reason for the low current in the Si subcell is the low absorption. Silicon, as opposed to GaAs and GaInP, is an indirect semiconductor and light has to be captured inside the crystal to increase the absorption length. This is typically achieved by surface texturing leading to lower incident angles of the light at the rear surface and total internal reflection. Such surface structuring is not applicable to the front side of the GaInP/GaAs//Si solar cell but can be used at the rear side. This should allow reaching higher quantum efficiencies between 1000 and 1200 nm close to the Si bandgap. Moreover, the thicknesses of the top and middle cells could be reduced to reach current matching between the subcells. This leads to a theoretical current density of 14.6 mA/cm^2 [5].

The I–V characteristics of the solar cell were further investigated under concentrated illumination. The highest efficiency is reached at 71 suns with an efficiency of 23.6% (see Fig. 6). The V_{OC} increases to 3.33 V, whereas the fillfactor is reduced to 83% due to voltage losses under load (see Fig. 4). For higher concentrations of 288 suns, the I–V characteristics show significant influence by the series resistance. Similar results were observed for a GaInP/GaAs dual junction solar cell bonded to a highly doped nonactive Si substrate. This leads to the conclusion that the bond interface is the main reason for the reduced fillfactor under concentrated sunlight.

IV. SUMMARY AND CONCLUSION

Direct wafer bonding was shown to be a method to realize III–V multijunction solar cells on silicon, including an active silicon bottom junction. GaInP/GaAs//Si triple-junction devices were fabricated with efficiencies reaching 23.6% at 71-suns concentration of the AM1.5d spectrum. The solar cells with an area of 5.5 mm^2 show excellent quantum efficiencies and high transparency of the bond interface. No voids could be observed by TEM. The argon fast atom beam treatment of the surfaces before wafer bonding leads to a 4–5-nm-thin amorphous layer which causes voltage losses under high current densities. Therefore, the fillfactor is reduced from 86% at 1 sun to 83% at 71 suns. Additional losses are associated with the limited absorption of photons in the silicon bottom cell which is, consequently, the current limiting junction. Enhancement of light absorption by back surface texturing and a better control of current matching by tailoring subcell thicknesses will allow reaching III–V solar cell efficiencies > 40%, as seen for conventional devices on Ge. The cost benefits and the availability of Si are significant advantages of these devices.

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