Comparison of Direct Growth and Wafer Bonding for the Fabrication of GaInP/GaAs Dual-Junction Solar Cells on Silicon

Frank Dimroth, Tobias Roesener, Stephanie Essig, Christoph Weuffen, Alexander Wekkeli, Eduard Oliva, Gerald Siefer, Kerstin Volz, Thomas Hannappel, Dietrich Häussler, Wolfgang Jäger, and Andreas W. Bett

***Abstract*—Two different process technologies were investigated for the fabrication of high-efficiency GaInP/GaAs dual-junction solar cells on silicon: direct epitaxial growth and layer transfer combined with semiconductor wafer bonding. The intention of this research is to combine the advantages of high efficiencies in III–V tandem solar cells with the low cost of silicon. Direct epitaxial growth of a GaInP/GaAs dual-junction solar cell on a $GaAs_yP_{1-y}$ buffer on silicon yielded a 1-sun efficiency of 16.4% (AM1.5g). Threading dislocations that result from the 4% lattice grading are still the main limitation to the device performance. In contrast, similar devices fabricated by semiconductor wafer bonding on n-type inactive Si reached efficiencies of 26.0% (AM1.5g) for a 4-cm^2 solar cell device.**

***Index Terms*—Heterojunctions, silicon, wafer bonding, III–V multijunction solar cells.**

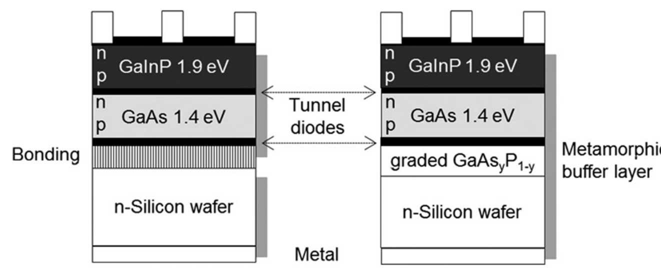


Fig. 1. Schematic of two investigated concepts for the integration of high-efficiency III–V solar cells on silicon. $Ga_{0.5}In_{0.5}P$/GaAs tandem solar cell structure transferred to Si by wafer bonding (left) and direct growth of $Ga_{0.5}In_{0.5}P$/GaAs structure on a GaAsP metamorphic buffer layer on Si (right). Both solar cell structures have an n-on-p polarity and are grown on n-Si. Tunnel diodes are used to connect the top and bottom subcells, as well as the bottom subcell and the n-Si wafer.

I. Introduction

The combination of III–V multijunction solar cells and silicon offers many advantages. The high mechanical strength, excellent heat conductivity, nontoxicity, availability in large diameters, and comparably low cost are just some of the most important properties which favor silicon as a semiconductor material. Therefore, the research and development of monolithic III–V solar cells on Si has a long history, but challenges in the fabrication processes, cracking or bowing of films because of high thermal mismatch, and high dislocation densities have so far prohibited the commercial success of this technology [2]. This situation is currently changing for optoelectronic devices like GaN-based LEDs, for which the first commercial products are entering the market. The reasons being that the transition between nonpolar Si and polar III–V crystals is better understood and high-quality nucleation layers of III–V on Si are more widely available today [3]–[7]. Furthermore, the understanding of lattice-mismatched growth has significantly improved over the years [8]–[12]. This also opens new opportunities for III–V multijunction solar cells to be manufactured on Si, especially if high efficiencies can be demonstrated. In this paper, we are investigating two pathways to achieve high-efficiency III–V multijunction solar cells on Si: direct epitaxial growth and thin layer transfer combined with wafer bonding (see Fig. 1). Both of these approaches are viable for industrial applications of III–V on Si solar cells.

Direct epitaxial growth of III–V on Si for solar cells was successfully developed in the 1990s, for example, by Umeno *et al.* [13] and Yang *et al.* [14]. They proved efficiencies up to 20% for AlGaAs/Si devices under AM0. Ringel *et al.* were following a different approach by combining SiGe templates grown by chemical vapor deposition with MBE growth of a GaAs or GaInP/GaAs solar cell structure [15]–[18]. The best devices showed a total area efficiency of 16.8% under AM1.5g conditions. More recently, GaP nucleation layers on Si with high crystalline quality and low density of antiphase domains (APDs) became available [3], [4], [7], and publications are concentrating

Manuscript received June 13, 2013; revised October 7, 2013; accepted December 10, 2013. Date of current version February 17, 2014. This work was supported in part by the German Ministry for education and research BMBF under the Contract III–V-Si Solar 03SF0329A and in part by the European Union by the project NGCPV under Contract 283798. The Ph.D. work of S. Essig and T. Roesener was supported by the German Federal Environmental Foundation (DBU) and Reiner–Lemoine Foundation.

F. Dimroth, S. Essig, C. Weuffen, A. Wekkeli, E. Oliva, G. Siefer, and A.W. Bett are with the Fraunhofer Institute for Solar Energy Systems ISE, D-79110 Freiburg, Germany (e-mail: frank.dimroth@ise.fraunhofer.de; stephanie.essig@ise.fraunhofer.de; christoph.weuffen@ise.fraunhofer.de; alexander.wekkeli@ise.fraunhofer.de; eduard.oliva@ise.fraunhofer.de; gerald.siefer@ise.fraunhofer.de; bett@ise.fraunhofer.de).

T. Roesener was with the Fraunhofer ISE, D-79110 Freiburg, Germany. He is now with the AZUR Space Solar Power GmbH, D-74072 Heilbronn, Germany (e-mail: tobias.roesener@azurspace.com).

K. Volz is with the Philipps University Marburg, D-35032 Marburg, Germany (e-mail: kerstin.volz@physik.uni-marburg.de).

T. Hannappel is with the Technische Universität Ilmenau, D-98693 Ilmenau, Germany (e-mail: Thomas.Hannappel@tu-ilmenau.de).

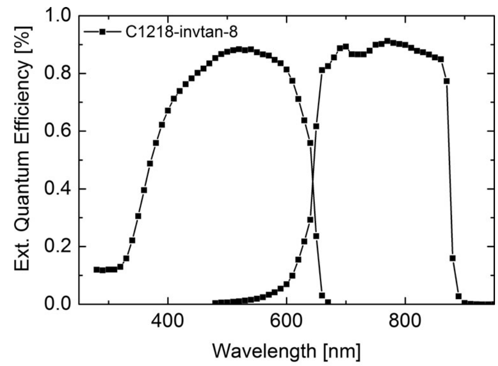
D. Häussler and W. Jäger are with the Institute of Materials Science, Christian-Albrechts-University, D-24118 Kiel, Germany (e-mail: dih@tf.uni-kiel.de; wj@tf.uni-kiel.de).

Digital Object Identifier 10.1109/JPHOTOV.2014.2299406

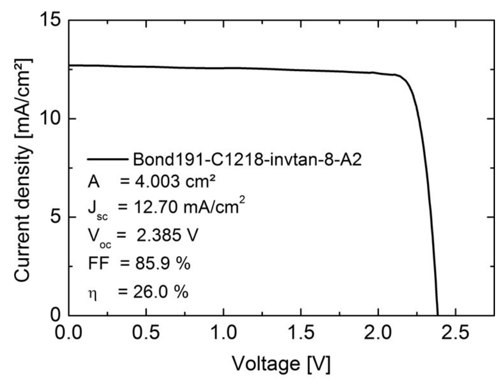
on $GaAs_yP_{1-y}$ transition layers to form III–V on silicon solar cell devices [19], [20].

An alternative approach was used to first create GaAs or Ge on Si templates by wafer bonding and lift-off before starting the epitaxial growth. This was followed by Schöne *et al.* in [21] as well as Zahler and Archer *et al*. [22], [23]. They demonstrated the metal-organic-vapor-phase-epitaxy (MOVPE) growth of GaInP/GaAs tandem solar cell devices on such templates reaching 16% efficiency. Difficulties were connected with the different thermal expansion of silicon and GaAs, which may lead to cracking of the thin solar cell layers when heated to the high growth temperatures of 600–700 °C. Postgrowth wafer bonding avoids such high temperatures and was recently demonstrated in a publication by Derendorf *et al.* [24]. In this case, a GaInP/GaAs tandem solar cell was first grown on a GaAs substrate and then combined with a Si bottom pn-junction to form a triple-junction device. Efficiencies of 23.6% were reported under concentrated illumination showing the high potential of this approach.

This paper presents GaInP/GaAs dual-junction solar cells on inactive n-type silicon. Both wafer bonding and direct growth have been investigated, and the results are discussed, together with challenges of each method.



(a)



(b)

Fig. 2. (a) EQE (b) and *I–V*-characteristic under AM1.5g spectral conditions of a GaInP/GaAs tandem solar cell transferred and bonded to silicon.

II. Experimental Details

GaInP/GaAs tandem solar cells with n-on-p polarity were entirely grown by MOVPE. The bandgap energies of the top and bottom subcells were 1.88 and 1.43 eV, respectively. n^+ GaAs/p^+ AlGaAs tunnel diodes were used for the series connection between the top and bottom cells, as well as the bottom subcell and the n-Si substrate. In the wafer bonding approach (see Fig. 1 left), a GaInP/GaAs solar cell structure was first grown inverted on GaAs wafers (100) 6° off toward $\langle 1\ {-1}\ 1\rangle$, including an etch-stop layer. The film was polished and then bonded to silicon using fast atom beam activated direct wafer bonding [25] in an Ayumi SAB-100 system at 120 °C and removed from the GaAs substrate by wet chemical etching.

Then, the bonded solar cell structure was annealed for 1 min at 400 °C and finally processed to solar cell devices with a total area of 4 cm^2. All cells were covered with a TaO_x/MgF_2 antireflective coating on the front side. Standard ohmic metal contacts were applied to the GaAs cap layer on the front side of the cell and the Si rear side, respectively.

In the case of direct growth (see Fig. 1 right), the epitaxy process started with a 300-nm homoepitaxial silicon layer on n-Si, followed by the growth of a 60-nm thick n-GaP nucleation layer and a $GaAs_yP_{1-y}$ graded buffer with seven steps to overcome the 4% difference in lattice constant between Si and GaAs. Typical growth temperatures of 640 °C and growth rates of 0.94 nm/s were used. Afterward, the samples were transferred to a second MOVPE system where the GaInP/GaAs layer structure with n-on-p polarity was deposited. A CRIUS closed-coupled showerhead reactor served for the direct III–V growth on Si, whereas an AIX 2800-G4 system was used for the GaInP/GaAs solar cell structures. In future, both processes shall be combined in the same chamber. Device processing was the same as described previously for wafer bonded solar cells.

Measurements of the external quantum efficiency (EQE) and current–voltage characteristics were carried out in the Fraunhofer ISE Callab. The incident spectral conditions were matched to the AM1.5g spectrum. More details of the procedures can be found in [26] and [27].

III. Results and Discussion

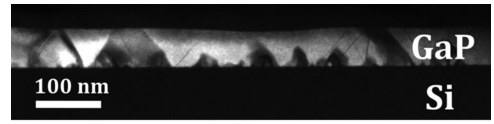
A. Wafer Bonded GaInP/GaAs Solar Cells on Si

Fig. 2(a) shows the EQE of a GaInP/GaAs tandem solar cell (1.0-μm thick $Ga_{0.5}In_{0.5}P$ and 1.8-μm GaAs absorber) which has been first grown inverted on a GaAs substrate and then transferred to n-Si by wafer bonding. The overall thickness of the epitaxy structure including buffer layers and tunnel diodes was 4.6 μm. It is important to note, that such thin crystalline layers are not stable enough to handle and must always be supported by a carrier. This was achieved by bonding the solar cell layers to silicon before removal of the GaAs substrate. The dual-junction solar cell shows an excellent characteristic with both junctions reaching EQE values above 88%.

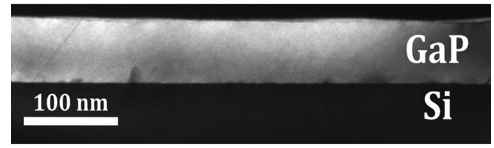
I–V characteristics of solar cells with 4-cm^2 total area were measured under AM1.5g standard test conditions [see Fig. 2(b)]. The best devices reach an efficiency of 26.0% with an open-circuit voltage of 2.39 V, a short-circuit current density of 12.7 mA/cm^2, and a fillfactor of 85.9% (C1218-invtan-8-T504-M43-A2). The high performance is due to the good crystal

TABLE I
I–V-CHARACTERISTICS OF GaInP/GaAs TANDEM SOLAR CELLS UNDER AM1.5g CONDITIONS, CELL AREA 4 cm^2

Solar Cell Type	J_{sc} [mA/cm2]	V_{oc} [V]	FF [%]	η [%]
GaInP/GaAs tandem cell from Ref. [1]	14.22	2.49	85.6	30.3
Wafer bonded cell on silicon	12.7	2.39	85.9	**26.0**
Upright reference on GaAs substrate	13.15	2.45	84.2	27.1
Upright direct growth on silicon	11.20	1.94	75.3	16.4



(a)



(b)

Fig. 3. Dark-field transmission electron microscopy images, (0 0 –2) reflex of GaP nucleation layers on Si with (a) high and (b) low density of APDs.

quality and low dislocation density which are obtained for lattice-matched growth on GaAs. This is also supported by the high open-circuit voltage of 2.39 V, which is only 100 mV below the best GaInP/GaAs tandem solar cell from [1] (see also Table I). Although these solar cell structures are not directly comparable due to the upright versus inverted growth and probable differences in the layer structure, the voltage is a sensitive measure of the crystal quality, and the value of 2.39 V for the GaInP/GaAs tandem solar cells on silicon proves the high material quality which has been achieved.

Further optimization of the GaInP and GaAs solar cell structure is needed especially to increase the short-circuit current density. This requires a reduction of parasitic absorption losses in the window, antireflection, and tunnel diode layers, as well as better current matching of the subcells. The AM1.5g current generation of the GaInP top cell is calculated from the EQE to be 12.9 mA/cm^2 compared with 14.4 mA/cm^2 for the GaAs bottom cell. Improvements of the response in the short-wavelength range are possible and subject of current developments. This should allow us to reach efficiencies above 30% with this approach.

For an economic success of the wafer-bonded cell, multiple reuse of the GaAs substrate is mandatory. The solar cells in this paper were processed after wet-chemical etching of the GaAs substrate which leads to a loss of the GaAs material. In addition, the preparation steps of bonding the 4.6-μm thick inverted III–V layer structure to silicon and removing the GaAs substrate must be carried out with high yield and in high throughput equipment. The wafer bonding process itself can be fast if performed at room temperature, as in the present experiments.

B. Directly Grown GaInP/GaAs Solar Cells on Si

The direct growth of III–V solar cell structures on Si is more challenging but has the advantage of using only one substrate and one epitaxial process. This allows for lower manufacturing costs. In the present experiments, the growth of an n-GaP nucleation layer on Si has been separated from the growth of the $GaAs_{1-y}P_y$ metamorphic buffer and the GaInP/GaAs tandem solar cell structure to avoid any source of potential cross contamination. It has to be carefully analyzed in the future how these processes can be combined, avoiding nucleation-related defects on Si induced by previously grown III–V material, as well as high background doping levels of the III–V elements in silicon and *vice versa*.

The n-GaP nucleation layer in our experiments was directly grown on Si to form the transition between the singular group IV and the polar III–V crystal lattice. Modulated flows of TEGa and TBP were used for the monolayer growth of GaP following the procedure described in [3] for singular (1 0 0) Si substrates. In this paper, the process was adapted to the large CRIUS MOVPE reactor and silicon wafers with 6° offcut angle toward ⟨1 –1 1⟩.

Fig. 3 shows two dark-field transmission electron microscopy (TEM) images of a 60-nm thick GaP nucleation layer with high (top) and low (bottom) density of APDs. Phases with different polarity appear light or dark under these imaging conditions. It turned out that the formation of APDs is very sensitive to the flow of TEGa during the pulsed nucleation as excess Ga can accumulate on the surface. If the TEGa flow is chosen carefully, the density of remaining APDs was found to be very low [see Fig. 3(b)], and most APDs at the interface annihilate within the first 10–30 nm of GaP growth. The surface of the 60-nm thick GaP nucleation layer was virtually free of APDs which was also confirmed by reflection anisotropy spectroscopy (RAS). A distinct RAS spectrum for single-domain GaP was found for these layers, similar to [28]. Still, in some cases, planar defects like twins or stacking faults are found in the TEM micrographs. These defects originate at the GaP/Si interface and propagate throughout the crystal layers. It is important to avoid such threading dislocations as they can have a severe impact on the minority carrier diffusion length in the active solar cell layers. Further work is required to understand the origin and avoid the formation of these planar defects.

$GaAs_yP_{1-y}$ was used for grading the lattice constant between GaP and GaAs. Fig. 4 shows a TEM image of a typical buffer structure that comprises of seven step-graded $GaAs_yP_{1-y}$ layers with increasing As content followed by the GaAs target layer. The thickness of each $GaAs_yP_{1-y}$ layer was 100 nm in this structure. An additional $Ga_{0.97}In_{0.03}As$ over-shooting layer (GaInAs-ÜSS) was added on top of the GaAs target layer to fully relax the in-plane lattice constant and ensure that further growth of the GaInP/GaAs tandem cell continues unstrained.

Unfortunately, a rather high density of threading dislocations resulted from the lattice grading in the metamorphic buffer. Counting threading dislocations in the TEM image (see Fig. 4)

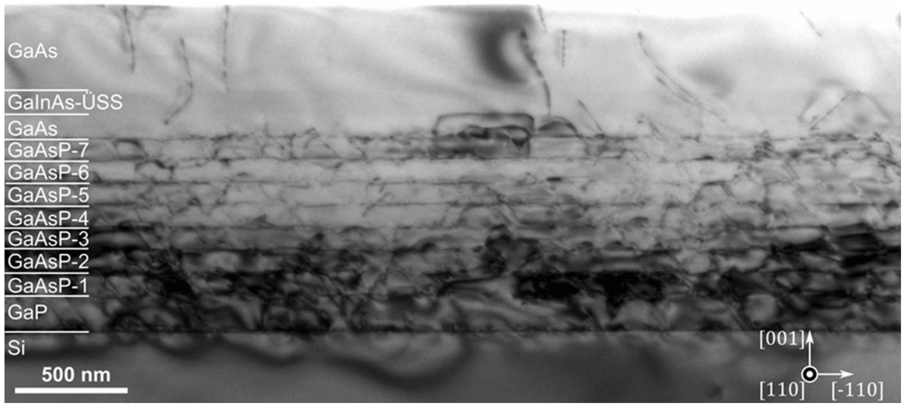


Fig. 4. TEM image of a $GaAs_yP_{1-y}$ metamorphic buffer layer on Si. The structure consists of a GaP nucleation layer on Si, seven $GaAs_yP_{1-y}$ layers, a GaAs target layer, and a GaInAs over shooting layer (ÜSS) to relax the in-plane lattice constant and finally 400 nm of GaAs.

suggest that the density is exceeding 10^8 cm^{-2} after the buffer growth. Atomic force microscopy images of the surface showed small pits with a density of 2 $\times 10^8$ cm^{-2} in the upper GaAs layer, which correlates well with the TEM results and suggests that the threading dislocations influence the local growth mode. Single-junction GaAs solar cells with p-on-n polarity were investigated on the same $GaAs_{1-y}P_y$ buffer layers on silicon and the devices showed open-circuit voltages of 795 mV (compared with 1038 mV for a reference cell on GaAs). This loss in voltage is expected for a threading dislocation density of 2×10^8 cm^{-2}, following the model of Yamaguchi *et al.* [29]. The different analysis methods lead to the same conclusion that the threading dislocation density in the GaAs target layer on silicon is still high and of the order of 10^8 cm^{-2}. The growth conditions and composition of the buffer layers need to be further optimized in the future. An important parameter to reduce dislocations is for example the grading rate (i.e., lattice mismatch per micrometer of growth) [30].

GaInP/GaAs tandem solar cell structures (790-nm-thick $Ga_{0.5}In_{0.5}P$ and 1.9-μm GaAs absorber) were grown on the GaAsP/Si templates. The thickness of the $GaAs_yP_{1-y}$ layers in the metamorphic buffer was increased to 180 nm. Otherwise, all parameters were identical to the structure in Fig. 4. A reference tandem cell was grown on the GaAs substrate in the same epitaxy process together with the GaAsP/Si template. Fig. 5 shows results for the quantum efficiencies of both devices. While the GaInP top cell shows similar performance on GaAs and Si substrates, the GaAs bottom cell suffers significantly from the low diffusion length of minority carriers. There are two possible explanations for this result: either the additional growth of the GaAs cell and tunnel diodes on the GaAsP buffer layer leads to a reduction of the threading dislocation density, or the GaInP top cell material is less sensitive to dislocations. This can be expected as the thickness of the GaInP base layer (660 nm) is much lower compared with the GaAs base layer (1750 nm). Therefore, minority carriers need higher diffusion length in GaAs to reach the pn-junction and contribute to the photocurrent. Due to the low quantum efficiency of the GaAs bottom cell on Si, this subcell limits the overall current of the tandem cell under AM1.5g.

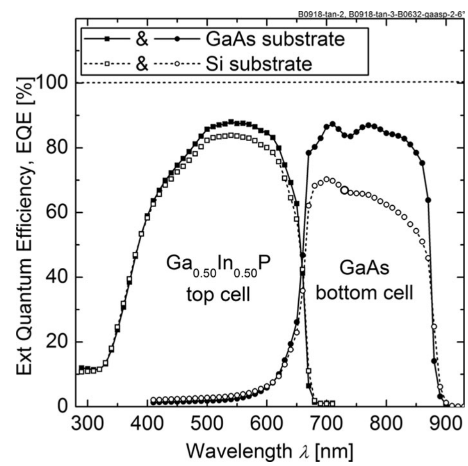


Fig. 5. EQE of a GaInP/GaAs tandem solar cell grown on Si compared with an identical reference structure on GaAs.

An efficiency of 16.4% (AM1.5g) was measured for the best directly grown GaInP/GaAs tandem solar cell on Si in comparison with 27.1% for the reference structure on GaAs (see Table I). It is obvious that the high dislocation density for the growth on silicon leads to losses in short-circuit current density J_{sc}, fillfactor FF, and open-circuit voltage V_{oc}. The V_{oc} of the tandem cell on Si drops by 510 mV compared with the reference structure. This is approximately twice the voltage drop measured for a GaAs single-junction cell on Si. This result is expected as both junctions in the dual-junction device contribute approximately the same voltage loss to the series-connected dual-junction cell. Higher open-circuit voltages of 2.2 V were reported by Lueck *et al.* [16] for GaInP/GaAs tandem cells on SiGe/Si buffer layers with a low dislocation density of 2×10^6 cm^{-2}. This shows that further optimization of the $GaAs_yP_{1-y}$ buffer layer is necessary to improve the threading dislocation density and the overall performance of our tandem solar cells on silicon. It should be mentioned that none of the devices on Si showed any indication of cracking due to differences in the thermal expansion coefficient of Si and GaAs. Direct MOVPE growth of III–V solar cells on Si, therefore, is also a viable process to realize high-efficiency devices.

IV. Conclusion

This paper discusses two approaches how III–V tandem solar cells can be realized on silicon as a substrate material. This is an important step toward reducing the cost of III–V solar cells and making the technology attractive for terrestrial applications. III–V materials in multijunction solar cells offer the opportunity to overcome the Shockley–Queisser limit of single-junction devices [31]. In this paper, we have investigated dual-junction solar cells with an active $Ga_{0.5}In_{0.5}P$ top cell and a GaAs middle cell. The solar cells were realized on inactive silicon as a mechanical support and electrical conductor. One approach was based on the epitaxy of an inverted GaInP/GaAs solar cell on GaAs followed by bonding to Si and GaAs substrate removal. For the first time, such tandem solar cells achieved 26.0% AM1.5g efficiency on Si. A second approach was to grow the III–V materials directly on Si, and an efficiency of 16.4% AM1.5g was obtained. The solar cell structures had different layer thicknesses, but it was evident that a high threading dislocation density was leading to significant losses for the GaInP/GaAs solar cells grown directly on Si. Further optimization of the graded $GaAs_yP_{1-y}$ buffer will be necessary to reduce such dislocations and improve the device performance.

The concept of the III–V solar cell on Si can be further extended to include an active Si junction as a third bottom subcell in the future. With this approach, one-sun efficiencies above 30% are realistic and offer one of the most promising roadmaps for the realization of high-efficiency photovoltaic modules.

Acknowledgment

The authors would like to thank E. Schäffer, E. Fehrenbacher, M. Scheer, K. Wagner, I. Semke, K. Mayer, and R. Koch for solar cell fabrication and characterization at Fraunhofer ISE.

References

[1] M. A. Green, K. Emery, Y. Hishikawa, and W. Warta, "Solar cell efficiency tables (ver. 35)," *Prog. Photovoltaics: Res. Appl.*, vol. 18, pp. 144–150, 2010.

[2] S. F. Fang, K. Adomi, S. Iyer, H. Morkoç, H. Zabel, C. Choi, and N. Otsuka, "Gallium arsenide and other compound semiconductors on silicon," *J. Appl. Phys.*, vol. 68, pp. R31–R58, 1990.

[3] K. Volz, A. Beyer, W. Witte, J. Ohlmann, I. Németh, B. Kunert, and W. Stolz, "GaP-nucleation on exact Si (001) substrates for III/V device integration," *J. Crystal Growth*, vol. 315, pp. 37–47, 2011.

[4] H. Döscher, B. Borkenhagen, G. Lilienkamp, W. Daum, and T. Hannappel, "III–V on silicon: Observation of gallium phosphide anti-phase disorder by low-energy electron microscopy," *Surface Sci.*, vol. 605, pp. L38–L41, 2011.

[5] A. Dadgar, P. Veit, F. Schulze, J. Blasing, A. Krtschil, H. Witte, A. Diez, T. Hempel, J. Christen, R. Clos, and A. Krost, "MOVPE growth of GaN on Si–substrates and strain," *Thin Solid Films*, vol. 515, pp. 4356–4361, 2007.

[6] B. Kunert, I. Németh, S. Reinhard, K. Volz, and W. Stolz, "Si (001) surface preparation for the antiphase domain free heteroepitaxial growth of GaP on Si substrate," *Thin Solid Films*, vol. 517, pp. 140–143, 2008.

[7] T. J. Grassman, J. A. Carlin, B. Galiana, L.-M. Yang, F. Yang, M. J. Mils, and S. A. Ringel, "Nucleation-related defect-free GaP/Si(100) heteroepitaxy via metal-organic chemical vapor deposition," *Appl. Phys. Lett.*, vol. 102, pp. 142102-1–142102-4, 2013.

[8] V. I. Vdovin, "Misfit dislocations in epitaxial heterostructures: Mechanisms of generation and multiplication," *Phys. Status Solidi A*, vol. 171, pp. 239–250, 1999.

[9] W. Guter, J. Schöne, S. P. Philipps, M. Steiner, G. Siefer, A. Wekkeli, E. Welser, E. Oliva, A. W. Bett, and F. Dimroth, "Current-matched triple-junction solar cell reaching 41.1% conversion efficiency under concentrated sunlight," *Appl. Phys. Lett.*, vol. 94, pp. 223504–223506, 2009.

[10] A. W. Bett, C. Baur, F. Dimroth, and J. Schöne, "Metamorphic GaInP–GaInAs layers for photovoltaic applications," in *Proc. Mater. Res. Soc. Symp.*, 2005, vol. 836, pp. 223–234.

[11] T. J. Grassman, M. R. Brenner, M. Gonzalez, A. M. Carlin, R. R. Unocic, R. R. Dehoff, M. J. Mills, and S. A. Ringel, "Characterization of metamorphic GaAsP/Si materials and devices for photovoltaic applications," *IEEE Trans. Electron Devices*, vol. 57, no. 12, pp. 3361–3369, Dec. 2010.

[12] M. W. Wanlass, S. P. Ahrenkiel, R. K. Ahrenkiel, D. S. Albin, J. J. Carapella, A. Duda, J. F. Geisz, S. Kurtz, T. Moriarty, R. J. Wehrer, and B. Wernsman, "Lattice-mismatched approaches for high-performance, III–V photovoltaic energy converters," in *Proc. 31st IEEE Photovolt. Spec. Conf.*, Orlando, FL, USA, 2005, pp. 530–535.

[13] M. Umeno, H. Shimizu, T. Egawa, T. Soga, and T. Jimbo, "First results of AlGaAs/Si monolithic two-terminal tandem solar cell grown by MOCVD," in *Proc. 22nd IEEE Photovolt. Spec. Conf.*, Las Vegas, NV, USA, 1991, pp. 361–364.

[14] M. J. Yang, T. Soga, T. Jimbo, and M. Umeno, "High efficiency monolithic GaAs/Si tandem solar cells grown by MOCVD," in *Proc. 1st World Conf. Photovoltaic Energy Convers.*, Waikoloa, HI, USA, 1994, pp. 1847–1850.

[15] J. A. Carlin, S. A. Ringel, E. A. Fitzgerald, and M. Bulsara, "High quality GaAs growth by MBE on Si using GeSi buffers and prospects for space photovoltaics," *Progress Photovoltaic: Res. Appl.*, vol. 8, pp. 323–332, 2000.

[16] M. R. Lueck, C. L. Andre, A. J. Pitera, M. L. Lee, E. A. Fitzgerald, and S. A. Ringel, "Dual junction GaInP/GaAs solar cells grown on metamorphic SiGe/Si substrates with high open circuit voltage," *IEEE Electron Device Lett.*, vol. 27, no. 3, pp. 142–144, Mar. 2006.

[17] J. A. Carlin, S. A. Ringel, E. A. Fitzgerald, M. Bulsara, and B. M. Keyes, "Impact of GaAs buffer thickness on electronic quality of GaAs grown on graded Ge/GeSi/Si substrates," *Appl. Phys. Lett.*, vol. 76, pp. 1884–1886, 2000.

[18] S. A. Ringel, C. L. Andre, E. A. Fitzgerald, A. J. Pitera, and D. M. Wilt, "Multijunction III–V photovoltaics on lattice-engineered Si substrates," in *Proc. 31st IEEE Photovoltaic Spec. Conf.*, Orlando, FL, USA, 2005, pp. 567–570.

[19] T. Roesener, H. Döscher, A. Beyer, S. Brückner, V. Klinger, A. Wekkeli, P. Kleinschmidt, C. Jurecka, J. Ohlmann, K. Volz, W. Stolz, T. Hannappel, A. W. Bett, and F. Dimroth, "MOVPE growth of III–V solar cells on silicon in 300 mm closed coupled showerhead reactor," in *Proc. 25th Eur. Photovoltaic Sol. Energy Conf. Exhib.*, Valencia, Spain, 2010, pp. 964–968.

[20] S. A. Ringel, J. A. Carlin, T. J. Grassman, B. Galiana, A. M. Carlin, C. Ratcliff, D. Chmielewski, L. Yang, M. J. Mills, A. Mansouri, S. P. Bremner, A. Ho-Baillie, X. Hao, H. Mehrvarz, G. Conibeer, and M. A. Green, "Ideal GaP/Si heterostructures grown by MOCVD: III–V/active-Si subcells, multijunctions, and MBE-to-MOCVD III–V/Si interface science," in *Proc. 39th IEEE Photovoltaic Spec. Conf.*, Tampa, FL, USA, 2013.

[21] J. Schöne, F. Dimroth, A. W. Bett, A. Tauzin, C. Jaussaud, and J. C. Roussin, "III-V solar cell growth on wafer-bonded GaAs/Si-substrates," in *Proc. 4th World Conf. Photovoltaic Energy Convers.*, Waikoloa, HI, USA, 2006, pp. 776–779.

[22] J. M. Zahler, C.-G. Ahn, S. Zaghi, H. A. Atwater, C. Chu, and P. Iles, "Ge layer transfer to Si for photovoltaic applications," *Thin Solid Films*, vol. 403–404, pp. 558–562, 2002.

[23] M. J. Archer, D. C. Law, S. Mesropian, M. Haddad, C. M. Fetzer, A. C. Ackerman, C. Ladous, R. King, and H. A. Atwater, "GaInP/GaAs dual junction solar cells on Ge/Si epitaxial templates," *Appl. Phys. Lett.*, vol. 95, pp. 103503-1–103503-3, 2008.

[24] K. Derendorf, S. Essig, E. Oliva, V. Klinger, T. Roesener, S. P. Philipps, J. Benick, M. Hermle, M. Schachtner, G. Siefer, W. Jäger, and F. Dimroth, "Fabrication of GaInP/GaAs//Si solar cells by surface activated direct wafer bonding," *IEEE J. Photovoltaics*, vol. 3, no. 4, pp. 1–6, Oct. 2013.

[25] T. R. Chung, L. Yang, N. Hosoda, and T. Suga, "Room temperature GaAs-Si and InP-Si wafer direct bonding by the surface activated bonding method," *Nuclear Instrum Methods Phys. Res. B*, vol. 121, pp. 203–206, 1997.

[26] M. Meusel, R. Adelhelm, F. Dimroth, A. W. Bett, and W. Warta, "Spectral mismatch correction and spectrometric characterization of monolithic III-V multi-junction solar cells," *Prog. Photovoltaics: Res. Appl.*, vol. 10, pp. 243–255, 2002.

[27] M. Meusel, C. Baur, G. Létay, A. W. Bett, W. Warta, and E. Fernandez, "Spectral response measurements of monolithic GaInP/Ga(In)As/Ge triple-junction solar cells: Measurement artifacts and their explanation," *Prog. Photovoltaics: Res. Appl.*, vol. 11, pp. 499–514, 2003.
[28] H. Döscher and T. Hannappel, "In situ reflection anisotropy spectroscopy analysis of heteroepitaxial GaP films grown on Si(100)," *J. Appl. Phys.*, vol. 107, pp. 123523-1–123523-12, 2010.
[29] M. Yamaguchi and C. Amano, "Efficiency calculations of thin-film GaAs solar cells on Si substrates," *J. Appl. Phys.*, vol. 58, pp. 3601–3606, 1985.
[30] A. Y. Kim, W. S. McCullough, and E. Fitzgerald, "Evolution of microstructure and dislocation dynamics in $\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{P}$ graded buffers grown on GaP by metalorganic vapor phase epitaxy: Engineering device-quality substrate materials," *J. Vac. Sci. Technol. B (Microelectron. Nanometer Struct.)*, vol. 17, pp. 1485–1501, 1999.
[31] W. Shockley and H. J. Queisser, "Detailed balance limit of efficiency of p-n junction solar cells," *J. Appl. Phys.*, vol. 32, pp. 510–519, 1961.

Authors' photographs and biographies not available at the time of publication.