Investigation of room-temperature wafer bonded GaInP/GaAs/InGaAsP triple-junction solar cells

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Abstract

We report on the fabrication of III-V compound semiconductor multi-junction solar cells using the room-temperature wafer bonding technique. GaInP/GaAs dual-junction solar cells on GaAs substrate and InGaAsP single junction solar cell on InP substrate were separately grown by all-solid state molecular beam epitaxy (MBE). The two cells were then bonded to a triple-junction solar cell at room-temperature. A conversion efficiency of 30.3% of GaInP/GaAs/InGaAsP wafer-bonded solar cell was obtained at 1-sun condition under the AM1.5G solar simulator. The result suggests that the room-temperature wafer bonding technique and MBE technique have a great potential to improve the performance of multi-junction solar cell.

Keywords: Multijunction solar cell, GaInP/GaAs/InGaAsP, Room-temperature wafer bonding, Molecular beam epitaxy

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1. Introduction

Multi-junction solar cells (MJSCs) have been one of the most promising options to efficiently convert the sunlight into electricity.^[1~3] Especially, III–V MJSCs are the most efficient photovoltaic devices because of superior properties in terms of material quality, stability, radiation hardness, miscibility, and tunability of bandgap and lattice constants. At present, the monolithic epitaxial growth technique is the main method to fabricate multi-junction solar cell. However, this method limits the choice of materials and cell combinations for four or more junctions, because it is very difficult to simultaneously satisfy the requirements of lattice-matching and current-matching between sub-cells.^[4~7] Therefore, reported efficiencies have been much lower than theoretically predicted efficiencies, particularly in case of four- or more-junction solar cells.^[8,9] Besides the direct epitaxial growth, multi-junction solar cells can also be fabricated by mechanical stacking,^[10~13] but there is a great disadvantage for mechanically stacked solar cells that they require a metallic grid or intermediate layer at the interface which causes optical losses.

Direct wafer bonding technique applied to two different substrates can overcome these issues. A wafer-bonding interface with a low resistance is an essential physical property of the semiconductor bond.^[14~16] However, in conventional wafer-bonding techniques, such as fast-atom-beam-activated wafer bonding^[17,18] and fused bonding^[14,16], high-temperature or long annealing was generally required to achieve high mechanical strength and low electrical resistances. High temperature annealing would not only bring about wafer bending and void formation at a bonding interface owing to the difference in thermal expansion coefficients, but also cause the diffusion of dopants from heavily doped tunnel junctions between sub-cells, leading to the degradation of the tunnel junctions.^[19~21] To solve these problems, room-temperature wafer bonding technique without high-temperature annealing has been applied to fabricating wafer-bonded MJSCs. An interface resistance of $2.5 \times 10^{-5} \Omega \cdot \text{cm}^2$ was obtained for a p^+ -GaAs/n-InP bond by using this method.^[22] Most researchers used n-n bond which had a relatively high bonding resistance. This high resistivity was due to the high defects density at the bond interface. They have reduced the defects density by high temperature annealing, leading to the lower resistance. On the other hand, we found the special bonding technique using p^+ -n bond and Ar-ion plasma activation which was not requested in the case of the high-temperature annealing. Because this method enabled the low resistance by enhancing the tunnel current flow

through the defects levels, which was demonstrated in detail Ref [22].

According to detailed balance principle^[23], the best bandgap combination and its corresponding efficiency limits for the multi-junction cells was estimated. While cell designs with multi-junctions present tantalizing opportunities for higher efficiencies, all such designs require near 1 eV bandgap materials.^[16] Taking four-junction cells for example, the ideal efficiency of 55% can be achieved with an optimized bandgap combination of 1.9/1.4/1.0/0.7 eV.^[24] Furthermore, compared with ternary compound semiconductor material such as InGaAs, the InGaAsP quaternary alloy has the wide range of bandgap available (0.75 eV ~ 1.35 eV)^[25] and the independent regulation of bandgap and lattice constant. Therefore, 1.0 eV InGaAsP solar cell, lattice-matched to InP substrate, is an ideal choice as bottom sub-cell in triple-junction solar cell.^[26] However, there are only a few previous successful achievements of InGaAsP-based solar cell grown by metal-organic chemical vapor deposition (MOCVD)^[27, 28]. Molecular beam epitaxy (MBE) has the potential to grow high quality InGaAsP materials, because it proceeds under an ultra-high vacuum condition and uses ultra-high purity metal sources.^[29, 30]

In this work, a room-temperature wafer-bonded triple-junction solar cell was grown by all-solid state MBE. We investigated the surface and interfacial properties of triple-junction solar cells by using scanning transmission electron microscopy (STEM) and optical microscope. A conversion efficiency of 30.3% was obtained under the AM1.5G solar simulator.

2. Experimental details

The typical structure of the triple-junction solar cell is shown in Fig. 1. The material growth was performed by a Veeco GEN20A dual-chamber all solid-state MBE equipped with a valved phosphorus cracker cell and a valved arsenic cracker cell. Silicon and beryllium were used as the n- and p-type doping sources, respectively. The growth rate was 1 $\mu\text{m/h}$. During the material growth, the RHEED of the surface reconstruction was in real-time monitored. The beam equivalent pressure ratio of each element was calibrated by a combination of beam flux gauge. The detailed description of the material growth and properties has been described in our previous work^[31, 32]. The GaInP/GaAs top tandem cell was grown inverted on GaAs substrate and electrically interconnected by a GaAs tunnel junction. The InGaAsP solar cell was grown upright on InP substrate. Heavily doped p-GaAs layer and n-InP layer with the doping density of $10^{18} \sim 10^{19} \text{ cm}^{-3}$ were applied at the bonding interface to achieve low interface resistance.

The GaInP/GaAs/InGaAsP triple-junction solar cell was fabricated by bonding the GaAs-based top cell and InP-based bottom cell using the room-temperature wafer bonding technique. The bonding process was carried out in a room-temperature wafer-bonding machine (MWB-06-R, Mitsubishi Heavy Industries) equipped with an Ar ion gun in a high-vacuum chamber ($<10^{-5}$ Pa). The bonding layer was prepared for the direct wafer bonding by chemical mechanical polishing (CMP). The CMP process was performed by polishing machine (PHOENIX BETA, Buehler) with rotating speed of polishing pad of 30 ~ 40 RPM and polishing pressures of 100 ~ 120 g/cm². We chose colloid SiO₂ suspension as polishing solution. Thereby, a low surface roughness of 0.374 nm was obtained to ensure close contact between the bonding surfaces. After CMP, the two wafers were exposed to low energy Ar ions to activate their surfaces and generate dangling bonds. The Ar ions were accelerated with a voltage of only 100V. The argon atoms and ions reach the surface under an angle of approximately 45°, respectively. Then they were brought into close contact for the optimized time under a force of 5000 N in a high-vacuum chamber. After successful wafer bonding, the GaAs substrate was removed by wet chemical etching in 1: 3: 3 NH₄OH: H₂O₂: H₂O solutions for 2 hours. Alternatively, the growth substrate could be removed by a lift-off process^[33], which could reuse the GaAs wafer and thereby reduce the manufacturing cost of the triple-junction devices. Then we made a triple-junction solar cell following conventional III-V solar cell art. AuGe/Ni/Au ohmic contact metals were formed on a GaAs contact layer and an anti-reflection coating film deposited onto the window layer of the GaInP top cell by RF sputtering. The size of wafer-bonded solar cells was 5.0×5.0 mm². The photovoltaic current-voltage curves were measured under the AM1.5G solar simulator.

3. Results and discussion

The typical structure of the GaInP/GaAs/InGaAsP triple-junction solar cell is shown in Fig.1. The structure of each sub-cell consisted of a p-type base layer, an n-type emitter layer, and hetero-junctions acting as the back-surface field (BSF) layer and window layer to reduce surface recombination. For the Ga_{0.52}InP cell, a 750 nm base layer (3.5×10^{16} cm⁻³) and an 80 nm emitter layer (1×10^{18} cm⁻³) were included. A 15 nm Si-doped AlInP (4×10^{17} cm⁻³) and a 30 nm Be-doped AlGaInP layer (1×10^{19} cm⁻³) were used as the window layer and the BSF layer, respectively. The GaAs cell consisted of a 1000 nm base layer (5×10^{16} cm⁻³) and a 100 nm emitter layer ($1 \times$

10^{18} cm^{-3}). The window and BSF layers were 30 nm GaInP ($3 \times 10^{18} \text{ cm}^{-3}$) and 500 nm GaInP ($2 \times 10^{18} \text{ cm}^{-3}$), respectively. The GaInP top cell was coupled with the GaAs middle cell by a heavily doped tunnel junction which was composed of 15 nm p^+ -GaAs ($3 \times 10^{19} \text{ cm}^{-3}$) and 15 nm n^+ -GaAs ($1 \times 10^{19} \text{ cm}^{-3}$). The InGaAsP cell had a 2500 nm base layer ($5 \times 10^{16} \text{ cm}^{-3}$) and a 200 nm emitter ($2 \times 10^{18} \text{ cm}^{-3}$). Si-doped InP ($5 \times 10^{18} \text{ cm}^{-3}$) and Be-doped InP ($3 \times 10^{18} \text{ cm}^{-3}$) were used as the window layer and BSF layer, respectively. In our previous research^[34], the InP barrier was more promising than InAlAs as the BSF layer, because surface recombination at InP/InGaAsP interface was relatively smaller than that of InAlAs/InGaAsP. The material of the base layer was selected $\text{In}_{0.78}\text{Ga}_{0.22}\text{As}_{0.48}\text{P}_{0.52}$ with a bandgap energy of 1.0 eV. Figure 2 shows the optical micrograph image of InGaAsP epitaxial layer. Very few flecks and no micro cracks were found in the surface.

Figure 3(a) shows the dependence of photoluminescence (PL) spectra on the temperature for InGaAsP material. With the temperature increasing, the PL peak energy demonstrates a clear red-shift toward the lower energy direction and the spectral line shape becomes broader. The shift of peak energy with increasing temperature follows the band gap shrinking pattern predicted by the well-known Varshni's empirical formula^[35]:

$$E_g(T) = E_g(0) - \frac{\alpha T^2}{T + \beta}$$

Where $E_g(0)$ is the energy gap of material at 0 K, T is the temperature, and α and β are Varshni's coefficients. β can be approximated as by the Debye temperature of the material.^[36] $E_g(0) = 1.105 \text{ eV}$, $\alpha = 3.3 \times 10^{-4} \text{ eV/K}$ and $\beta = 248 \text{ K}$ can be obtained by fitting for Temp-Energy plot shown in the inset of Fig. 3(a). These fitting parameters are in good agreement with previous results.^[36~38] At 300 K, the PL peak energy is 1.05 eV. In addition, Time-resolved PL measurements were made to measure the carrier's PL lifetime, which was a quite important performance index for the quality of semiconductor materials and devices. PL decay curves for InGaAsP material were measured at different temperature from 10K to 300 K, as shown in Fig. 3(b). The PL integral intensities were consistent with mono-exponential decay with time constant τ for all of the temperature between 10 K and room temperature:

$I(t) = I_0 \exp(-t/\tau)$. The temperature dependence of the PL decay time τ was calculated, as shown in the inset of Fig. 3(b). The decay times remain at a high level about ~ 10 ns, which indicates that radiative recombination plays a dominant role in the recombination process.

In order to lower the barrier height of the bonding interface, heavily doped p^+ -GaAs/n-InP rather than n-GaAs/n-InP with the doping density of $10^{18} \sim 10^{19} \text{ cm}^{-3}$ were used as the contact layers. In our previous work [22], we obtained the lowest reported interface resistance of $2.5 \times 10^{-5} \Omega \cdot \text{cm}^2$ for the p^+ -GaAs/n-InP bond and discussed that the n-GaAs/n-InP bond has an interface potential barrier, and a high interface resistance.

A GaInP/GaAs/InGaAsP triple-junction cells has been fabricated by wafer-bonding technique. The scanning transmission electron microscope (STEM) image of the triple-junction solar cell was shown in Fig. 4. Clear interface between each epitaxial layer can be observed, which indicates a perfect material growth using MBE. Threading dislocations and planar defects which typically arise in the lattice-mismatched epitaxial growth were not observed in each sub-cell. Figure 4(b) and Figure 4(c) illustrate that the thicknesses of both the contact and the tunnel junction area have a good agreement with the design. In the wafer-bonding interface, no voids were found owing to a high mechanical stability in wafer-bonding process. The thickness of the amorphous interface layer was about 7 nm, as shown in Fig. 4(d).

The external quantum efficiency curves (EQE) of triple-junction cells are shown in Fig. 5. The bottom tandem sub-cell is photovoltaically active and an overlap between the GaAs sub-cell and InGaAsP sub-cell between 700 and 900 nm indicates a highly transparent bonded interface. Low optical loss could be achieved in the bonded interface, because the two wafers were taken together and directly bonded. Figure 6 shows the I-V characteristics of the room-temperature wafer-bonded GaInP/GaAs/InGaAsP triple-junction solar cells at one-sun condition under the AM1.5G solar simulator and Table 1 shows the corresponding electrical properties. The wafer-bonded triple-junction solar cell has a photovoltaic convention efficiency of 30.3% with the open circuit voltage (V_{oc}) of 2.753 V, a short-circuit current density (J_{sc}) of 12.8 mA/cm^2 and a fill factor (FF) of 86.1%. The top two sub-cells have been thinned substantially to achieve current matching. According to EQE curves in Fig.5, each J_{sc} value of GaInP, GaAs and InGaAsP cell was estimated to be 13.7, 10.9 and 10.7 mA/cm^2 . Therefore, InGaAsP cell with the lowest J_{sc} dominated the J_{sc} of the

triple-junction cell. Considering this large difference, we reexamined the measuring condition and repeated the measurement several times. It was found the discrepancy lies in the inaccuracy of the solar simulator at the side of the long wavelength. However, the standard AM 1.5G spectrum was used to calculate current density. So there is a discrepancy between the two data. Maybe the efficiency was overestimated. In addition, the measured EQE curve also was a little bit lower than the averaged value. For comparison, the I–V characteristics of GaInP/GaAs dual-junction with relative thicker base layers and InGaAsP single junction SC with the same structures are also presented. The GaAs/GaInP dual-junction SC has a photovoltaic conversion efficiency of 27% with the V_{oc} of 2.310 V, a J_{sc} of 13.6 mA/cm² and FF of 86%. This dual-junction SC has a higher J_{sc} (13.6 mA/cm²) than that of the triple-junction SC due to the thicker base layers. The InGaAsP bottom cell has an efficiency of 16.2 % with a V_{oc} of 0.517 V, a J_{sc} of 41.5 mA/cm², and an FF of 75.3%. The sum of the un-bonded GaInP/GaAs and InGaAsP sub-cells is 2.83 V, which means that voltage drops at the wafer-bonding interface are as low as 0.074 V. That suggests that the electrical loss at the bonding interface is very low. The J_{sc} of the triple-junction solar cell is dominated by the InGaAsP sub-cell with the lowest J_{sc} , which is reasonable in terms of a series circuit with each sub-cell. The theoretical efficiency of the triple-junction cell with bandgap combination of 1.9/1.4/1.0 eV can reach up to 38% at one sun. ^[39] There is still a large room to improve the efficiency of the wafer-bonded GaInP/GaAs/InGaAsP solar cell by optimizing the base layer thickness of each sub-cell as well as the device performance of each single junction. Further studies concerning band-gap energies, doping density and growth parameters of InGaAsP would be essential to improve the performance of wafer-bonded multi-junction solar cell.

4. Conclusion

A GaInP/GaAs/InGaAsP triple-junction solar cell using the room-temperature wafer bonding technique was investigated. GaAs-based dual-junction solar cell and InP-based single junction solar cell were separately grown by all-solid state MBE, and then the two wafers were bonded to a triple-junction solar cell at room-temperature. The fabricated wafer-bonded triple-junction solar cell reached a conversion efficiency of 30.3% with an open circuit voltage (V_{oc}) of 2.753 V, a short-circuit current density (J_{sc}) of 12.8 mA/cm² and a fill factor (FF) of 86.1% at 1-sun condition under the AM1.5G solar simulator. These results indicate that the room-temperature wafer bonding technique and MBE growth are very promising to improve the performance of

multi-junction solar cell.

5. Acknowledgements

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6. References

- [1].D.J. Friedman, S.R. Kurtz, K.A. Bertness, A.E. Kibbler, C. Kramer, J.M. Olson, D.L King, B.R. Hansen, J.K. Snyder, Prog Photovolt. 3 (1995) 47.
- [2].M. Yamaguchi, Sol Energy Mater Sol Cells 75 (2003) 261.
- [3].F Dimroth, R Beckert, M Meusel, U Schubert, A.W. Bett, Prog Photovoltaics 9 (2001) 165.
- [4].J. F. Geisz, S. Kurtz, M. W. Wanlass, J. S. Ward, A. Duda, D. J. Friedman, J. M. Olson, W. E. McMahon, T. E. Moriarty, and J. T. Kiehl, Appl. Phys. Lett. 91 (2007) 023502.
- [5].M. Yamaguchi, K. Nishimura, T. Sasaki, H. Suzuki, K. Arafune, N. Kojima, Y. Ohsita, Y. Okada, A. Yamamoto, T. Takamoto, and K. Araki, Sol. Energy 82 (2008) 173.
- [6].P. T. Chiu, S. J. Wojtczuk, X. Zhang, C. Harris, D. Pulver and M. Timmons: Proc. 37th IEEE Photovoltaic Specialists Conf. (2011) 771.
- [7].K. Sasaki, T. Agui, K. Nakaido, N. Takahashi, R. Onitsuka, and T. Takamoto, 9th International Conference on Concentrator Photovoltaic Systems. Miyazaki, Japan: AIP Conference Proceedings (2013) 22.
- [8].S. Kurtz, D. Myers, W. E. McMahon, J. Geisz, and M. Steiner, Prog. Photovoltaics 16 (2008) 537.
- [9].M.A. Green, K. Emery, Y. Hishikawa, W. Warta, and E.D. Dunlop, Prog. Photovoltaics 22 (2014) 701.
- [10].M. Gee and G. F. Virshup, in Proc. Conf. Rec. 20th IEEE Photovoltaic Spec. Conf., Las Vegas, NV, USA (1988) 754.
- [11].Y. Yazawa, K. Tamura, S. Watahiki, T. Kitatani, H. Ohtsuka, and T. Warabisako, in Proc. 26th IEEE Photovoltaic Spec. Conf., Anaheim, CA, USA (1997) 899.
- [12].J. Yang, Z. Peng, D. Cheong, and R.N. Kleiman, in Proc. 27th Eur. Photovoltaic Sol. Energy Conf. Exhib., Frankfurt, Germany (2012) 160.

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- [13].T. Sugaya, T. Mochizuki, K. Makita, R. Oshima, K. Matsubara¹, Y. Okano, and S. Niki, *Jpn. J. Appl. Phys.* 54 (2015) 08KE02.
 - [14].K. Tanabe, A. Fontcuberta i Morral, H. A. Atwater, D. J. Aiken, and M. W. Wanlass, *Appl. Phys. Lett.* 89 (2006) 102106.
 - [15].K. Tanabe, K. Watanabe, and Y. Arakawa, *Sci. Reports.* 2 (2012) 349.
 - [16].P. T. Chiu, D. C. Law, R. L. Woo, S. B. Singer, D. Bhusari, W. D. Hong, A. Zakaria, J. Boisvert, S. Mesropian, R. R. King, and N. H. Karam, *IEEE J. Photovoltaics* 4 (2014) 493.
 - [17].S. Essig and F. Dimroth, *ECS J. Solid State Sci. Technol.* 2 (2013) Q178.
 - [18].F. Dimroth, M. Grave, P. Beutel, U. Fiedeler, C. Karcher, T. N. Tibbits, and K. Schwarzburg, *Prog. Photovoltaics* 22 (2014) 277.
 - [19].C. Amano, H. Sugiura, A. Yamamoto, and M. Yamaguchi, *Appl. Phys. Lett.* 51 (1987) 1998.
 - [20].N. Kojima, M. Okamoto, S. J. Taylor, M. J. Yang, T. Takamoto, M. Yamaguchi, K. Takahashi, and T. Unno, *Sol. Energy Mater. Sol. Cells* 50 (1998) 237.
 - [21].T. Takamoto, M. Yamaguchi, E. Ikeda, T. Agui, H. Kurita, and M. Al-Jassim, *J. Appl. Phys.* 85 (1999) 1481.
 - [22].S. Uchida, T. Watanabe¹, H. Yoshida, T. Tange, M. Arimochi, M. Ikeda, P. Dai, W. He, L. Ji, S.L Lu, and H. Yang, *Appl. Phys. Express* 7 (2014) 112301.
 - [23].A. Marti, G.L. Araujo, *Sol. Energy Mat. Sol. C.* 43 (1996) 203.
 - [24].D.C. Law, R.R. King, H. Yoon, M.J. Archer, A. Boca, C.M. Fetzer, S. Mesropian, T. Isshiki, M. Haddad, K.M. Edmondson, D. Bhusari, J. Yen, R.A. Sherif, H.A. Atwater, N.H. Karam, *Solar Energy Mater. & Solar Cells* 94 (2010) 1314.
 - [25].P. R. Sharp, M. L. Timmons, R. Venkatasubramanian, R. Pickett, J. S.Hills, J. Hancock and J. Hutchby: *Proc. 23th IEEE Photovoltaic Specialists Conf.* New York, (1993) 633.
 - [26].B.C. Chung, F.G. Virshup, M. Ladle Ristow, M.W. Wanlass and M. Klausmeier, in *Proc. 22th IEEE Photovoltaic Specialists Conf.* New York (1991) 54.
 - [27].F. Dimroth, M. Grave, P. Beutel, U. Fiedeler, C. Karcher, T.N.D. Tibbits, E. Oliva, G. Siefer, M. Schachtner, A. Wekkeli, A.W. Bett, R. Krause, M. Piccin, N. Blanc, C. Drazek, E. Guiot, B. Ghyselen, T. Salvetat, A. Tauzin, T. Signamarcheix, A. Dobrich, T. Hannappel and K. Schwarzburg, *Prog. Photovoltaics: Res. Appl.* 22 (2014) 277.

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- [28].H.J. Schimper, Z. Kollonitsch, K. Moller, U. Seidel, U. Bloeck, K. Schwarzburg, F. Willing and T. Hannappel, *J. Cryst. Growth* 287 (2006) 642.
- [29].S.L. Lu, L. Ji, W. He, P. Dai, H. Yang, M. Arimochi, H. Yoshida, S. Uchida, and M. Ikeda, *Nanoscale Res. Lett.* 6 (2011) 576.
- [30].Ji L, S.L. Lu, Y.Y. Wu, P. Dai, L.F. Bian, M. Arimochi, T. Watanabe, N. Asaka, M. Uemura, A. Tackeuchi, S. Uchida and H. Yang, *Sol. Energy Mat. Sol. C.* 127 (2014) 1.
- [31].P. Dai, M. Tan, Y. Y. Wu, L. Ji, L. F. Bian, S. L. Lu, and H. Yang, *J. Cryst. Growth* 413 (2015) 71.
- [32].P. Dai, S.L. Lu, M. Arimochi, S. Uchida, T. Watanabe, X.D. Luo, and H. Yang, *Solid State Commun.* 200 (2014) 9.
- [33].J.J. Schermer, P. Mulder, G.J. Bauhuis, M.M. A. J. Voncken, J. van Deelen, E. Haverkamp, and P.K. Larsen, *Phys. Status Solidi (a)*, 202 (2005) 501.
- [34].L. Ji, M. Tan, K. Honda, R. Harasawa, Y. Yasue, Y.Y. Wu, P. Dai, A. Tackeuchi, L.F. Bian, S.L. Lu and H. Yang. *Sol. Energy Mat. Sol. C.* 137 (2015) 68.
- [35].Y.P. Varshni, *Physica* 34 (1967) 149.
- [36].C.F. Li, D.Y. Lin, Y.S. Huang, Y.F. Chen, K.K. Tiong, *J. Appl. Phys.* 81 (1997) 400
- [37].T. P. Pearsall, L. Eaves, and J. C. Portal, *J. Appl. Phys.* 54 (1983) 1037.
- [38].K. Satzke, G. Weiser, R. Hoger, W. Thulke, *J. Appl. Phys.* 63 (1988) 5485.
- [39].M Stan, D Aiken, B Cho, A Cornfeld, J Diaz, V Ley, A Korostyshevsky, P Patel, P Sharps, T Varghese, *J. Cryst. Growth* 310 (2008) 5204.

n ⁺ -GaAs contact 200nm
n ⁺ -AlInP winow 15nm
n-GaInP emitter 80nm
p-GaInP base 750nm
p ⁺ -AlGaInP BSF
GaAs-TJ 30nm
n ⁺ -GaInP winow 30nm
n-GaAs emitter 100nm
p-GaAs base 1000nm
p ⁺ -GaInP BSF
p ⁺ -GaAs bonding
n-InP bonding
n-InGaAsP emitter 200nm
p-InGaAsP base 2500nm
p-InP BSF
p ⁺ -InGaAs 500nm buffer
p-InP substrate

Fig. 1. The schematic of the GaInP/GaAs/InGaAsP room-temperature wafer-bonded solar cell structure. Electrodes and etched contact layers are omitted.

Fig. 2. The optical micrograph image of $\text{In}_{0.78}\text{Ga}_{0.22}\text{As}_{0.48}\text{P}_{0.52}$ epitaxial layer.

Fig. 3. (a) Temperature-dependent PL spectra of the $\text{In}_{0.78}\text{Ga}_{0.22}\text{As}_{0.48}\text{P}_{0.52}$ material. PL peak energy versus temperature is shown in the inset. (b) A typical PL decay curve for $\text{In}_{0.78}\text{Ga}_{0.22}\text{As}_{0.48}\text{P}_{0.52}$ material at 10K. The temperature dependence of the PL decay time is shown in the inset.

Fig. 4. Typical cross-sectional STEM image of (a) the room-temperature wafer-bonded GaInP/GaAs/InGaAsP triple-junction solar cells, (b) the contact region of top sub-cell, (c) the tunnel junction of GaInP/GaAs dual-junction solar cells and (d) bonding interface.

Fig. 5. The quantum efficiency curves in the wavelength range of 3 sub-cells in the triple-junction wafer bonded solar cell.

Fig. 6. The I-V characteristics of the wafer-bonded GaInP/GaAs/InGaAsP triple-junction solar cell at one-sun condition under the AM1.5G solar simulator.

	Short-circuit current density (mA/cm ²)	Open-circuit voltage (V)	Fill factor (%)	Efficiency (%)
GaInP/GaAs Dual-junction	13.6	2.310	86%	27%
GaInAsP Single-junction	41.5	0.517	75.3%	16.2%
GaInP/GaAs/In GaAsP triple-junction	12.8	2.753	86.1%	30.3%

Table 1. Typical electrical properties of GaInP/GaAs/InGaAsP room-temperature wafer-bonded solar cells at 1 sun condition under AM1.5G solar simulator.

n ⁺ -GaAs contact 200nm
n ⁺ -AlInP winow 15nm
n-GaInP emitter 80nm
p-GaInP base 750nm
p ⁺ -AlGaInP BSF 30nm
GaAs-TJ 30nm
n ⁺ -GaInP winow 30nm
n-GaAs emitter 100nm
p-GaAs base 1000nm
p ⁺ -GaAs /p ⁺ -GaInP BSF
p ⁺ -GaAs bonding
n-InP bonding
n-InGaAsP emitter 200nm
p-InGaAsP base 2500nm
p-InP BSF
p ⁺ -InGaAs 500nm buffer
p-InP substrate