Direct Semiconductor Bonding Technology (SBT) for High Efficiency III-V Multi-Junction Solar Cells

D. Bhusari, D. Law, R. Woo, J. Boisvert, S. Mesropian, D. Larrabee, W. Hong and N. Karam
Boeing-Spectrolab, Inc., 12500 Gladstone Ave., Sylmar, CA 91342 U.S.A.

INTRODUCTION

In recent years, the concept of wafer bonding has attracted significant attention since this approach allows direct integration of lattice-mismatched hetero-structure devices grown on different substrates by eliminating the major limitations of lattice matching requirements. The wafer bonding approach is particularly attractive for III-V based device structures since elimination of the lattice matching constraints allows novel device designs with otherwise impossible band-gap combinations, such as in multi-junction photo-voltaic devices with subcell band gaps tailored for optimum absorption of the solar spectrum. Several other optoelectronic applications, such as photonic crystals, resonant cavity photo-detectors and surface emitting lasers, have also extensively investigated the wafer bonding approach [1]. For III-V based photo-voltaic devices in particular, which have continued to yield the highest conversion efficiency amongst all photo-voltaic technologies [2], the possibility of integration of devices grown lattice matched to GaAs and InP with optimum band-gap combinations provides a way to break the barrier posed by lattice matching constraints and achieve even higher conversion efficiencies. Recently, fabrication of a simple 2-junction solar cell has been reported by Tanabe *et al* [3] via direct bonding of GaAs and InP wafers.

In the direct semiconductor-semiconductor bonding approach, a high temperature anneal of the bonded interface, usually in the range of 500-600^{0}C, is employed to achieve high mechanical bonding strength that will allow substrate removal and subsequent processing steps for fabrication of devices. However, for several applications, such high temperature exposure is undesirable since it may cause dopant diffusion and introduce thermal stresses which may result in local debonding. To avoid the high temperature annealing, a few indirect bonding approaches have recently been explored, such as using SiO_2 or SiN intermediate bonding layers [4], which have yielded mechanically strong bonded interfaces at relatively lower temperatures of 200-400^{0}C. However, these indirect bonding methods are not suitable for applications wherein the bonded interface needs to be electrically conductive, such as in photo-voltaic devices, while the direct bonding approach involving high temperature annealing is also not suitable due to the degradation of the highly doped tunnel junctions. We have developed a new low temperature direct bonding method that allows high quality bonding to occur below 400^{0}C. The resulting bonded interface is mechanically strong, electrically conducting and optically transparent.

SBT technology has certain distinct advantages over the Inverted Metamorphic (IMM) technology from the perspective of next generation of III-V multi-junction solar cells - such as low defect density in the active layers as compared to IMM since all III-V layers can be grown lattice matched for SBT, and low thermal load on the grown layers since long growth times associated with growth of transparent graded buffer layers for IMM are eliminated for SBT. We have developed this technology for joining the component subcells grown on different substrates to fabricate integrated multi-junction solar cells, and have achieved 33.5% AM0 conversion efficiency.

EXPERIMENTAL DETAILS

All III-V epitaxial layers including the solar cell and bonding layer were grown in the Veeco Enterprise-400 MOVPE system, the details of which have been published elsewhere [5]. The surface quality of the epi layers was determined in terms of RMS surface roughness and defect density (particle counts) with AFM and Surface defect mapping, respectively. Typically the ‘as-grown’ layers showed an RMS roughness of 2-5nm (measured on 40μm x 40μm area) and particle counts of a few thousands to few tens of thousands. These surfaces were then polished down to the roughness of less than 0.5nm by using a proprietary chemical-mechanical polishing (CMP) process. The bonding was carried out using Karl Suss wafer bonding equipment. The bonding parameters such as temperature, pressure and bonding time were carefully optimized to achieve high mechanical strength and low electrical resistance across the bonded interface. Infrared transmission imaging was used to determine the uniformity and quality of the bonded interface. The bond strength was measured with the commonly used method of initiating a crack at the interface with a razor blade and measuring the length of the crack via infrared imaging [1]. Electrical resistance across the bonded interface was determined by measuring the I-V characteristics between the metal contacts deposited on both sides of the bonded interface, while optical transparency of the bonded interface was determined by recording the optical transmittance spectra and applying appropriate corrections for the absorption in the substrate.

RESULTS AND DISCUSSION

Wafer Bonding Process Development :

One of the most critical parameters that determine the quality of wafer bonding is the surface roughness. In the present work, an effective CMP process was developed to polish the surfaces to low roughness values of less than 0.5nm. This CMP process was also capable of significantly reducing the defect density (particle count) on the surface. As an example of the effectiveness of this process, Fig.1 presents the Surface defects and AFM scans of the wafer surface before and after CMP. Fig.1(A) shows that the ‘as-grown’ surface had a particle count of nearly 50000 over the entire 4” wafer and the rms roughness on the 40μm x

40μm area was 2.68nm. CMP of this wafer for 10 min reduced the particle count to below 1000 and surface roughness to below 0.5nm, rendering the surface suitable for direct bonding.

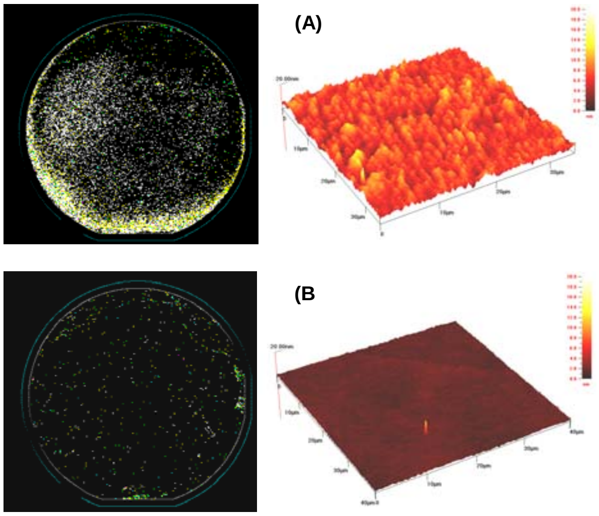


Figure 1. (A) Surfscan image and 40μm x 40μm AFM scan of the 'as-grown' epitaxial layers grown on 4" substrate. The particle count in the Surfscan image is 49482 and the surface roughness is 2.68nm. (B) Surfscan and AFM of the same sample after 10min CMP. The particle count is reduced to 993 and surface roughness to 0.36nm

Fig.2 presents the infrared transmission image of a 2" InP wafer bonded with 4" GaAs wafer. Excellent uniformity of the bonding over almost the entire 2" wafer surface is observed. The only unbonded area is the small spot near the InP wafer flat. This image also shows the bonded interface to be practically free of any defects such as bubbles that are very common in the direct bonding process [6]. The critical bonding parameters such as temperature, pressure, temperature ramp-rates and bond times etc. were optimized to achieve high quality bonding with high mechanical strength, low electrical resistivity and high optical transmittance across the bonded interface. Attempts to determine the mechanical strength of bonding by initiating a crack at the interface with a razor blade were unsuccessful since bond energy was greater than the InP fracture energy, resulting in fracturing of the InP wafer instead of opening a crack at the interface even when 650mm thick InP wafers were used. Comparatively, typical GaAs/InP bonding exhibited a lower magnitude of bond strength, since the interface could be opened with a crack, which yielded a value of 4.1 J/m^2 for the interface surface energy. Notably, this magnitude of surface energy for GaAs/InP bonding in itself is significantly higher than the values reported in the literature, typically being in the range of 1-2 J/m^2. The highest value of surface energy for direct bonding of III-V semiconductors has been reported to be 3.0 J/m^2, by Kopperschmidt *et. al.* [7] for GaAs/Sapphire wafer bonding obtained by annealing the interface at 500^{0}C. As mentioned above, the surface energy for directly bonded GaAs/InP interface using our proprietary bonding layer exceeded 4.1 J/m^2 in the present work.

To further evaluate the suitability of this process for fabrication of active solar cell devices, electrical resistance and optical transparency across the bonded interface were measured, which yielded the values of 0.3Ωcm^2 and 97%, respectively. The magnitudes of both of these parameters are significantly improved compared to the values reported in the literature. The 2-junction direct bonded solar cell device reported by Tanabe *et. Al* [3] exhibited the interface resistance of ~1.0 Ωcm^2. A comparable magnitude of interface resistance (~ 0.5 Ωcm^2) as obtained in this work is reported by Ouyang *et. al* [8] for p^{++} doped GaAs/GaAs direct substrate-substrate bonding annealed at 600^{0}C. Further, the bonded samples were subjected sequentially to complete removal of GaAs substrate by chemical etching, isolation of the devices by mesa etch, antireflective coating deposition, contact metal deposition, metal lift-off process, saw dice and soldering of interconnects. Large areas of bonded interface survived these processes and allowed fabrication of several electrically active photovoltaic devices of 4cm^2 area. The soldered interconnects were further subjected to pull test, wherein fracture occurred at the metal/interconnect interface at the load exceeding 400g leaving the bonded interface intact. Clearly, the mechanical strength of the bonding achieved is sufficiently high to allow fabrication of large area solar cell devices, with sufficiently low electrical resistance and optical absorption across the bonded interface to minimize electrical and optical losses.

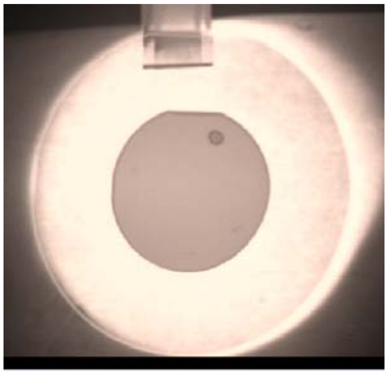


Figure 2. Infrared transmission image of 2" InP wafer bonded with 4" GaAs wafer. The wafers are bonded uniformly over almost the entire area except for the small spot near the wafer flat.

Solar Cell Fabrication :

Integrated multi-junction solar cells were fabricated by using this technology to join subcells grown on GaAs and InP substrates. For 4- and 5-junction cells, the subcell materials were chosen so as to be lattice matched to GaAs and InP substrates, and offer a band gap combination that would optimally utilize the solar spectrum. Thus, for 4-junction cells, two of the subcells were grown inverted on GaAs substrate and two of the subcells were grown upright on the InP substrate. For 5-junction cells, three of the subcells were grown inverted on GaAs substrate and two subcells were grown upright on InP. Appropriate current balance was achieved between the top GaAs-based and bottom InP-based subcells for 4- as well as 5-junction cells. The MOVPE growth conditions for each of these subcells were optimized to yield a high quality material with minimum defects and optimal electrical performance. Each of the component wafers were polished to a high quality of surface finish prior to subjecting the wafers to bonding. Post wafer bonding, the GaAs substrate was removed and the now-upright cells on InP substrate were processed with deposition of metal contacts and anti-reflective coating. Fig.3 and Fig.4 present the external quantum efficiency of the 4-junction and 5-junction integrated cell respectively. Notably, EQE of the InP-based subcell which lies below the bonded interface can be seen to be exceeding 90% in both 4- as well as 5-junction cells, attesting to the low optical loss at the bonded interface.

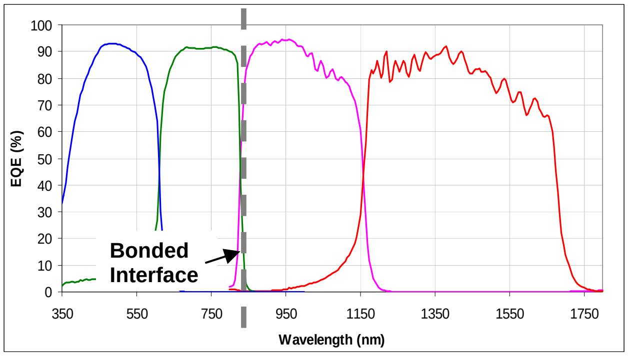


Figure 3. External quantum efficiency (EQE) of wafer-bonded 4-junction solar cell

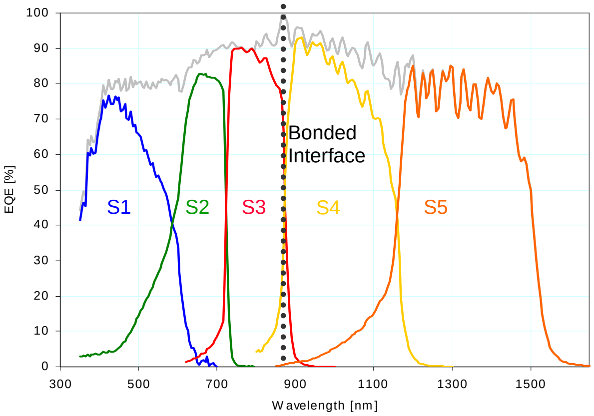
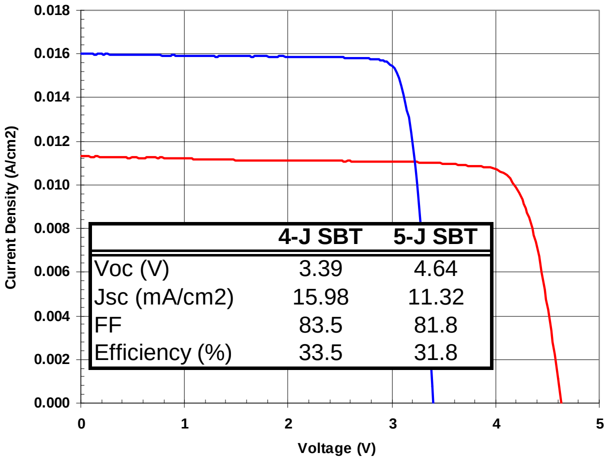


Figure 4. External quantum efficiency (EQE) of wafer-bonded 5-junction solar cell

Fig.5 presents the 1-sun AM0 light I-V curves for the 4- and 5-junction cells described above. The data was measured using the AX-25 solar simulator, which has a close matching spectrum with AM0, that was calibrated with Lear-Jet flown 3-junction IMM standards. Appropriate balloon-flown standards are not available for SBT cells. Although 3-junction IMM is not an appropriate standard for measuring 4- and 5-junction SBT cells since the band gaps are significantly different, the short circuit current density (Jsc) as obtained from these measurements closely matched with those obtained from the EQE measurements for 4-junction as well as 5-junction cells, respectively. Note that the fill factor for the 4-junction cell is >83%, attesting to the negligible electrical resistance across bonded interface. The efficiencies as obtained the light I-V measurements are 33.5% for 4-junction and 31.8% for the 5-junction cell. These are the highest efficiencies for direct wafer bonded multi-junction solar cells achieved to date.



	4-J SBT	5-J SBT
Voc (V)	3.39	4.64
Jsc (mA/cm2)	15.98	11.32
FF	83.5	81.8
Efficiency (%)	33.5	31.8

Figure 5. AM0 1-sun light I-V characteristics of wafer bonded 4-junction (blue curve) and 5-junction (red curve) solar cells.

CONCLUSION

In summary, we have demonstrated a high quality direct bond between GaAs and InP wafers. The wafers were polished to an excellent surface finish with RMS roughness of below 0.5nm, making them suitable for direct wafer bonding. A mechanically robust bonded interface with electrical resistance of as low as 0.3 Ωcm^2 and optical absorption loss of less than 3% across the bonded interface is achieved by optimizing the bonding process parameters. This technique was applied to fabricate 4- and 5-junction solar cells grown on GaAs and InP substrates and integrated through the bonding process. The multi-junction solar cells thus fabricated have exhibited greater than 83% fill factor and external quantum efficiencies exceeding 90% in the bottom subcells, attesting to the low electrical resistance and high optical transmittance of the bonded interface. The highest AM0 efficiency of 33.5% is achieved for 4-junction cells.

ACKNOWLEDGEMENTS

The authors would like to thank the entire R&D team at Spectrolab for their valuable contributions. Thanks also to the US Government, The Boeing Company and the Air Force Research Laboratory, Space Vehicles Directorate (AFRL/RVSV), Kirtland AFB, NM for financial support.

REFERENCES

[1] Q.-Y.Tong and U.Goesele, *Semiconductor Wafer Bonding – Science and Technology,* John Wiley & Sons Inc. (1999).

[2] R.King, D.Bhusari, A.Boca, D.Larrabee, X.Liu, W.Hong, C.Fetzer, D.Law and N.Karam, *Progress in Photovoltaics, Research and Applications* (2010).

[3] K.Tanabe, A. Fontcuberta i Morral, H.Atwater, D.J.Aiken and M.W.Wanlass, *Appl. Phys. Lett.,* **89**, 102106 (2006).

[4] S.Hayashi, M.S.Goorsky, R.Sandhu and M.Wojtowicz, *Proc. Int. Conf. on InP and Related Mateials,* Kagoshima, Japan (2004).

[5] C.Fetzer, W.Hong, X.Liu, J.Chang, M.Lau, A.Boca, D.Larrabee, R.King, P.Hebert, J.Ermer and A.Parekh, *Proc. 15th ICMOVPE,* Lake Tahoe, NV (2010).

[6] Q.Y.Tong, G.Kaido, L.Tong, M.Reiche, F.Shi, J.Steinkirchner, T.Y.Tan and U.Goesele, *J. Electrochem. Soc.,* **142**, L 201 (1995).

[7] P.Kopperschmidt, G.Kaestner, St.Senz, D.Hesse and U.Goesele, *Appl. Phys. (A),* **64**, 533 (1997).

[8] H.Ouyang, Y.S.Wu, J.H.Cheng, C.L.Lu, S.H.Chiou and W.Ouyang, *Appl. Phys. Lett.,* **88**, 172104 (2006).