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High-efficiency thin-film InGaP/InGaAs/Ge tandem solar cells enabled by controlled spalling technology

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In this letter, we demonstrate the effectiveness of the controlled spalling technology for producing high-efficiency (28.7%) thin-film InGaP/(In)GaAs/Ge tandem solar cells. The controlled spalling technique was employed to separate the as-grown solar cell structure from the host Ge wafer followed by its transfer to an arbitrary Si support substrate. The structural and electrical properties of the thin-film tandem cells were examined and compared against those on the original bulk Ge substrate. The comparison of the electrical data suggests the equivalency in cell parameters for both the thin-film (spalled) and bulk (non-spalled) cells, confirming that the controlled spalling technology does maintain the integrity of all layers in such an elaborate solar cell structure. © *2012 American Institute of Physics*. [doi:10.1063/1.3681397]

High conversion efficiency of direct bandgap III-V tandem solar cells makes them an attractive candidate for applications in space satellites and terrestrial concentrated photovoltaics (C-PV). However, the high cost of III-V solar cells has been the main impediment for their widespread terrestrial adoption. Hence, there has always been a great deal of interest in reducing material and processing costs, while attempting to further improve the conversion efficiency of the cells. In addition to the introduction of advanced multi-junction structures that are grown metamorphically on Ge or GaAs substrates,[1–4] the continuous increase in conversion efficiency of conventional InGaP/(In)GaAs/Ge tandem solar cells has come about by improving the device design and the quality of the epitaxial layers.[5] Despite the advancements in design and growth of high-efficiency tandem solar cells, the substrate cost still constitutes a large portion of the total cell cost. This, therefore, calls for the development of a commercially viable layer transfer technology platform that offers the possibility of substrate reuse while maintaining the integrity of the solar cell structure during the layer transfer process. Although various epitaxial lift-off (ELO) techniques are shown to provide decent laboratory-scale thin-film single-junction GaAs (Ref. 6) and inverted metamorphic tandem solar cells,[7] these techniques do not appear to offer a manufacturable path to low cost PV. The conventional ELO techniques notably utilize concentrated hydrofluoric (HF) acid for the lateral removal of an AlAs sacrificial layer embedded in between the actual device structure and the substrate.[8] It is crucial to note that the use of concentrated HF solutions for enhancing the lateral etch rate severely exacerbates the surface roughness of the host GaAs substrate,[9] rendering the GaAs surface not suitable for subsequent epitaxial growths. Furthermore, the timescale for separating the device structure from its host substrate inevitably increases for larger size wafers that will therefore curtail the process throughput.

We have recently introduced an elegant and versatile layer transfer technique, known as the "controlled spalling technology," which allows the kerf-free removal of thin crystalline Si, Ge, and III-V layers at room-temperature.[10] This technique permits the engineering of the fracture depth by adjusting the intrinsic mechanical properties of an external stressor (usually a metal) while inhibiting the spontaneous spalling of the layer. Subsequently, the desired layer can be removed from its host substrate by applying a flexible adhesive film to the metal stressor surface to mechanically assist the spalling of the metal/thin-film layer in a controllable manner. In addition, the controlled spalling technique can be used in combination with an engineered cleave layer to facilitate substrate reuse. The details of the controlled spalling technique have been described elsewhere.[10]

In this paper, a quintessential InGaP/(In)GaAs/Ge tandem solar cell was utilized due to its rather intricate structure to demonstrate effectiveness of controlled spalling for producing high-efficiency solar cells. The structural integrity and overall performance of the thin-film tandem solar cell was examined by transmission electron microscopy (TEM) and electrical characterizations.

A conventional InGaP/(In)GaAs/Ge solar cell structure was epitaxially grown on 180 μm thick 4″ diameter p-type (100) Ge substrates at 640 °C using Veeco's K475 commercial MOCVD reactor.[11] Next, the top $\sim$14 μm of the solar cell structure consisting of the entire stack of epitaxially grown III-V layers and $\sim$7 μm Ge was separated from its host Ge substrate by controlled spalling process, schematically illustrated in Fig. 1. The thin-film solar cell was then bonded to a heavily doped p-type Si support substrate using a conductive silver-filled epoxy at temperatures below 200 °C. Subsequently, the flexible handle layer was detached, followed by the chemical removal of the tensile stressor. Figure 2 illustrates the cross-sectional scanning electron microscope (SEM) image of the entire thin-film solar cell structure. Furthermore, the thin-film solar cell was structurally examined by TEM. It is important to note that the TEM images from the top, middle and bottom portions

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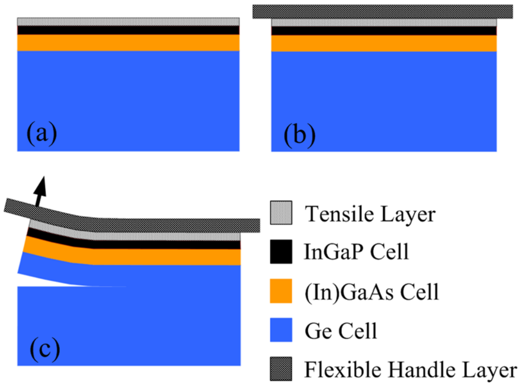

FIG. 1. (Color online) Schematic illustration of the controlled spalling process used to separate the top ∼14 μm of the tandem solar cell structure from its host Ge substrate.

of the cell (respectively labeled (a), (b), and (c) in Fig. 2) exhibit no visible defects while confirming the abruptness of the various interfaces.

Since TEM can only examine a small volume of a specimen, solar cells (1 cm × 1 cm) were fabricated on both thin-film and bulk samples using identical processing steps to further elucidate the impact of the controlled spalling process on the intrinsic material properties of the cells. A low-temperature fabrication scheme was devised to fabricate solar cells due to the temperature limitation imposed by the bonding process. The cell fabrication involves the formation of lithographically defined front contact grid with coverage of ∼2% through electron-beam evaporation of the Pd/Ge/Au (100 Å/400 Å/600 Å) multilayer followed by the lift-off process in acetone. Subsequently, a Ti/Al stack (250 Å/1 μm) was evaporated to form the back contact. The samples were then annealed at 180 °C to obtain low-resistivity contacts to the n^+ GaAs layer.[12] The specific contact resistance was measured to be $<6 \times 10^{-6}\,\Omega\,cm^2$ using the circular transmission line method (C-TLM).[13] The cell area was defined by

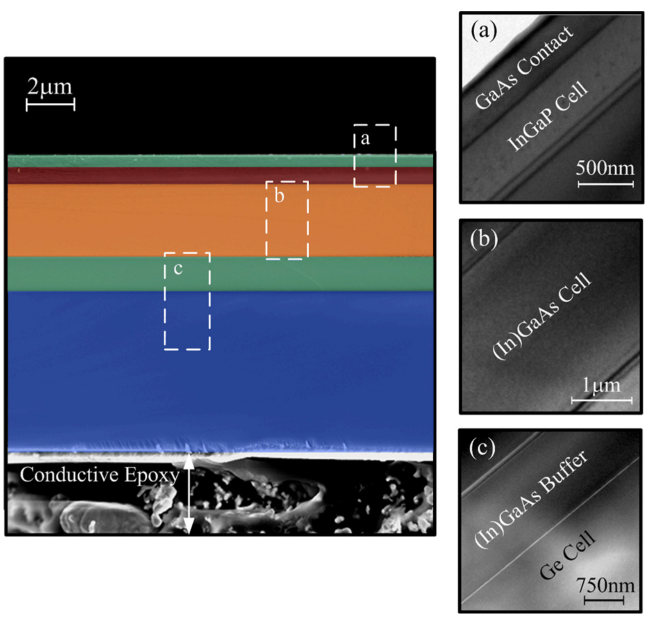

FIG. 2. (Color online) Cross-sectional SEM image of the entire thin-film solar cell structure (left). TEM images from the (a) top, (b) middle, and (c) bottom portions of the thin-film cell show no discernable defect.

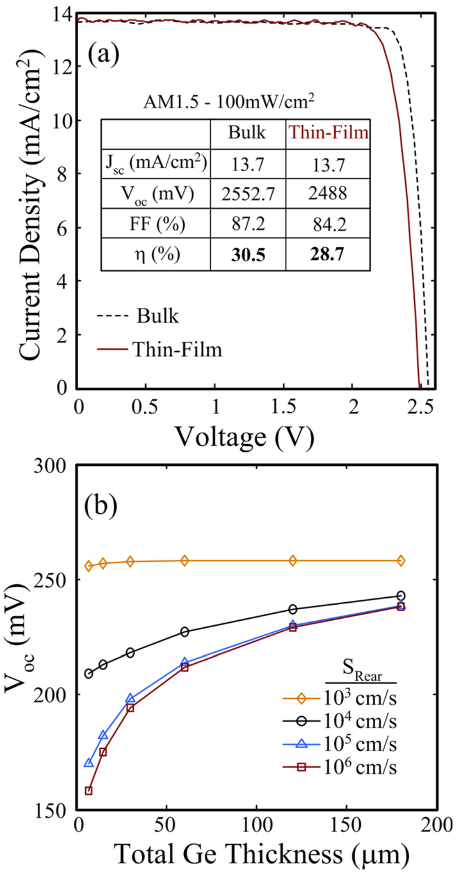

FIG. 3. (Color online) (a) Representative *J-V* characteristics of corresponding thin-film and bulk cells measured under one sun intensity. (b) 1D simulation results illustrating the V_{oc} of the bottom cell versus the total Ge thickness as function of S_{rear}, consistent with the observed V_{oc} difference between the thin-film and bulk cells.

chemical mesa etch followed by the light-induced copper plating of the front contact to a thickness of 7 μm. Finally, the GaAs contact layer between Cu-plated grid contacts was selectively removed followed by the deposition of ZnS/MgF_2 antireflection coating to complete the cell fabrication.

The *J-V* characteristics of the thin-film and bulk cells were measured under simulated AM1.5 solar spectrum at one sun intensity. Figure 3(a) shows the representative light *J-V* characteristics for two corresponding cells on the thin-film and bulk samples. As can be seen from the electrical data, the thin-film cell exhibits a respectable device performance with a conversion efficiency of 28.7%. However, somewhat lower conversion efficiency of the thin-film cell than that of the bulk cell is primarily attributed to the reduction in the open circuit voltage (V_{oc}) of the thin-film cell, while the short circuit current density (J_{sc}) for the thin-film and bulk cells is almost identical. We surmise that the high surface recombination velocity (S_{rear}) at the rear of the thin Ge bottom cell is responsible for the observed V_{oc} loss in the thin-film cells. It is important to consider that the effect of S_{rear} on the minority carrier effective diffusion length (L_{eff}) and the resulting dark current becomes more dominant by reducing the thickness of the base layer.[14] To further analyze the relation between the bottom Ge thickness and the V_{oc}, device simulations were carried out using PC1D program,[15] assuming bulk lifetime, surface recombination velocity at the front surface and junction depth of 100 μs, 100 cm/s, and 0.5 μm,

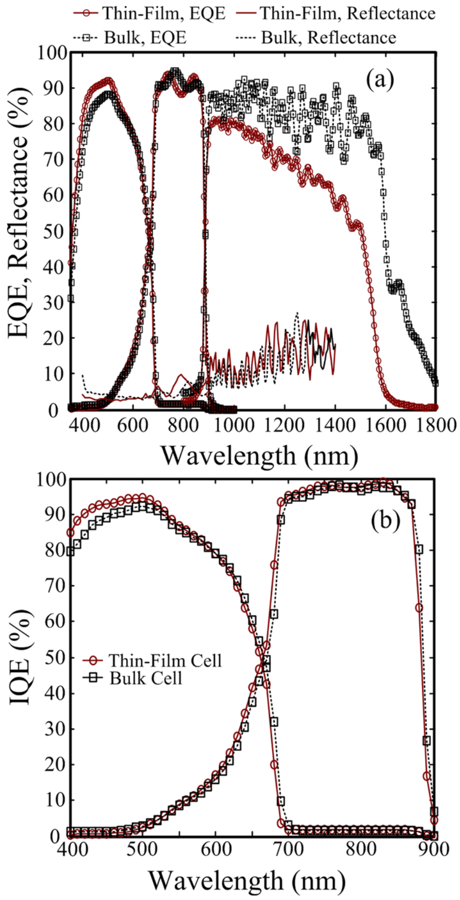

FIG. 4. (Color online) (a) Corresponding EQE and reflectance data for the measured cells in Fig. 3. (b) Comparison of the IQE data for the top InGaP and middle (In)GaAs sub-cells of the thin-film and bulk solar cells, confirming the structural integrity of the thin-film tandem solar cell.

respectively. The plot of simulated V_{oc} values for the Ge bottom cell versus the total thickness of the cell as a function of S_{rear} is shown in Fig. 3(b). The simulation results indicate a V_{oc} difference of 70–80 mV between the 180 and 7 μm thick Ge cells for S_{rear} values ranging from 10^5 to 10^6 cm/s, consistent with the observed ΔV_{oc} between the thin-film and bulk cells. Furthermore, it is evident from the simulation results that a moderately low S_{rear} of $\sim 10^3$ cm/s can effectively alleviate the V_{oc} loss problem. From the practical standpoint, considering the low resistivity of the Ge substrates coupled with the possibility of Ge surface passivation by amorphous Si,[16] the use of a localized back contact scheme can sufficiently reduce the recombination velocity at the rear surface of the Ge cell without compromising the total series resistance.

In order to obtain more detailed information about the characteristics of each individual sub-cell, the spectral response of the thin-film and bulk cells was measured. Figure 4(a) illustrates the corresponding external quantum efficiency (EQE) and the reflectance (R) of the measured cells in Fig. 3(a). The internal quantum efficiency (IQE) of the cells was then calculated using IQE = EQE/(1−R) to allow a more direct comparison of the collection efficiency, shown in Fig. 4(b). As can be seen, the IQE of top InGaP and middle (In)GaAs sub-cells from both thin-film and bulk cells are nearly identical further corroborating the structural integrity of the thin-film solar cell after layer transfer by controlled spalling. However, the relatively rapid decline in the measured EQE response of the thin Ge cell suggests a drastic reduction in L_{eff} due to the dominance of the minority carrier recombination at the rear surface.

In summary, we have fabricated high-efficiency (28.7%) thin triple-junction InGaP/(In)GaAs/Ge solar cells enabled by controlled spalling. The structural integrity of the thin-film solar cell was verified by TEM studies and electrical characterizations confirming the effectiveness of the spalling technology platform as a viable and simple method for the layer transfer of elaborate tandem III-V solar cell structures.

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[1]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**, 023502 (2007).
[2]F. Oimroth, W. Guter, J. SchOne, E. Welser, M. Steiner, E. Oliva, A. Wekkeli, G. Siefer, S. P. Philipps, and A. W. Bett, in *Proceedings of IEEE 34th Photovoltaic Specialist Conference*, Philadelphia, PA, 7–12 June 2009, p. 1038.
[3]T. Takamoto, T. Agui, A. Yoshida, K. Nakaido, H. Juso, K. Sasaki, K. Nakamora, H. Yamaguchi, T. Kodama, H. Washio, M. Imaizumi, and M. Takahashi, in *Proceedings of IEEE 35th Photovoltaic Specialist Conference*, Honolulu, HI, 20–25 June 2010, p. 412.
[4]H. Yoon, M. Haddad, S. Mesropian, J. Yen, K. Edmondson, D. C. Law, R. R. King, D. Bhusari, A. Boca, and N. H. Karam, in *Proceedings of IEEE 33rd Photovoltaic Specialist Conference*, San Diego, CA, 11–16 May 2008, p. 1.
[5]R. R. King, D. C. Law, K. Edmondson, C. M. Fetzer, R. A. Sherif, G. Kinsey, D. D. Krut, H. L. Cotal, and N. H. Karam, in *Proceedings of the Fourth World Conference on Photovoltaic Energy Conversion*, Waikoloa, HI, 7–12 May 2006, p. 760.
[6]G. J. Bauhuis, P. Mulder, E. J. Haverkamp, J. C. C. M. Huijben, J. J. Schermer, Sol. Energy Mater. Sol. Cells **93**, 1488 (2009).
[7]R. Tatavarti, A. Wibowo, G. Martin, F. Tuminello, C. Youtsey, G. Hillier and N. Pan, in *Proceedings of IEEE 35th Photovoltaic Specialist Conference*, Honolulu, HI, 20–25 June 2010, p. 2125.
[8]J. J. Schermer, P. Mulder, G. J. Bauhuis, M. M. A. J. Voncken, J. van Deelen, E. Haverkamp, and P. K. Larsen, Phys. Stat. Sol. A **202**, 501 (2005).
[9]S. Adachi and D. Kikuchi, J. Electro. Chem. Soc. **147**, 4618 (2000).
[10]S. W. Bedell, D. Shahrjerdi, B. Hekmatshoar, K. Fogel, P. Lauro, J. Ott, N. Sosa, and D. Sadana, "Kerf-less removal of Si, Ge and III-V layers by controlled spalling to enable low-cost PV technologies," IEEE J. Photovoltaics (to be published).
[11]C. Ebert, Z. Pulwin, D. Dyer, K. Schmieder, C. Haughn, M. Doty, A. Barnett, and F. Lu, in *Proceedings of 26th European Photovoltaic Solar Energy Conference*, Germany, 5–9 September 2011, p. 613.
[12]L. C. Wang, P. H. Hao, and B. J. Wu, Appl. Phys. Lett. **67**, 509 (1995).
[13]D. K. Schroder, *Semiconductor Material and Device Characterization*, 3rd ed. (John Wiley & Sons, Hoboken, NJ, 2006), p. 147.
[14]P. A. Basore, in *Proceedings of IEEE 23rd Photovoltaic Specialist Conference*, Louisville, KY, 10–14 May 1993, p. 147.
[15]P. A. Basore and D. A. Clugston, in *Proceedings of IEEE 26th Photovoltaic Specialist Conference*, Anaheim, CA, 29 Sep–3 Oct 1997, p. 207.
[16]N. E. Posthuma, G. Flamand, W. Geens, and J. Poortmans, Sol. Energy Mater. Sol. Cells **88**, 37 (2005).