MBE
Room Max Bell Auditorium - Session MBE-TuA
Solar Cells

Moderator: Paul Simmonds, Boise State University

1:30pm **MBE-TuA-1 Smart Stacked InGaP/GaAs/GaAs//Si Quadruple-Junction Solar Cells Grown using Molecular Beam Epitaxy*, Takeyoshi Sugaya,*** National Institute of Advanced Industrial Science and Technology (AIST), Japan

InGaP(1.9 eV)/GaAs(1.42 eV) on Si(1.1 eV) multijunction solar cells have been studied to realize low-cost and high-efficiency solar cells [1]. However, the current matching is not appropriate in this material system because the current generated in a Si subcell is smaller than that generated in InGaP and GaAs subcells. Therefore, a triple-junction top cell on a Si bottom cell configuration is suitable for obtaining the current matching among connected subcells. Although we demonstrated InGaAsP and AlGaAs second (1.7 eV) cells in the triple-junction top cells, InGaAsP cells were difficult to grow and AlGaAs cells exhibited poor performance when they were grown using molecular beam epitaxy (MBE) [2]. In this paper, we demonstrated an InGaP/GaAs/GaAs triple-junction solar cell grown using MBE to use as a top cell in a Si-based quadruple-junction solar cell.

The sample structure is shown in Fig. 1. A MBE-grown InGaP/GaAs/GaAs top cell was stacked to a Si bottom cell by smart stack technology which is a new semiconductor bonding technique using conductive nanoparticle alignments [3]. Figure 2 shows a *J-V* curve of a quadruple-junction solar cell. An efficiency of 18.5% with a high V_{oc} of 3.3V was obtained in InGaP/GaAs/GaAs//Si multijunction solar cells. External quantum efficiency (EQE) spectra of the solar cell are shown in Fig. 3. The highest and lowest current densities were generated by the first InGaP and second GaAs cells, respectively. The $J_{sc}$of 7.4 mA/cm^2 shown in Fig. 2 was in good agreement with the value estimated from the EQE measurements, which was limited by the second GaAs cell. This can be improved by reducing the absorption layer thickness of the first InGaP cell. In the presentation, we will discuss the role of substrate miscut on the properties of InGaP top cells.

[1] R. Cariou *et al*., IEEE J. Photovoltaics 7, 367 (2017).

[2] T. Sugaya *et al*., J. Vac. Sci. Technol. B 35, 02B103 (2017).

[3] H. Mizuno *et al*., Appl. Phys. Lett. 101, 191111(2012).

1:45pm **MBE-TuA-2 2.0 – 2.2 eV AlGaInP Solar Cells Grown by MBE*, Yukun Sun,*** Yale University*; S Fan,* University of Illinois Urbana-Champaign*; J Faucher,* Yale University*; B Li, M Lee,* University of Illinois Urbana-Champaign

$(Al_xGa_{1-x})_{0.51}In_{0.49}P$ (AlGaInP), with a tunable bandgap energy (E_g) of 1.9 – 2.2 eV, is an ideal top cell material for high-efficiency multi-junction (MJ) solar cells with 5 – 6 junctions. However, AlGaInP growth is challenging by both molecular beam epitaxy (MBE) and metalorganic vapor phase epitaxy (MOVPE) due to O-related defects. Recent work has shown that the performance of MOVPE-grown AlGaInP solar cells can be greatly improved by growth at very high temperatures of ~740 – 780 °C [1]. However, the MBE growth temperature of AlGaInP is typically restricted to < 500 °C, making post-growth annealing a crucial step to improve material quality [2]. In this work, we report on MBE-grown 2.0 – 2.2 eV AlGaInP solar cells, as well as effects of rapid thermal annealing (RTA). All aspects of cell performance were improved by RTA, though the enhancement diminished at the highest E_g and Al content. A 14.3% efficiency (η) was achieved in an anti-reflection-coated (ARC) 2.0 eV AlGaInP solar cell, closely matching record cells grown by MOVPE.

Cells with E_g = 2.02, 2.09, and 2.19 eV were grown by solid-source MBE at substrate temperatures of ~480 °C and V/III ratios of 10 – 15, while RTA was conducted at ~700 – 800 °C prior to device fabrication.

RTA led to improvements in internal quantum efficiency (IQE) for all cells, though the gain was most pronounced in the 2.02 eV AlGaInP. Short-circuit current density (J_{SC}) was accordingly boosted. V_{OC} also increased, together with a dark current reduction of 3 – 4 x. The boosts in J_{SC}, V_{OC}, and efficiency show that RTA substantially improves the minority carrier lifetime and diffusion length in AlGaInP. An efficiency of 14.3% was achieved in the 2.02 eV AlGaInP cell after RTA with ARC, closely matching the record set by MOVPE.

[1] Perl, E. E., et al. *J. Photovolt.* 6.3 (2016): 770-776.

[2] Faucher, J., et al. *Appl. Phys. Lett.* 109.17 (2016): 172105.

2:00pm **MBE-TuA-3 Optoelectronic Analysis of MBE Grown Symmetric and Asymmetric 1 eV Dilute Nitride Quantum Well Solar Cells*, Khim Kharel,*** *M Fitchette,* University of Houston*; K Shervin,* Alta Device*; W Wang,* First Solar Cell*; A Freundlich,* University of Houston

In order to minimize the effects of the degraded minority carrier transport properties of bulk dilute nitride GaAs, we have demonstrated that by incorporating MBE grown symmetric or asymmetric (i.e. resonantly coupled) dilute-nitride-GaAsN/GaAs multiple quantum wells (MQW's) into the intrinsic region of a p-i-n GaAs photovoltaic device (see figure 1) enables a significant sub-GaAs-bandgap photocurrent generation while maintaining a high open-circuit voltage (V_{oc}) [1]. In fact, for the case of a 1 eV resonantly coupled MQW cell, the V_{oc} (the figure of merit for the performance of a solar cell) showed a record-setting performance approaching the near ideal radiative limit (i.e. W_{oc}=Eg-V_{oc} ~ 0.4 V) [2].

To gain a better understanding of the photo-generated carrier escape and recombination mechanisms for these MQW devices, we examine their optical and electrical properties using the following characterization techniques: temperature dependent photoluminescence spectroscopy (PL), modulated photo-reflectance spectroscopy (PR), photo-current spectroscopy (i.e. the spectral response-SR or External Quantum Efficiency-EQE) under different applied bias and temperatures), and the temperature dependence current-voltage (IV) while the cell is under either dark or illuminated conditions.

The bias-dependent EQE analysis, performed at room temperature, shows 30X faster carrier escape times for the RTT devices than those of the conventional MQWs cell (0.2 ns and 6.38 ns, respectively). Similarly, the activation energies (which correspond to the effective barrier to electron extraction from the QW's) were determined from temperature dependence PL measurements are significantly lower (35meV and 75meV) than those of the conventional periodic MQWs cell (269meV); this contributes to the improvement in the carrier extraction for the RTT structure. The temperature dependent analysis enabled us to modulate and even freeze out the carrier thermalization phenomena. While the simultaneous measurement of the photogenerated current (SR) and radiative recombination (PL), as a function of the applied load (bias), enabled us to probe the correlation between the evolution of I-V characteristics and the physics at play. Finally, the electronic temperature of the photo-generated minority carriers' was extracted from the measured PL intensities which show a significantly high and unusual carrier temperature for a given lattice temperature; and this suggests the presence of a significant hot carrier effect.

1) D. Dang, G. Vijaya, A. Mehrotra, A. Freundlich, & D. J. Smith, JVST B. 34 (2016)

2) S. Shervin, W. Wang, K. Kharel, M. Fitchette & A. Freundlich, 33rd NAMBE, 2017, Galveston, TX

2:15pm **MBE-TuA-4 Reflections on NAMBE and MBE*, Charles Tu,*** University of California - San Diego **INVITED**

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