32.9% Efficient Tandem Solar Cell with Strain-Balanced GaInAs/GaAsP Quantum Wells

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32.9% efficient tandem solar cell with strain-balanced GaInAs/GaAsP quantum wells

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***Abstract*— We demonstrate single and dual junction solar cells with up to 80 strain-balanced GaInAs/GaAsP quantum wells (QWs), in order to extend the range of photon absorption. The net average stress in the quantum well layers is ≤12 MPa, despite coherent stresses in the individual layers that are 35-70 times greater. The GaAs-QW cell has a certified efficiency of (27.2 ± 0.2)% at one-sun; the GaInP/GaAs-QW tandem has a certified record one-sun efficiency of (32.9 ± 0.5)%. We will discuss the architecture of the devices, the physics behind the high performance, and pathways to further improvement.**

Keywords*— *III-V; photovoltaic; quantum well; strain balance

I. INTRODUCTION

Incorporating quantum wells (QWs) into a GaAs solar cell can extend the range of photon absorption toward the optimum bandgap of ~1.34 eV for the global spectrum. If the band edge can be extended out to the prominent water absorption band at 930 nm, with good collection efficiency, the resulting cell can in principle out-perform a baseline GaAs solar cell. Quantum wells can also lead to a boost in efficiency for a tandem cell, because of a similarly better match to the solar spectrum. In this work we demonstrate GaAs and GaInP/GaAs cells with carefully strain-balanced GaInAs/GaAsP quantum wells, and demonstrate the best strain-balanced QW solar cells as of this writing, with a record efficiency for a two-junction one-sun cell [1, 2]. As shown previously [3], the relationship between the composition and thickness in the QWs, as determined by the gas flows during growth, was adjusted to maintain a nearly zero-stress condition for up to 80 quantum wells, or >2 µm of coherently strained semiconductor material. The QWs extend the absorption edge without the need for compositionally graded buffer layers and metamorphic epitaxy, and we show the ability to shift the bandgap using QWs without sacrificing external radiative efficiency.

II. SOLAR CELL FABRICATION

The cells described in this work were grown by atmospheric pressure metalorganic vapor phase epitaxy (MOVPE) in a custom-built reactor. The cells were grown inverted on (100) GaAs substrates, miscut 2° toward <111>B, and reoriented during post-growth processing. Cells were processed into individual devices using standard cleanroom photolithography and wet chemical etching techniques. Briefly [4], a reflective gold back contact was electroplated to the AlGaAs back contact layer; the semiconductor was bonded with epoxy to a mechanical handle; the substrate was etched away; front grids were electroplated to the front contact; the cells were chemically isolated; a bilayer anti-reflection coating was deposited.

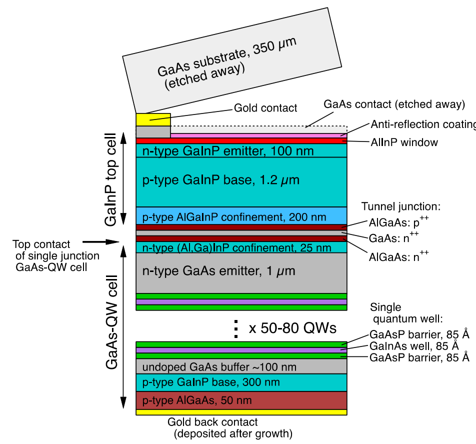

Figure 1 Schematic of the tandem solar cell, with 50-80 strain-balanced GaInAs/GaAsP quantum wells in the bottom cell. The cell is grown inverted and removed from the substrate during processing. For the single junction GaAs-QW cell, the top contact location is indicated.

The tandem cells were grown with a front homojunction GaInP top cell and a rear-heterojunction (RHJ) quantum well bottom cell [3], shown schematically in Fig. 1. A low flow of triethylantimony during growth of the top cell kinetically disordered the GaInP crystal, leading to a bandgap of 1.89 eV. The GaAs-QW cells included a thick n-type absorber layer followed by the undoped quantum wells, a thin, lightly p-doped GaAs transition layer and then a p-type GaInP base. The quantum wells were strain-balanced and consisted of compressive GaInAs wells and tensile GaAsP barriers. The target band edge for the MQWs was 930 nm, corresponding to the broad water absorption band in the global spectrum. Each repeated unit of the QW was designed to have 85 Å of $Ga_{0.894}In_{0.106}As$ with 85 Å of $GaAs_{0.902}P_{0.098}$ on each side, resulting in 170 Å GaAsP barriers [5]. The actual thicknesses were determined from a combination of (004) XRD rocking curves and TEM imaging, as shown in detail in reference [1].

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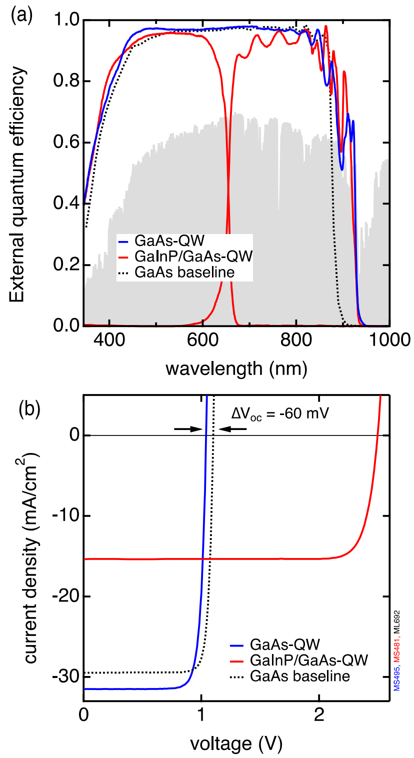

Figure 2 Photovoltaic characterization: (a) External quantum efficiency of the GaAs-QW and GaInP/GaAs-QW cells, as well as a GaAs baseline cell. The AM1.5 global spectrum is shown shaded. (b) Current-voltage curves at 1000 W/m^2, AM1.5G.

III. Experimental Results

A. *GaAs-QW single junction cells*

Figure 2 shows EQE and IV curves (in blue) for our best 0.25 cm^2 GaAs-QW cell, compared to a baseline GaAs cell in black. These data were measured by the NREL Cell and Module Performance group and are certified measurements of the efficiency. The absorption edge of the GaAs-QW devices extends out to ~920-930 nm, leading to an increase in the short circuit current density to as high as 31.5 mA/cm^2 in the newest cells. The measured Voc of 1.040 V corresponds simply to the shift in band edge from 1.414 eV for GaAs to 1.351 eV for the GaAs-QW cell, as determined from the detailed balance analysis of the EQE [6, 7]. The high Voc indicates that the radiative and non-radiative recombination rates remain in the same ratio as in the baseline cell, despite the many interfaces and the thick intrinsically-doped region. The efficiency of the GaAs-QW cell under the AM1.5 global spectrum is (27.2 ± 0.2)% at 1000 W/m^2, as measured on an X-25 class A solar simulator based on a xenon lamp.

B. *GaInP/GaAs-QW tandem cells*

Figure 2 also shows the EQE and IV for a tandem cell, composed of a GaInP top cell and a GaAs-QW bottom cell. The thickness of the top cell was chosen so that the tandem would remain slightly top-limited to boost the fill factor to >85%, without unnecessarily sacrificing photocurrent. With band edges of 1.89 and 1.35 eV, the average voltage-bandgap offset Woc = 0.36 V indicating excellent material quality in each junction. The efficiency of (32.9 ± 0.5)% is a new one-sun record for any two-junction solar cell, as of this writing. More details on the characterization of these cells can be found in [1].

We have previously shown record GaInP cells with a rear heterojunction architecture [8], similar to the GaAs cells, with the best of those cells demonstrating 22% efficiency at one-sun. We find, however, that the n-type absorber layer in the RHJ GaInP is limited to a maximum thickness of ~1 μm before bulk recombination degrades the voltage, whereas the front junction cells can be grown as thick as 3 μm. Moreover, the RHJ GaInP cells are sensitive to subsequent growth conditions and do not incorporate into tandems with good consistency. This is why we have used the front-junction GaInP design in this tandem. This sensitivity continues to be an area of study.

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