High Efficiency Tandem Solar Cells; Design and Experimental Considerations

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Introduction:

Tandem solar cells (SCs) are constructed from serially connected SCs of different band gaps, usually by monolithically growing the layers on a substrate. Although their efficiency is superior to that of a single junction SC (known as the Shockley-Queisser limit [1]) their use is limited due to high manufacturing cost. To further develop alternative photovoltaic technologies, an understanding of the tunnel junction (TJ) and band-gap engineering is imperative. Herein, a model two-cell tandem solar cell device is investigated and designed. A detailed balance analysis is performed on a tandem device composed of an aluminum gallium arsenide (AlGaAs) top cell and a band-gap tunable indium gallium arsenide (InGaAs/GaAs) quantum well (QW) bottom cell. A GaAs TJ (Esaki diode) was fabricated and its electrical characteristics elucidated.

Experimental Details and Methods:

The following devices were fabricated: (1) a QW device for the bottom sub-cell, and (2) a TJ that served to serially connect the sub-cells. They were grown on n-GaAs substrates at a substrate temperature of 580°C using molecular beam epitaxy. The QW device consisted of a p-i-n structure with 25 periods of 3.2 nm thick InGaAs and 15.8 nm GaAs layers embedded in the i-layer. The TJ device consisted of highly doped p and n layers. The TJ structure consisted of 30 nm n++-GaAs (doping density of 3E18 cm^{-3}) and a 30 nm p++-GaAs (doping density of 20E18 cm^{-3}). The dopants used were silicon (Si) and beryllium (Be). After growth, the samples were processed into mesa-shaped diodes. Electrical and optical characterization was performed on both devices.

The theoretical efficiencies were calculated via the detailed balance method for tandem SCs [2] assuming a black body emitter at 6000 K and an absorption coefficient of unity for photons above the band gap energy.

Results and Discussion:

The detailed balance optimization yields a maximum theoretical efficiency of 44% for a two-cell tandem SC. The band gaps of the top and bottom cells are 1.78 and 1.04 eV, respectively. For the top AlGaAs cell, this band gap could be easily realized with an Al composition of 0.29. However, because of strain contributions, the indium composition required of the bottom cell was not readily employed without risking deleterious strain defects and dislocations.

Further exacerbating the discrepancy between desired and experimentally achievable band gaps is quantum confinement. Quantum confinement of both electrons and holes in the band edges of the well material raised their energy, increasing the effective band gap further. This could be observed in the PL spectra of the QW device in Figure 1, where the observed transition energy/band gap was 180 meV higher than the intrinsic band gap of the constituent material.

To accommodate for the unrealizable bottom band gap, a local efficiency maximum was determined by constraining the bottom cell indium composition to 20% and the QW width to 6.4 nm. This corresponded to a bottom band gap of 1.18 eV. Optimizing the top cell band gap for efficiency yielded a band gap of 1.88 eV. The efficiency at this configuration is only 0.5% lower than the global maximum. Figure 2 shows that efficiency was insensitive to the band gap as long as the alternative cell's band gap was adjusted to compensate.

Figure 3 shows the IV behavior for the tunnel junction. The local maximum around 0.035 V was characteristic of tunnel junction behavior; although the extremely low current magnitude indicated issues with the tunneling mechanism. Capacitance measurements yielded a pn-junction depletion layer thickness of ~ 34 nm. Solutions to Poisson's equation for a step-junction gave thicknesses of ~ 30 nm, in rough agreement with experiment. A prohibitively large

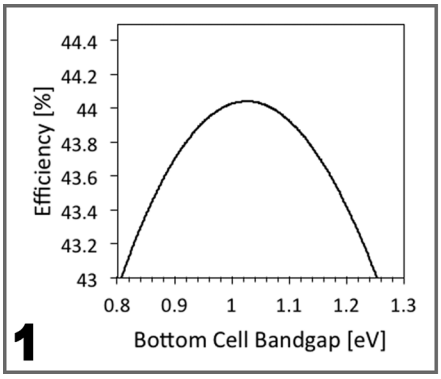

Figure 1: PL spectrum for the GaAs-InGaAs QW device. The dotted line shows the band gap of the bulk InGaAs. The energy difference is due to quantum confinement.

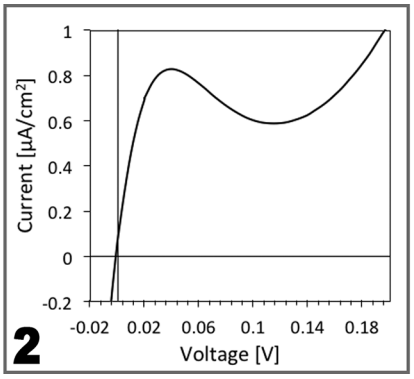

Figure 2: The theoretical efficiency of a two-cell tandem SC vs. the bottom band gap. The top band gap is variable; it is optimized for every point.

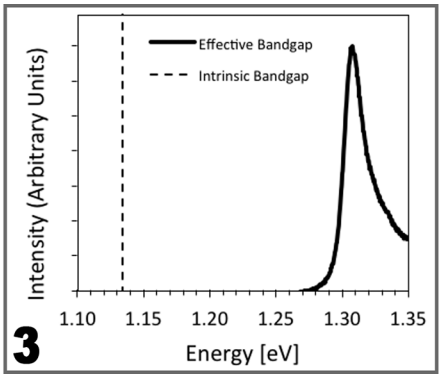

Figure 3: The IV characteristics the TJ. Current "hump" at 0.035 V indicates tunneling.

depletion layer thickness was likely the primary culprit for the low current densities. To improve upon the initial design, larger doping densities should be used for the n++-type side. Silicon concentrations of 8E18 cm^{-3} (almost triple the doping density used herein) have been successfully used in literature for the n++-layer in GaAs based tunnel junctions [3]. Increasing the doping density to this value could decrease the depletion layer width by 10 nm, likely drastically increasing the current in future devices.

Conclusions:

Design parameters for a two-junction tandem AlGaAs/GaAs solar cell with InGaAs QWs were determined via detailed balance. The parameters yield a theoretical device with optimized efficiency, considering material constraints due to intrinsic band limitations and quantum confinement effects. Their values are as follows: Top cell Al composition of 37%; QW In composition of 20%; and thickness of 6.4 nm. Additionally, a tunneling junction was fabricated and electrically characterized. The low current is attributed to a thick depletion layer.

Future Work:

The design parameters developed will be used to fabricate the next generation devices, which will be used to construct a complete device. Long term efforts will aim at increasing the number of cells in tandem and replacing the QW heterostructures with quantum dots.

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