Solar Energy Materials and Solar Cells 181 (2018) 46–52

Contents lists available at ScienceDirect

Solar Energy Materials and Solar Cells

journal homepage: www.elsevier.com/locate/solmat

Challenges and strategies for implementing the vertical epitaxial heterostructure architechture (VEHSA) design for concentrated photovoltaic applications

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ARTICLE INFO

Keywords:
Thin III–V junctions
Concentrated photovoltaics
Modelling

ABSTRACT

Monochromatic conversion efficiencies in excess of 60% have been achieved with Vertical Epitaxial HeteroStructure Architechture laser power converters (with anywhere from 5 to 20+ n/p junctions stacked vertically). We are presently investigating the applicability of this design to solar cells, whereby the individual junctions of a multi-junction cell are replaced with a current matched stack of subcells. If viable, such a design offers the potential for efficiency gains via reduced I^2R losses and elevated V_{oc}. Moreover, splitting the short-circuit current over additional junctions opens up the possibility of operation under concentration ratios otherwise considered impractical for conventional cells.

1. Introduction

III–V photovoltaic cells are fundamental to both laser power converters (LPCs) and concentrated photovoltaics (CPVs), and in turn, both of these technologies stand to benefit from the ability to produce higher efficiency cells. There is a growing interest in LPCs, as these can be useful to any system which requires galvanic shielding, e.g. sensory equipment [1,2], medical implants [3,4], telecommunications [5], etc. High conversion efficiencies for GaAs LPCs have been reported in the literature [6–29]. However, the Vertical Epitaxial HeteroStructure Architechture (VEHSA) technology [30–38] has presented a major breakthrough in the field, with reported conversion efficiencies just under 70% (c.f. a previous reporting of 53.4% in Ref. [9] in 2008), exceeding the approximately 65% limit stipulated in Ref. [9] for these kinds of cells.

A common goal within the CPV community is the manufacture of a solar cell with a conversion efficiency exceeding 50% [39,40], seen by many as the next major milestone. Research has focused on dilute nitrides [41], increasing the number of junctions via wafer bonding [42], perovskites [43] as well as alternative strategies oriented towards module design [44]. We would like to bridge the gap between research in LPCs and CPVs by proposing that we apply the very technology that makes VEHSA devices so efficient to CPV cells themselves, namely, stacked thin junctions. The working principle here is that splitting the photocurrent over many junctions reduces I^2R losses and loads on the tunnel junction, allowing for the possibility of operation under high solar concentration (with the goal being in excess of 1000 suns [45]). There is an added benefit of using a vertical arrangement of thin junctions since thin layers achieve a greater Fermi level splitting [46], which on a per-junction level offers a marginal boost in V_{oc} when compared to a planar arrangement of bulk cells (potentially 92 mV per junction [38]).

The outline of this text is as follows: we will begin with an overview of VEHSA LPC devices (those used for power-over-fibre applications). Section 3 contains a presentation of how the VEHSA design would be applied to solar cells, focusing on an "enhanced" tandem cell as a specific case. Sections 4 and 5 close with a discussion and our conclusions.

2. Overview of VEHSA monochromatic cells

A schematic representation of a typical VEHSA device is shown in Fig. 1 (not to scale, and omitting certain window / buffer layers). These devices consist of alternating stacked GaAs n/p (n-on-p) junctions separated by AlGaAs tunnel junctions and GaInP buffer / window layers. Illumination is via a monochromatic source within the range of wavelengths where the GaAs junctions are opaque while all other layers

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https://doi.org/10.1016/j.solmat.2017.11.034
Received 30 August 2017; Received in revised form 13 November 2017; Accepted 21 November 2017
Available online 12 December 2017
0927-0248/

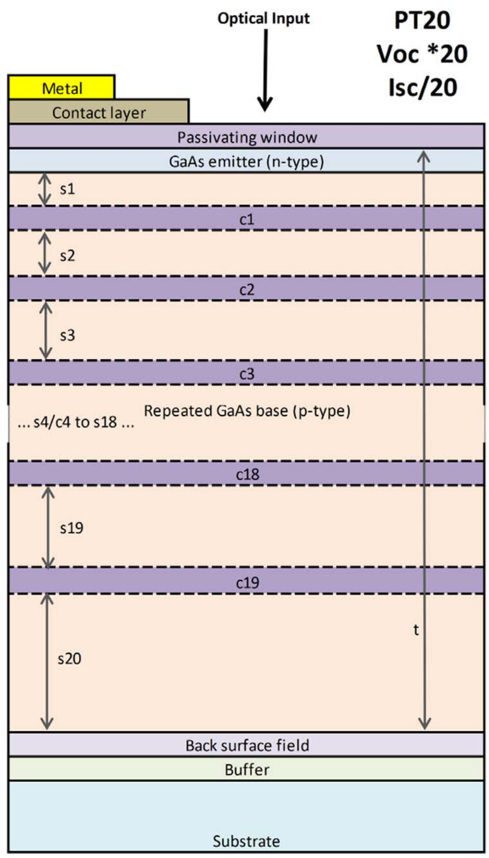

Fig. 1. A schematic of a typical VEHSA LPC (shown above for a 20 junction device). GaAs n/p junctions are labeled s1 through s20, and tunnel junctions are c1 through c19. The topmost n-type emitter is explicitly shown, though omitted for the other subcells. Reproduced from Refs. [47,38].

(generally AlGaAs and GaInP) are transparent (in effect, the upper frequency limit is set by the band gap of the AlGaAs tunnel junctions, for an allowable range of approximately 750 nm–875 nm, depending on the Al molar fraction). Since the topmost window layer is transparent to the source wavelength, we are able to employ a characteristically larger window than would be otherwise typical of multi-junction solar cells. Gridline density is assumed to be sufficient to allow for efficient carrier extraction even at high source intensities, with minimal shadowing.

VEHSA LPCs are grown via MOCVD with an Aixtron 2600 multi-wafer reactor. AlGaAs n + +/p + + tunnel junctions are employed with Al fraction in the range 10%–30% and dopant densities exceeding 1E19 cm^{-3}. GaAs junctions are typically doped over the range 5E17 cm^{-3}–1.5E18 cm^{-3}, with thinner junctions doped more heavily. Prior to a growth, the thicknesses of each junction are determined by initially targeting a specific wavelength (and hence uniform value of the absorption coefficient α in GaAs) and setting the layers such that each junction produces an equal amount of photocurrent. For a typical design wavelength of 850 nm, total GaAs thickness may reach 3.6 µm when summed over all junctions (so that the sum of the junctions is nearly fully absorbent). Due to variations in growth, the wavelength at which peak conversion efficiency is observed can generally deviate slightly from design, of the order 10 nm.

Actual devices are known experimentally to achieve a very high degree of current matching, supplemented by photon-recycling [35] which has made it possible to consistently observe efficiencies of 60–70% for a range of devices and experimental conditions, as captured by the $I(V)$ curves in Fig. 2. Broadcom (www.broadcom.com) now offers such devices commercially, with products for various applications. With regards to the labeling PTN, N represents the number of

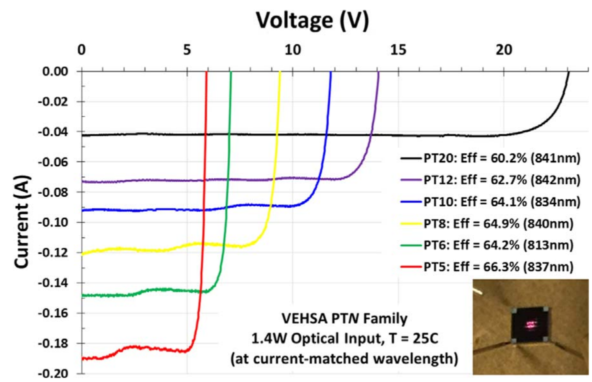

Fig. 2. $I(V)$ curves for N = 5 up to 20 junction devices, with an illuminated cell shown in the lower right corner. Reproduced from Refs. [32,38].

junctions, i.e. PT20 contains 20 stacked junctions. Devices with over 20 junctions have also been fabricated.

Though the text focuses on solar, it is worth mentioning that we are also actively seeking to develop phototransducers with $N \gg 20$ (e.g. PT60), discussed in Ref. [38]. A tentative PT100 device would contain individual subcells as thin as 10 nm (noting that this value is sensitive to the wavelength chosen, and in turn should be treated as an estimate) considered to be pushing the limits of viability, though such a device is interesting in its own right due to individual junctions effectively becoming quantum wells. When individual subcells reach this size, we are additionally able to consider altering their molar composition and strain, opening up the possibility of even further enhancements of V_{oc}, as well as fine tuning of the absorption per subcell.

2.1. Models

PTN devices are simulated using Atlas, employing standard values for carrier mobilities in GaAs and GaInP, radiative recombination rates of the order ~ 10^{-10} cm^3/s and SRH lifetimes of the order 10 ns for both species at 1E18 cm^{-3} doping (lifetimes are adjusting for doping). Parameters are tabulated in detail in Ref. [38], and these are generally consistent with other authors. Carrier lifetimes are sensitive to the quality of the crystal growth, and values obtained from the literature will not necessarily be well matched to a specific device, requiring some degree of calibration of the actual models.

In our case, all of our wafers have been grown using the same equipment, and therefore, we expect little variation of crystal quality between growths. Our models have been calibrated and exhibit very close agreement with the PV characteristics of single junction cells. The same set-up when used to model a PT12 device shows agreement with experiment at the level depicted in Fig. 3, which is still arguably a very close fit considering the random variation in layer thicknesses etc.

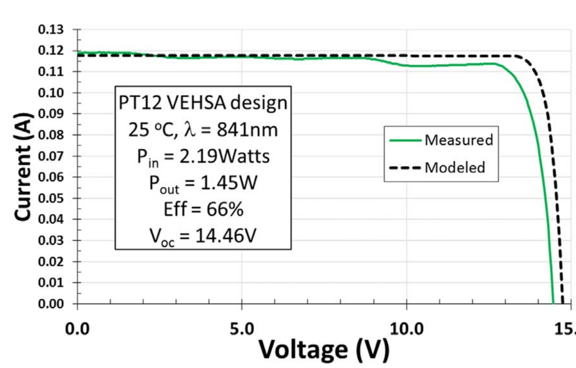

Fig. 3. Model and measured $I(V)$ curves for a PT12 cell. Reproduced from Refs. [32,37].