"High-performance concentrator solar cells for large scale electricity generation – critical issues"

B.E. Sağol, N. Szabo, H. Döscher, C. Höhn, K. Schwarzburg, T. Hannappel

Helmholtz-Zentrum Berlin, Glienicker Str. 100, 14109 Berlin-Germany

Multi junction solar cells built from III–V semiconductor compounds are the only type of solar cells, which have been realized so far to exceed the Shockley Queisser limit, and hold the solar energy conversion efficiency world record. Despite having non-optimized band gaps, three types of state-of-the-art III-V triple-junction solar cells have recently surpassed the 40% efficiency mark [1,2,3]. But still considerably higher efficiencies can be achieved with a four-junction configuration, which has optimized band gaps around 1.9, 1.4, 1.0 and 0.7 eV. This could be realized with a double tandem cell, either mechanically stacked or via monolithically, inverted metamorphic growth, bonding etc.. Here, the well-established GaInP/GaAs tandem could be utilized as the high band gap part, and for the low band gap part an InP-based InGaAsP/InGaAs tandem cell. For this purpose, we developed InGaAsP/InGaAs tandem solar cells lattice-matched to InP by metal organic chemical vapour deposition (MOCVD). The InGaAs bottom cell (E_{gap} = 0.72 eV) and the InGaAsP top cell (1.03 eV) were connected with a tunnel junction, which was composed of highly doped n-InGaAs and p-GaAsSb layers. In order to evaluate the performance of the tunnel junction, separate devices were grown without the photoactive layers. High current densities of several thousand A/cm^2 were achieved already in the bias regime of several 100 mV (Fig. 1). This corresponds to a total device resistance of 10^{-4} Ω cm^2 that includes the series resistance caused by the InP wafer, tunnel junction, ohmic contacts and bonding wires. Hence, voltage losses in the tunnel diode should not be of concern for the solar cell even under extreme concentration ratios (> 1000 suns). In-house measurements showed that our low band gap InGaAsP/InGaAs tandem bottom cells have reached efficiencies already above 10% underneath a GaAs filter (Fig. 2).

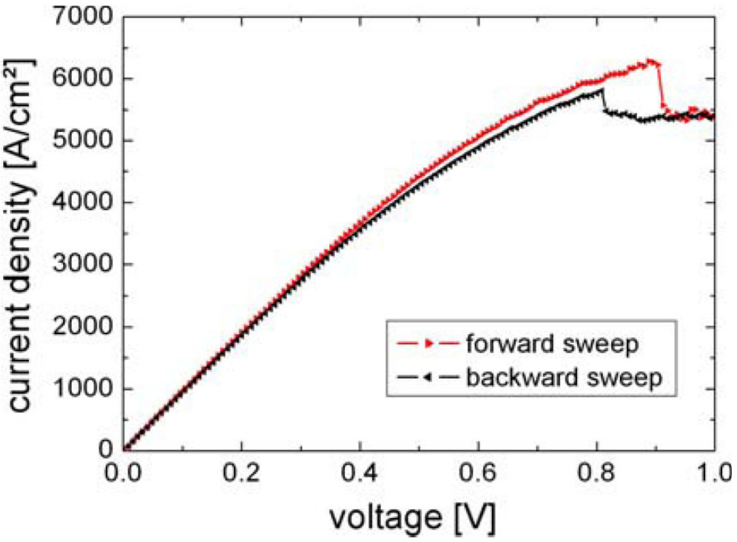

Fig. 1 I–V curve of an InGaAs/GaAsSb lattice matched tunnel diode, 100 µm diameter structure.

The epitaxial growth of III-V semiconductors on inexpensive substrates is another major challenge for the terrestrial application of III-V solar cells. But still, there is only little experience in the preparation of the crucial Si(100) surface with MOCVD and the respective interfaces to III-V materials. In many ways the applied process environment common for the opto-electronic industry differs from UHV conditions typical in surface science - e.g. by the distinct presence of hydrogen as precursor residue and as process gas. For the desired growth of polar materials on non-polar substrates, the hetero-interface represents a source of anti-phase disorder introducing defects. Ideally, this effect may be suppressed by the preparation of a completely double-stepped substrate surface with only a single reconstruction domain. For that, III-V growth on silicon was studied via optical in-situ monitoring employing reflectance difference/anisotropy spectroscopy (RDS/RAS) for the quantification of anti-phase domains on surfaces of thin GaP films deposited onto Si(100) by MOCVD. The successful deoxidation of Si(100) in the MOCVD reactor and the growth of a Si buffer layer was studied with various surface science tools (XPS, FTIR, UPS, LEED, STM) employing a contamination-free transfer from the MOCVD reactor to ultrahigh vacuum. The subsequent preparation of a single-domain GaP/Si(100) surface was determined via the analysis of RDS peak intensities in reference to the well-known P-rich atomic surface reconstruction of homo-epitaxially grown GaP(100) [4]. Both pre-processed Si(100) substrates and MOCVD as-grown GaP/Si(100) films were also characterized ex-situ by atomic force microscopy to identify the formation of mono- and diatomic surface steps and to analyze of the domain distribution, respectively.

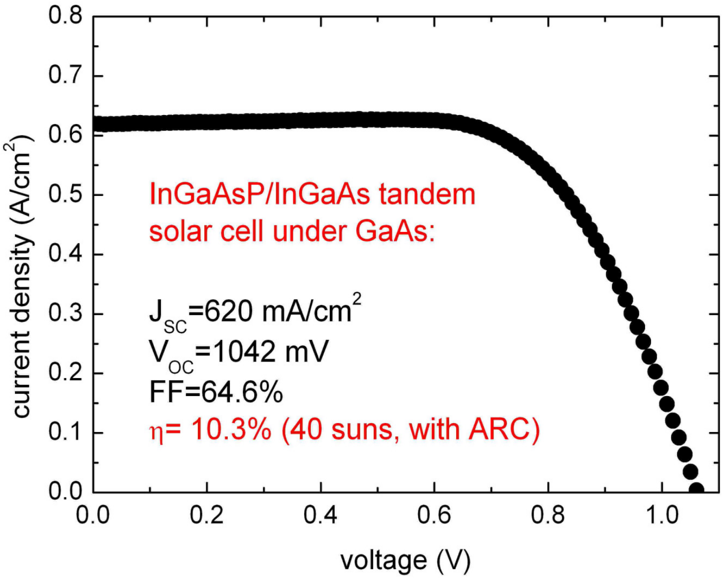

Fig. 2 I–V curve of our InGaAs/InGaAsP tandem solar cell under a GaAs-filter.

[1] R.R. King, D.C. Law *et al.*, Appl. Phys. Lett. 90, 183516 (2007)

[2] J.F. Geisz, D.J. Friedman *et al.*, Appl. Phys. Lett. 93, 123505 (2008)

[3] C. Baur, A. W. Bett, F. Dimroth *et al.*, J. Sol. Energy Eng., 129 (2007) 258; FhG ISE press release 01/2009

[4] H. Döscher, T. Hannappel *et al.*, Appl. Phys. Lett 93 (2008) 172110