"METACELLS"

Advanced epitaxy of metamorphic semiconductor structures for multijunction solar cells

Dr. Iván García (igarcia@ies-def.upm.es)

Instituto de Energía Solar, Univ. Politécnica de Madrid, Avda Complutense s/n, 28040 Madrid, Spain

The global objective of METACELLS project is "to develop the epitaxial technique for the growth of metamorphic semiconductor structures that allow realizing the full efficiency potential of multijunction solar cells, paying special attention to the subsequent manufacturability and cost effectiveness of the solar cells developed". During the first period (outgoing phase) of METACELLS project, the work towards this objective has led to outstanding results, which have advanced the technique and have enabled the attainment of world record efficiencies of photovoltaic conversion with quadruple-junction solar cells.

Lattice-mismatched subcells for 3-junction and 4-junction solar cells have been developed. The focus was put on developing the epitaxy process for the **1eV $Ga_{0.76}In_{0.24}As$ metamorphic junction**, which has a large lattice mismatch of ~2% with respect to the GaAs substrate. In summary, high quality ordered GaInP-based CGBs for $Ga_{0.75}In_{0.25}As$ grown on GaAs substrates have been achieved, with threading dislocation densities < $5 \cdot 10^5$ cm^{-2}. This has enabled the implementation of high quality 1eV $Ga_{0.76}In_{0.24}As$ metamorphic subcells with carrier collection efficiencies nearing 100%, internal luminescence efficiencies of ~ 90% and Eg/q-V_{oc} < 0.35 V (see Figure 1). **This result debunks the traditional belief that metamorphic semiconductor structures have necessarily poorer electronic characteristics than lattice-matched structures, and opens the way to further developments of metamorphic structures for solar cells or any other semiconductor device**.

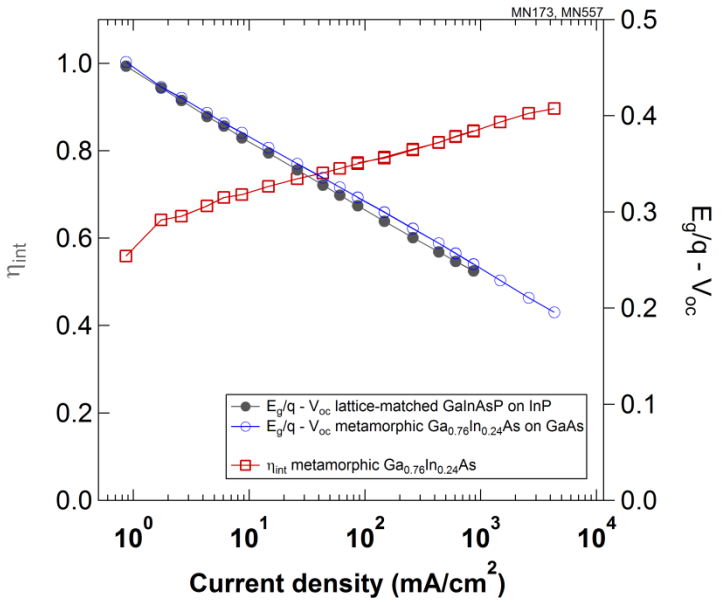

Figure 1. Eg/q – V_{oc} of the metamorphic $Ga_{0.76}In_{0.24}As$ solar cell developed, compared to a lattice-matched GaInAsP cell with similar bandgap, and internal luminescence efficiency of the metamorphic GaInAs cell.

Both **triple and quadruple-junction metamorphic solar cells** structures have been implemented successfully by tackling challenges such as the development of a high performance **$Ga_{0.76}In_{0.24}As/GaAs_{0.75}Sb_{0.25}$ metamorphic tunnel junction** and studying and minimizing the influence of the metamorphic growth on these complex solar cell structures. This work has enabled the implementation of both triple and quadruple-junction metamorphic solar cells structures, **achieving world record efficiencies for photovoltaic conversion**. The potential for future advancement in the performance of these devices has been analyzed, concluding that the **metamorphic multijunction solar cell technology will allow surpassing the 50% photovoltaic conversion efficiency for concentrator terrestrial applications in the medium term**. Moreover, metamorphic structures offer also the benefit of an easily tunable bandgap combination to **maximize the energy output** of concentrator or 1-sun systems

at sites with different spectral variations due to different climatic conditions. All in all, this technology will contribute decisively towards the goal of achieving a cost-competitive clean energy source.

Once completed the outgoing phase at the National Renewable Energy Laboratory (Colorado, USA), the return phase at Instituto de Energía Solar – Universidad Politécnica de Madrid (IES-UPM) started, aiming to **transfer the epitaxy processes to IES-UPM** and start a new research line for developing inverted metamorphic multijunction solar cells. A variety of challenges had to be faced, most of them derived from the differences in the epitaxy reactors used in both institutions. The main issue is due to the strong sensitivity of the compositionally graded buffers (CGBs) based on ordered GaInP to some epitaxy parameters, mainly the partial pressure of PH_3. It was also found that the n-type dopant precursors used normally at IES-UPM reactor, $DTBSi_2$ and DETe, gave rise to poorer quality CGBs. A thorough experimental study has allowed to overcome these limitations and a reasonable quality CGB has been implemented. Using this CGB, **the first inverted metamorphic multijunction solar cells were grown, processed and measured**. The technological processes used to fabricate inverted solar cell devices from these structures, including substrate removal and epilayers bonding to a handle, have been developed and implemented from scratch at IES-UPM. The performance of the 3-junction solar cells developed is very reasonable, and is summarized by the External Quantum Efficiency (EQE) and light current-voltage curves shown in Figure 2.

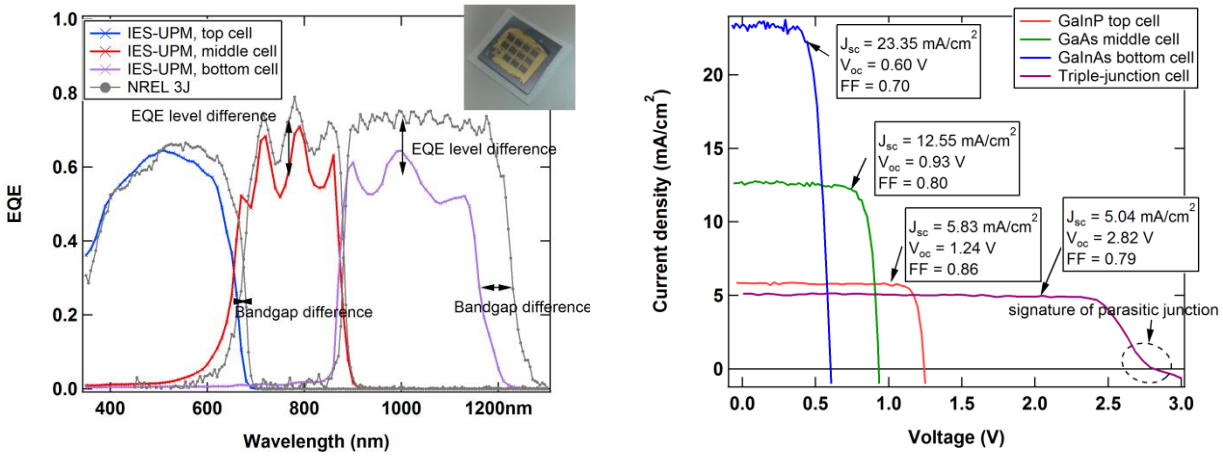

Figure 2. Left: External Quantum Efficiency of the inverted metamorphic 3-junction solar cell developed, compared to a similar device design developed at NREL during the outgoing phase. The inset shows a picture of one batch of inverted solar cell devices fabricated. Right: 1-sun current-voltage characteristics of inverted single-junction solar cells which are the components of an inverted metamorphic 3-junction solar cell, whose IV curve is also shown.

In summary, the objectives for the return phase of METACELLS project have been achieved beyond expectations. **In addition to successfully transfer the epitaxy routines for the epitaxial deposit of metamorphic materials, actual 3-junction inverted metamorphic solar cell devices have been implemented and characterized**. These first devices show a reasonable performance, and the routes to follow for their improvement have been identified. Moreover, **the medium term work to carry out at IES-UPM for the development of the high efficiency inverted metamorphic multijunction solar cell technology beyond the state of the art has been established**. While the near term work will be funded by already awarded Spanish projects, new proposals are being prepared to obtain the resources to fund more advanced designs. All in all, **METACELLS project has been not only a decisive contributor to the advancement of the metamorphic multijunction solar cell technology, but also to bringing this technology back to Europe and setting up the track for future work to continue its development**.