Thin-Film light-trapping enhanced Quantum Dot photovoltaic cells (TFQD): an enabling technology for high power-to-weight ratio space solar arrays

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First ELO processed regular and QD cells from UCL epi-structures

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Abstract

The present document provides the presentation of the first ELO processed regular and QD cells from UCL epi-structures. ELO and subsequent cell processing of complete 3-inch films was demonstrated successfully at tf2-devices and RBU. This provides a good starting point to increase the thin-film cell performance to the level aimed for in this project.

Keywords

Epi-structures, ELO, thin-film processing.

Change Records

Table 1-1

Issue	Date	Change Record	Authors
draft	24/12/2016	First Release	J. Schermer G. Bissels
final	02/01/2017	Final	J. Schermer G. Bissels F. Cappelluti

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List of Acronyms

DJ: Deep-Junction
EL: ElectroLuminescence
ELO: Epitaxial Lift-Off
EQE: External Quantum Efficiency
MBE: Molecular Beam Epitaxy
MOCVD: Metal-Organic Chemical Vapour Deposition
SJ: Shallow Junction
TBC: To Be Confirmed
TFQD: Thin Film Quantum Dot
QD: Quantum Dot

1. INTRODUCTION

The specific objective of TFQD is to develop and demonstrate up to TRL4 thin-film light-trapping enhanced quantum dot solar cells matching the following specifications:

- absolute efficiency larger than 30%
- eightfold increase of power-to-weight ratio vs. triple junction III-V solar cells
- bending radius lower than 3 cm

Demonstration up to TRL4 will be carried out through on ground testing under representative “in orbit” conditions over a batch of 44 bare cell prototypes. The aim of the present deliverable is to present the first ELO processed QD cells from UCL epilayers.

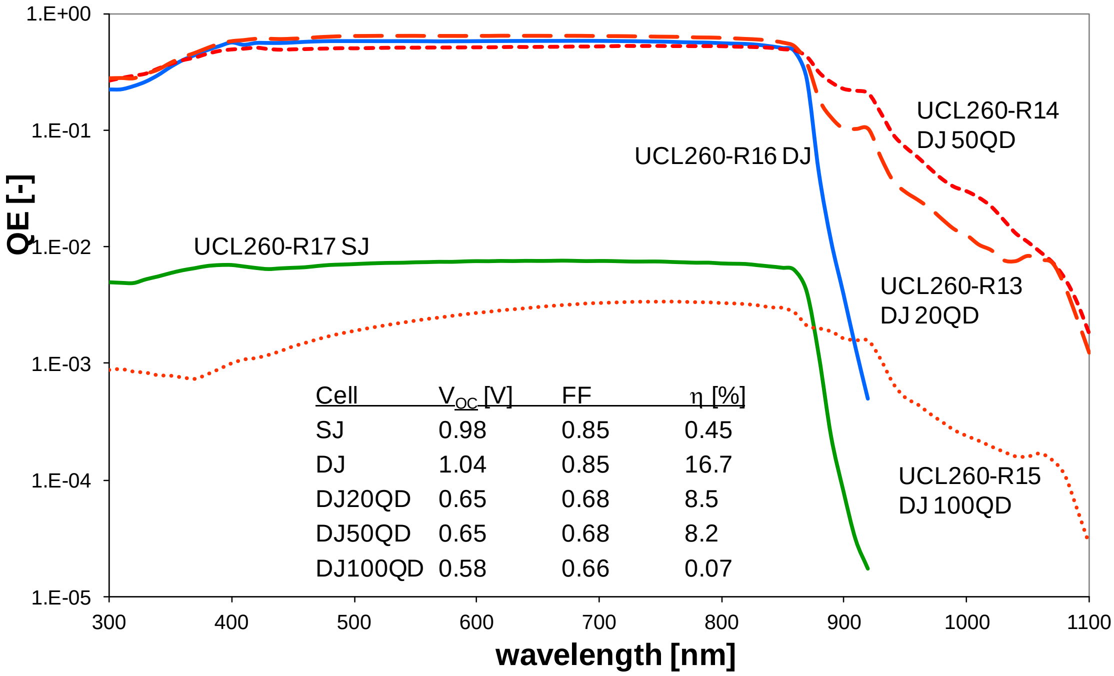
The document is organized as follows. Section 1 summarizes the results of the experiments on wafer based cells from UCL epilayers that were produced as a benchmark. Section 3 describes the results of the first regular and QD ELO cells from UCL epilayers. Section 4 provides the conclusions on this deliverable.

2. WAFER-BASED CELLS FROM UCL EPI-STRUCTURES

As a preparation on the ELO processing of thin-film solar cells, regular and QD cells were produced from a first set of epi-structures delivered by UCL. Before processing visual inspection revealed a high defect density on all epi-structures (cracks, oval defects, particles, misfits and in particular the structures with 50 and 100 layers of QDs appear to be highly strained as evidenced by a high density of misfit dislocations (see figure 2.1).

Figure 2.1. Typical particle-like and oval defects observed on all epi-structures of the first batch (upper images) and high density of misfit dislocations on the epi-structures with 50 and 100 layers of QDs (lower images).

Nevertheless, multiple 0.25 cm^2 cells (grid coverage 15.9%) and 1 cm^2 cells (grid coverage 9.5%) were produced from each wafer (without ARC). 1 sun AM1.5 J-V analysis and EQE measurements (best result from each structure is presented in figure 2.2) indicate that for all structures the 0.25 cm^2 cells perform better because these small sized cells might have the best opportunity to coincidently coincide with an small area of relatively low defect density. From this it can be concluded that the defect level of the epi-structures should be significantly reduced to obtain 1 cm^2 cells of sufficient performance or aim for smaller cells in the final batch of cells for this project.



Cell	V_{OC} [V]	FF	η [%]
SJ	0.98	0.85	0.45
DJ	1.04	0.85	16.7
DJ20QD	0.65	0.68	8.5
DJ50QD	0.65	0.68	8.2
DJ100QD	0.58	0.66	0.07

Figure 2.1. EQE analysis and results from 1 sun AM1.5 J-V measurements of the best cells produced from each epi-structure investigated.

Figure 2.2 shows that for the regular cells the deep-junction design has a far better performance (η = 16.5% without ARC, and high grid contact coverage) than the shallow junction design. For the QD cells the best results are obtained with cells having 20 and 50 layers of QDs (η = 8.2 - 8.5%) showing about equal reduction in FF (maximally around 0.68) and V_{oc} (maximally around 0.65 V) as compared to the regular deep-junction cells. The cell with 100 QD layers (η = 0.07%) has equally reduced FF (0.66), further reduced V_{oc} (0.58 V) and highly reduced QE. Based on these results it was decided to concentrate on the development of thin-film cells with 20 layers of QDs (also to avoid strain issues) in this TFQD project. Sufficient absorption of light has to be obtained by a) maximizing the performance of the deep-junction host cell structure (maximize photon-recycling by minimizing non-radiative recombination) b) ultimate confinement of light as obtained by nano-structuring the surfaces (WP4).

A second batch of epi-structures including both regular cell structures and structures with 20 layers of QDs still revealed quite some particle-like defects and residual strain as evidenced by misfit dislocation lines (also see figure 3.1). Based on this it was decided not to proceed with fully extended processing (i.e. 1 cm^2 cells, including ARC and thickened grid contacts) but only produce 0.25 cm^2 cells without ARC and thin contacts.

Although the spread in cell performance was reduced with respect to that obtained for the first batch of epi-structures, the maximum obtained efficiency for the regular cell actually appeared lower (η = 14.9%). With η = 15.2% the efficiency of the 20 layer QD cell seems almost doubled compared to the that of the first batch of epi-layers but QE analysis does not show any evidence of QDs in these structures (see figure 2.3) which probably means that this is also a regular cell structure. Further analysis on this issue will be performed at UCL but is of no consequence for this report.

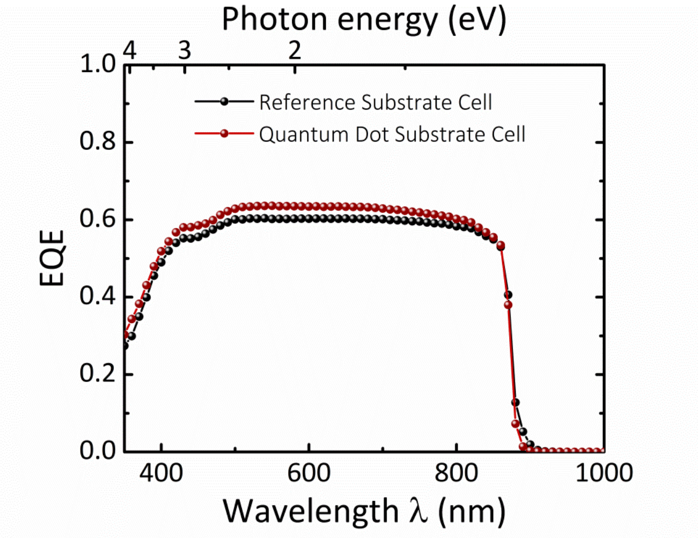


Figure 2.3. EQE curves of the wafer-based regular and "QD" cells.

3. ELO CELLS FROM UCL EPI-STRUCTURES

For the development of a suitable ELO process, UCL in a first batch provided 3 wafers with DJ epi-structures having release layers of 7, 10 and 13 nm, respectively. Visual inspection confirms the presence of several surface defects and cross-hatch patterns (also see section 2).

Thin-film lift-off experiments demonstrated that epi-structures with 13 nm thick release layers could be released with a decent etch rate (25-30 mm/h) at the start, but that this soon drops off as the process proceeds. Lift-off issues occurred at the edge of the film because in contrast to MOCVD grown epi-structures the MBE epi-structures do not extend to the wafer edge. This necessitated a re-design of the dimensions of the flexible carrier of which the first prototype was produced prior to receiving the first epi-structure batch.

Based on these results, tf2 devices re-designed, ordered and implemented the flexible carrier for ELO processing of the epi-structures with release layers of 7 and 10 nm. Lift-off using the thinner layers proved not successful (i.e. incomplete at locations at the edge or centre of the samples). Nevertheless, the samples were useful to test the processing with the new flexible carrier as a preparation for the next series of ELO samples. Based on these results UCL provided regular and QD cell structures with 18 nm release layers (safe but slow etching) as part of the second batch of epi-structures.

Before processing visual inspection revealed particle-like defects and in particular at the edges of the epi-structures misfit dislocations (see figure 3.1). Based on this it was decided to continue with basic rather than extended processing (i.e. 0.25 cm^2 cells, no ARC and no thickening of contacts). The ELO and cell processing of both the regular and QD cell structures went very well, yielding 3" films that were processed into cells without processing related defects visible by the naked eye (see figure 3.2). This marks the point “Customized ELO process ready” i.e. UCL has identified a release structure that allows us to lift-off of a complete 3” thin-film and process it in thin-film cells without film rapture or delamination from the metal carrier.

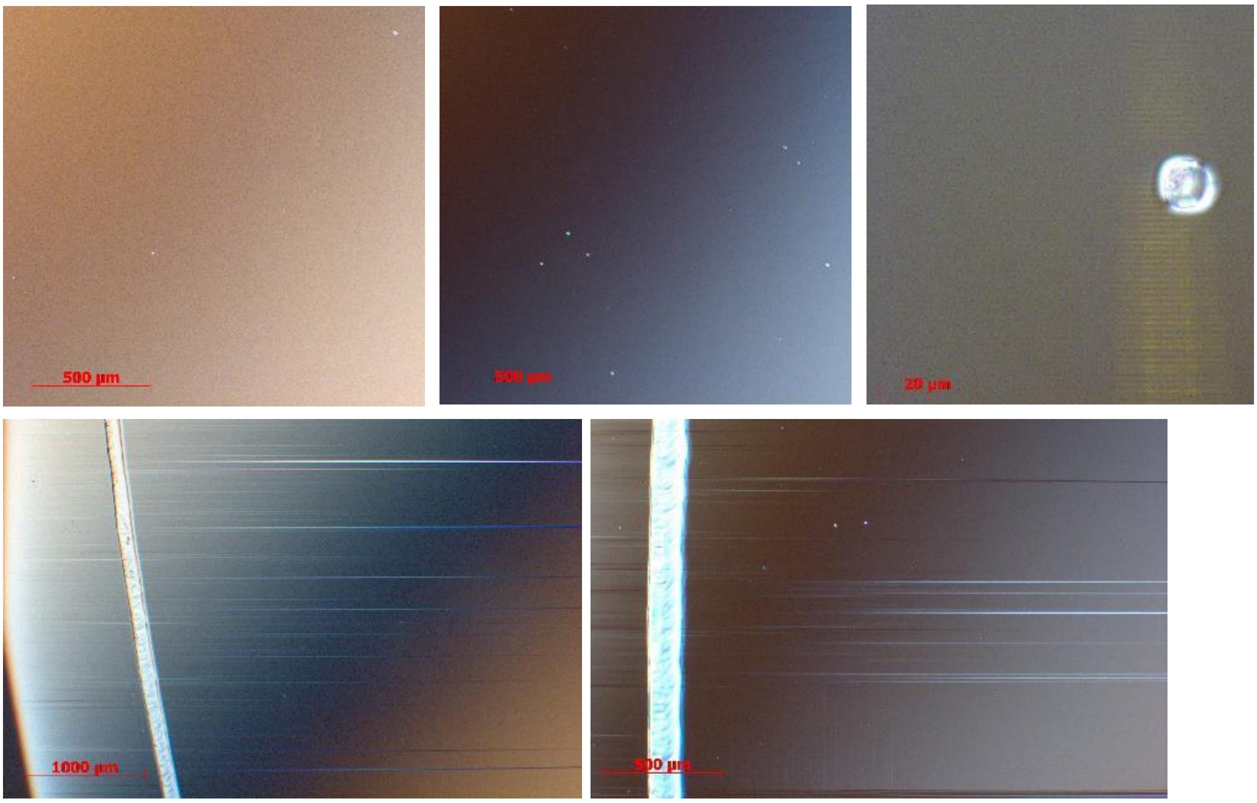


Figure 3.1. Typical particle-like defects (upper images) and strain induced misfit dislocations at the edges (lower images) on the epi-structures from the second batch. The upper images show a close-up (right) as well as areas of low density (left) and high-density (middle) of the particle-like defects (on average a few/mm^2).

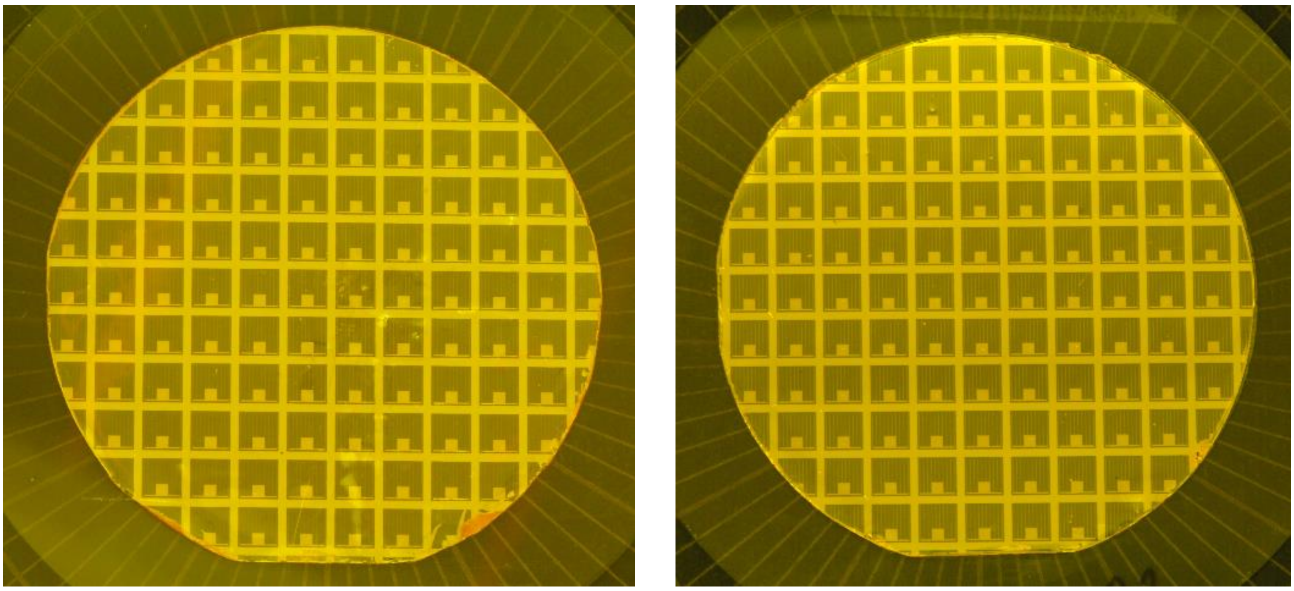


Figure 3.2. Regular (left) and QD (right) thin-film cells on 3-inch diameter epi-structures from UCL.

First analysis of cell performance shows that a large number of cells are not operational. Registration of working cells as a function of wafer position as shown in figure 3.3 reveals that cell position and performance are totally non-correlated indicating that the cell failure is not related to any particular process step but should be associated to randomly occurring imperfections in the epi-structure as will also become clear upon further analysis.

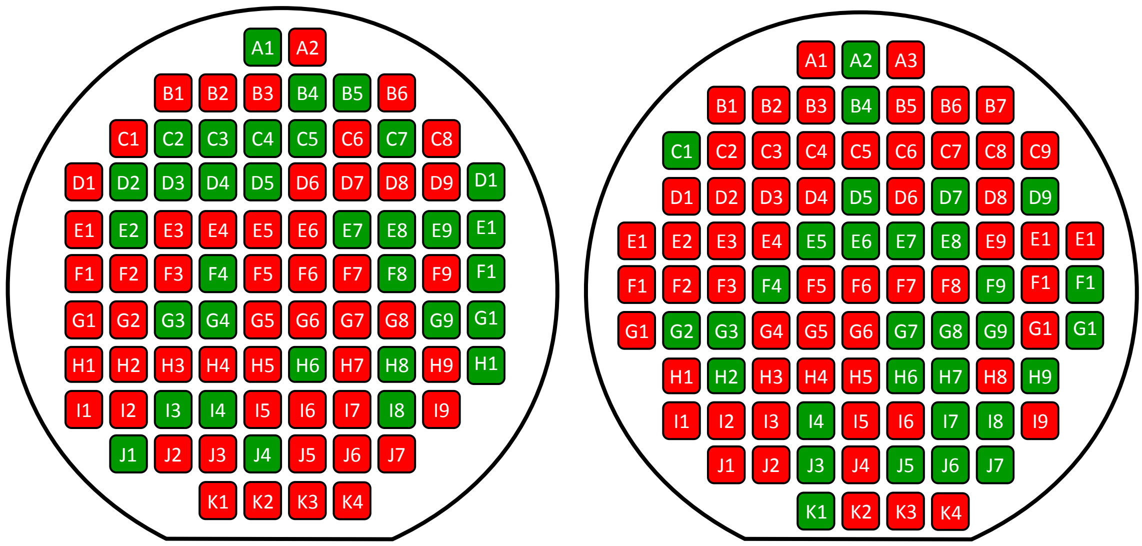


Figure 3.3. Operational (green) and non-operational (red) cells for the regular (left) and QD (right) 3-inch thin-film epi-structures from UCL indicating a yield of about 35%.

J-V and QE analysis of the best performing thin-film cells are shown in figure 3.4. The cell parameters deduced from J-V analysis (see table 3.1) indicate that because of a reduced V_{oc} and FF the thin-film cells perform significantly worse than the substrate-based cells from the same epi-structure batch. However, the thin-film QD cell shows an improved performance (η = 10.9%) with respect to the substrate-based QD cell (with 20 QD layers) from the first epi-structure batch (η = 8.5%). This improved performance is mainly related to an improved V_{oc} and FF of the thin film cell indicating that the quality of the epi-structures has been improved with respect to the first batch. Compared to the regular cell the enhanced current from sub-bandgap photon conversion in the thin-film QD cell is clearly observable in the EQE graph of figure 3.4.

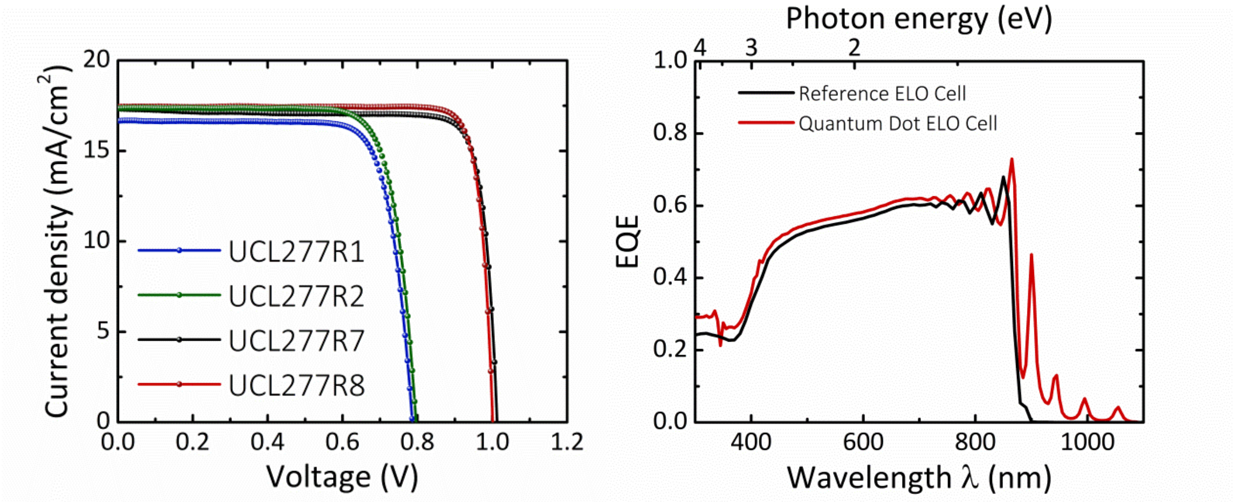


Figure 3.4. J-V curves of the best regular (R1) and QD (R2) thin-film cells in comparison with the substrate cells (R7&R8) from the same batch (right) and EQE curves of the best thin-film cells (left).

Table 3.1. Cell parameters deduced from the J-V curves of the best cells from epi-batch 2.

Cell type	J_{sc} [mA/cm^2]	V_{oc} [V]	FF [%]	η[%]
Regular wafer-based	17.3	1.013	84.7	14.9
QD wafer-based	17.5	1.002	87.0	15.2
Regular thin-film	16.7	0.786	78.7	10.3
QD thin-film	17.4	0.796	78.7	10.3

In figure 3.5 the typical electroluminescence of the operational thin-film cells in comparison to that of a wafer-based cell is shown. These images show that the lower V_{oc} and FF of the thin-film cells is related to random particle like defects and residual strain which were already in the epi-structures on forehand (see figure 3.1).

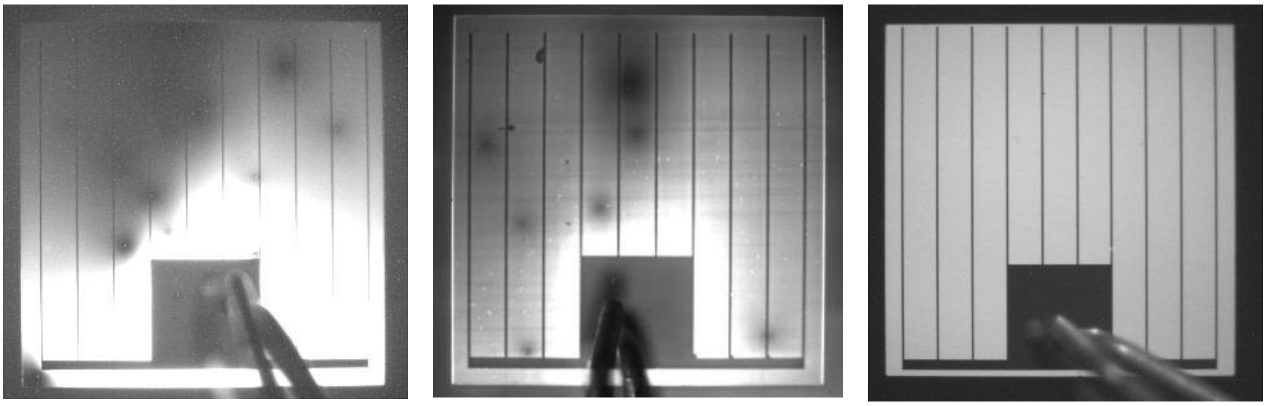


Figure 3.5. Representative electroluminescence images of the regular (left) and QD (middle) thin-film cells in comparison to that of a substrate based cell (right). The thin-film cells showing point defects and misfit dislocation lines typically require currents in the 40-80 mA while the substrate based cells showing homogeneous luminescence require currents in the 0.5-5 mA range to obtain an image.

The fact that both the QD as well as the regular thin-film cells perform significantly less compared to the substrate-based cells indicates that they are more sensitive to imperfections in the epi-structure. This is what we generally observe and is fully understandable because they are subjected to more elaborate processing and lattice imperfections are more prone to be attacked during ELO and subsequent thin-film processing. Also during ELO the thin-film epi-structures are bent away from the wafer which induces extension of the existing misfit dislocations at the edges towards the central areas of the epi-structure where the cells are. Both the particle point-like defects (circular dark areas) and misfit dislocations (horizontal dark lines best visible in the middle image) can be clearly identified in the electroluminescence images of the thin-film ELO cells.

4. CONCLUSIONS

In this report the first ELO and thin-film processed regular and QD cells from UCL epi-structures are described. The cells were produced from complete wafer sized films which means that UCL has identified a suitable release layer structure that allows RBU and tf2-devices to lift-off complete 3" thin-films and process them in thin-film cells without film rapture or delamination from the metal carrier. This marks the point "Customized ELO process ready".

Because inspection on forehand revealed particle-like defects and in particular at the edges of the epi-structures misfit dislocations the structures were subjected to basic rather than extended processing (i.e. 0.25 cm^2 cells, no ARC and no thickening of contacts). Related to the presence of these defects the yield of operational cells after processing is only about 35%.

J-V analysis of the best cells obtained shows that because of a reduced V_{oc} and FF the thin-film cells perform significantly worse than substrate-based cells produced from the same epi-structure batch. Compared to the regular cell an enhanced current from sub-bandgap photon conversion in the thin-film QD cell is clearly demonstrated by EQE analysis.

The thin-film QD cell also shows an improved performance (η = 10.9%) with respect to the substrate-based QD cell (with 20 QD layers) from the first epi-structure batch (η = 8.5%). This improved performance is mainly related to an improved V_{oc} and FF of the thin-film cell indicating that the quality of the epi-structures has been improved with respect to the first batch. It should, however, be noted that in order to obtain the project aims the epi-structures have to be improved to near perfection in order to reduce any non-radiative recombination and maximally benefit from the photon recycling in the thin-film cell geometry.

The fact that both the QD as well as the regular thin-film cells perform significantly less compared to the substrate-based cells is related to the fact that they are subjected to more elaborate processing and lattice imperfections are more prone to be attacked during ELO and subsequent thin-film processing. Also, during ELO the thin-film epi-structures are bent away from the wafer which induces extension of the existing misfit dislocations at the edges towards the central areas of the epi-structure where the cells are. Both the particle point-like defects and misfit dislocation lines can be clearly identified in the electroluminescence images of the thin-film ELO cells. Only with state of the art epi-structure quality thin-film ELO cells will surpass the performance of their substrate-based counterparts.