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F. Cappelluti*, A. P. Cédola*, A. Khalili*, Farid Elsehrawy*, G. Bauhuis†, P. Mulder†, J. Schermer†,
G. Bissels‡, T. Aho§, T. Niemi§, M. Guina§, D. Kim¶, J. Wu¶, H. Liu¶
*Department of Electronics and Telecommunications, Politecnico di Torino, Italy
†Institute for Molecules and Materials, Radboud University, Nijmegen, The Netherlands
‡tf2 devices B.V., Nijmegen, The Netherlands
§Optoelectronics Research Centre, Tampere University of Technology, Tampere, Finland
¶Department of Electronic and Electrical Engineering, University College London, London, United Kingdom

***Abstract*—We report thin-film InAs/GaAs QD solar cells fabricated by epitaxial lift-off of 3-inch wafers containing QD epi-structures with high in-plane QD density. External quantum efficiency measurements demonstrate enhanced QD harvesting in the thin-film configuration. Numerical simulations show that remarkably high increase of the QD photocurrent may be achieved by replacing the planar rear mirror with micro-structured photonic gratings. Measurements of diffraction efficiency of grating prototypes realized on GaAs wafers by nanoimprint lithography are presented.**

***Index Terms*—solar cell, epitaxial lift-off, thin-film, quantum dot, light trapping**

I. Introduction

Quantum dots are very attractive band-engineered materials for the development of high-efficiency single-junction and multi-junction solar cells. Studies of quantum dot solar cells (QDSCs) were motivated by the idea of taking advantage of sub-bandgap transitions to absorb otherwise wasted low energy photons and improve short circuit current [1]. If properly engineered, QDSCs can be exploited to realize the intermediate band operation [2]. Despite their great potential, the improvement in conversion efficiency, if any, with QDs is still marginal. The most challenging issue to demonstrate high-efficiency QDSCs is achieving at the same time a large increase of the short circuit current (J_{sc}) and preservation of high open circuit voltage (V_{oc}). In QDSCs, regardless of their operating regime (thermally-limited or intermediate band), increasing the number of QD layers or the QD density, besides being technologically challenging, causes a larger V_{oc} penalty. Thus, a trade-off exists between maximizing the J_{sc} and conserving the V_{oc}. On the other hand, implementing light-trapping schemes to strongly enhance the QD photon harvesting can yield efficiency comparable to or higher than the one of single-junction cells even for thermally-limited QDSCs [3], and enable the demonstration of QDSCs operating in the intermediate band regime [4].

In this work, we report our recent results in the development of high-efficiency thin-film GaAs cells integrating QDs and photonic nanostructures. These devices can be fabricated using cost-effective and scalable fabrication processes such as Epitaxial Lift-Off [5] for the thin-film processing and NanoImprint Lithography (NIL) to pattern even sub-wavelength period gratings over large areas [6].

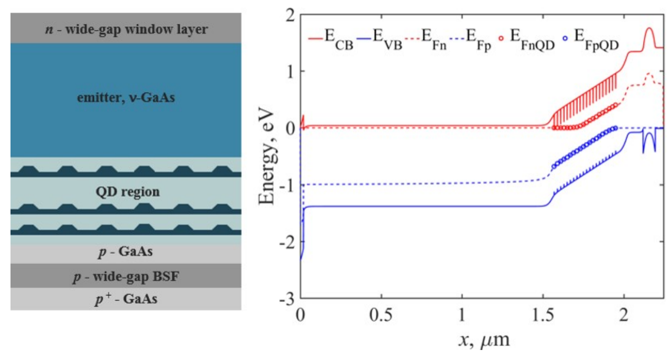

Fig. 1. Cross-section of the analysed QD-based solar cell and calculated energy band diagram at short-circuit condition under AM1.5G illumination.

II. Theoretical background and Experiment

The photovoltaic performance of InAs/GaAs QDSCs are studied within a drift-diffusion framework accounting for the peculiar carrier transfer dynamics between QD states and transport bands [7]. Such cells work in the thermally limited operation, i.e. the second photon absorption is negligible with respect to the thermal escape of carriers from QD states to transport bands, and the V_{oc} is limited by the radiative recombination through the QD ground-state [7]. Such a penalty, which indicatively ranges between 50-250 mV depending on the QD size and effective Ground State (GS) bandgap [8], [7], [9], can be substantially reduced by partially charging the QD states and inhibiting the carrier capture and subsequent recombination through the GS [10], [11], [12]. A further advantage of QD charging is the passivation of defects induced by the strained epitaxy, thus limiting the V_{oc} degradation due to non radiative recombination in real QD solar cells [12]. By combining QD charging and light-trapping, QDSCs with efficiency higher than their bulk counterpart are theoretically feasible [3], [13].

In this work, we adopt a device design based on a deep junction structure with lightly doped emitter and thin base, as shown in Fig.1. The cell behavior is studied for different photonic configurations: a) wafer-based cell (single-pass); b) thin-film cell with planar metallic reflector at the bottom (double-pass); c) thin-film cell with light-trapping scheme yielding in

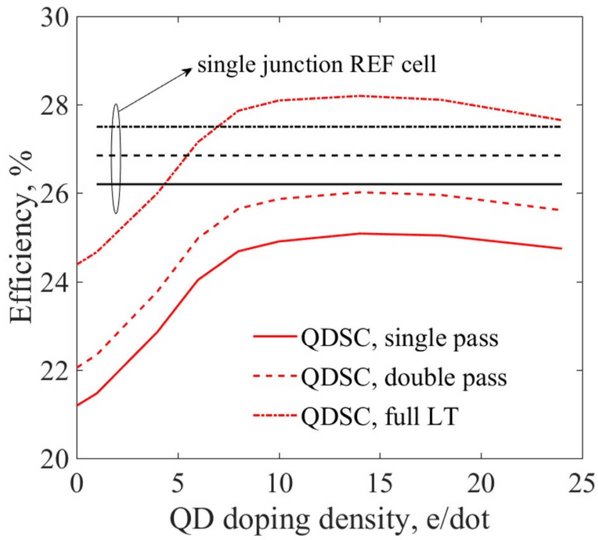

Fig. 2. Efficiency of the QD cell vs. QD doping density for different photonic configurations (see text). The horizontal lines show the efficiency of the reference single-junction cells.

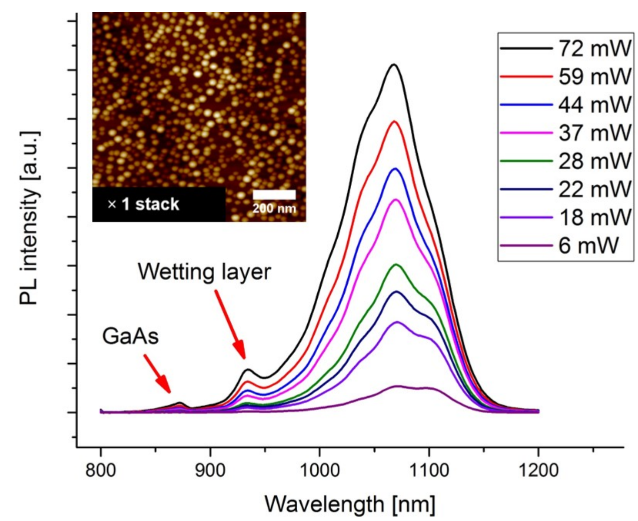

Fig. 3. AFM image of one stack of InAs/GaAs QDs with high in-plane density and photoluminescence spectra at T=300 K and different excitation powers.

the weak absorption limit an optical path enhancement of $2n^2$, n being the GaAs refractive index [3]. QDs are described as a three level system characterized by energy levels identified by the measured photoluminescence spectra (GS bandgap = 1.17 eV) and radiative lifetime of 1 ns [7], [12]. Doping-dependent SRH recombination lifetime of minority carriers is set to 500 ns in the emitter and 20 ns in the base. Fig. 2 shows an overview of the impact of the various photonic configurations and of QD doping (implemented through direct doping) on the achievable efficiency of the QD cells. The efficiency of the corresponding single-junction GaAs cells is also shown. A significant efficiency increase is achieved in both single-junction and QD thin-film cells with respect to their wafer counterpart. Moreover, in the light-trapping configuration, an absolute improvement of about 0.7% is calculated for the thin-film QD cell with optimum doping level (around 14 e/dot) with respect to the thin-film single junction cell.

The fabricated cells include high in-plane density (over 8×10^{10} cm^{-2}, see Fig. 3) QD layers fabricated through the Sb-mediated QD growth technique [14]. Three 3-inch wafers, one for wafer-based processing of the single-junction baseline cell and two for ELO thin-film processing of single-junction and QD solar cells were grown. 3-inch films were released by ELO and processed into cells (area=0.25 cm^2) with planar gold mirror on the backside, as shown in Fig. 4. No ARC was used.

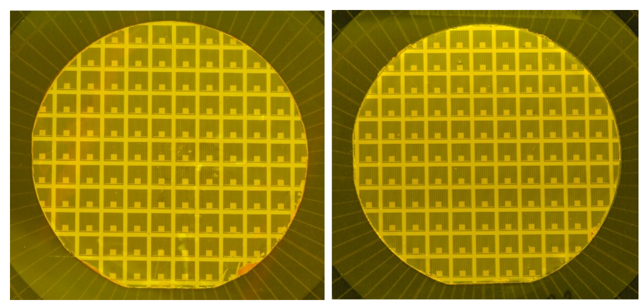

Fig. 4. Single-junction GaAs (left) and QD InAs/GaAs (right) thin-film cells from epitaxial lift-off of 3-inch diameter epi-structures.

III. Results and Discussion

Measured current-voltage characteristics are reported in Fig. 5. The thin-film single-junction and QD cells show comparable $V_{\rm oc}$, with a reduction with respect to the wafer-based cell which is attributed to lattice defects propagating from the substrate to the epilayers. The dark current of all the thin-film cells is in fact dominated by the presence of a diode-like

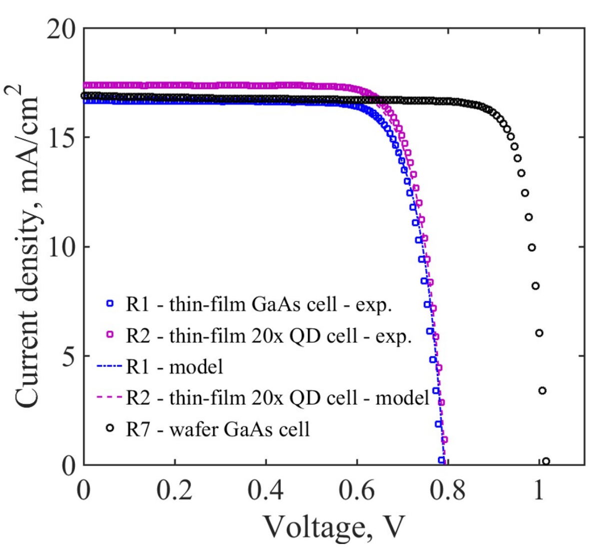

Fig. 5. Current-Voltage characteristics of wafer-based regular GaAs cell and thin-film GaAs and QD cells measured under AM1.5G illumination.

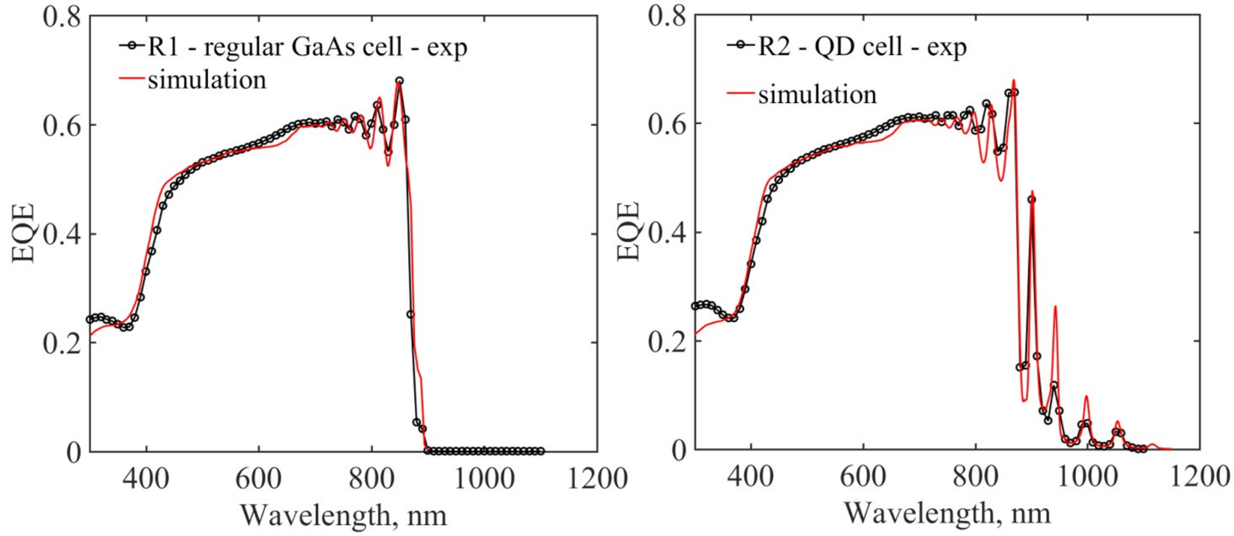

Fig. 6. Measured and simulated EQE spectra of thin-film single-junction GaAs solar cells (left) and thin-film QD solar cells (right).

shunt defect, with reverse saturation current density of about 4 nA/cm^2 and ideality factor of 2.

External Quantum Efficiency (EQE) spectra of the thin-film cells are reported in Fig. 6, showing the typical extension of the EQE in the long wavelength range due to the insertion of QDs: for $\lambda > 880$ nm, the wafer QDSC - not shown here - provided a short-circuit current of about 0.4 mA/cm^2, which increases to 0.6 mA/cm^2 in the thin-film QDSC.

By moving to a micro-structured grating realized on the bottom of the cell, the QD absorbance can be enhanced more significantly. In particular, we are studying diffraction grating configurations where light-trapping is pursued by coupling light into high order diffraction modes propagating outside of the cell escape cone. These gratings require a period length larger than the incident wavelength. Several designs were studied through simulations based on the Rigorous Coupled-Wave Analysis (RCWA) method. The QD photogenerated current was studied as a function of the grating period and height. From the results, the relevant parameter for light-trapping optimization turned to be the aspect ratio (height/period), whose optimum ranges between 0.32 and 0.36 for grating periods between 2-3 μm [15]. By exploiting optimized grating configurations, the simulated absorbance spectra (Fig. 7) show a remarkable increase at the GaAs band edge and in the QD range. With pyramidal gratings, an enhancement of QD photocurrent of about 13 times with respect to the wafer-based configuration is predicted.

Prototype gratings (Fig. 8(a)) were fabricated on a GaAs wafer and diffraction efficiency measured by the scanning angle detector technique (Fig. 8(b)). A comparison between measured and simulated diffraction efficiency of one prototype is reported in Fig. 8(c)-(d) showing good agreement. Significant power coupling to the first two diffraction orders is found. Further optimization of the grating can be carried

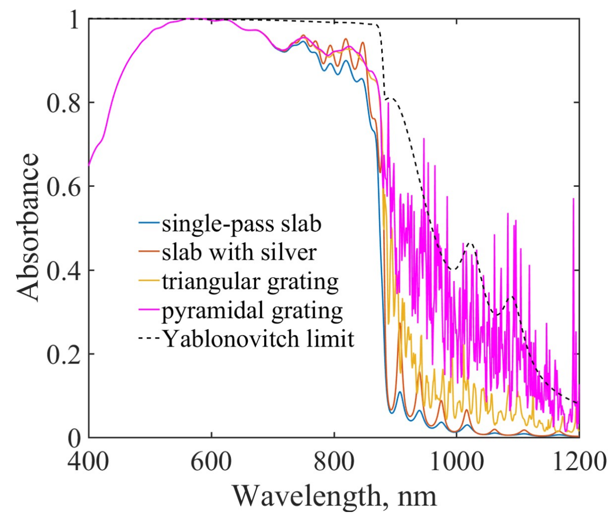

Fig. 7. Calculated absorbance spectra for different photonic configurations. The dashed line indicates the classical Yablonovitch limit [16].

out in order to better match the diffraction spectrum to the QD absorption spectrum. Experimental demonstration of light trapping enhancement by integration of a rear diffraction grating in the thin-film QDSC is ongoing.

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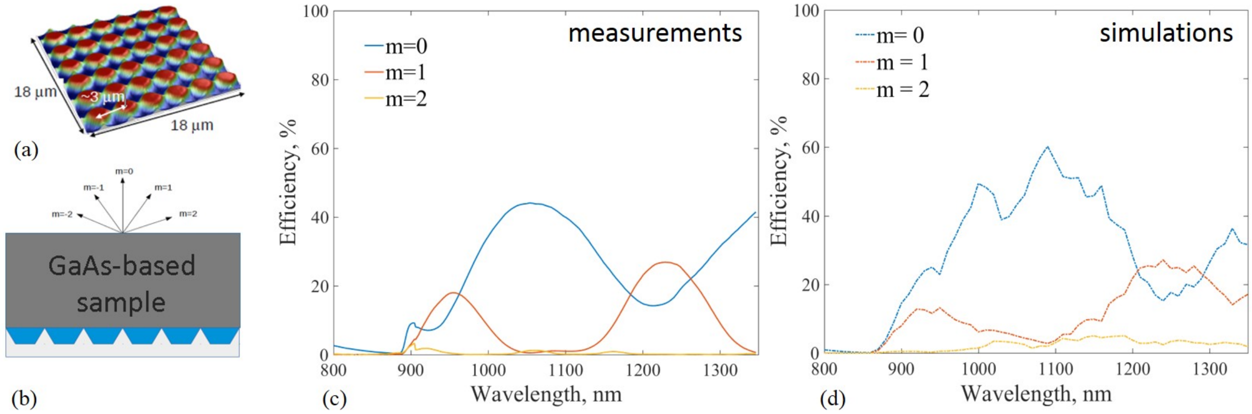

Fig. 8. Profilometer image of back grating of 3 μm period fabricated by NIL (a) and sketch of the prototype samples realized on GaAs wafer (b). Measured (c) and simulated (d) diffraction efficiency.

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