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Light-trapping enhanced thin-film III-V quantum dot solar cells fabricated by epitaxial lift-off

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ABSTRACT

We report thin-film InAs/GaAs quantum dot (QD) solar cells with $n - i - p^{+}$ deep junction structure and planar back reflector fabricated by epitaxial lift-off (ELO) of full 3-in wafers. External quantum efficiency measurements demonstrate twofold enhancement of the QD photocurrent in the ELO QD cell compared to the wafer-based QD cell. In the GaAs wavelength range, the ELO QD cell perfectly preserves the current collection efficiency of the baseline single-junction ELO cell. We demonstrate by full-wave optical simulations that integrating a micro-patterned diffraction grating in the ELO cell rearside provides more than tenfold enhancement of the near-infrared light harvesting by QDs. Experimental results are thoroughly discussed with the help of physics-based simulations to single out the impact of QD dynamics and defects on the cell photovoltaic behavior. It is demonstrated that non radiative recombination in the QD stack is the bottleneck for the open circuit voltage (V_{oc}) of the reported devices. More important, our theoretical calculations demonstrate that the V_{oc} offset of 0.3 V from the QD ground state identified by Tanabe et al., 2012, from a collection of experimental data of high quality III-V QD solar cells is a reliable – albeit conservative – metric to gauge the attainable V_{oc} and to quantify the scope for improvement by reducing non radiative recombination. Provided that material quality issues are solved, we demonstrate – by transport and rigorous electromagnetic simulations – that light-trapping enhanced thin-film cells with twenty InAs/GaAs QD layers reach efficiency higher than 28% under unconcentrated light, ambient temperature. If photon recycling can be fully exploited, 30% efficiency is deemed to be feasible.

1. Introduction

Nanostructured absorbers based on quantum-dots (QD) provide tunable sub-bandgap transitions to enhance the infrared photoresponse of single-junction solar cells [1] and to improve current matching in multijunction cells [2,3]. Also, they offer a promising path towards the development of novel photovoltaics concepts, beyond the Shockley-Queisser (SQ) limit, such as the intermediate band (IB) solar cell [4,5]. By leveraging on second photon absorption or hot phonons, power conversion efficiency well above the SQ limit is theoretically achievable in QD enhanced single-junction cells [5–7].

The most widely investigated structure of QD solar cells (QDSCs) exploits a stack of InAs/GaAs QD layers embedded in a single-junction GaAs solar cell [1]. A clear enhancement of the infrared spectral response is usually observed in these devices, but the maximum demonstrated efficiency (18.7% at 1 sun) [8] lags well behind that one of state-of-art GaAs single-junction cells (28.8% at 1 sun [9,10]), not to mention the gap with respect to the efficiency predicted by the IB theory (≈ 36% for the InAs/GaAs material system at 1 sun). The large discrepancy between demonstrated and theoretical efficiency is often ascribed to the fact that reported devices do not work in the IB operating regime, because at room temperature – and especially under unconcentrated light – the second photon absorption is irrelevant compared to the thermally activated escape. However, for QD cells operating in such thermally-limited regime, a conservative reference value for the attainable efficiency is given by a conventional single-junction cell with bandgap comparable to the optical transition energy of the QD ground state: assuming a band gap of 1 eV (representative of the InAs/GaAs QD system [8]), the SQ limit efficiency is above 30% under 1 sun, a value remarkably higher than the demonstrated 18.7%.

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The issue arises primarily from the weak increase of the short circuit current provided by the inclusion of QDs, owing to the small optical absorption cross-section of the sub-bandgap transitions and the reduced QD volume fraction within the absorbing region. On the other hand, one of the conditions to attain the single-gap SQ limit is complete interband absorptivity, while approaching the IB operating regime requires very high – and similar – interband and intraband photon absorption [11–13]. Detailed balance calculations in [11] show that high efficiency InAs/GaAs QDSCs operating in the IB regime require a total QD density larger than 5×10^{13} cm^{-2}, but present QDSCs usually have a few tens of layers and in-plane density about 5×10^{10} cm^{-2}. Thus, significant research efforts are being carried out to increase the areal density of III-V QDs [14–17] and the number of QD layers [18,19] without compromising crystal quality. In-plane density up to 10^{12} cm^{-2} [17] and number of QD stacks up to 400 [19] have been reported, but QDSCs with both high number of QD layers and high in-plane QD density have not yet been demonstrated. Moreover, present QDSCs often suffer of severe open circuit voltage (V_{oc}) degradation, which tends to get worse as the density or the number of layers are increased [19]. In general, achieving high crystal quality is one of the major technological challenges within QDSC research, since QD-growth induced defects markedly impair the V_{oc} [20,21]. In high-quality QDSCs operating in the thermally-limited regime, experimental [20,8] and theoretical [22,23] works show that the maximum attainable V_{oc} is linearly correlated with the energy band gap of the QD ground state. V_{oc} approaching 1 V has been demonstrated only in 10× and 40× QD layer cells (with shallow QDs and in-plane density well below 10^{11} cm^{-2}) by implementing complex strain compensation techniques during the epitaxial growth [24–26].

A promising alternative (and even somewhat complementary) path to effectively enhance QD photogeneration is offered by light management schemes that can be implemented within a thin-film solar cell architecture [27,26,28]. Thin-film III-V technologies based on epitaxial lift-off (ELO) [29,30,9] are among the most promising approaches in view of the remarkable reduction of mass and cost (because ELO makes possible wafer reuse), and flexibility. Moreover, photon trapping and recycling enabled by the thin-film design have been proven to be essential to push the efficiency of III-V single-junction cells towards the SQ limit [31–33], and are in fact at the root of the world-record 28.8% efficiency held by an ELO thin-film GaAs cell with planar mirrored rear surface [9,10]. ELO thin-film InAs/GaAs QD cells with planar rear mirror were first reported in [34,35]. More recently, ELO thin-film cells with textured back surface reflectors have been reported in [26], demonstrating a 30% increase of QD current contribution compared to a cell with planar reflector. Effective light-trapping by back side periodic grooves has been demonstrated in multiple quantum well solar cells in [36], attaining a fivefold increase of the sub-bandgap optical path length.

In this work, we report thin-film InAs/GaAs QD solar cells fabricated by epitaxial lift-off of full 3-in wafers. Nearly doubled QD photocurrent is demonstrated in the thin-film ELO QD cell with planar gold mirror with respect to a baseline wafer-based QD cell. Moreover, collection efficiency within the GaAs wavelength range is perfectly preserved in the ELO QD cell compared to the ELO baseline single-junction cell. Solar cell performance are analyzed with the support of device-level physics-based simulations, with the aim at providing an assessment of the needs in terms of material optimization and QD photogeneration enhancement to attain high efficiency InAs/GaAs QDSCs. The practical implementation of photonic structures able to provide the desired high QD sub-bandgap harvesting is discussed based on rigorous wave-optics simulations of broadband antireflection coatings and diffraction gratings that can be fabricated by patterning the front and rear surface of the thin-film cell.

The rest of the paper is organized as follows. Section 2 summarizes the details of device fabrication and characterization, while Section 3 describes the theoretical background and numerical tools used for the analysis of experimental results and the design of light-trapping enhanced cells. The experimental results of wafer-based and thin-film ELO cells are discussed in Section 4.1 and 4.2, respectively, with the help of physics-based simulations. Finally, in Section 4.3, the performance of thin-film QD cells integrating photonic structures are discussed based on transport and full-wave electromagnetic simulations.

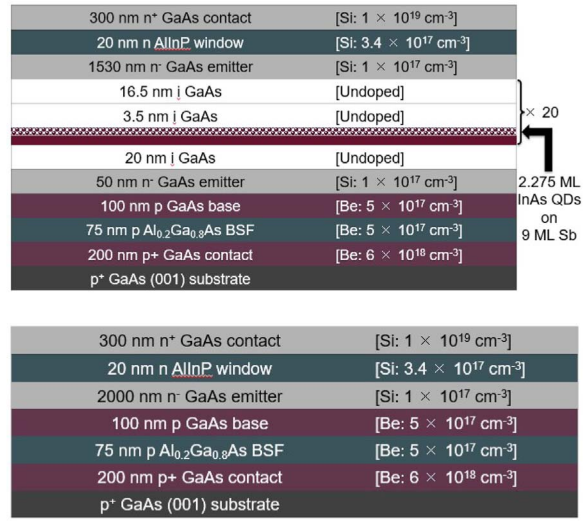

Fig. 1. Sketch of the epilayer structure of the 20 × InAs/GaAs QD layers (top) and regular GaAs (bottom) solar cells. In the 50× QD cell (not shown) the topmost part of the emitter has a reduced thickness of 930 nm to keep the whole emitter (topmost doped region + intrinsic QD stack + bottom emitter region) thickness to ≈ 2 μm.

2. Material and methods

QD and regular GaAs cells with a deep junction design with lightly *n*-doped emitter and thin *p*-doped base are studied. Several batches of wafers, both for wafer-based processing and for ELO thin-film processing, were grown by molecular beam epitaxy (MBE). Fig. 1 reports the detailed epilayer structure for the wafer-based InAs/GaAs QD and regular GaAs solar cells. The QDSCs exploit high in-plane density (over 8×10^{10} cm^{-2}) InAs/GaAs QD layers fabricated through the Sb-mediated QD growth technique, following the method already demonstrated in [16]. The QD periodic stack is placed in the bottom part of the emitter and uses 20 nm thick spacer layers of intrinsic GaAs. Samples with 20× and 50× QD layers were fabricated. All the cells – GaAs-only and QD-based – have a total emitter thickness of ≈ 2 μm. For the thin-film configuration the epilayer structures were identical, except for the window and back surface field layers which were made by InGaP, and the inclusion of ad-hoc release and etch stop layers for the ELO processing. The ELO thin-film processing was performed as described in detail in [37]. Because the cell structures were only produced for mutual comparison no efforts were made to optimize the front grid contact coverage or to apply an ARC to minimize the reflection from the front surface. The thin-film cells exploit a planar gold mirror on the backside.

$I - V$ characterization of the solar cells was performed using an ABET Technologies Sun 2000 Class A solar simulator, which provides homogeneous illumination over a 100 × 100 mm^2 area. An Ushio 550 W Xenon short arc lamp is used to approximate the AM1.5 spectrum. The setup is equipped with a Keithley 2600 sourcemeter and data acquisition is performed using ReRa Tracer3 software. The solar cells are kept at 25 °C during measurement by water cooling. External Quantum Efficiency (EQE) measurements were performed with a ReRa SpeQuest Quantum Efficiency system. Data acquisition is performed using ReRa Photor 3.1 software. The system uses both a Xenon and halogen light source to access all wavelengths present in the solar spectrum. A monochromator is used to generate quasi-monochromatic light and a chopper for intensity modulation. This generates a test light of variable