# Enhancement of EQE for MBE grown InAs/GaAs Quantum Dot Solar Cell with Back Reflector

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***Abstract* — We report on molecular beam epitaxy grown InAs/GaAs quantum dot solar cells incorporating thin-film configuration with back surface reflectors. External quantum efficiency measurements reveal two times higher current generation for the quantum dots with the thin-film solar cell with the back reflector compared to a standard reference solar cell without back reflector. A high open-circuit voltage of 0.884 V is demonstrated. Furthermore, the benefits of using more advanced designs for a back reflector employing pyramidal diffraction gratings are discussed.**

***Index Terms* — III-V solar cell, back reflector, diffraction gratings, external quantum efficiency, molecular beam epitaxy, quantum dot solar cell.**

## I. INTRODUCTION

Quantum dot (QD) heterostructures provide an attractive choice to extend the solar spectral response of single-junction GaAs solar cells [1] or a tailorable spectral response for implementation as sub-junctions in multijunction solar cells [2]. To date, solar cells with InAs QDs embedded in GaAs have been widely investigated. To achieve reasonable photon absorption, a high number of QD sheets and a high QD density are required. Fabrication of such devices is challenging due to defects formed in the crystal structure during the epitaxial growth [3]. In addition, the open circuit voltage ($V_{oc}$) of QD solar cells (QDSCs) tends to be lower compared to GaAs solar cells without QDs [4]. One solution to alleviate these issues is to grow fewer QD sheets and simultaneously apply a reflector on the backside of the QD solar cell. With this, the photocurrent generation in the QD sheets can be increased and the $V_{oc}$ of the GaAs SCs can be maintained, leading to higher efficiencies. This configuration requires thin-film design employing substrate removal. In turn, a thin-film architecture provides additional benefits in applications where flexibility and high power-to-weight ratio are needed, such as space power systems and unmanned aerial vehicles. Moreover, they make possible the reutilization of the substrates, which are a major cost section of III-V solar cells.

With highly reflective planar back surface reflectors, the length of the optical path in the photogeneration layers can be effectively doubled. Metallic planar reflectors have been proposed for different type of III-V solar cell architectures, as for example demonstrated in [5], [6]. To further enhance the absorption in the photogeneration layers, diffractive gratings with reflector can be applied on the backside of the solar cells. These gratings could be fabricated either into the back surface field (BSF), into a dielectric material, or into a polymer. The effect of different types of diffraction gratings have been also reported [7].

Here, we analyze the response of InAs/GaAs QDSCs grown by molecular bean epitaxy (MBE) and incorporating a backside planar reflector. The solar cells are processed as a standard substrate based design as well as a thin-film configuration. For the implementation of the back reflector, we investigated contacts based on Ti/Au, Au, and Ag, and their suitability to offer high reflectivity and good conductivity was assessed. Secondly, pyramidal gratings were fabricated and their diffraction properties were shown to be high, indicating that they could be integrated together with a reflector in QDSCs in order to further enhance the absorption efficiency of thin-film structures.

## II. EXPERIMENTAL SETUP

The InAs/GaAs QDSCs were grown by MBE employing a shallow junction design with n-doped emitter and p-doped base; the structure is schematically described in Fig. 1.

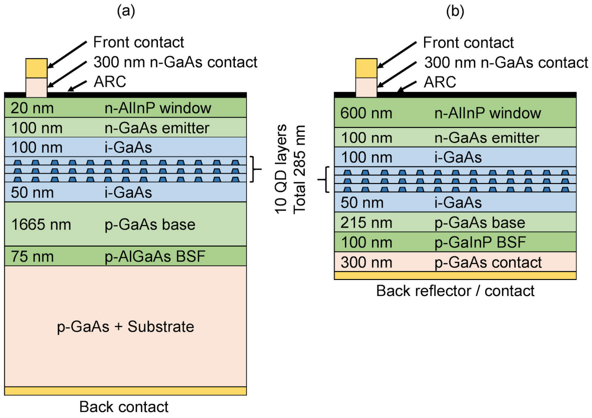

Fig. 1. Schematic drawing of the QDSCs studied.

The QD stack included 10 QD layers with in-plane density of ~6×$10^{10}$ $cm^{-2}$, and being separated by ~30 nm GaAs. The total thicknesses of the photogeneration layer were 2.20 µm and 0.75 µm for the substrate QDSC and the thin-film QDSC with the back reflector, respectively. Despite the differences in the structure, the comparison of the QD photocurrent generation is valid, the QD stack being the same in the two samples and the expected $V_{oc}$ is comparable.

### *A. Back reflectors*

The planar back reflectors were optimized on the backside of double-side polished semi-insulating GaAs wafers. Specular reflectance was measured with PerkinElmer spectrophotometer. The detailed fabrication process and characterization of the reflectors is described in [8]. In addition to planar reflectors, pyramidal diffraction gratings were fabricated into polymer, covered with an Ag reflector. To define the diffused reflectance, total and specular reflectance spectra were measured with integrating sphere and URA modules of PerkinElmer spectrophotometer, respectively. Moreover, the effect of the pyramidal grating on the reflectance was simulated. More detailed description of the grating structures are presented in [9].

### *B. Processing of the solar cells*

The QDSC epi-structures were processed either with the substrate or as a thin-film. For the substrate based SC, the front contact Ni/Au and back contact Ti/Au metals were deposited by electron beam (e-beam) evaporation using a shadow mask. Prior to the deposition of a $TiO_2/SiO_2$ antireflection coating (ARC) by e-beam evaporation, the contact GaAs layer was removed by selective wet etching. Regarding the thin-film QDSCs with the planar back reflector, the fabrication involved more steps described next. First, the planar Au, Pt, and Au were deposited on top of the contact GaAs layer by e-beam evaporation to act as a reflector, a diffusion barrier, and a bonding contact layer, respectively. Subsequent to the metal deposition, the QDSC was bonded to a carrier with Au layer on top. The QDSC was thinned down to the thickness of ~100 µm with a Logitech PM5 Precision lapping machine and the rest of the substrate was removed with wet etching solution. Front contacts were fabricated by e-beam evaporation using photolithography lift-off process. In addition, the solar cells were electrically isolated with wet etching using a photoresist mask. Finally, the contact GaAs was wet etched and $TiO_2/SiO_2$ ARC was deposited on top of the cell by e-beam evaporation.

### *C. Electrical characterization*

EQEs of the QDSCs were measured with a setup equipped with a 250 W quartz tungsten halogen lamp. The narrow excitation wavelength span for the probe beam was selected by using a Digikrom DK240 monochromator and an 800 nm long-pass filter. The QDSCs and a NIST-calibrated Ge reference detector were measured using an SRS SR830 lock-in amplifier and chopped light.

Current-voltage (IV) characteristics were measured with an OAI solar simulator using AM1.5D spectrum (1000 W/m$^2$). During the measurements, the solar cells were kept at 25 °C.

## III. RESULTS AND DISCUSSIONS

The reflectance results of the metal back reflectors are presented in Fig. 2(a). The conventional Ti/Au back contact showed a reflectance of 40% in the wavelength range of InAs QDs. However, with the Au reflector the reflectance can be increased to ~70%, thus being a more suitable back reflector. The Ag reflector showed the highest reflectance and it will be applied to our further back reflector processes.

The pyramidal gratings in Fig. 2(b) showed diffuse reflectance of ~65%, which is at an appropriate level to increase the length of the optical path in photogeneration layers even more than with planar reflectors. The simulations of the total reflectance of the pyramidal grating were ~10 percentage points lower than measured since the simulations probably overestimated the losses in the structured metallic reflector.

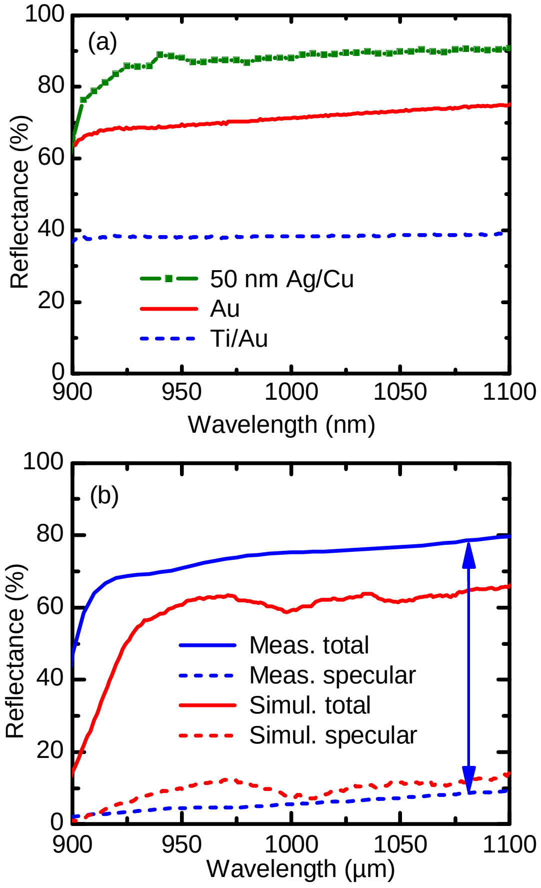

Fig. 2. (a) Reflectance of the planar back reflectors; (b) Measured and simulated reflectance of the pyramidal back gratings. The blue double-headed arrow represents the diffused reflectance.

The measured EQE results, presented in Fig. 3(a), showed an increased photogeneration in the QDSC with the back reflector when compared to the substrate based QDSC. The photocurrent density ($J_{sc}$), originating from the QDs, was calculated by integrating the EQE over the AM1.5D spectrum (1000 W/m$^2$) for the wavelength range of 900-1100 nm, resulting in $J_{sc}$ of 0.17 mA/cm$^2$ and 0.35 mA/cm$^2$ for the substrate QDSC and QDSC with the back reflector, respectively. Thus, the QDSC with the back reflector produces two times higher current generation. However, the substrate QDSC has a thicker p-GaAs base, which may reduce the charge carrier collection, potentially resulting in a decrease in the EQE for QDs.

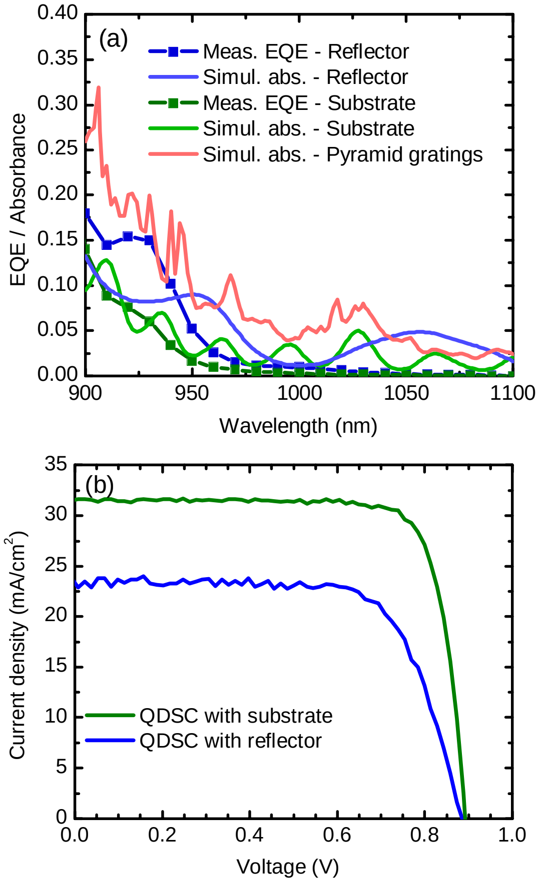

Fig. 3. (a) Measured EQE results and simulated absorbance results of the QDSCs; (b) IV results of the QDSCs.

The absorbance spectrum of the QDSCs was simulated by using the rigorous coupled wave analysis method and is presented in Fig. 3(a). Simulated results provide a qualitative benchmark since the optical absorption model of the QDs was calibrated for a previous generation of samples [10]. The simulations showed that with pyramidal grating, the $J_{sc}$ from the QDs is the highest. The maximum $J_{sc}$ estimated from the absorbance spectra are 0.34 mA/cm$^2$, 0.47 mA/cm$^2$, and 0.81 mA/cm$^2$ for the substrate QDSC, the QDSC with the back reflector, and the QDSC with pyramidal gratings, respectively. The $J_{sc}$ values predicted by the simulated absorbance might be higher than the measured ones also because simulations assume unitary charge carrier collection efficiency.

The measured IV characteristics are presented in Fig. 3(b) and the corresponding data are collected into Table I. The QDSC with the back reflector has $V_{oc}$ closely comparable to that one of the substrate QDSC, verifying that the high $V_{oc}$ is preserved during the thin-film process. The $V_{oc}$ of 0.884 V achieved by the QDSC with the back reflector is high when compared to reported values for thin-film QDSCs [10], [11]. The significant difference of $J_{sc}$ between the two QDSCs is mainly attributed to the differences in the cell structures. For example, the QDSC with the back reflector has a 600 nm thick window layer, which absorbs photons lowering the $J_{sc}$. In addition, the thicker p-GaAs base can explain the high $J_{sc}$ of the substrate QDSC compared to the QDSC with the back reflector.

TABLE I

RESULTS OF IV MEASUREMENTS

| **Sample** | $J_{sc}$ (mA/cm$^2$) | **FF** (%) | $V_{oc}$ (V) | **η** (%) |
|---|---|---|---|---|
| QDSC with reflector | 23.4 | 71 | 0.884 | 14.7 |
| QDSC with substrate | 31.5 | 80 | 0.892 | 22.4 |

## IV. SUMMARY OF THE WORK

The effect of planar back reflectors on the performance of the MBE grown InAs/GaAs thin-film QDSCs was assessed. The photocurrent generation in the QD layers increased by a factor of two in the thin-film configuration with the back reflector with respect to the substrate QDSC. Simulations showed that even higher photocurrent generation in QD layers could be achieved by implementing pyramidal diffractive gratings as backside reflector. The thin-film QDSC with the planar back reflector exhibited a $V_{oc}$ of 0.884 V, which is amongst the highest values reported for MBE-grown QDSCs.

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