

# Enhancement of GaAs solar cell efficiency by type-II GaSb quantum dots located outside of the depletion region

A. Kechiantz<sup>\*,&</sup>, A. Afanasev<sup>\*</sup>, J.-L. Lazzari<sup>\*\*,\*</sup>

<sup>\*</sup>Department of Physics, The George Washington University, 725 21st Street, NW, Washington, DC, 20052, USA; [kechiantz@gwu.edu](mailto:kechiantz@gwu.edu); [afanas@gwu.edu](mailto:afanas@gwu.edu)

<sup>\*\*</sup>Centre Interdisciplinaire de Nanoscience de Marseille, CINaM, UMR 7325 CNRS – Aix-Marseille Université, Campus de Luminy, Case 913, 163 Avenue de Luminy, 13288 Marseille Cedex 9, France; [lazzari@cinam.univ-mrs.fr](mailto:lazzari@cinam.univ-mrs.fr)

<sup>&</sup>On leave of absence: Institute of Radiophysics and Electronics, National Academy of Sciences, 1 Brothers Alikhanyan st., Ashtarak 0203, Armenia; [mrs\\_armenia@yahoo.com](mailto:mrs_armenia@yahoo.com)

## ABSTRACT

We present a model of a new GaAs intermediate band (IB) solar cell with strained GaSb/GaAs type-II quantum dot (QD) absorber. This absorber is placed within the p-doped part of the cell such that it is spatially separated from the depletion region. We use the continuity equations along with the detailed balance principle and take into consideration the non-radiative recombination through IB-states to calculate both photocurrents and conversion efficiency of the IB cell. Our calculation shows that the newly proposed design may increase the efficiency of GaAs solar cells from 30% to 50% in response to concentration of sunlight from 1-sun to 500-sun. Noteworthy, though non-radiative recombination in QDs degrades the efficiency, it is still above the Shockley-Queisser limit by 5% to 10%.

**Keywords:** intermediate band, quantum dot, GaAs/GaSb, solar cell, two-photon absorption

## 1 INTRODUCTION

The well-developed economies aim to partially substitute their production of electricity starting from oil or nuclear origin with that of ecologically clean renewable sources like solar energy for reducing their dependence on oil- and uranium-producing nations. This makes imperative the development of third generation solar cells with higher efficiencies and lower costs. Sustained progress in development of these solar cells is firmly connected with involvement of nanotechnology as well as new ideas and physical effects into photovoltaics.

In 1997, A. Luque and A. Marti offered to involve the effect of two-photon absorption to the generation of additional photocurrent in semiconductor single-junction solar cells [1]. For enforcing this non-linear optical effect, they suggested two-photon resonant absorption via intermediate band (IB) electronic states embedded into the absorber. The effect benefits from concentration of incoming light. This work attracted much attention because

it showed that, in principle, the two-photon absorption allows to achieve 63% conversion efficiency in IB solar cells, which is much more than the Shockley-Queisser limit, 37%.

However, the experiments have shown that extrinsic IB states, for instance, formed by artificial QDs imbedded in the depletion region of p-n-junction, facilitate electron-hole recombination [1]. The latter dramatically increases the dark current and reduces the open circuit voltage of IB solar cells.

In this report we present a model of a new GaAs IB solar cell with strained GaSb type-II QD absorber. This absorber is placed within the p-doped part of the cell such that it is spatially separated from the depletion region. We use the continuity equations along with the detailed balance principle and take into consideration non-radiative recombination through IB-states to calculate both photocurrents and conversion efficiency of the proposed IB cell.

## 2 TYPE-II QD ABSORBER

The depletion region is the most sensitive part of solar cells. We already showed that the built-in field of depletion region might facilitate recombination through QD IB electronic states [2]. We also showed that spatial separation of IB-states from the depletion region adds more flexibility to the cell design in sense of improving the device characteristics [3]. In particular, the separation eliminates dark current leakage through IB-states. It may also limit recombination through IB-states so much that moderate concentration of incoming sunlight may essentially increase the additional photocurrent generated by the two-photon resonant absorption in QDs.

The key idea of the proposed IB solar cell is spatial separation of the type-II QD absorber of sub-band gap photons from the depletion region of ideal p-n-junction. The separation is illustrated in Figure 1 of the energy band diagram. A thin p<sup>+</sup>-doped Al<sub>x</sub>Ga<sub>1-x</sub>As buffer layer grown on an n<sup>+</sup>-doped GaAs substrate separates the QD absorber from the p<sup>+</sup>-doped Al<sub>x</sub>Ga<sub>1-x</sub>As cap layer. The QD absorber

is an epitaxial stack comprising GaSb strained QD layers alternating with p-doped  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  spacers.

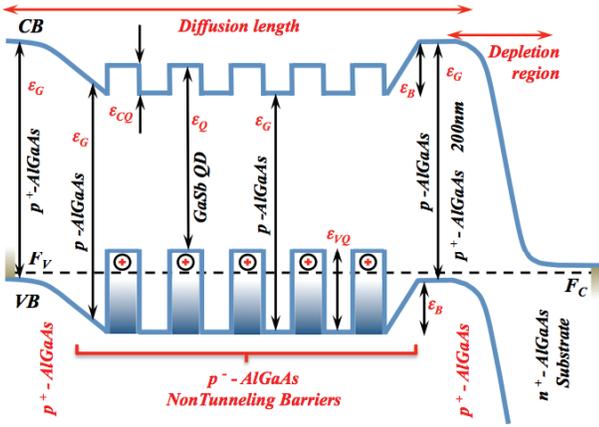


Figure 1. Energy band diagram of GaSb/AlGaAs type-II QD absorber spatially separated from the p-n-junction in IB solar cell.

All layers of the stack are within the electron diffusion length distance from the depletion region. The spacers compose non-tunneling barriers surrounding QDs in the valence band. The buffer and the substrate compose an ideal p-n-junction. The buffer also prevents direct electron tunneling through the p-n-junction into electronic states confined in QDs.

Since the absorber is about un-doped, injection of holes from the  $p^+$ -doped  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  cap and buffer layers equalizes Fermi level across the cell and determine the density of holes in the absorber region. Such injection of holes lowers by  $\epsilon_B$  the conduction and valence band edges in absorber relative to that in  $p^+$ -doped  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  buffer layer as shown in Figure 1. Therefore, the density of mobile holes is  $\exp(\epsilon_B/kT)$  times less in absorber than that in the buffer layer. Another consequence of the lowering of the band edges is that photoelectrons generated in absorber face blocking barrier  $\epsilon_B$  in conduction band on their way to the p-n-junction. This  $\epsilon_B = \psi_B - \psi_A$  blocking barrier is given by the Poisson equation

$$\frac{\partial^2 \psi}{\partial x^2} = \frac{2kT}{L_{Deb}^2} \left( 1 - \exp \frac{\psi_A - \psi + eV}{kT} + \frac{n_A^2}{N_A^2} \exp \frac{\psi - \psi_A}{kT} \right) \quad (1)$$

where  $\psi(x)$  is the conduction band edge bending,  $\psi_B$  is the edge in the buffer,  $\psi_A$  is the edge in the absorber,  $N_A$  and  $L_{Deb}$  are the doping and the Debye length in absorber.

Due to the type-II misalignment of energy bands shown in Figure 1, conduction band electrons also face  $\epsilon_{CQ}$  offset-barrier that spatially separates them from holes confined in QDs. Such spatial separation slows down the non-radiative recombination lifetime of conduction band electrons with holes confined in QDs. In GaSb/GaAs strained type-II QD system, the lifetime becomes 10 ns [5]. It is important that the  $\epsilon_{CQ}$  offset-barriers do not limit electron diffusion in

conduction band of absorber as shown in Figure 2.

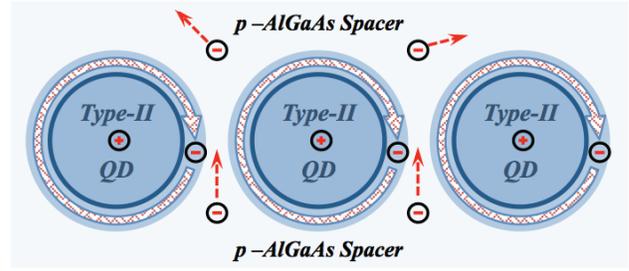


Figure 2. A schematic picture of the conduction band in absorber of the proposed solar cell. GaSb type-II QDs are sandwiched between p-doped  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  spacer layers so that electrons can pass between QDs.

Illumination with concentrated sunlight changes the band bending and splits the Fermi level of proposed IB solar cell. The energy band diagram shown in Figure 3 displays the change in the band bending and quasi-Fermi levels of mobile electrons in the conduction band  $F_C$ , mobile holes in the valence band  $F_V$ , and the holes confined in QDs  $F_Q = F_V + \mu_Q$ . The red dashed arrows denote the photon absorptions resulting in electron-transfers to higher energy states.

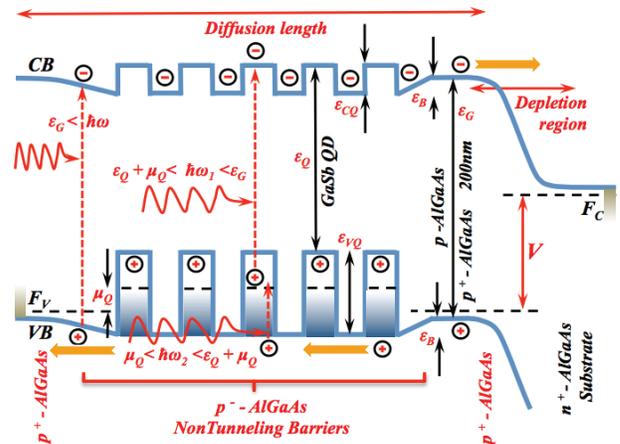


Figure 3. Energy band bending in proposed GaSb/GaAs type-II QD IB solar cell under concentrated sunlight illumination. Accumulation of generated electrons in the conduction band of absorber and holes in the buffer moves up the conduction and valence band edges of the absorber, which reduces the blocking barrier  $\epsilon_B$  as compared to that shown in Figure 1.

Mobile holes generated in the valence band of absorber swiftly diffuse from QDs into the  $p^+$ -doped  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  cap layer while a positive charge accumulated in the  $p^+$ -doped  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  buffer layer balances the diffusion of those holes into the buffer. Mobile photoelectrons generated in

the conduction band of QDs swiftly escape from the top of the  $\varepsilon_{CQ}$  offset-barrier into the  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  spacers and relax to the conduction band edge there. Since photoelectrons accumulate in the conduction band of the QD absorber, their negative charge reduces the blocking barrier  $\varepsilon_B$  so much that generated photoelectrons may pass through the depletion region as shown in Figure 3.

In the case of graded  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  spacers in absorber, a drift driven by the pulling field of the spacers may enforce photoelectron diffusion so much that they pass through the  $1\mu$  thick absorber in  $0.1\text{ns}$ , which is much shorter than their inter-band recombination lifetime,  $1\text{ns} - 10\text{ns}$  [5].

### 3 CURRENTS

The photocurrent  $j$  generated in QD IB solar cell consists of two components, which are the photocurrent  $j_C$  generated due to absorption of the above-band gap photons directly in the conduction band and the additional photocurrent  $j_Q$  generated due to the two-photon absorption of sub-band gap photons in QDs,

$$j = j_C + j_Q \quad (2)$$

Lets refer  $C$  to the conduction band,  $V$  to the valence band,  $Q$  to QDs,  $S$  to the solar irradiation, and  $N$  to the non-radiative electron transition so that e.g.  $j_{CV}$  denotes radiative electron transitions from the conduction band into the valence band while  $j_{NQV}$  denotes non-radiative electron transitions from QD confined states into the mobile hole states in the valence band. Assuming absorption of all incoming solar photons in each of  $[\varepsilon_i, \varepsilon_j]$  spectral ranges, one can use the principle of detailed balance to reduce currents generated by radiative electron transitions to integrals  $j_{ji} \exp(\mu/kT)$  [4], where  $j_{ji}$  is

$$j_{ji} = \frac{2eX}{h^3 c^2 GF} \int_{\varepsilon_i}^{\varepsilon_j} \frac{\exp[-(\mu)/kT] \varepsilon^2 d\varepsilon}{\exp[(\varepsilon-\mu)/kT]-1} \quad (3)$$

For electron transitions related to solar photon absorption,  $X$  is the concentration of solar light,  $\mu = 0$ , and  $GF = 4.6 \times 10^4$  is the geometrical factor related to the angle that Earth is seen from Sun. For radiative recombination related to photon emission from the solar cell,  $X = GF = 1$  and  $\mu$  is the splitting of the relevant quasi-Fermi levels.

Since the conduction band electrons have the same quasi-Fermi level in both n- and p-doped sides of the p-n-junction, the non-radiative currents can be written as

$$j_{NQV} [1 - \exp(-\mu/kT)] \quad (4)$$

$$j_{NCQ} [1 - \exp\{(eV - \mu)/kT\}] \quad (5)$$

where currents  $j_{NQV} = (ep_0 n_Q \Omega L / \tau_{ph}) \exp(-\varepsilon_B/kT)$  and  $j_{NCQ} = (en_i^2 L / p_0 \tau_c) \exp(\varepsilon_B/kT)$  are linked with QDs;  $p_0$  is the concentration of holes in the cap and buffer  $p^+$ -doped

layers;  $n_Q$  is the density of QDs;  $\Omega$  is the volume of QD;  $n_i$  is the intrinsic concentration of carriers in  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  spacers in absorber;  $L$  is the thickness of the absorber;  $\tau_{ph}$  is the lifetime of intra-band relaxation in QDs due to inelastic scattering of holes on optical phonons;  $\tau_c$  is the lifetime of non-radiative inter-band recombination through QDs;  $\mu = F_Q - F_V$  is the split of quasi-Fermi level in QD;  $kT$  is the temperature of the cell; and  $V = F_C - F_V$  is the bias voltage.

Balance  $j_C = j_{VC} - j_{CV}$  of  $j_{VC}$  and  $j_{CV}$  currents yields the same expression for the photocurrent  $j_C$  as it is for the conventional solar cells without QDs,

$$j_C = j_{SV C} - j_{CV} [\exp(eV/kT) - 1] \quad (6)$$

Balance  $j_Q = j_{SVQ} - j_{QV} - j_{NQV}$  of  $j_{SVQ}$ ,  $j_{QV}$  and  $j_{NQV}$  currents yields the net photocurrent into QDs from the valence band. The similar balance  $j_Q = j_{SQC} - j_{CQ} - j_{NCQ}$  of  $j_{SQC}$ ,  $j_{CQ}$  and  $j_{NCQ}$  currents yields the net photocurrent from QDs into the conduction band. Both net currents are equal to the additional photocurrent  $j_Q$  generated due to the type-II QDs in proposed IB solar cell,

$$j_Q = j_{SQC} - (j_{CQ} + j_{NCQ}) \left( \exp \frac{eV - \mu}{kT} - 1 \right) \quad (7)$$

$$j_Q = j_{SVQ} - j_{VQ} \left( \exp \frac{\mu}{kT} - 1 \right) - j_{NQV} \left( 1 - \exp \frac{-\mu}{kT} \right) \quad (8)$$

where  $j_{NCQ} \sim \exp(\varepsilon_B/kT)$  and  $j_{NQV} \sim \exp(-\varepsilon_B/kT)$ .

### 4 RESULTS AND DISCUSSION

In addition to the radiative electron transitions discussed in [1], in this work we include into consideration non-radiative electron transitions associated with QDs, namely, the inter-band recombination of the conduction band electrons with holes confined in QDs and the intra-band relaxation of holes in QDs due to inelastic scattering of holes on optical phonons. Solution of Equations (1) - (8) yields the photovoltaic characteristics of such IB solar cell with GaSb/AlGaAs strained type-II QD absorber spatially separated from the depletion region. Our calculation shows that both non-radiative transitions increase the dark current. However, we showed earlier [6] that the rate of these non-radiative transitions could be reduced if the QD absorber is spatially separated from the depletion region.

Figure 4 displays the photocurrent  $j$  of proposed IB solar cell as a function of the bias voltage  $V$ . The shape of photo and dark  $j - V$  curves of ideal p-n-junctions must be congruent. However, in case of proposed IB solar cell the congruency is broken as shown in Figure 4. This occurs due to accumulation of negatively charged photoelectrons in the QD absorber spatially separated from the depletion region.

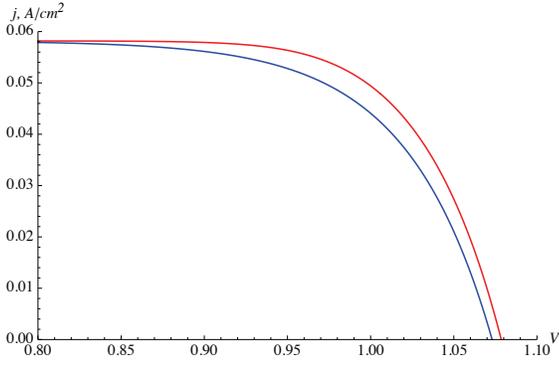


Figure 4: Current-voltage plot of proposed GaSb/GaAs type-II QDs IB solar cell. The dark current (blue curve) is superimposed on the photocurrent (red curve).

The conversion efficiency  $\eta$  of proposed QD IB solar cell shown in Figure 5 rises with sunlight concentration  $X$  for two reasons. First, the concentration supports generation of additional photocurrent by the two-photon absorption of sub-band gap photons. Second, it lowers the blocking barrier,  $\varepsilon_B$ , so much that enables transfer of photoelectrons through the buffer layer from the absorber into the depletion region.

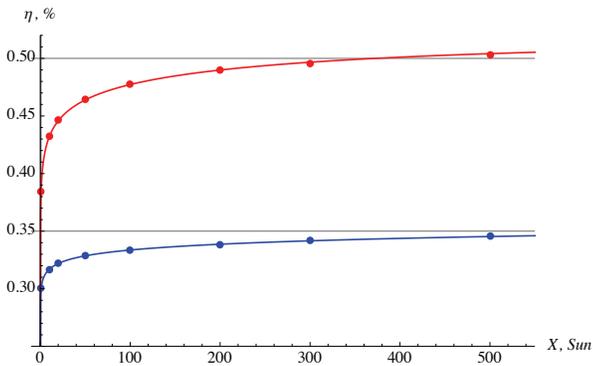


Figure 5. Shockley-Queisser limit for GaAs solar cell (blue dots) and the conversion efficiency  $\eta$  of proposed GaSb/GaAs QD IB solar cell (red dots) as a function of sunlight concentration  $X$ . Solid lines are guide for eyes.

Figure 5 shows that concentration of sunlight from 1 to 500-suns raises the conversion efficiency of proposed IB solar cell from 30% to 50%. Our calculation shows that further concentration has little effect since in ideal case about 300-sun concentration reduces the blocking barrier  $\varepsilon_B$  to the thermal energy of mobile carriers  $kT$ . Such barrier is so small that the efficiency meets the Luque-Marti limit.

## 5 CONCLUSIONS

In conclusion we have studied photovoltaic performance of GaSb/GaAs type-II QD absorber spatially separated from the depletion region of p-n-junction in IB solar cell. Such absorber enables generation of additional photocurrent by

resonant two-photon absorption of concentrated sunlight. The additional photocurrent strongly correlates with the blocking barrier  $\varepsilon_B$  and accumulation of charge in absorber. Our calculation shows that the newly proposed design may increase efficiency of GaAs solar cells from 30% to 50% in response to concentration of sunlight from 1-sun to 500-sun. Further concentration has little effect since in ideal case about 300-sun concentration reduces the blocking barrier  $\varepsilon_B$  to the thermal energy of mobile carriers  $kT$ . Such barrier is so small that the efficiency meets the Luque-Marti limit. Noteworthy, though non-radiative recombination in QDs degrades the efficiency, it is still above the Shockley-Queisser limit by 5% to 10%. Other possibilities may be considered for the absorber composition. Another option would be  $\text{Al}_y\text{Ga}_{1-y}\text{Sb}$  QDs embedded within a gradual  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  absorber ( $0 < x = y < 0.40$ ).

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