# CONTRIBUTION OF TYPE II QUANTUM DOTS INTO DARK CURRENT IN INTERMEDIATE-BAND SOLAR CELLS

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## 1. Introduction

The concept of intermediate-band (IB) solar cells (SC) offered the promise of achieving higher conversion efficiency devices than the multi-junction SCs [1]. Like the conventional solar cells, IB SCs exploit one-photon absorption for generation the photocurrent. However, these SCs also exploit the two-consecutive-photon induced electrons transitions via the intermediate states for generation an extra photocurrent [2,3]. In fact, the IB SC concept exploits nonlinearity in absorption and must gain from the sunlight concentration.

Recently the IB SCs have been fabricated from InAs quantum dots (QD) sandwiched between n- and p-doped GaAs layers [4]. The operation under the IB SC principles has been demonstrated [4]. However, the photovoltage was lower than in the control GaAs SC due to the thermal generation of carriers in InAs QDs. These carriers can escape with a high efficiency from the QDs embedded in the build-in electric field and produce an extra dark current that reduces the separation of the quasi-Fermi levels and suppresses the photovoltage.

Separation of quasi-Fermi levels is a paramount problem for the energy conversion in IB SCs [1-4] since the QD confined states are like the electronic states of impurity centers. They easily convert into fast recombination centers and come into equilibrium with one of continuous bands. For example, impurity centers embedded in GalnNAs solar cells arrest the quasi-Fermi level, increase the recombination, and impact the photovoltage of the cells [5].

In this paper we discuss the type II QDs embedded in IB SC, at the distance less than the carrier diffusion length but far from the depletion layer and far from the built-in electric field. The hint on this design is the interband recombination in the type-II GaSb QDs buried in GaAs and in the type-II Ge QDs buried in Si that are extended up to 1 μs [6, 7]. Despite its importance for IB SCs there has been little work done on integration of the type II QD with IB SCs. We report on the contribution of QDs into the dark current in this type II QD IB SC.

## 2. Dark current

Figure 1 displays the stack of QD layers and the p-n-junction in the type II QD IB SC connected in series. In this circuit, the stack of QDs operates as a pump engine injecting electron-hole pairs into the p-n-junction while the p-n-junction generates the photovoltage and photocurrent. Since the junction and stack are separated in the space, one can expect that the dark current of the type II QD IB SCs is induced by the p-n-junction only. In fact, the stack embedded at the distance less than the carrier diffusion length may have some contribution into the dark current. To evaluate this contribution into the dark current, we call the detailed balance arguments [1].

According to equations (6) and (7) of Ref. [1], the dark current $j_{DK}$ can be written as $j_{DK} = j_{DJ} + j_{DV}$ under the condition $j_{DC} = j_{DV}$, where $j_{DC}$ and $j_{DV}$ are the dark components of the electron transitions from the confined state into the conduction band and from the valence band into the confined states in QDs, and $j_{DJ}$ is the dark current of the ideal p-n-junction. Using equation (5) of Ref. [1], these currents can be expressed as

$$j_{DJ} \approx \left(2kT\varepsilon_C\varepsilon_V / h^3c^2\right) \times exp\left[-\varepsilon_J / kT\right] \exp\left(V/kT\right),$$

and

$$j_{DV} = j_{DC} \approx \left(2kT\varepsilon_C\varepsilon_V / h^3c^2\right) \times exp\left[-\left(\varepsilon_V + \varepsilon_C + V\right)/2kT\right] \exp\left(V/kT\right).$$

The ratio of these currents $J_{DJ}/J_{DV}$ gives the condition for neglecting the contribution of QDs into the dark current in the type II QD IB SCs

$$exp\left[\left(\varepsilon_V + \varepsilon_C - 2\varepsilon_J + V\right)/2kT\right] > \varepsilon_C\varepsilon_V / \varepsilon_J^2 , \quad (1)$$

where $V$ is the bias voltage, $2\varepsilon_J > \varepsilon_V + \varepsilon_C > \varepsilon_J > \varepsilon_V, \varepsilon_C$, $\varepsilon_V$ is the band gap between the confined state and the Γ valley in the valence continuum band, $\varepsilon_C = \varepsilon_\Gamma - \varepsilon_V$, $\varepsilon_\Gamma$ is the band gap between the confined state and the Γ valley in the conduction band, $\varepsilon_J$ is the band gap in the p-n-junction.

It is seen that, in the frame of the detailed balance arguments [1], until $V < 2\varepsilon_J - \varepsilon_V + \varepsilon_C$, the contribution of QDs into the dark current dominates and the QDs operate as fast recombination centers. However, the contribution reduces as the bias increases. The contribution of the QDs into the dark current becomes small and can be neglected at large biases, $V > 2\varepsilon_J - \varepsilon_V + \varepsilon_C$, e.g., under concentrated sunlight, when a large photovoltage is induced.

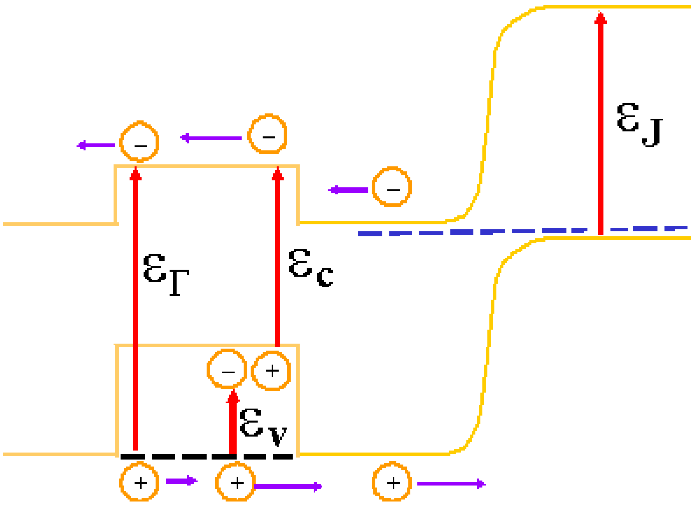


Fig.1

## 3. Conclusions

In conclusion we modeled the effect of the type II band alignment of QDs embedded at the distance less than the carrier diffusion length but far from the depletion layer and the built-in electric field in IB SCs on the dark current. We showed that increasing sunlight concentration leads to the suppression of their recombination activity. Instead the two-photon absorption in the type II QDs increases rapidly and dominates over recombination while the quasi-Fermi level of the confined holes splits off from the continuum bands.

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