Recent Progress Towards Quantum Dot Solar Cells with Enhanced Optical Absorption

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Abstract

Quantum dot solar cells, as a promising candidate for the next generation solar cell technology, have received tremendous attention in the last 10 years. Some recent developments in epitaxy growth and device structures have opened up new avenues for practical quantum dot solar cells. Unfortunately, the performance of quantum dot solar cells is often plagued by marginal photon absorption. In this review, we focus on the recent progress made in enhancing optical absorption in quantum dot solar cells, including optimization of quantum dot growth, improving the solar cells structure, and engineering light trapping techniques.

Review

Introduction

The world energy and environmental crisis urgently calls for development of renewable energies. Among various renewable energy sources, solar energy is abundant and clean. Although solar energy has been an ideal renewable energy, the harvesting of the free and abundant sunshine can be quite costly, which limits the wide deployment of solar power. The next generation of solar cells with high efficiency over 50% is in urgent need to achieve affordable rates below 0.10 €/kWh (0.14 $/kWh) [1]. In the last 10 years, a lot of efforts have been devoted to low-dimensional structures as building blocks for next generation solar cells [2–7]. Among these nanostructures, the zero-dimensional nature of quantum dots (QDs) with discrete energy levels makes an ideal candidate for intermediate band-based solar cells with a theoretical efficiency of 63% [8]. Since Luque and Martí proposed the concept of intermediate band solar cell (IBSC), QD solar cells (QDSCs) have attracted great attention and substantial progress has been made in this field [9–14].

Compared with conventional single junction solar cells, an IBSC allows two sub-bandgap photons to create an electron-hole pair via a mid-gap intermediate band. The intermediate energy band introduces additional photon absorption, which in turn contributes to higher photocurrent [8]. The improved utilization of the solar spectrum via intermediate band-assisted transitions to absorb otherwise wasted low-energy photons can largely improve photocurrent and potentially exceed the Shockley–Queisser limit [15–17]. Although the early work has provided solid understanding of the operational principles of IBSCs [18–24], the experimental studies of QD-IBSCs have not achieved any notable improvement in their overall conversion efficiency. QDSCs have often shown improved short-circuit currents compared with the bulk single junction solar cell without QDs, but the overall contribution to efficiency enhancement from the QDs is marginal. Therefore, research efforts in the last 10 years have been mainly focused on improving the photocurrent generation.

In this paper, we review the recent progress made in QDSCs with main focus on the recent effects involving photocurrent enhancement, which has been the major limited to realize high-efficiency QDSCs. A variety of methods used to enhance the optical absorption and photocarrier collection have been reviewed. Finally, this review summarizes the progress of QDSCs with enhanced photocurrent. More comprehensive discussion can also be found in Ref. [14, 25].
Principles of Quantum Dot Solar Cells
As schematically shown in Fig. 1a, apart from the conduction band and valence band, the IBSC has an intermediate band in between these two bands for additional absorption of low-energy photons. Electron-hole pairs can be produced by photon absorption via the primary bandgap (VB-CB) as in a conventional single junction solar cell. Additionally, electron-hole pairs can also be generated by optical transitions from valence band to the intermediate band (VB-IB) and then from the intermediate band to the conduction band (IB-CB). The quasi-Fermi level splitting and two-photon absorption preserve the open-circuit voltage as well as generate substantially higher photocurrent. As a result, a very high power conversion efficiency of 63 % is calculated from the ideal IBSC under maximum concentration [8].

QDSCs share same device structures with the quantum well solar cells (QWSCs), which incorporate low-dimensional nanomaterials made from narrow band-gap semiconductors and hence boost the device efficiency by capturing low-energy photons below the primary bandgap. Compared with QWSCs, QDs, instead of QWs, are used at a solar cell junction. The atom-like density of states in QDs not only enables additional photocurrent generation via the discrete energy levels but also preserves the open-circuit voltage [15]. The carrier confinement in all three-dimensions in QDs can enable isolated quasi-Fermi levels which are required to realize IBSCs [4, 8]. As a result, much higher conversion efficiency is expected from QDSCs compared with QWSCs. Therefore, the unique properties of QDs and the attractive concept of IBSCs have led to intensive research efforts on QD-IBSCs. The research of QD-IBSCs is also largely benefited from the well-established fabrication methods of high-quality QDs in the last couple of decades. Most of the QDSCs adopt a device structure with self-assembled QDs imbedded between the emitter and base of a bulk single junction solar cell, as shown in Fig. 1b. In(Ga)As/GaAs QD system is most used because of its mature fabrication techniques and well-understood optical properties. On the other hand, the transition energies in In(Ga)As/GaAs QDs are quite different from the optimal values for the ideal IBSC, and high-efficiency QDSCs have not been realized yet, although a high theoretical efficiency of 52.8 % is still predicted [26]. Nonetheless, In(Ga)As/GaAs QDSCs have successfully demonstrated the basic operating principles of the IBSCs [25], including splitting of quasi-Fermi levels [2] and QD-mediated two-photon absorption [11, 27]. Therefore, in the last few years, many of the research efforts of QDSCs have been focused on realizing practical QD-IBSCs with high efficiency. In order to achieve this goal, the major challenges associated with QDSCs are yet to be addressed, including recombination in the QDs (radiative and non-radiative), marginal photocurrent collected from the QDs, and degradation of open-circuit voltage [17]. The radiative recombination via the QD intermediate band can be largely suppressed under concentrated light when CB-VB recombination dominates. However, additional non-radiative recombination paths are presented in the QDSCs due to accumulated strain in S-K QDs [28]. To tackle this issue, improvement in QD fabrication and development of new growth techniques have been explored [29–32]. In addition to the strain-induced defects that largely limit the QD absorption volume, the sub-bandgap absorption in QDSCs is rather low and only contributes to ~1 % of the overall efficiency [17]. Moreover, the slightly improved photocurrent has been largely undermined by the voltage loss as a result of thermal coupling of the QD states and the continuum states [10, 30, 33]. Therefore, the major research activities have been focused on addressing these challenges facing QD-IBSCs. The following sections will review the recent efforts to achieve practical high-efficiency QDSCs through improving photocurrent.

Recent Efforts to Improve Photocurrent of QDSCs
Although the addition of QDs in a single junction solar cell normally shows additional photocurrent, improvement in short-circuit current is well below the expectation for high-efficiency solar cells. The marginal improvement in the device efficiency with QDs is largely attributed to the non-radiative recombination, low QD absorption...
volume, and low optical transition rate [34]. In order to obtain high photocurrent, both the QD material quality and device structure have to be optimized. Moreover, photonic structures can also be used to boost the light absorption in the QDSCs. Here, these efforts are summarized.

**Optimization of QDs**

A straightforward way to improve short-circuit current is to increase the absorption volume of QDs. Multiple stacked In$_{0.4}$Ga$_{0.6}$As/In$_{0.2}$Ga$_{0.8}$As (In$_{0.4}$Ga$_{0.6}$As) QDSCs with 50 (30) layers of QDs have shown distinct improvement in short-circuit current density [35, 36]. Using similar method, highly stacked In$_{0.4}$Ga$_{0.6}$As QDs up to 400 layers were also reported. Although improvement in short-circuit current has also been observed from QDSCs with up to 150 layers of QDs, significant degradation in open-circuit voltage results in degradation of the overall device efficiency [12, 35], as shown in Fig. 2.

The difficulty to increase the absorption volume QDs, e.g., the number of QD layers, is that the accumulated strain generates various types of defects and largely undermines the improvement of photon absorption [22, 37]. To minimize the number of strain-induced defects that are deleterious to both optical and electronic properties, strain-compensation layers are deposited for multiple stacked QDSCs [38]. By using GaP strain compensation layers, InAs QDs with good structural and optical properties up to 50 layers have been reported [39]. The improved material quality has also led to increase in short-circuit current and reduced dark current [40]. Additionally, the reduced strain-induced defects also decrease non-radiative recombination, and then, high open-circuit voltage can be obtained [10]. Bailey et al. reported 0.5 % enhancement in absolute efficiency from a 40-layer QDSC with reduced InAs coverage and GaP strain compensation layers compared with the GaAs reference cell [30].

A number of different materials have also been explored to improve QD quality. Highly stacked QDs up to 100 layers are also achieved by using dilute nitride GaAsN strain compensation layers [41, 42]. The effectively compensated strain results in a distinct improvement in short-circuit current as high as 2.47 mA/cm$^2$ [41]. Strain-balanced In$_{0.47}$Ga$_{0.53}$As/GaAs$_{1-x}$P$_x$ QDs have also been reported with improved quality as well as uniformity on GaAs (311) substrates [29]. Furthermore, strain-compensated InAs/GaNAs QDs with additional strain-mediating GaInNAs layers can not only shift the absorption to long wavelength but also increase the surface density of QDs [43]. Strain reducing layers is also beneficial for realizing high-performance QDSCs. It has also been reported that an addition of Ga$_{0.90}$In$_{0.10}$As strain-reducing layers in an InAs/GaAs

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**Fig. 2**  
(a) SEM micrographs of the surface plane on top of 400-stack In$_{0.4}$Ga$_{0.6}$As QD structures. The ultra-high stacked structures have good surface morphologies even after the stacking of 300 or 400 QD layers.  
(b) Enlarged cross-sectional STEM images of bottom portions of 300-stack In$_{0.4}$Ga$_{0.6}$As QD layers. No dislocations were generated after the stacking of 300 layers, even though no strain balancing was employed during the growth.  
(c) EQE spectra of multi-stacked In$_{0.4}$Ga$_{0.6}$As QD solar cells and a GaAs reference cell. The EQEs of the 10-, 20-, 30-, 50-, 100- and 150-stack In$_{0.4}$Ga$_{0.6}$As QD solar cells are indicated. Reproduced from Ref. [12] with permission from The Royal Society of Chemistry
QDSC results in a 1.19% improvement of the conversion efficiency of a GaInP/Ga(In)As/Ge triple junction solar cell due to reduced Shockley–Read–Hall recombination centers [44].

Another effective way to increase the absorption volume is to increase the surface density of QDs. In Fig. 3, a QDSC with a high sheet density of \(7.0 \times 10^{10} \text{ cm}^{-2}\) was obtained via optimization of growth temperature and V/III flux [45]. Despite the high QD density, the formation of defective QDs, e.g., In segregation, resulted in poor short-circuit current [45, 46]. Sb-mediated growth was capable of achieving high QD density over \(1 \times 10^{11} \text{ cm}^{-2}\) with a low density of defective QDs, which thus led to a distinct enhancement in short-circuit current [47]. Apart from the Stranski–Krastanov (S-K) QDs, high-density QDs can also be obtained by using another growth mode. Submonolayer (SML) QDs have been reported to have high areal density (\(~10^{11} \text{ cm}^{-2}\) ), adjustable aspect ratio, uniform size distribution of QDs, and absence of wetting layer [48, 49]. By using InGaAs/GaAs SML QDs, the solar cell has shown improved performance compared with an InGaAs/GaAs quantum well solar cell of the same structure [48]. Similar to S-K QDs, SML QDs can also significantly contribute to photocurrent enhancement. Kim et al. recently demonstrated an improved short-circuit current of the InAs/GaAsSb SML QDSC compared with the reference GaAs solar cell [50]. Also, an InGaAs/GaAs SML QDSC is also demonstrated with better short-

![Fig. 3](image-url)
circuit current than the reference S-K QDSC [49]. It should be noted that SML QDs show a higher compressive strain and thus more non-radiative recombination centers than S-K QDs [49]. Nonetheless, the high areal density of QDs can compensate the non-radiative recombination centers generated. In combination with strain compensation technique, further improvement in short-circuit current can be expected.

Apart from the strained S-K QDs and SML QDs, quantum structures grown by different modes can be used as promising alternatives for improving photocurrent. Quantum well dots (QWD), two-dimensional layers with lateral modulation of thickness and composition, have unity surface coverage, which facilitates higher absorption as compared with S-K QDs and demonstrates significantly improve sub-bandgap photocurrent [51]. Strain-free quantum structures fabricated by droplet epitaxy have also show promise in boosting photon absorption [52–55]. Based on these strain-free nanostructures grown by droplet epitaxy, additional photocurrent was clearly demonstrated [56–59]. Although further efforts to improve material quality are needed, the two-photon absorption observed in strain-free QDSCs opens new opportunities for QD-based high-efficiency intermediate band solar cells [59, 60].

**Optimization of Device Structures**

In addition to increase absorption with more QDs, engineering the QD structures also plays a critical role in boosting the photocurrent. For example, through simple truncation of the dot height, an increase in both short-circuit current density and open-circuit voltage has been observed as a result of improved photocarrier extraction and reduced carrier reapture probability by the QDs [61]. To boost photon absorption, Wei et al. proposed a quantum-dot-in-a-fence (DFENCE) structure which consists of InAs QDs enclosed by thin Al$_x$Ga$_{1-x}$As “fence” layers of larger energy bandgap [62], as shown in Fig. 4a. The fences facilitate sub-bandgap photocarrier generation rather than recombination in the QDs, and hence, a very high solar power conversion efficiency of 45 % can be expected for InAs QDSCs with Al$_x$Ga$_{1-x}$As “fence” layers under AM1.5 conditions. Experimentally, such structures have not shown any clear improvement in device performance yet, but the thermal extraction of carriers was suppressed due to improved quantum confinement [63].

Engineering the QDs locally to change the carrier dynamics can also lead to a higher short-circuit current. A simple but effective way to achieve this goal is doping in the QD region, which has been reported to reduce non-radiative recombination via defect passivation [64] and to improve the photocarrier collection by build-in field [65]. The doping in the QD region forms charged QDs that also reduce the probability of electron capture. Although state filling can also decrease interband quantum dot absorption [66], the charged QDs enhance the collection of photocarriers generated above bandgap and lead to overall improvement in photocurrent [67, 68]. It has also been shown that the positioning of the QD layers can also largely affect the performance of QDSCs [69], which also reflects the effects of doping [70].

Substantial efforts have also been made to type II QDs to improve short-circuit current [20, 71–75]. QDSCs can benefit from largely enhanced absorption coefficient, particularly for transitions from extended states to bound states, by using type II QDs rather than type I QDs [76], as depicted in Fig. 4b. Yet, it is still needed to find new material system with even high absorption coefficient to compete with the higher bound-to-bound state absorption coefficient in type I QDs. Another attractive feature of the type II QDSCs is the extremely
long radiative lifetime over 200 ns [77]. Such a long carrier radiative lifetime facilitates the photocarrier collection as long as non-radiative recombination centers are suppressed with the presence of additional strain [78]. Moreover, the reduced Auger recombination rate in type II structure can also benefit the QDSC performance [72].

**Light Trapping**

A very interesting and promising method to improve photocurrent of QDSCs is light trapping. To fulfill the promise of QDSCs, the QD density needs to be significantly improved (>1000). Such a requirement poses a significant challenge for material growth. If the optical path can be improved, high density of QDs is not necessarily required [24]. For example, given a QD density achievable by existing growth techniques, an optical absorption enhancement over 50 can potentially realize high-efficiency QDSCs beyond the Shockley–Queisser limit [24].

Plasmonic structures can be an effective way to enhance the optical absorption in QDSCs. It has been shown that it is possible to obtain an absorption enhancement factor up to ~300 by using the strong scattered near-field potential from metal nanoparticles [79]. Although metallic nanoparticles cannot be placed in close proximity to QDs without undermining the material quality, surface nanoparticles can be used as good light scatter to improve optical path in QDSCs [80]. The effective forward scattering of metal nanoparticles deposited on QDSC surface has shown distinct improvement in short-circuit current [81]. Using similar technique but with novel metal nanoparticles, e.g., nanostars, a broadband enhancement in photon absorption has been observed in QDSCs [82], as illustrated in Fig. 5. Especially, external quantum efficiency in short-wavelength region has been improved by fourfold. The enhancement is originated from both the near-field enhancement and effective light scattering. It also demonstrates that appropriate control of shape, size, and density of the metallic nanoparticles plays a critical role in achieving panchromatic photon absorption. However, the surface plasmonic structures do not show clear improvement in absorption in the QD region. By inserting a TiO$_2$ between the QDSC and metal nanoparticles, the plasmon resonance wavelength was red-shifted to the QD wavelength region [83]. As a result, a pronounced improvement in long-wavelength photon absorption has been achieved in the QDSCs with TiO$_2$/Ag back reflector and led to 5.3 % enhancement in short-circuit current. Back reflector has also been developed by growing a bragg reflector beneath the QDSC. A bragg reflector centered at 920 nm leads to about ~2 % increase in short-circuit current due to enhanced absorption in the long-wavelength region [84]. As a result, a maximum efficiency of 24.93 % (AM 1.5D, 30 suns) has been obtained from the QDSCs with bragg reflector, which is nearly as high as the efficient GaAs reference cell (25.75 % at AM 1.5D, 10 suns). Interestingly, an epitaxial lift-off QDSC thin film can act as a resonance cavity by itself [85]. In addition to the enhancement of photon absorption in the QDSC film, there is no need for additional processing steps to create photonic structures, which is desired in terms of reducing cost. Further development and optimization of photonic structures will enable substantial improvement of solar energy harvesting by using QDs.

**Conclusions**

In the present paper, we have briefly reviewed the efforts to improve the photocurrent in QDSCs. A number of different methods have so far been examined to improve the optical absorption as well as photocarrier collection in QDSCs. Although each of these methods shows promise in boosting the cell performance in terms of photocurrent, there is still a lot of room to improve. Till
now, the absorption from the QDs is still much inferior to the bulk absorption. Undoubtedly, novel designs and further improved growth of QDSCs need to be in place to achieve efficiency exceeding that of single junction solar cells. Nonetheless, the progress made so far discussed here, including growth of high-density QDSCs, modification of carrier dynamics, and light trapping, provides helpful guidelines for further development of high-efficiency QDSCs.

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Authors’ contributions
ZZ collected the documents and wrote the manuscript. PY drew and prepared all figures in the manuscript. HJ and ZMW provided the indispensable guidance. All authors read and approved the final manuscript.

Competing interests
The authors declare that they have no competing interests.

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References
1. King RR, Bhusari D, Larrabee D, X-Q L, Rehder E, Edmondson K, Cotal H, Jones RK, Emer JE, Fetzer CM (2012) Solar cell generations over 40% efficiency. Prog Photovolt Res Appl 20:801
2. Luque A, Martí A, López N, Antolín E, Cánovas E, Stanley C, Farmer C, Caballero Li (2005) Experimental analysis of the quasi-Fermi level split in quantum dot intermediate-band solar cells. Appl Phys Lett 87:083505
3. Krogstrup P, Jørgensen Hi, Heiss M, Demichel O, Holm Jv, Aagesen M, Nygaard J, Fontcuberta i Morral A (2013) Single-nanowire solar cells beyond the Shockley-Queisser limit. Nat Photonics 7:306
4. Luque A, Martí A, Stanley C (2012) Understanding intermediate-band solar cells. Nat Photonics 6:146
5. Wu J, Liu L, Liu S, Yu P, Zheng Z, Shafr M, Zhou Z, Li H, Ji H, Wang ZM (2014) High responsivity photodetectors based on iron pyrite nanowires using sulfurization of anodized iron oxide nanotubes. Nano Lett 14:6002
6. Davis NJ, Böhm ML, Tabachnyc M, Wisniewsky-Rocca-Rivarola F, Jellicce TC, Ducati C, Ehler B, Greenham NC (2013) Multiple-exciton generation in lead selenide nanorod solar cells with external quantum efficiencies exceeding 120%. Nat Commun 4:2695
7. Wang H, Sun P, Cong S, Wu J, Gao L, Wang Y, Dai X, Yl Q, Zou G (2016) Nitrogen-doped carbon dots for “green” quantum dot solar cells. Nanoscale Res Lett 11:1
8. Luque A, Martí A (1997) Increasing the efficiency of ideal solar cells by photon induced transitions at intermediate levels. Phys Rev Lett 78:5014
9. López N, Martí A, Luque A, Stanley C, Farmer C, Diaz P (2007) Experimental analysis of the operation of quantum dot intermediate band solar cells. J Sol Energy Eng 129:319
10. Bailey CG, Forbes DV, Raffaelle RP, Hubbard SM (2011) Near 1 V open circuit voltage InAs/GaAs quantum dot solar cells. Appl Phys Lett 98:163105
11. Ahsan N, Miyashita N, Islam MM, Yu KM, Waliawickicz W, Okada Y (2012) Two-photon excitation in an intermediate band solar cell structure. Appl Phys Lett 100:127111
12. Sugaya T, Numakami O, Oshima R, Furue S, Komaki H, Amato T, Matsubara K, Okano Y, Niki S (2012) Ultra-high stacks of InGaAs/GaAs quantum dots for high efficiency solar cells. Energy Environ Sci 5:6233
13. Hlawig J, Lee K, Teran A, Forrest S, Phillips JD, Martin AJ, Millunchick J (2014) Multiphoton sub-band-gap photoconductivity and critical transition temperature in type-II gap quantum-dot intermediate-band solar cells. Phys Rev Appl 1:051003
14. Wu J, Chen S, Seeds A, Liu H (2015) Quantum dot optoelectronic devices: lasers, photodetectors and solar cells. J Phys D 48:363001
15. Aroutiounian V, Petrosyan S, Khachatryan A, Touryan K (2001) Quantum dot solar cells. J Appl Phys 89:2268
16. Okada Y, Morioka T, Yoshida K, Oshima R, Shojo Y, Inoue T, Kita T (2011) Increase in photocurrent by optical transitions via intermediate quantum states in direct-doped InAs/GaAs strain-compensated quantum dot solar cell. J Appl Phys 109:24301
17. Luque A, Martí A (2010) The intermediate band solar cell progress toward the realization of an attractive concept. Adv Mater 22:160
18. Martí A, Cuadra L, Luque A (2001) Partial filling of a quantum dot intermediate band for solar cells. IEEE Trans Electron Devices 48:2394
19. Martí A, Cuadra L, Luque A (2002) Design constraints of the quantum-dot intermediate band solar cell. Physica E: Low-dimensional Systems and Nanostructures 14, 150.
20. Cuadra L, Martí A, Luque A (2002) Type II broken band heterostructure quantum dot to obtain a material for the intermediate band solar cell. Physica E: Low-dimensional Systems and Nanostructures 14, 162.
21. Luque A, Martí A, López N, Antolín E, Cánovas E, Stanley C, Farmer C, Diaz P (2006) Operation of the intermediate band solar cell under nonideal space charge region conditions and half filling of the intermediate band. J Appl Phys 99:094503
22. Ahsan N, López N, Antolín E, Cánovas E, Luque A, Stanley CR, Farmer CD, Diaz P (2007) Emitter degradation in quantum dot intermediate band solar cells. Appl Phys Lett 90:233510
23. Li T, Bartolo RE, Dagenais M (2013) Challenges to the concept of an intermediate band in InAs/GaAs quantum dot solar cells. Appl Phys Lett 103:141113
24. Mellor A, Luque A, Tobías I, Martí A (2014) The feasibility of high-efficiency InGaAs/GaAs quantum dot intermediate band solar cells. Solar Energy Mater Solar Cells 130:225
25. Ramiro I, Martí A, Antolín E, Luque A (2014) Photovoltaics. IEEE Journal of 4:736
26. Hu WG, Inoue T, Kojima O, Kita T (2010) Effects of absorption coefficients and intermediate-band filling in InAs/GaAs quantum dot solar cells. Appl Phys Lett 97:193106
27. Martí A, Antolín E, Stanley CR, Farmer CD, López N, Diaz P, Cánovas E, Linares PG, Luque A (2006) Production of photocurrent due to intermediate-to-conduction-band transitions: A demonstration of a key operating principle of the intermediate-band solar cell. Phys Rev Lett 97:247701
28. Wu J, Shao D, Dorogan VG, Li AZ, Wang ZM, Mazur YI, Salamo GJ (2010) Intersublevel infrared photodetector with strain-free GaAs quantum dots pairs grown by high-temperature droplet epitaxy. Nano Lett 10:1512–1516
29. Popescu V, Bester G, Hanna MC, Norman AG, Zunger A (2008) Theoretical and experimental examination of the intermediate-band concept for strain-balanced (In, Ga)As/GaAs, P quantum dot solar cells. Phys Rev B 78:205231
30. Bailey CG, Forbes DV, Poll JJ, Bittner ZS, Dai Y, Mackos C, Raffaelle RP, Hubbard SM (2012) Photovoltaics. IEEE Journal of 2:269
31. Liu W-S, Wu H-M, Tsao F-H, Hsu T-L, Chu Y, Mackos C, Raffaelle RP, Hubbard SM (2012) Photovoltaics. IEEE Journal of 2:269
32. Wu J, Hirono Y, Li X, Wang ZM, Lee J, Benamara M, Luo S, Mazur YI, Kim ES, Salamo GJ (2014) Self-assembly of multiple stacked nanowires by vertically correlated droplet epitaxy. Adv Funct Mater 24:530
33. Wu J, Makableh YFM, Vasan R, Manasreh MO, Liang B, Reyner CJ, Huffaker DL (2012) Strong interband transitions in InAs quantum dot solar cells. Appl Phys Lett 100:051907
34. Martí A, López N, Antolín E, Cánovas E, Stanley C, Farmer C, Cuadra L, Luque A (2006) Novel semiconductor solar cell structures: The quantum dot intermediate band solar cell. Thin Solid Films 511:638
35. Sugaya T, Furue S, Komaki H, Amato T, Mori M, Komori K, Niki S, Numakami O, Okano Y (2010) Highly stacked and well-aligned InGaAs quantum dot solar cells with InGaAs cap layer. Appl Phys Lett 97:183104
36. Sugaya T, Kamikawa Y, Furue S, Amato T, Mori M, Niki S (2011) Multi-stacked quantum dot solar cells fabricated by intermittent deposition of InGaAs. Solar Energy Mater Solar Cells 95:163
37. Roh CH, Park YJ, Kim KM, Park YM, Kim EK, Shim KB (2001) Defect generation in multi-stacked InAs quantum dot solar cells. J. Cryst Growth 226:1
38. Laghumavarapu RB, El-Mamawy M, Nuntawong N, Moscho A, Lester LF, Huffaker DL (2007) Improved device performance of InAs/GaAs quantum dot solar cells with GaP strain compensation layers. Appl Phys Lett 91:243115
39. Alonso-Álvarez D, Taboada AG, Ripalda JM, Alen B, González Y, González L, García JM, Briones F, Martí A, Luque A, Sánchez AM, Molina SI (2008) Carrier recombination effects in strain compensated quantum dot stacks embedded in solar cells. Appl Phys Lett 93:123114
40. Hubbard SM, Cress CD, Bailey CG, Raffaelli RP, Bailey SG, Will DM (2008) Effect of strain compensation on quantum dot enhanced GaAs solar cells. Appl Phys Lett 92:123512

41. Oshima R, Takata A, Okada Y (2008) Strain-compensated InGaAs/GaInAs quantum dots for use in high-efficiency solar cells. Appl Phys Lett 93:083111

42. Takata A, Oshima R, Shoji Y, Akahane K, Okada Y, 001877 (2010) Fabrication of 100-layer stacked InGaAs/GaNAs strain-compensated quantum dots on GaAs (001) for application to intermediate band solar cell.

43. Pavellescu E-M, Polokjari V, Schramm A, Tukainen A, Aho A, Zhang W, Puustinen J, Salminen J, Guina M (2016) Effects of insertion of strain-engineering GaIn)nAs layers on optical properties of InGaAs/GaAs quantum dots for high-efficiency solar cells. Opt Mater 52:177

44. Li S, Bi L, Li M, Yang M, Song M, Liu G, Xiong W, Li Y, Fang Y, Chen C (2015) Investigation of GaNAs strain reducing layer combined with InN quantum dots embedded in GaInAs subcell of triple junction GainP/GaInAs/Ge solar cell. Nanoscale Res Lett 10:1

45. Zhou D, Sharma G, Thomassen SF, Reenaas TW, Finnland BO (2010) Optimization towards high density quantum dots for intermediate band solar cells grown by molecular beam epitaxy. Appl Phys Lett 96

46. Sugiyama Y, Nakata Y, Inamura K, Muto S, Yokoyama N (1996) Stacked InAs self-assembled quantum dots on (001) GaAs grown by molecular beam epitaxy. Jpn J Appl Phys 35:1320–1324

47. Tutu FK, Wu J, Lam P, Tang M, Miyashita N, Okada Y, Wilson J, Allison R, Liu H (2013) Antimony mediated growth of high-density InAs quantum dots for photovoltaic cells. Appl Phys Lett 103:034901

48. Lam P, Wu J, Tang M, Jiang Q, Hatch S, Beilard R, Wilson J, Allison R, Liu H (2014) Submonolayer InGaAs/GaAs quantum dot solar cells. Solar Energy Mater Solar Cells 126:63

49. Kim Y, Ban K-Y, Honsberg CB (2015) Multi-stacked InGaAs/GaAs quantum dots grown with different growth modes for quantum dot solar cells. Appl Phys Lett 106:222104

50. Kim Y, Ban K-Y, Zhang C, Honsberg CB (2015) Material and device characteristics of InAs/GaAs sub-monolayer quantum dot solar cells. Appl Phys Lett 107:151303

51. Mintairov SA, Kalyuzhnyy NA, Maximov MV, Nadtochiy AM, Rouvimov S, Zhukov AE (2015) GaAs quantum well-dots solar cell. Nanoscale Res Lett 10:1

52. Elborg M, Noda T, Mano T, Jo M, Sakuma Y, Sakoda K, Han L (2015) Voltage dependence of two-step photocurrent generation in quantum dot multi-junction solar cell performance. Prog Photovoltaics Res Appl 23:793

53. Laghumavarapu RB, Moscho A, Koshkalghah A, El-Emawy M, Lester LF, Huffaker DL (2007) GaSb/ GaAs type II quantum dot solar cells for enhanced infrared spectral response. Appl Phys Lett 90:173125

54. Takata A, Oshima R, Shoji Y, Akahane K, Okada Y, 001877 (2010) Fabrication of 100-layer stacked InGaAs/GaNAs strain-compensated quantum dots on GaAs (001) for application to intermediate band solar cell.

55. Vyskočil J, Gladkov P, Petřiček O, Hospodářek A, Pangerl J (2015) Growth and properties of A0B0"QB0 structures for intermediate band solar cells. J Cryst Growth 414:172

56. Luque A, Linares PG, Mellor A, Andreev V, Martí A (2013) Some advantages of intermediate band solar cells based on type I quantum dots. Appl Phys Lett 103:123901

57. Luque A, Linares PG, Mellor A, Andreev V, Martí A (2013) Some advantages of intermediate band solar cells based on type I quantum dots. Appl Phys Lett 103:123901

58. Kechiantz A, Afanasev A, Lazzari J-H. (2015) Impact of spatial separation of type-II GaSb quantum dots from the depletion region on the conversion efficiency and areal power output of GaSb solar cells. Proc Photovoltaics Res Appl 23:1003

59. Mendes MJ, Luque A, Tobias I, Martí A (2009) Plasmonic light enhancement in the near-field of metallic nanophotonic arrays for intermediate band solar cells. Appl Phys Lett 95:071105

60. Atwater HA, Polman A (2010) Plasmonics for improved photovoltaic devices. Nat Mater 9:205

61. Wu J, Mangham SC, Reddy VR, Manasreh MO, Weaver BD (2012) Solar Energy Mater. Solar Cells 102:44

62. Wu J, Yu P, Susha AS, Sablon KA, Chen H, Zhou Z, Li H, Ji H, Niu X, Govorov AO (2015) Broadband efficiency enhancement in quantum dot solar cells coupled with multipikled plasmonic nanostars. Nano Energy 13:827

63. Lu H, Mokkapati S, Fu L, Jolley G, Tan HH, Jagadish C (2012) Plasmonic quantum dot solar cells for enhanced infrared response. Appl Phys Lett 100:113904

64. Yang X, Wang K, Yongxian G, Ni H, Wang X, Yang T, Wang Z (2013) Improved efficiency of InAs/GaAs quantum dots solar cells by Si-doping. Solar Energy Mater Solar Cells 113:144

65. Sablon KA, Little JW, Mitin V, Sergeev A, Vagidov N, Reinhardt K (2011) Strong enhancement of solar cell efficiency due to quantum dots with built-in charge. Nano Lett 11:2311

66. Wu J, Passmore B, Manasreh MO (2015) The impact of quantum dot filling on dual-band optical transitions via intermediate quantum states. J Appl Phys 110:084501

67. Lee KS, Lee DJ, Kim EK, Choi WJ (2015) Effect of space layer doping on photovoltaic conversion efficiency of InAs/GaAs quantum dot solar cells. Appl Phys Lett 106:253904

68. Zhou D, Vullum PE, Sharma G, Thomassen SF, Holmedal R, Reenaas TW, Finnland BO (2010) Positioning effects on quantum dot solar cells grown by molecular beam epitaxy. Appl Phys Lett 96:038318

69. Walker AW, Thériault D, Hinzer K (2015) Positioning and doping effects on quantum dot multi-junction solar cell performance. Prog Photovoltaics Res Appl 23:793

70. Laghumavarapu RB, Moscho A, Koshkalghah A, El-Emawy M, Lester LF, Huffaker DL (2007) GaSb/GaAs type II quantum dot solar cells for enhanced infrared spectral response. Appl Phys Lett 90:173125

71. Tomić S (2013) Effect of Si induced type II alignment on dynamical processes in InGaAs/GaAs/InAs quantum dots: Implication to solar cell design. Appl Phys Lett 103:072112

72. Choy CM, Fan L, Xiang C, Zhang Y, Liu H, 001877 (2010) GaSb/InAs quantum dot–well hybrid structure active regions in solar cells. Solar Energy Mater Solar Cells 114:165

73. Takata A, Oshima R, Shoji Y, Akahane K, Okada Y, 001877 (2010) Fabrication of 100-layer stacked InGaAs/GaNAs strain-compensated quantum dots on GaAs (001) for application to intermediate band solar cell.

74. Elborg M, Noda T, Mano T, Jo M, Sakuma Y, Sakoda K, Han L (2015) Voltage dependence of two-step photocurrent generation in quantum dot intermediate band solar cells. Solar Energy Mater Solar Cells 134:108

75. Zribi J, Illahí B, Paquette B, Jaoaud A, Theriault O, Hinzer K, Chretion R, Patriarche G, Faëfard S, Amiez V (2016).

76. Wei G, Forrest SR (2007) Intermediate-band solar cells employing quantum dots embedded in an energy fence barrier. Nano Lett 7:218

77. Sablon KA, Little JW, Oliver KA, Zhm W, Dorogan VG, Mazur YI, Salamo GJ, Towner FJ (2010) Effects of AlGaAs energy barriers on InAs/GaAs quantum dot solar cells. J Appl Phys 108:074405

78. Mentall M, Noda T, Mano T, Jo M, Sakuma Y, Sakoda K, Han L (2015) Voltage dependence of two-step photocurrent generation in quantum dot intermediate band solar cells. Solar Energy Mater Solar Cells 134:108

79. Zribi J, Illahí B, Paquette B, Jaoaud A, Theriault O, Hinzer K, Chretion R, Patriarche G, Faëfard S, Amiez V (2016).

80. Wei G, Forrest SR (2007) Intermediate-band solar cells employing quantum dots embedded in an energy fence barrier. Nano Lett 7:218

81. Sablon KA, Little JW, Oliver KA, Zhm W, Dorogan VG, Mazur YI, Salamo GJ, Towner FJ (2010) Effects of AlGaAs energy barriers on InAs/GaAs quantum dot solar cells. J Appl Phys 108:074405