

Review Article

Development and Prospect of Nanoarchitected Solar Cells

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This paper gives an overview of the development and prospect of nanotechnologies utilized in the solar cell applications. Even though it is not clearly pointed out, nanostructures indeed have been used in the fabrication of conventional solar cells for a long time. However, in those circumstances, only very limited benefits of nanostructures have been used to improve cell performance. During the last decade, the development of the photovoltaic device theory and nanofabrication technology enables studies of more complex nanostructured solar cells with higher conversion efficiency and lower production cost. The fundamental principles and important features of these advanced solar cell designs are systematically reviewed and summarized in this paper, with a focus on the function and role of nanostructures and the key factors affecting device performance. Among various nanostructures, special attention is given to those relying on quantum effect.

1. Introduction

“There’s plenty of room at the bottom”—a famous talk given by physicist Richard Feynman, who mentioned the concepts of nanotechnology for the first time about 50 years ago. Since then, people have made continuous efforts to attain structural manipulation of matters on an atomic and molecular scale in order to make use of their unique properties. The emergence of nanotechnology opens a lot of opportunities for new materials and devices with a vast range of applications. Recently, it has been extensively implemented in the development of novel solar cell structure in order to boost the energy conversion efficiency and reduce the production cost.

Generally speaking, the nanostructure could refer to any objects in which at least one of the three dimensions has an intermediate size between molecular and micrometer size structure (usually between 0.1~100 nm). In this scale, some interesting physical phenomena that are not present in bulk system become pronounced and the material properties are artificially changed. Although quite a few different kinds of nanostructures have been developed so far, they can be classified into two major categories according to their function and role in the solar cells, those serving as supporting structures and those serving as light absorbers. In either case, different advantages of nanostructures, such as large surface area, good carrier transportation, high

absorption coefficient, long-term stability, and tunable band-gap, have been used independently or jointly to enhance the solar cell performance. Among these features, the band-gap modulation by quantum confinement effect (QCE) is a very unique characteristic of nanostructures in which the size of dimension is comparable or smaller than the Bohr radius of the element. This size effect makes nanostructures a perfect candidate for the high efficiency tandem solar cells, because in principle it is possible to use nanostructures to build absorbers with any desired electronic band-gap that can match different parts of the sunlight spectrum. Furthermore, we should realize that besides electronic band structure the QCE is also able to change the phonon band structure of the material.

In this paper, we give a review of the fundamental principles and important features of various nanostructured solar cells. The benefits of nanostructures to conventional thin film solar cells are first described and then solar cells built on nanostructured absorbers are discussed in detail, particularly those relying on quantum effect.

2. Nanostructures in Conventional Thin Film Solar Cells

2.1. Nanocrystalline Silicon Solar Cell. For tens of years, hydrogenated amorphous silicon (a-Si:H) has been widely

used as the absorbing material in thin film solar cells. In order to boost the conversion efficiency, multijunction structures have been studied and a record stable active area efficiency of 13% has been demonstrated [1]. Further improvement of cell performance requires the discovery of new materials with a low defect density and good transport properties. Since 1990s, hydrogenated nanocrystalline silicon (nc-Si:H) has been extensively studied as a potential candidate for the low band gap absorbers in the multijunction cells [2].

In fact, nc-Si:H material is a mixture of nanometer-sized crystallites and amorphous tissues [3]. Small crystallites with size of a few nanometers are embedded in amorphous silicon matrix. In nanocrystalline thin film, the presence of small crystallites provides crystalline paths for carrier transport, where the carrier mobility is much higher than pure amorphous system. Hence, the nc-Si:H absorber layer can be thick producing high photocurrent density. Another advantage of nc-Si:H over a-Si:H or hydrogenated amorphous silicon germanium (a-SiGe:H) is the reduced light-induced degradation in the solar cell efficiency. It is shown that the performance improvement in nc-Si:H solar cells is attributed to the presence of small crystallite network and the crystallites are actually not absorbers and do not contribute to the light absorption process. Therefore, it is not that essential to optimize the optical and electrical properties of the crystallites.

2.2. Nanostructured Metal Oxide in Dye-Sensitized Solar Cell. Compared to macroscopic systems, nanostructures have much larger surface area which can alter mechanical, thermal, and catalytic properties of materials. This feature has been widely investigated in order to increase the absorption of dye-sensitized solar cells (DSCs) and hence improve their conversion efficiency.

In DSCs, energy conversion is realized by charge separation in sensitizer dyes adsorbed on a wide band gap semiconductor electrode, such as transparent TiO₂ [4]. The energy conversion efficiency of early DSCs was not high though the sensitizer itself exhibited a very efficient charge separation process. This was because of the very limited light absorption by the monolayer of the dyes, resulting in low absorption coefficient of the solar cells. This problem was solved later by the utilization of nanoporous TiO₂ electrode instead of relatively flat polycrystalline electrode as shown in Figure 1 [5]. The huge surface area of nanoporous TiO₂ significantly increases the effective light absorption area of the dyes and thereby improves the cell conversion efficiency to higher than 10% [6].

Unlike in nc-Si:H film, the particle size of TiO₂ nanocrystals plays an important role in the design of DSCs. This is mainly correlated with the electron transport process in the nanoporous TiO₂ electrode, which is evaluated by the diffusion length of electrons $L = (D * \tau)^{1/2}$, where D is the electron diffusion coefficient and τ is the electron lifetime. Experimental results have shown that D increases with nanocrystal size, and this is probably due to the lower number of boundaries between particles. Nevertheless, the increase of particle size also results in a decrease of total cross-sectional area of the boundaries (required for reasonable absorption)

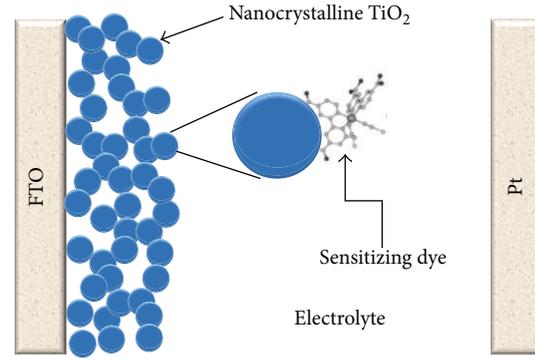


FIGURE 1: Schematic diagram of the dye-sensitized solar cell with nanoporous TiO₂ electrodes.

which increases the resistance for electron transport. In addition, it is found that is inversely proportional to D . These competing effects indicate that there should be an optimal particle size that gives maximum diffusion length and best cell performance. In high efficient DSCs, the typical diameter of the TiO₂ nanoparticles is between 10 nm and 20 nm.

Other nanostructured metal oxides have also been investigated as alternative n-type electrodes including ZnO, Nb₂O₅, and SnO₂. Particularly, ZnO has attracted much attention since the 1960s, because of its good carrier mobility and flexibility in synthesis and morphology (spherical particles, rod, wires, and hollow tubes) [7, 8]. However, DSCs using these electrodes have not shown conversion efficiency comparable to TiO₂-based DSCs and a lot of optimization is required to be done.

3. Advanced Solar Cells with Nanostructured Absorbers

3.1. Organic/Inorganic Hybrid Solar Cell. As a low cost alternative to silicon solar cells, hybrid solar cells consisting of organic thin films and inorganic nanostructures are being actively studied due to their promising performance. In this type of cell, inexpensive and easily processable organic materials are used and inorganic semiconductor nanostructures are embedded in the film to improve the absorption capability and tailor the absorption spectra through QCE [9].

One of these hybrid approaches is the nanoparticle sensitized solar cell, which is conceptually similar to conventional DSCs but replaces the organic dyes with inorganic nanoparticles [10]. The band gap of incorporated nanoparticles can be properly tuned by controlling the particle size, and thus desired absorption range and characteristics are able to be obtained. Nanocrystals as absorption material also have the advantage of stability due to the large extinction coefficients and intrinsic dipole moments [11].

Another strategy for hybrid solar cells is to use inorganic nanocrystals/conductive polymer blends which combine the flexibility of polymers with the stability and high mobility of inorganic nanoparticles. This approach is based on the concept of bulk heterojunction that initially originated from organic solar cells [12] but replaces the organic/organic

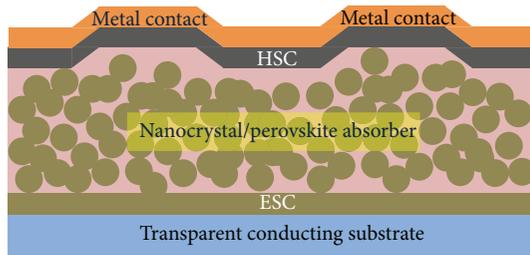


FIGURE 2: Schematic diagram of a hybrid perovskite solar cell. The “HSC” and “ESC” represent the hole selective contact and electron selective contact, respectively.

heterojunction with inorganic/organic heterojunction. Various inorganic semiconductor nanocrystals including CdSe, CuInS₂, CdS, or PbS have been implemented in such a structure [9, 11, 13–15]. This strategy indeed provides several promising potential advantages: (1) inorganic materials have high absorption coefficients, photoconductivity, and stability; (2) the doping characteristics of nanostructures can be easily tuned; (3) the size dependent QCE can change the electronic and optical properties of nanostructures, so that hybrid solar cells containing nanostructures with different sizes can be used for tandem solar cells. The challenge in hybrid solar cells using inorganic nanostructures mainly lies on the accessibility and reproducibility of the nanostructure synthesis routes.

Recently, the emergence of hybrid organic-inorganic perovskite solar cell attracts much interest due to its significant performance advantage over conventional hybrid solar cells [16, 17]. This kind of solar cell utilizes the metal halide based material most commonly CH₃NH₃PbI₃ nanocrystal or a closed variant (such as Cl, Br, I) as the light absorbers, and the perovskite pigment is a mixture of CH₃NH₃X (X = Cl, Br, I) and PbX₂ prepared by sequential vapour deposition or solution process [18, 19]. A structural diagram of the hybrid perovskite solar cell is schematically shown in Figure 2. Since the first report in 2009, the conversion efficiency of hybrid perovskite solar cell has been boosted at an unanticipated rate by exploring novel nanomaterials and device architectures [20–36]. Particularly, the progress in the development of solid state transport layer with high carrier mobility has substantially improved the device performance, and a breaking efficiency of 15.7% has been achieved by employing ZnO nanoparticles as the electron-transport layer of the solar cell [22, 35, 36]. In fact, besides prominent electron transport property, ZnO nanoparticle layer can be simply deposited by spin coating and requires no heating or sintering step, which makes it suitable for devices on thermally sensitive substrates. Therefore, hybrid perovskite solar cell based on ZnO nanoparticles is considered to be a promising candidate for low cost or flexible applications.

Although efficiencies up to 20% are predicted to be realistically achievable [37, 38], there are still several issues which need to be resolved before hybrid perovskite solar cells can be commercialized. The first one is the development of large-area fabrication method with good uniformity and

reproducibility, both of which are important for mass production. Nevertheless, almost all the best-performing cells reported to date only have areas smaller than 0.1 cm² [39]. Another more challenging issue involves the fast degradation of the solar cell performance. The structure and function of organic components are easily influenced or even destroyed once the ambient gas or moisture penetrates the packaging materials and reaches the solar cell. This problem in fact has held back the commercialization process of most organic solar cells. Although long-term stability may be attained for hybrid perovskite solar cell in future work, there has not yet been any convincing report up to now [40].

3.2. Nanowire Solar Cell. In general, a nanowire is defined as a wire-like nanostructure with a diameter of the order of several nanometers. Due to the lack of grain boundaries along its length, the use of nanowire as a direct conduction path for charge carriers offers various merits in device performance, such as large charge transport rate and small carrier recombination probability. In addition, the nanowire structure also exhibits superior light trapping characteristics, resulting in much less surface reflection compared with conventional planar structure. These advantages indicate that it is possible to achieve high conversion efficiency in nanowire solar cells, and, more importantly, the employment of nanowire structure reduces the consumption of material and releases the requirement of material quality, both of which give rise to a substantial cost reduction. So far, there are no rigorous classification and criterion on nanowire solar cells. Nevertheless, they can be roughly divided into two categories, the nanowire dye sensitized solar cell and the nanowire solar cell based on pn junction structure.

The earliest report of nanowire dye sensitized solar cell was from Huynh et al. in 2002, in which CdSe nanowires were utilized as the hole conducting layer and an efficiency of 1.7% was achieved under AM1.5 irradiation [9]. Later Law et al. [41] demonstrated a similar structure using ZnO nanowires instead of CdSe nanowires. This kind of solar cell exhibited a maximum power conversion efficiency of 1.5% under AM1.5 condition. Compared with nanowire dye sensitized solar cells, the nanowire solar cells based on pn junction structure attract more interest and are being extensively studied. Generally, this kind of nanowire solar cell can be divided into three types according to the pn junction location as shown in Figure 3.

Direct deposition of nanowire array as an antireflection layer on the surface of traditional cells is the simplest application of nanowires to solar cells. Theoretical analysis suggests that semiconductor nanowires have a very low luminous reflectance, especially in the long wavelength range. For instance, the silicon nanowire has been demonstrated to have much lower reflectance in the infrared range than that of single crystalline and multicrystalline silicon materials [42]. This inherent optical characteristic can be attributed to the multiscattering of light in the nanowire structure and thereby it is advised that the effect of incident light trapping can be optimized by adjusting the diameter and refractive index of nanowires. So far, the conversion efficiency of nanowire array solar cells is still relatively low compared to conventional

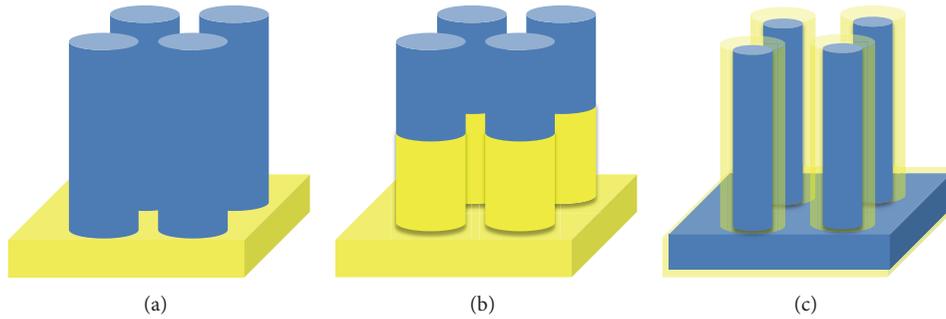


FIGURE 3: Schematic diagrams of nanowire solar cells based on (a) substrate junction structure, (b) axial junction structure, and (c) radial junction structure.

silicon solar cells [43, 44]. The efficiency loss can be explained by the presence of a large number of surface states which results from the high density of nanowires. These surface states are difficult to be fully passivated, so that the surface recombination velocity is significantly increased. This finding means that a trade-off between the nanowire density and surface passivation effect needs to be resolved to maximize the performance of nanowire array solar cells.

Besides using nanowire array as antireflection layer, novel device structures with pn junction located on the nanowire surface or inside the nanowire have also attracted increasing interests. Researchers from Harvard University have developed an axial junction nanowire solar cell with a conversion efficiency of 3.4% [45]. Later, Garnett and Yang proposed a novel orthogonal network of photon absorption path and charge carrier transport path in a radial junction nanowire solar cell, in which the long nanowire axial enhances photon absorption and the radial junction improves the charge carrier collection. Theoretical calculation predicts that a conversion efficiency of up to 11% can be obtained in a radial junction nanowire solar cell with an electron diffusion length of 100 nm, which is much higher than that of nanowire solar cells with planar structure [46].

3.3. Intermediate Band Solar Cell. The approach of intermediate band solar cells (IBSCs) is to introduce a continuous electronic band within the band gap of another semiconductor material as shown in Figure 4 [47, 48]. In the operation of IBSCs, subband gap photons of specific energy first pump electrons from valence band (VB) to IB (Process (1) in Figure 4). Before occurrence of nonradiative recombination, the electrons in IB are further emitted to CB through absorption of another subband gap photons (Process (2) in Figure 4). The wave function of the electrons in IB should be delocalized, which is similar as the property of the electron wave function in CB and VB, so that radiative absorption and recombination dominate at these energy levels and the photons do not necessarily have to be absorbed by the same electron in the two steps. In order to provide both empty states for capture of electrons from VB and occupied states for injection of electrons to CB, the IB has to be partially filled with electrons (i.e., “metallic”). Ideally, half-filled IB is needed to ensure that both capture and emission

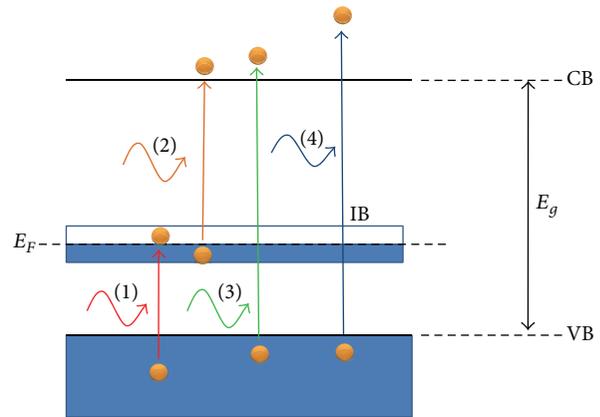


FIGURE 4: Band structure of an intermediate band material in equilibrium. E_F is the Fermi level of the intermediate band material. The photon absorption processes involving photons with different energies (marked as 1, 2, 3, and 4) are also shown.

processes are equally likely. The absorption of subband gap photons enhances the photocurrent while the output voltage is preserved. This leads to a limiting efficiency as high as 63.2% (under maximum sun concentration 46,050 suns) for IBSCs. This efficiency is similar as that for a three-cell tandem solar cell and is much higher than the 40.7% conversion efficiency for an ideal single band gap solar cell that is made from the same material.

The existence of materials with an IB characteristic was once controversial. However, people have now suggested quite a few candidates, mostly in III-V, II-VI, and chalcopyrite systems alloyed with a transition metal [49–53]. As an alternative approach, quantum dots (QDs) were also proposed to form IBSCs [49, 54]. In this approach, the energy levels comprising the IB arise from the confined electron states in the QDs. The use of QDs has a few advantages over other nanostructures such as quantum wells or wires. This is because of the following. (1) Only QDs provide a true zero density of states between the IB and CB [55]. This prevents nonradiative recombination between the CB and IB [56]. (2) The optical transition from IB to CB is strictly forbidden by selection rules in quantum wells for

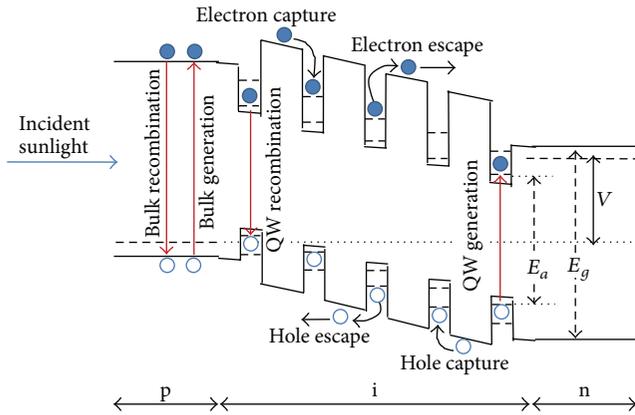


FIGURE 5: Band diagram for the QWSC with the MQW structure in the intrinsic region. The photogeneration and recombination processes are shown for both bulk and QW regions. The carrier capture and escape routes are also shown in the figure.

light incidence perpendicular to the plane of growth. This is definitely detrimental for the solar cell applications [57].

Although several material systems have been proposed for the implementation of QD IBSCs, the practical experimental work still mainly focuses on the InAs/GaAs QD superlattice structure grown by molecular beam epitaxy using the Stranski-Krastanov growth method [54, 58]. The photocurrent generation due to the IB to CB transition, an important indicator of true IBSC operation, has recently been demonstrated in these devices. Nevertheless, there is still a long way to go to achieve the advantage of conversion efficiency in IBSCs.

3.4. Quantum Well Solar Cell. The quantum well (QW), a 1D confinement nanostructure, has been applied widely in semiconductor devices since its emergence, including photodetectors, light emitting diodes, lasers, optical modulators, and high mobility transistors. The optical and electrical properties of QWs are engineered to meet the particular requirements of different applications. It is thus reasonable to speculate that there may be some advantages of using QWs in solar cells. The ability to modulate the band gap of QW structures through QCE provides a means of achieving high energy conversion efficiency due to the better band gap match to the solar spectrum. The multiple quantum well (MQW) structure was proposed in the early 1990s, making a solid step in the utility of QW solar cells (QWSCs) [59]. The band diagram of a MQW solar cell is shown schematically in Figure 5.

The QWs are located in the intrinsic region of a p-i-n structure, and carrier photogeneration and recombination occur in both the barrier and QW layers. For the carriers generated in QWs to be effectively collected at the external electrodes and thereby contribute to the photocurrent, the carriers must be able to escape from the QWs. Besides quantum tunneling process, thermal escape is also crucial for achieving efficient carrier escape from QWs, which indicates a requirement of the thermal energy and transverse electric

field in the operation of QWSCs [60–62]. Fortunately, the thermal energy at room temperature is usually sufficient and the probability for carrier escape can be close to unity in the presence of a strong electrical field.

High quality growth techniques with monolayer accuracy, such as molecular beam epitaxy (MBE) and metal organic vapour phase epitaxy (MOVPE), have been used to fabricate QWSCs. According to lattice constant difference between barrier and well layers, the material systems used in QWSCs can be categorized into lattice matched systems, such as AlGaAs/GaAs, InGaP/GaAs, InP/InGaAs, and InGaAsP/InP, and lattice mismatched systems including GaAs/InGaAs, InP/InAsP, GaAsP/InGaAs, GaAs/InGaAs, and InGaAs/InGaAsP. The initial studies of QWSCs were mainly based on the lattice matched material systems using GaAs or InP as the well material. Therefore, the absorption threshold is adjusted to higher energies over a conventional, homojunction cell formed from the GaAs or InP. Such material systems show good solar cell performance and it is a good way to avoid the complications caused by the strain so that it is easier to reveal the effects from QWs and to understand the underlying operation mechanisms.

For most solar cell applications, however, lower absorption threshold is indeed desirable. A good example is to enhance the long wavelength absorption of high efficiency GaAs cells. A major problem here is that there are no lattice-matched, lower band-gap systems in nature to act as the wells. For example, InGaAs is a particular good choice as a well material for devices using GaAs as barriers, but it has larger lattice constant so that compressive strain is required to grow the InGaAs QWs. The strain builds up in each well layer and finally results in numerous threading dislocations through strain relaxation at the top and bottom of the MQW stack, causing larger leakage current, worse short wavelength quantum efficiency, and loss in open circuit voltage [63, 64].

To solve this problem, strain-balanced QWSCs have been proposed to minimize the build-up of strain. The idea is to compensate the strain from QWs by using barrier layers with opposite strain [65]. A typical example of such cell is the strain-balanced GaAsP/InGaAs QWSCs as shown in Figure 6. Over each period, the compressive strain from the InGaAs well layer with larger lattice constant is compensated by the tensile strain from the GaAsP barrier layer with smaller lattice constant. The average lattice constant equals that of GaAs and the average strain in the cell should approach zero, leading to significant reduction of dislocations in this structure.

To date, QWSCs have shown advantages in engineering the absorption spectrum and improving the photocurrent. However, there are still a few challenges remaining. The most important one is the increase of absorption of the MQW stack. This may be solved by growing more QWs, but this strongly depends on the availability of high quality and yield growth technology. Another widely studied approach is the use of light trapping schemes [66].

3.5. All Quantum Dot Tandem Solar Cell. Among various high efficiency approaches, tandem structure is the only

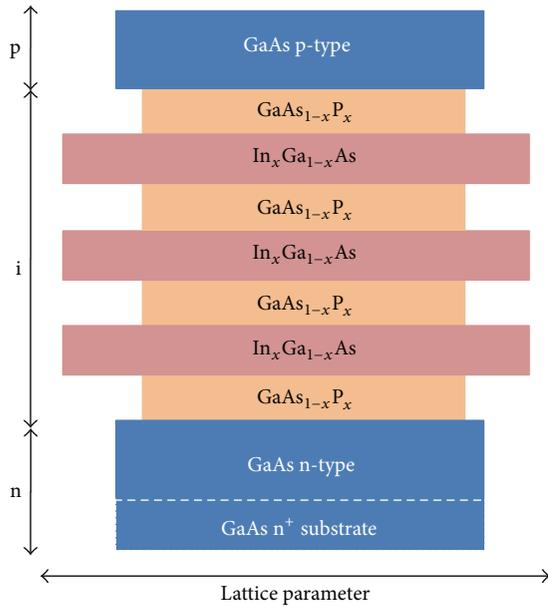


FIGURE 6: Schematic diagram of a strain-balanced GaAsP/InGaAs 3-period MQW solar cell.

approach that has shown the capability to achieve high conversion efficiencies (44% at ~ 500 suns) beyond the Shockley-Queisser limitation [67]. However, these cells require the use of expensive III-V materials and manufacturing process, which are only viable for concentrating systems. Therefore, it would be very attractive if alternative low cost materials and process can be adopted in such a tandem cell design.

In recent years, all quantum dot tandem solar cells which use band-gap engineered nanocrystals as absorbing material have been proposed as a promising high efficiency approach [68–72]. Most of these tandem solar cells are designed to use the most common elements such as Si, Ge, PbSe, and PbS. This not only reduces the material cost but also secures the long term availability of raw materials. Besides, this kind of tandem solar cell has a good potential for large scale manufacturing, which benefits from the integrated circuit industries. The all quantum dot tandem solar cell with three subcells is schematically shown in Figure 7. In the tandem stack, the top and intermediate subcells are composed of nanocrystals with engineered band gaps and a conventional single junction solar cell is used as the bottom cell. The effective band gaps of the two upper cells can be tuned by the size of nanocrystals and their optimized values depend on the selection of the bottom cell.

There is a series of steps involved in the realization of a working all quantum dot tandem solar cell, including the fabrication of band gap engineered nanocrystals, formation of a rectifying p-n junction, and the interconnection of cells through a tunneling layer. Of these challenges, the ability to adjust the material's band gap through quantum confinement effect is the basis of the concept. During the past two decades, a lot of efforts have been made in the investigation of the low dimensional confinement properties of various nanocrystals [72–75]. Despite intensive studies, the reliable production

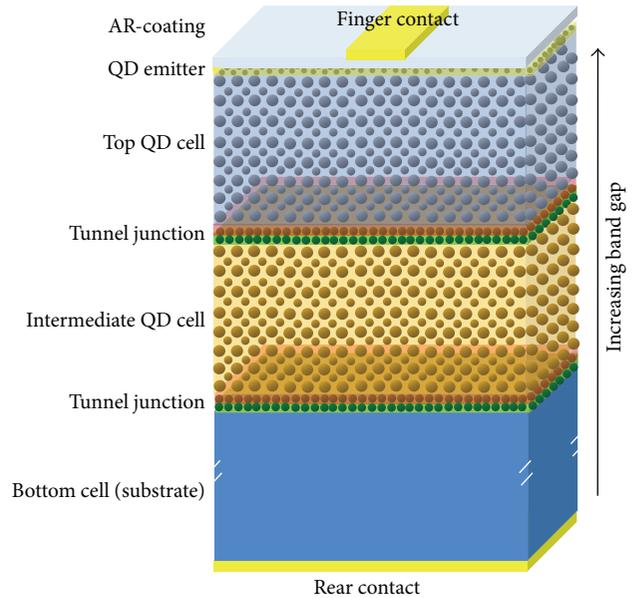


FIGURE 7: Schematic diagram of the all quantum dot tandem solar cell with three subcells.

of nanocrystals using low cost fabrication techniques is still an area of difficulty. This is because in order to accurately tune the band gap, certain aspects of nanocrystal materials need to be precisely controlled, such as crystallite size and distribution, barrier thickness, and defect passivation. Recently, two interesting techniques have been reported to provide relatively controllable growth of nanocrystals with size-tunable energy gaps [72, 76–80]. The superlattice structure fabricated using traditional thin film techniques such as sputtering allows for an easy integration with current silicon process technology, while the solution-based process which produces colloidal semiconductor nanocrystals shows great advantages for the fabrication of low-cost structures. Besides controllable synthesis of nanocrystals, the manipulation of electrical properties of nanocrystals also needs to be studied in order to form a rectifying pn junction for charge separation [81]. In summary, continued efforts are required to further improve the quality of the nanostructures and understand more deeply the underlying physics on the path to the realization of a working all quantum dot tandem solar cell.

3.6. Hot Carrier Solar Cell. In traditional solar cells, photocarriers relax from their initial energetic position to the band edge by thermal emission process before they can be extracted out from the devices. As a consequence, a huge amount of absorbed energy is wasted especially for high energy photons. In 1982, a kind of photovoltaic device called hot carrier solar cells (HCSCs) was proposed to timely extract the energetic photocarriers, so that the thermalization loss can be minimized and the solar cell efficiency can be remarkably improved [82]. In principle the efficiency of HCSCs can be as high as 67% under AM1.5 irradiation and even achieve 86% under concentrated illumination [83].

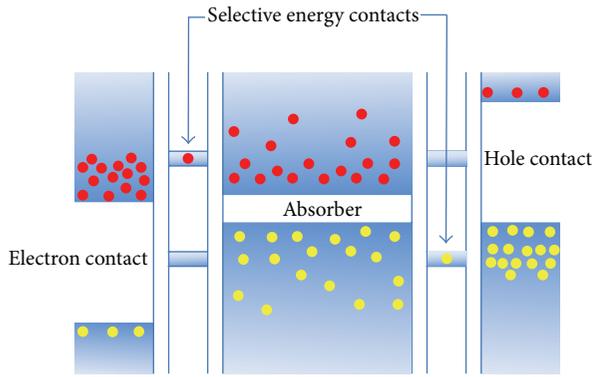


FIGURE 8: The energy band diagram of a hot carrier solar cell. Photogenerated electron-hole pairs in the absorber are kept hot at an elevated temperature before they are extracted out from the energy-selective contacts.

As shown from the schematic diagram in Figure 8, in order to build a complete HCSC, we need to figure out two things: the absorber with extremely slow cooling rate of hot carriers and the extraction contact with a narrow energy range [83–85]. During the last decade, most efforts in this area are devoted to the discovery of appropriate hot carrier absorber material. In fact, since the emergence of HCSC, low dimensional structures are considered to be most promising for reducing the hot carrier cooling rate [86, 87]. Theoretical and experimental work have demonstrated that the unique properties of nanostructures are responsible for the reduced cooling rate, such as more stringent conservation rules in the carrier-phonon interaction which couple carriers to fewer vibration modes and the carrier localization effect that prevents carrier cooling by out-diffusion from the hot phonon regions [88–90]. In the meantime, nanostructures have also shown some potential in the fabrication of selective energy contact [85, 91–93]. Unfortunately, however, until now no working device has yet been made for HCSCs, which more or less reflects that the development of HCSCs is now facing serious challenge. This might be related to the fact that it is quite difficult to use current manufacturing techniques to produce the nanostructures required by HCSCs. Moreover, the lack of customized characterization facilities and methods also hinders the development of new materials and device structures.

4. Conclusions and Future Directions

There has been a long history of using nanostructures in photovoltaic devices. The first application of such strategy was made to improve the performance of conventional thin film solar cells. Although some positive effects of nanostructures are clearly observed in these devices, they are still less competitive due to the inherent limitation of the absorber performance. Therefore, the development of nanostructured absorbers which combines advantages of quantum confined energy levels and low cost processes is considered to be rather important for the realization of next-generation photovoltaic concepts. Up to now, diverse designs have been proposed to

utilize the unique flexibility of nanostructures to optimize photon absorption, carrier generation, and charge separation. Theoretical calculation illustrates promising high efficiencies for these devices despite of their different approaches. In practice, however, a competitive technology needs to meet other requirements besides efficiency such as spectral robustness, ease of manufacture, and long-term stability. None of nanostructured solar cells matches all these goals yet.

Hybrid solar cells combining inorganic nanoparticles and conductive polymer blends are the best developed so far and further improvement is likely to reduce the overall dollar per watt cost. Recently, the discovery of perovskite material significantly improves the absorption capacity of hybrid solar cells thus leading to an efficiency boost. This makes hybrid perovskite solar cell an ideal candidate for the portable or flexible applications. In such kind of solar cells, long-term stability seems to be a more challenging issue than conversion efficiency according to existing research and experiment results. The development of more stable hybrid structure and appropriate packaging technique is important for the future development of hybrid perovskite solar cell.

Tandem solar cells with multiple energy thresholds in theory have very high efficiency. More importantly, their embedded QW and QD absorbers could be made from low cost, abundant, nontoxic, and stable materials. Therefore, tandem solar cells are considered to be a competitive technology that can significantly increase the implementation of photovoltaics. Nevertheless, despite the well-developed methods for the preparation of nanostructures, these devices still have difficulties in carrier transportation and extraction. Further research should focus on the suppression of carrier recombination and the formation of high quality junctions and metal contacts.

Compared with hybrid cells and tandem cells, work on other approaches is still at a much earlier stage. The nanowire solar cells suffer from relatively low efficiency limit, and intermediate level devices and hot carrier cells still have serious theoretical questions to answer. In addition to the solar cells mentioned in this paper, some more advanced concepts can also be realized by the implementation of nanostructures, such as multiple carrier generation, up/down conversion, thermophotonics, and thermophotovoltaics [94–97]. These esoteric approaches seem to be impractical at present, but a few of them might become possible as understanding of the topic continues to improve.

Besides being used as absorber materials, nanostructures are attracting increasing attention as alternative light trapping structures for thin film solar cells. During the last few years, several different approaches have been developed for nanophotonic light trapping. The periodic structure is the best developed approach with good understanding of fundamental mechanisms and mature processing technologies. According to the number of dimensions, there are three kinds of periodic structures, Bragg stacks, gratings, and photonic crystals [98–102]. Plasmonic structure is another promising approach for nanophotonic light trapping. The discrete metal nanoparticles on the surface randomly scatter incident light into the active layer of solar cell, thus resulting in enhancement of light absorption [103–107]. In contrast

to the traditional method such as surface texturing, the use of nanophotonic structures is a better choice for thin film solar cells, since they will not affect the surface topography of the thin films, which has a notable impact on the device performance. In future work, the manufacturing cost of these structures needs to be significantly reduced, particularly for large area substrates. Otherwise, they are unlikely to be used for commercial production.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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