1. Depleted heterojunction solar cells

2. Deposition of semiconductor layers with solution process

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Outline

1. Solar cells
   - P-N junction solar cell
   - Schottky barrier solar cell
   - DSC (or QDSC)
   - Depleted heterojunction solar cell
     - Energy level alignment
     - Funnel structure

2. Deposition of semiconductor layers by solution method
   - Spray pyrolysis deposition for CdS
   - Successive ionic layer adsorption and reaction for CdSe
   - Chemical bath deposition for Sb$_2$S$_3$
   - Spin-coating deposition using single source precursor for Sb$_2$Se$_3$
Electron-hole pair generation

Solar cells

How to collect such electrons and holes?
Potential Energy
Silicon p-n junction solar cell

http://www.electronics-tutorials.ws/articles/solar2.gif?81223b
http://education.mrsec.wisc.edu/SlideShow/images/pn_junction/pn_junction_solar.jpg
Depleted heterojunction solar cell

Figure 1. Comparison of three CQD photovoltaic architectures under photovoltaic operation close to maximum \( V_{oc} \). (a) The Schottky design has lower FF and \( V_{oc} \) for a given \( J_{sc} \), due to the poor barrier for hole injection into the electron-extracting contact. (b) The depleted heterojunction design combines the advantages of the other two cells, leading to simultaneously maximized FF, \( V_{oc} \), and \( J_{sc} \). (c) The CQD sensitized cell employs a thin layer of absorber on a high surface area electrode. The light-absorbing capacity of this design is lower, leading to poor \( J_{sc} \), while it provides good FF and \( V_{oc} \). \( E_{F,n} \) and \( E_{F,p} \) are the electron and hole quasi-Fermi levels; \( E_c \) and \( E_v \) are the conduction and valence band edges; \( J_{p, PV} \) and \( J_{n, PV} \) are the hole and electron photocurrents (and are equal at steady state); \( J_{p, fwd} \) is the hole current in the forward bias direction.
Energy level alignment of TiO$_2$ and CQDs

Colloidal quantum dots

ACS Nano 2010, 4, 3374.
Energy level alignment of TiO$_2$ and CQDs

Figure 11. Top row: Depleted heterojunction energy band diagrams using undoped TiO$_2$, antimony-doped TiO$_2$, and zirconium-doped TiO$_2$. Reprinted with permission from ref 103. Copyright 2011 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim. Bottom row, first and second columns: Bandgap and electron affinity of undoped, Sb-doped and Zr-doped sol–gel TiO$_2$. Bottom row, third to sixth columns: Performance metrics of 1.3 eV PbS CQD DH solar cells using the undoped, Sb-doped, and Zr-doped sol–gel TiO$_2$ including $V_{OC}$, $J_{SC}$, FF, and $\eta$. Bottom row, seventh to tenth columns: Performance metrics of 1.0 eV PbS CQD DH solar cells of same.

CQD solar cells using quantum funnels

Figure 16. Spatial band diagrams of a DH CQD solar cell (left column), a DH CQD solar cell with an appended quantum funnel (middle column), and a slightly truncated DH CQD solar cell with an appended quantum funnel (right column) at short-circuit (top row) and maximum power point conditions (bottom row).
Back surface field (BSF)

Source: K. Mertens: textbook-pv.org

http://www.textbook-pv.org/figures.html
Hole transport materials (HTM)

1. FTO/TiO$_2$(n)/CdTe(p)/Au

Without HTM

2. FTO/TiO$_2$(n)/CdTe(p)/P3HT/Au

With HTM
Deposition of semiconductor layers with solution process
1. CdS by spray pyrolysis deposition (SPD)

2. CdSe by successive ionic layer adsorption and deposition (SILAR)

3. Sb$_2$S$_3$ by chemical bath deposition (CBD)

4. Sb$_2$Se$_3$ by spin-coating of single-source precursors (SSP)
Selective etching of CdCl₂

Washing with water

(a) CdS by spray pyrolysis deposition

(b) Washing with water

(c) SEM images
X-ray diffraction (XRD) patterns of film deposited on glass substrate.
CdS by spray pyrolysis deposition;

Surface morphology engineering by successive oxidation and etching

Oxidation by thermal annealing

Etching by HCl

CdS
CdO
X-ray diffraction patterns of as-deposited, oxidized and oxidized/HCl treated CdS deposited on a bare glass
TEM images of (a) as-deposited CdS on mp-TiO$_2$ and (b) reconstructed CdS on mp-TiO$_2$ by thermal annealing and etching
Device characterization of CdS-SSC in I⁻/I₃⁻ electrolyte system. (a) J-V curves and (b) EQE and UV-Visible transmittance of as-deposited (black solid line) and thermally oxidized (red solid line) CdS/mp-TiO₂ film.
Successive Ionic Layer Adsorption and Reaction (SILAR): CdSe by SILAR:
0.03 M Cd(NO₃)₂, 0.03 M Se²⁻ in EtOH, glove bag under N₂.

(a) Schematic illustration of energy band diagram of CdSe-sensitized heterojunction solar cell, (b) cross-sectional SEM image, and (c) TEM image of CdSe deposited on mesoscopic TiO₂ electrode.

(a) UV-Visible transmission spectra of CdSe deposited on mesoscopic TiO₂ film according to the number of SILAR cycles: inset = photograph, (b) J-V curves, and (c) EQE spectra of CdSe-sensitized heterojunction solar cells.

The table summarizing device performance with the number of SILAR cycles:

<table>
<thead>
<tr>
<th></th>
<th>( J_{sc} ) (mA/cm²)</th>
<th>( V_{oc} ) (V)</th>
<th>FF (%)</th>
<th>( \eta ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CdSe-8</td>
<td>2.9</td>
<td>0.47</td>
<td>64.0</td>
<td>0.94</td>
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<tr>
<td>CdSe-10</td>
<td>3.6</td>
<td>0.47</td>
<td>60.7</td>
<td>1.09</td>
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<tr>
<td>CdSe-12</td>
<td>1.8</td>
<td>0.46</td>
<td>59.7</td>
<td>0.52</td>
</tr>
</tbody>
</table>
Sb$_2$S$_3$ sensitized solar cells

FIGURE 1. (a) Energy structure diagram and schematic configuration of our devices. (b) Absorption spectra of P3HT and Sb$_2$S$_3$-deposited mp-TiO$_2$ for various deposition times on the surface of mesoporous TiO$_2$ layer in chemical bath. (c) Incident-photon-to-current conversion efficiency (IPCE) for mp-TiO$_2$/P3HT/Au and mp-TiO$_2$/Sb$_2$S$_3$/P3HT/Au. The illumination intensity for the IPCE measurements was $\approx 0.5$ mW cm$^{-2}$. (d) Current density—voltage ($J$—$V$) curves for TiO$_2$/P3HT/Au and TiO$_2$/Sb$_2$S$_3$/P3HT/Au fabricated with different deposition times. The Sb$_2$S$_3$ layers formed by chemical bath deposition were annealed at 330 °C for 30 min in Ar atmosphere after washing well with deionized water and drying and were then cooled in air. Masks (0.085 cm$^2$) made of black tape were attached to each cell before measurement for IPCE and $J$—$V$ characteristics.

Nano Lett. 2010, 10, 2609.
Chemical bath deposition (CBD) of $\text{Sb}_2\text{S}_3$

- TiO$_2$ electrode
- As-prepared a-Sb$_2$S$_3$ films
- Au counter electrode
- c-Sb$_2$S$_3$ after annealing
- Deposition of HTM
Deposition of Sb$_2$Se$_3$ using a single source precursor (SSP)

Scheme 1. Fabrication process for Sb$_2$Se$_3$-sensitized inorganic–organic heterojunction cells. Poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS) was used as the HTL.
After annealing, 300°C/10 m, $N_2$ * $Sb_2Se_3$ (PDF# 01-075-1462)

Figure 4. a) $J$–$V$ curve under light (■) and dark (▲) conditions and b) IPCE spectrum of the most efficient cell that was prepared in this study. c) Histogram of device efficiencies for the 135 devices that were fabricated independently.
Deposition of $\text{Sb}_2(\text{S}_x\text{Se}_{1-x})_3$ graded-composition sensitizer

**Figure 4.** a) Relative energy band diagram of $\text{TiO}_2$, $\text{Sb}_2\text{Se}_3$, $\text{Sb}_2\text{S}_3$, and P3HT. b) Proposed cascaded-band alignment on the T/Se/S structure.

**Figure 3.** XRD patterns of T/Se, T/Se/S, and T/S. T/Se and T/S correspond to mp-$\text{TiO}_2$/Sb$_2$Se$_3$ and mp-$\text{TiO}_2$/Sb$_2$S$_3$, respectively.

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5. a) J-V curves measured under simulated sun light over a range of intensities of the champion device. b) Histogram of device efficiencies obtained from over 50 individually fabricated devices. c) IPCE spectrum of the champion device in the present study.