Fundamentals of photovoltaic energy conversion and conventional solar cells

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ICMAB, Campus UAB, Barcelona
Outline

- Fundamentals of photovoltaic energy conversion
- Conventional (inorganic) solar cells
Outline

• Fundamentals of photovoltaic energy conversion
  • Conventional (inorganic) solar cells
What is needed for a PV converter?

$E_l$
What is needed for a PV converter? A material sensitive to light

\[ E_I \]

\[ \text{A} \]
\[ \text{B} \]
\[ \text{C} \]
What is needed for a PV converter?: Transport x lifetime
What is needed for a PV converter? Selective contacts

Efficiency \( \equiv \eta = \frac{E_2}{E_1} \)
A material sensitive to light: A semiconductor

By Enricoros at English Wikipedia
Transport x lifetime

Diffusion length $\propto \sqrt{\text{mobility} \times \text{lifetime}}$
Selective contacts: p-type and n-type semiconductors

\[ E_1 < E_2 \]
Selective contacts: p-type and n-type semiconductors

\[ E_1 \]

\[ E_2 < E_1 \]
The solar cell as pn junction

**Figure 3.1** A schematic of a simple conventional solar cell. Creation of electron–hole pairs, e⁻ and h⁺, respectively, is depicted.
Current-voltage characteristic of a solar cell

Current-voltage characteristic of a solar cell

\[ \eta = \frac{I_{MP} \times V_{MP}}{\text{Incident Pw}} = \frac{I_{MP} \times V_{MP} \times FF}{\text{Incident Pw}} \]

Impact of series resistance on FF

Input power (solar spectra)
Selective contacts: p-type and n-type semiconductors

$E_1$}

$E_2 < E_1$
Pn junction bandgap diagram

P region

Conduction band

Valence band

N region

\( e^- \)  \( e^- \)

\( h^+ \)  \( h^+ \)
Figura 7. Un semiconductor, sin estructura $p$-$n$, (izquierda) aunque se ilumine no provoca la circulación de corriente eléctrica. La unión $p$-$n$ hace posible la circulación de la corriente eléctrica gracias a la presencia de un campo eléctrico.
The solar cell as pn junction (wrong argument)

- p, n regions absorb light and the electric field is negligible.
- Instead, the concept of electrochemical potential as driving force must be used.
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• Conventional (inorganic) solar cells
  – silicon
  – III-Vs (multi-junction solar cells, GaAs, InGaP, InGaAs…)
  – thin films
Solar Cell Efficiency records (as in 2018)

Best Research-Cell Efficiencies

See https://www.nrel.gov/pv/assets/pdfs/cell_efficiency_explanatory_notes.pdf for key to company/laboratory/organization acronyms & abbreviations.
The abundance of materials problem

- Si – not a problem
- Cu(InGa)Se$_2$ -> In
- CdTe -> Te
- Multijunction -> Ge

Impact of stability on cost

Metric Sets to Achieve the Utility Scale SunShot Goal

Iso-LCOE Curves of 6 cents per kWh Without Federal or State Incentives and With 1,480 kWh/kW First-Year Performance

Module Price (U.S. Dollars per Watt DC)

- 0.2% per year degradation (50 yr)
- 0.2% per year degradation (30 yr)
- 0.75% per year degradation (30 yr)
- 2.0% per year degradation (10 yr)

Efficiency

SunShot 2020 Baseline for Utility Scale PV:
20% Efficiency, 0.2%/yr,
$0.40/W Module,
$0.10/W Inverter, and
$0.60/W BOS and Overhead

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Silicon: some properties

- Weak absorption
- Recombination limited by Auger
Silicon dominates the market.

Production 2016 (GWp)

- Thin film: 4.9
- Multi-Si: 57.5
- Mono-Si: 20.2

PHOTOVOLTAICS REPORT (2017). Fraunhofer ISE.
Monocrystalline and Multicrystalline modules

Mono

Multi
Monocrystalline and Multicrystalline modules

Mono

Multi
June 25, 1946.

R. S. OHL

2,402,662

LIGHT-SENSITIVE ELECTRIC DEVICE

Filed May 27, 1941

5 Sheets-Sheet 3

FIG. 14

1. SIMULATaneously COOL IN ELECTRIC FIELD IN VACUUM OR HEATED ATMOSPHERE

2. HEAT SLOWLY TO SOME POINTS ABOVE THE FUSION POINT WHICH IS APPROXIMATELY 500°C

3. COOL TO FUTURE UTILIZATION AT ABOUT 10°C AND DOWN TO 800-1000°C AT 50°C PER MIN.

4. COOL TO ROOM TEMPERATURE AT 80-120°C PER MINUTE

5. CUT FROM A SLAB CONTAINING COLUMNAR AND NON-COLUMNAR ZONES WITH AN INTERVINCING BARRIER INTERSECTING THE SLAB

6. GRIND TWO SURFACES OF SLAB PARALLEL TO THE BARRIER USING 300 MESH DIAMOND WHEEL & WATER LUBRICANT

7. ERODE THE SURFACES IN HOT SODIUM HYDROXIDE

8. WASH SURFACES WITH DISTILLED WATER

9. ELECTROPLATE SURFACES PARALLEL TO BARRIER WITH RHODIUM FROM A HOT SOLUTION OF RHODIUM TRIPHOSPHATE SLIGHTLY ACIDIFIED WITH PHOSPHORIC ACID OR SAPPHIRE ACID

10. WASH AND DRY THE RHODIUM PLATING

11. PLOW RHODIUM PLATING (AT LOW TEMPERATURE) WITH ORDINARY LEAD TIN SOLDER USING AN AGED LEAD ZINC CHLORIDE FLUX

PLACE "SOLDER" ELECTRIC TERMINAL ELEMENTS WITH FLAT SURFACES IN CONTACT WITH THROUGH HOLE SURFACES AND HEAT JOINT UNTIL SOLDER FLOWS

FIG. 26

FIG. 27

FIG. 28

FIG. 29

FIG. 30

FIG. 31

INVENTOR
R. S. OHL

ATTORNEY

Russel Ohl
(Technology Review)
1954 (6%)

Person, Chapin, Fuller (Perlin, The silicon solar cell turns 50)
1956 advisement of “Look magazine” (Perlin, The silicon solar cell turns 50)
1958-1972 – 14 % “Space”

Vanguard I (1958)

(Source: M.A.Green, Chap 4 in Clean Energy from Photovoltaics)
1972 – 15 % (Violet cell)

(Source: M.A.Green, Chap 4 in Clean Energy from Photovoltaics)
1974 – 18% (Black cell)

(Source: M.A. Green, Chap 4 in Clean Energy from Photovoltaics)
Texturing

Flat Silicon Substrate  Textured Silicon Substrate

Source: PVEducation
1983 – 18% (Metal to insulator np junction - MINP cell)

1990 – 22 % (back contact, rear junction solar cell)

R. Swanson & Sinton
Back contact, rear junction cell (commercial)
Solar Cell Efficiency records (as in 2018)

Best Research-Cell Efficiencies

Multijunction Cells (2-terminal, monolithic)
LM = lattice matched
IMM = metamorphic
III = inverted, metamorphic
 Three-junction (concentrator)
 Two-junction (concentrator)
 Two-junction (non-concentrator)
 Four-junction (concentrator)
 Four-junction or more (concentrator)
 Single-Junction GaAs
 Single crystal
 Concentrator
 Thin-film crystal
 Crystalline Si Cells
 Single crystal (concentrator)
 Single crystal (non-concentrator)
 Multicrystalline
 Silicon heterostructures (HT)
 Thin-film crystal

Thin-Film Technologies
- CIGS (concentrator)
- CIGS
- CdTe
- Amorphous Si:H (stabilized)

Emerging PV
- Dye-sensitized cells
- Perovskite cells (not stabilized)
- Organic cells (various types)
- Organic tandem cells
- Inorganic cells (CZTS,Se)
- Quantum dot cells (various types)

See https://www.nrel.gov/pv/assets/pdfs/cell_efficiency_explanatory_notes.pdf
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2014- 26 % HIT cell

Panasonic

Thin-films: a:Si

- Hydrogenated amorphous silicon: a-Si:H
- Greater absorption (thinner cells)
- Fabricated by CVD technology (RF PECVD)
- Degradation problems
- Tunable bandgap (1.7 eV):
  - with Ge, decreases (1.45 eV)
  - with C,N increases (2 eV)
- Possibility of tandem solar cells
Band diagram of a HIT cell

Shen et al. Solar Energy 97:168-175
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Figure 12.4 The conversion efficiency in a-Si:H-based solar cells declines noticeably upon the first exposure to sunlight. The figure illustrates this decline under a solar simulator (100 mW/cm²) for a single-junction cell (260 nm i-layer thickness) and for a triple junction module made at United Solar Ovonic [16, 17]; the dashed lines indicate the initial power measured for each device.
Bifacial solar cells and modules

Source: Sanyo Energy Corporation

Source: Silfab (Oregon park)
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What means III-Vs?

![Periodic Table of Elements](image)

For elements with no stable isotopes, the mass number of the isotope with the longest half-life is in parentheses.

Design and Interface Copyright © 1997 Michael Dayah (michael@dayah.com). http://www.ptable.com/
III-Vs: some properties

- Strong absorption
- Difficult to stack
- Work in the radiative limit
- Today driving market are space applications

Substrate: also a semiconductor!
Tandem cells

Tandem cells: Limiting efficiency

Number of cells

- 1: 40.7%
- 2: 55.5%
- 3: 63.4%
- 4: 68.3%

Efficiency (%)

- 86.8%
Tandem cells: conexión en serie

The current has to be the same for all the cells
Multi-junction solar cells: lattice matched and metamorphic

Solar Cell Efficiency records (as in 2018)

Best Research-Cell Efficiencies

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L.L. Kazmerski, National Renewable Energy Laboratory (NREL), Golden, CO, September 2018
**Figure 8.21** (a) Inverted metamorphic three-junction cell as grown. The tunnel-junction interconnects are not shown. The drawing is not to scale. (b) Finished device structure after back-contact deposition, handle mounting, substrate removal, and front-contact deposition
Solar Cell Efficiency records (as in 2018)

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Wafer bonding

Solar Cell Efficiency records (as in 2018)

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- Four-junction (concentrator)
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- Thin-film crystal

Thin-Film Technologies
- CIS (concentrator)
- CIGS
- CdTe
- Amorphous Si:H (stabilized)

Emerging PV
- Dye-sensitized cells
- Perovskite cells (not stabilized)
- Organic cells (various types)
- Organic tandem cells
- Inorganic cells (CZTS, Se)
- Quantum dot cells (various types)

Crystalline Si Cells
- Single crystal (concentrator)
- Single crystal (non-concentrator)
- Multicrystalline
- Silicon heterostructures (HIT)
- Thin-film crystal

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L.L. Kazmerski, National Renewable Energy Laboratory (NREL), Golden, CO, September 2018
Used in concentration systems
Concentration
Tandem cells: independent conexión
Tandem cells: spectrum splitting
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    • CdTe
    • CIGS
    • (a-Si)
Solar Cell Efficiency records (as in 2018)

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Thin film properties

- Strong absorption coefficient
- Deposited as polycrystalline materials

![Absorption Coefficient vs Energy](image)

**Figure 14.1** Theoretical solar cell efficiency (dotted) for AM1.5 spectral irradiance versus bandgap and absorption coefficient (solid) versus energy. Common absorber materials are highlighted.

Thin film properties

- Strong absorption coefficient
- Deposited as polycrystalline materials on cheap substrates
- Second in the market after silicon

Figure 3.1 SEM micrograph showing cross section of CdS/CdTe superstrate device produced at NREL. Certain layers have been color-enhanced for clarity.

Why it works?

Figure 2: Band diagram of TCO/CdS/CdTe cell without electron reflector layer.

http://www.hindawi.com/journals/ijp/2013/576952/fig2/
TCO: Transparent conductive oxide

ITO: Indium Tin Oxide, 4 eV
**Figure 13.1** Schematic cross-section of a typical Cu(InGa)Se₂ solar cell
Figure 13.2  TEM cross-section of a Cu(InGa)Se$_2$ solar cell
Figure 13.18  Band diagram of a ZnO/CdS/Cu(InGa)Se$_2$ device at 0 V in the dark. The recombination current $J_{REC}$ is greatest where $p = n$ in the space charge region of the Cu(InGa)Se$_2$ and not at the interface. A Cu-poor surface layer is shown by a dashed line.
Fig. 3. Variation of energy band gap, $E_g$, with gallium concentration in CuGa$_x$In$_{1-x}$Se$_2$ films.
CTZS: Cupper Zinc Tin Sulphide (kesterites)
Thank you!