Motivation: Widespread adoption of PV requires reduction in costs
How do PV costs breakdown?

- Power electronics
- BOS/Installation
- Module
How important is module efficiency?

The Impact of BOS Varies with Module Efficiency (2009 BOS costs)
The Impact of BOS Varies with Module Efficiency (2009 BOS costs)

Implied BOS Cost by Module Efficiency (before installer margin)

Ken Zwiebel, GWU

For example, a 5% module costing nothing would have the same system price ($3.5/W) for residential rooftops as a 15% module costing about $1.5/W
A single bandgap does not match the solar spectrum.
Where does the energy go?

- Conduction band (a)
- Incident photon ($h\nu$)
- Valence band
- $E_g$

Non-absorption loss

- $h\nu < E_g$
- (c)

Thermalization loss

- $h\nu > E_g$
- (d)

Radiative recombination

- (e)
Where does the energy go?

Problem

- Energy loss in Carnot cycle
- Entropy loss in absorption or emission
- Entropy loss due to non-reciprocity

- Energy loss due to thermalization or lack of absorption

- Entropy loss due to lack of angle restriction
- Entropy loss to incomplete light trapping and reduced QE

Conventional single-junction solar cell

A. Polman & H. A. Atwater, Nat. Mat. 11, 174 (2012).
Multijunction solar cells

(a) Schematic diagram of a multijunction solar cell.

- **Top Cell**
  - n<sup>+</sup>
  - Al<sub>In</sub>Ga<sub>P</sub> (1.86 eV)
  - n

- **Middle Cell**
  - n<sup>+</sup>
  - In<sub>Ga</sub>P
  - p
  - In<sub>Ga</sub>As (1.4 eV)
  - p<sup>+</sup>

- **Bottom Cell**
  - n
  - In<sub>Ga</sub>P
  - p<sup>+</sup>
  - Ge (0.65 eV)
  - n

(b) Spectral Irradiance (W/m<sup>2</sup>·μm) plot showing the AM1.5 spectrum and the spectral response of the top, middle, and bottom cells.
Lattice Matching
Current Matching

AM1.5D (ASTM G173), (mA/cm² in 5 nm interval)

300 nm - 800 nm - 1300 nm - 1800 nm

Relative current output

Current limiting value = 1.0

Excess Current (~50%)
Expensive!

- No absorption
- Radiative recombination loss
- Thermalization loss

Diagram:
- $n_{ph} (10^{17} \text{ cm}^{-2} \text{ sec}^{-1})$
- $W (0.9 \text{ eV})$
- $E_g = 1.35 \text{ eV}$
- $W < E_g$
- $h\nu > E_g$

Equation:
- $W = \frac{J_m}{J_{sc}} \text{ eVm}$
- AIR MASS = 1.5
- $P/A = 844 \text{ W/m}^2$
- $\langle h\nu \rangle = 1.37 \text{ eV}$
- $N_{ph} = 3.85 \times 10^{17} \text{ cm}^{-2} \text{ sec}^{-1}$
Efficiencies of multi-band-gap Solar Cell
(Henry, C. H. J. Appl. Phys. 51, 4494)
Hybrid Photovoltaic & Thermal Power Generation
Thermophotovoltaic (TPV) Approaches

Early coaxial TPV design with optical filtering

A solar TPV design proposed by Swanson

primary parabolic mirror concentrator
~ 20,000 suns, temp ~ 2400K
Cassegrainian solar TPV system presented by Horne

Solar TPV system with thermal storage
Spectral-splitting in photovoltaics

(A) back-silvered coatings

(B) coolant can be passed through hollow interior.
Spectral-splitting in photovoltaics

PV cells of different bandgap values

Cavity receiver

Concentrated solar radiation

Photovoltaic cavity converter
Increasing bandgap PV cells

Refractive Spectrum Splitting

Prism spectrum splitting.

Incident white light

Spectrally dispersed light

Increasing bandgap PV cells

Prism
Spectrum Splitting via luminescent concentrators

Incident sunlight

PV 1

PV 2

Reflective coating

Thermal receiver

Luminescent concentrator plates coupled to PV cells
Spectrum Splitting via Holographic concentrators

Transmission and reflection holograms, splitting the sunlight into multiple bands for PV cells

Prism technologies Inc.
Polychroic mirror based spectral splitting

Unwanted diffraction orders, optical aberrations, angular sensitivity
Holographic lens for two-cell PV operation

Short wavelength focussing hologram

Long wavelength focussing hologram

PV 1

PV 2

Thermal absorber
Line-focussing holographic system for PV cell receivers

Spectral bandwidth is typically limited (visible)

Lifetime issues with holographic material

Sensitivity to incident angle.

Single hologram avoids cross-coupling effects & minimizes aberrations.
Total solar co-generation system proposed by Soule

An implementation of this system is shown in Fig. 19 [124], where a tracking linear Fresnel lens is focusing light through a cylindrical plano-concave lens and onto a linear PV array which is thermally anchored to a copper substrate containing cooling channels. A spectrally selective heat-mirror positioned between the plano-concave lens and the PV receiver splits part of the beam off to an evacuated tube receiver, placed out of the path of the incident rays. Reflective wing secondary concentrators are provided at the aperture of both the PV and evacuated tube receivers for improved light collection. The optical losses could be substantial in this design, hence attention should be given to whether the concentration achieved will be sufficient for the efficient operation of both PV and thermal receivers.
PV/thermal collector designs proposed by Izumi

Fig. 20A shows a transparent glass pipe enclosing the PV and thermal receivers, the upper half being of circular or elliptical cross section and the lower half of parabolic cross section. The lower half is coated with a thin aluminium layer to reflect long wavelengths onto a thermal receiver. A one-axis tracking mechanism aligns the collector in such a way that solar energy is approximately normally incident on a parabolic cold mirror located in the centre of the glass pipe. The cold mirror reflects the short wavelength component onto a PV receiver mounted on a rectangular water-cooled aluminium tube. The long wavelength component is transmitted to the lower half of the receiver and redirected onto an evacuated tube receiver. The evacuated tube is painted black for increased absorption and contains a heat transfer medium of low boiling point, producing vapour which eventually rotates a turbine for electricity generation.

Fig. 20B shows an alternative design, in which a Fresnel lens is positioned in the upper opening of a cylindrical collector of quadrilateral cross-section. Solar radiation is concentrated onto a convex parabolic cold mirror positioned above the heat tube receiver, and is split into two components for PV and thermal conversion.

In Fig. 20C, double-faced PV cells are employed in a sun-tracking panel assembly. Fresnel lenses converge the long-wave solar radiation onto evacuated tubes containing a black heat-transfer medium. A reflective aluminium plate is placed below the tubes to improve light utilization. The upper half of each evacuated tube is shaped like an inverted V and is coated with a semi-transparent thin film coating for short-wave reflection. The short wavelengths are directed onto the rear surfaces of double-faced solar cells, positioned on each side of the Fresnel lenses. The solar cells also receive direct solar radiation on their front surfaces. The waste heat extracted from cooling of the PV cells is suggested utilized in greenhouses to promote plant growth or for domestic hot water purposes.
Our Solution

incident sunlight

polychromat

array of PV cells
Optical Efficiency can be >90%

Efficiency (%)

Avg. efficiency = 74%

\[ \lambda \text{ (nm)} \]
Our Solution

incident sunlight

polychromat

array of PV cells
Fabricated Polychromat

- Bright-field image
- Dark-field image
- Optical-profilometer image
- Optical-profilometer linescans

4 height levels confirmed
Grayscale Lithography to pattern master

Distinctive height levels with varying exposure times
4 height levels confirmed
Low-cost, high-volume manufacturing

**Polychromat™ Replication**

- Main embossing drum
- Replicated layer
- Heating plates
- Substrate

**Polychromat™ Parquet**

- Single-sheet laminated layer
- Substrate
Optical Characterization Setup
Optical Characterization Setup
Our Solution

incident sunlight

polychromat

array of PV cells
Optical Performance

Simulated

Measured

Wavelength (nm)

Position (mm)

400

500

600

700

800

900

1000

1

2

3

4

5

6

7

8

9

10

1

2

3

4

5

6

7

8

9

10

Simulated

Efficiency (%)

Avg. efficiency = 74%

Measured

Efficiency (%)

Avg. efficiency = 69%
So what sort of efficiency is possible?

Efficiencies of multi-band-gap Solar Cell
(Henry, C. H. J. Appl. Phys. 51, 4494)

Simulation of polychromat with 4 spectral bands