

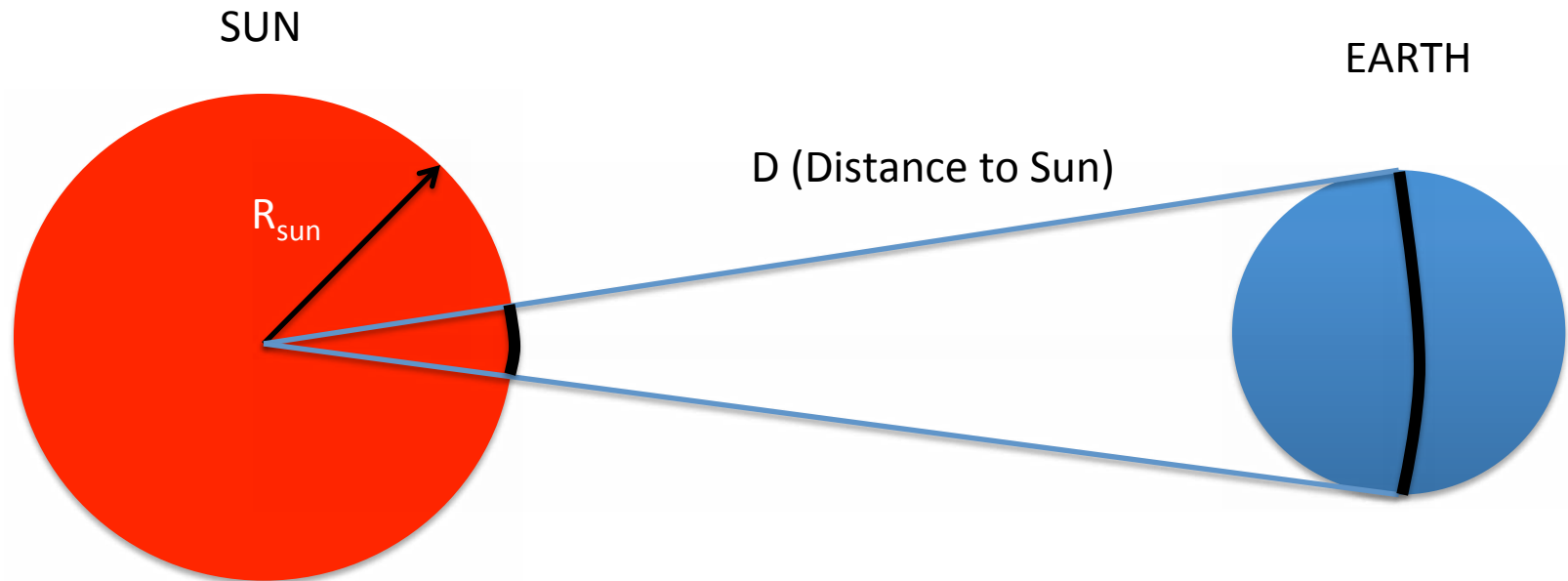
Nanomaker

Lab #11: Silicon Photovoltaics (PV)

Photograph and illustration of BigBelly smart trash can removed due to copyright restrictions.

Solar Energy
Fabrication
Material Defect
Efficiency

Solar Energy



Total radiative power of sun
(Stefan-Boltzmann law, $T=5762\pm 50K$)

$$P_{sun} = \frac{\sigma T^4}{4\pi R_{sun}^2}$$

Radiative power of
sun per unit area
($5.961 \times 10^7 \text{ W/m}^2$)

Surface area of Sun

Ratio of
surface area

$$P_{earth} = \frac{R_{sun}^2}{D^2} P_{sun}$$

Average power
(1366 W/m^2)

Solar Spectrum

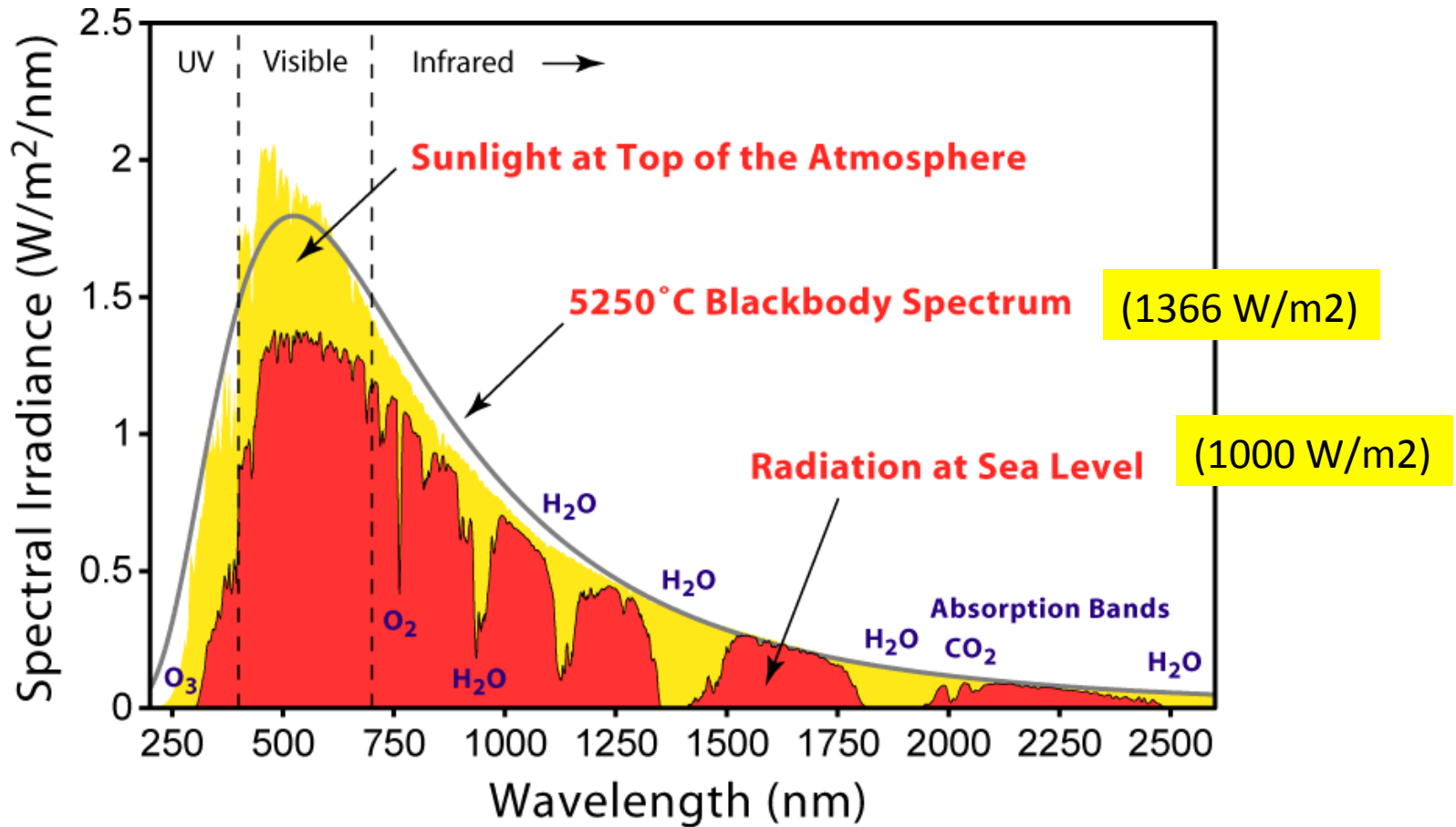


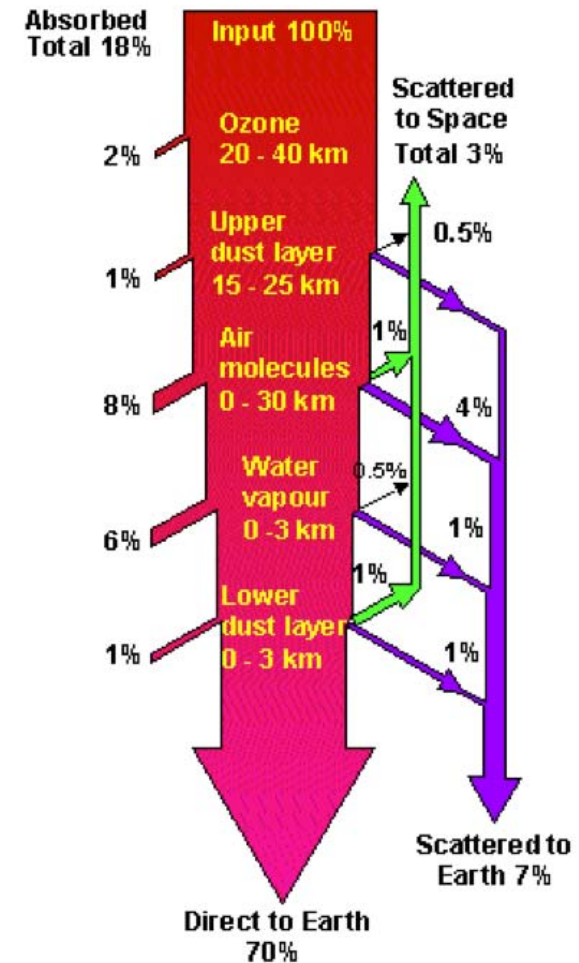
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Nearly ~50% of the solar irradiance is in the visible spectrum
Lots of solar power is in the form of IR light

Atmospheric Effects

Atmospheric effects have several impacts on the solar radiation at the Earth's surface. The major effects for photovoltaic applications are:

- A reduction in the power of the solar radiation due to absorption, scattering and reflection in the atmosphere;
- A change in the spectral content of the solar radiation due to greater absorption or scattering of some wavelengths;
- The introduction of a diffuse or indirect component into the solar radiation; and
- Local variations in the atmosphere (such as water vapor, clouds and pollution) which have additional effects on the incident power, spectrum and directionality

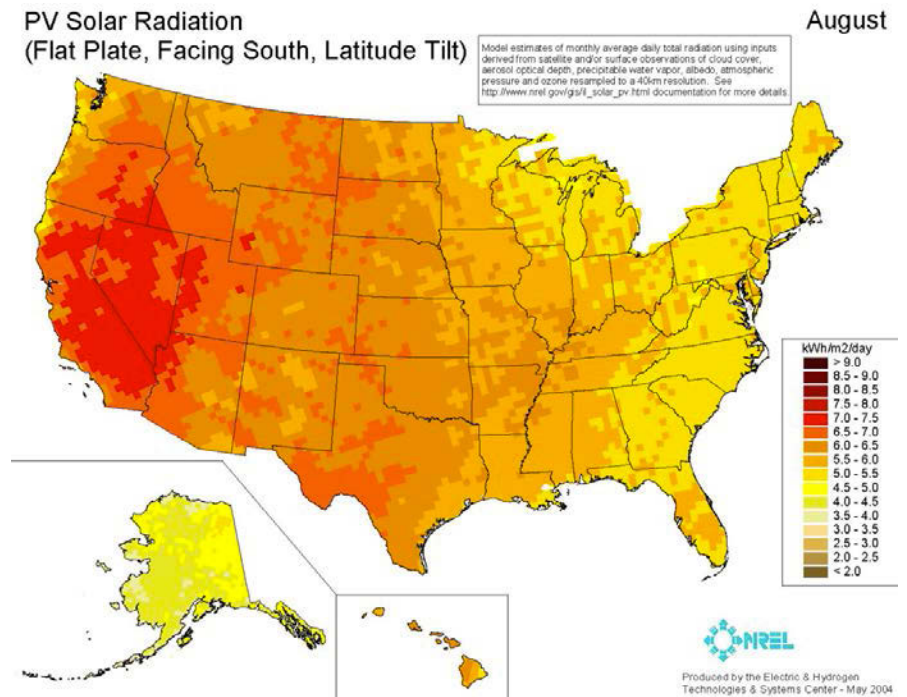
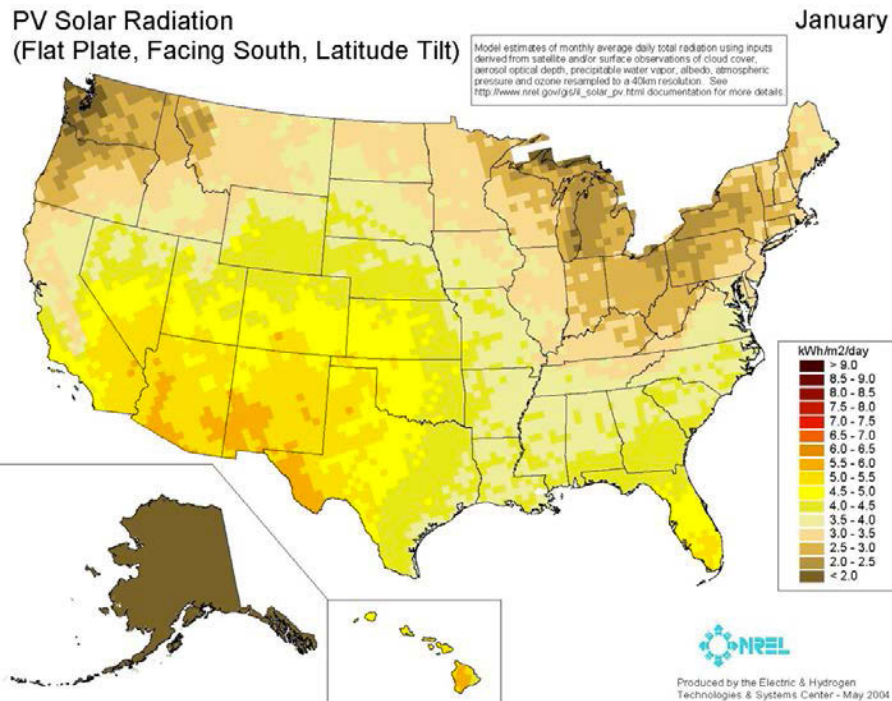


Courtesy of [PVCDROM](#), Christiana Honsberg and Stuart Bowden. Used with permission.

Insolation

Insolation: Incoming Solar Radiation

Energy per Unit Area per Unit Time (kWh/m²/day)



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Solar Energy
Fabrication
Material Defect
Efficiency

Silicon Crystal Growth

Single Crystal Si Boule



Silicon Wafers

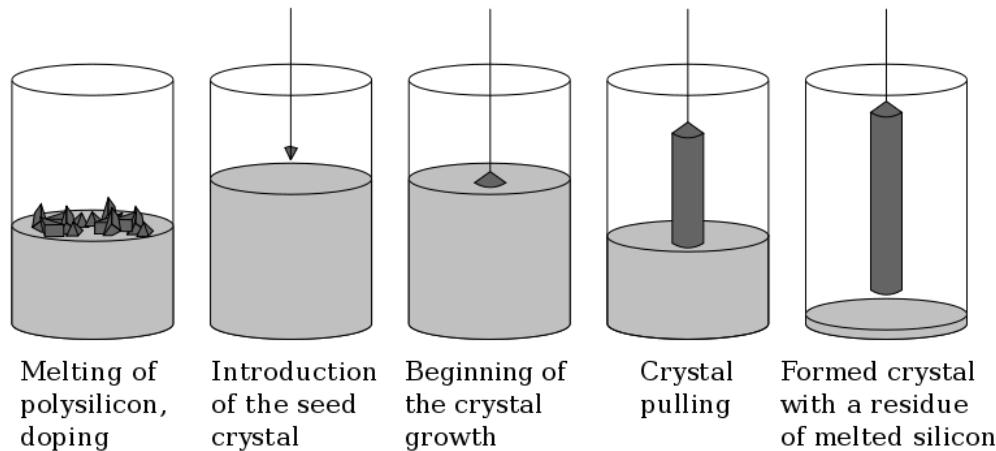


Polycrystalline Silicon Solar Cell



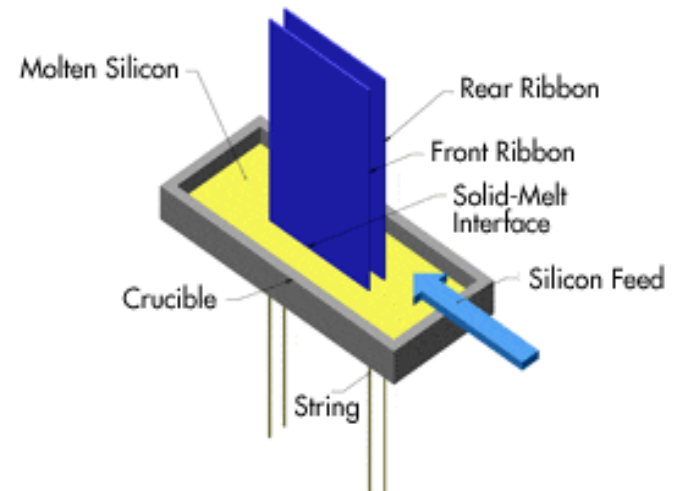
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Czochralski growth

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Ribbon growth

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Silicon Crystal

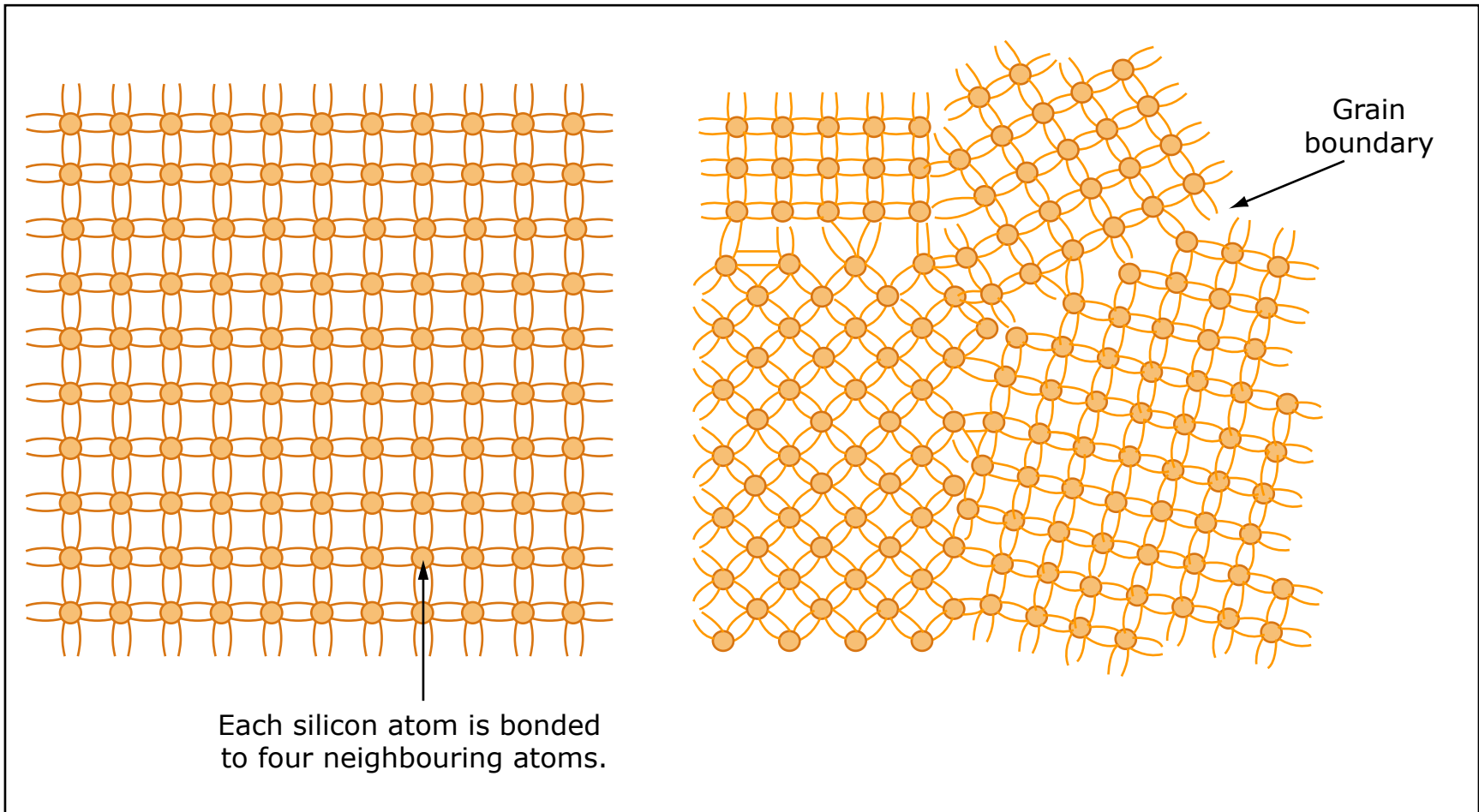


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	Width (cm)	Growth rate (mm/min)	Throughput (m²/day)	Energy use (kWh/m²)	Best efficiency
Czochralski	15	0.6 - 1.2	30	21 - 48	20%
Ribbon Silicon	8-80	15 - 20	20	20	18%

Why Purple?

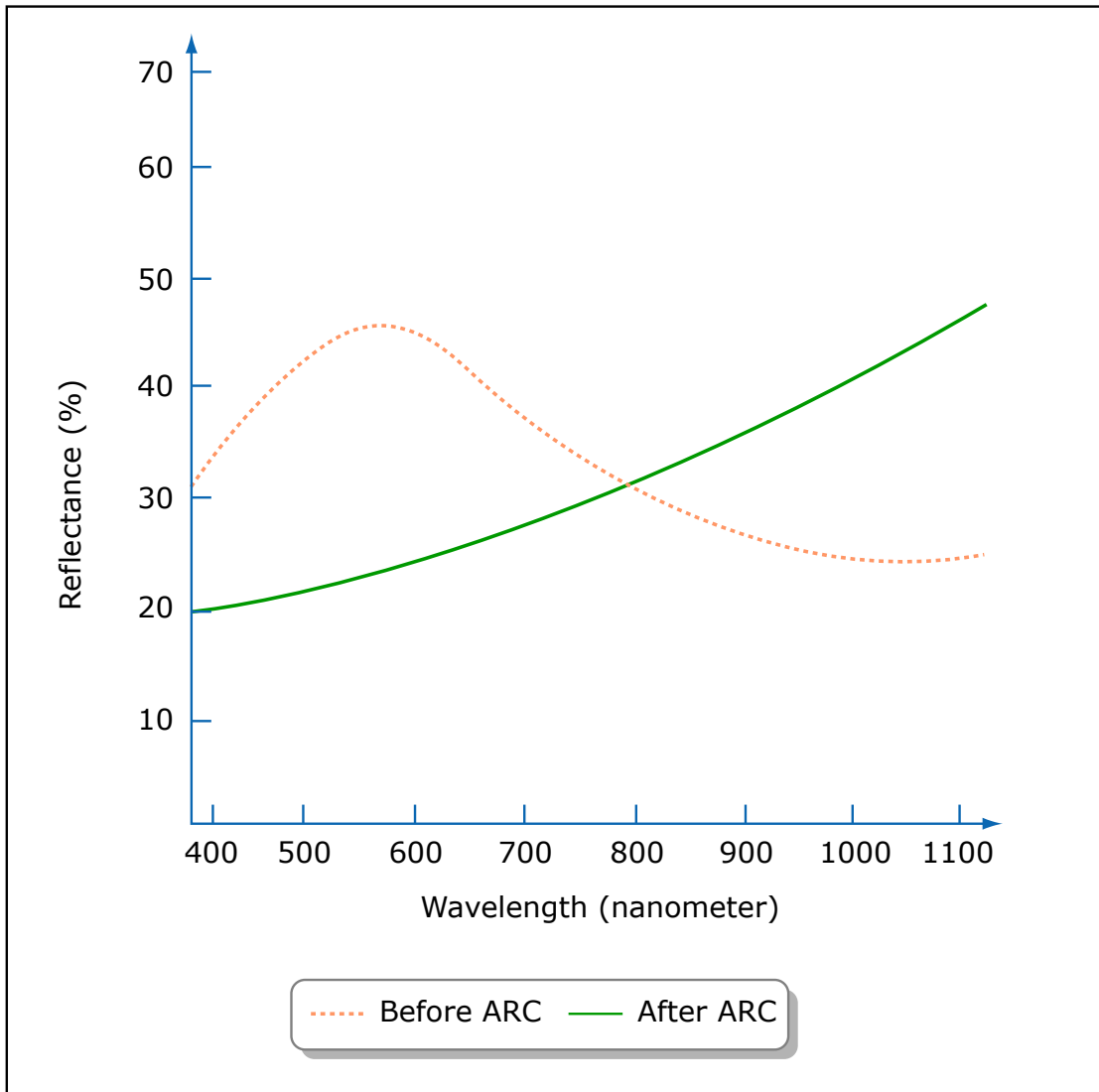


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Reflectance curve of a polycrystalline silicon solar cells before and after silicon nitride coating

Low-Cost: Roll-to-Roll Vacuum Coating



Photographs of the vacuum coating process removed due to copyright restrictions.

Amorphous Silicon Solar Cell
Nine miles of solar cells in three days



Photo courtesy of [US Army Africa](#) on Flickr.

Solar Energy
Fabrication
Material Defect
Efficiency

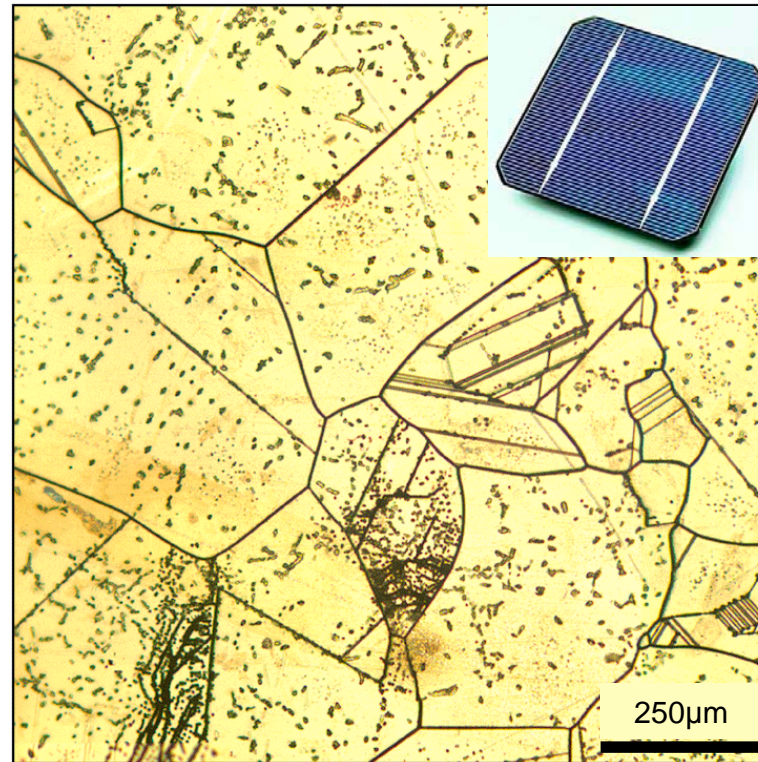
Polycrystalline Silicon

Metal Impurities

*Iron, Titanium, Nickel,
Chromium, Copper*

Non-Metal Impurities

*Oxygen, Nitrogen
Carbon*



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Dislocations

Edge, Screw, Mixed, Loops

Grain boundaries

Small-angle, Large-angle

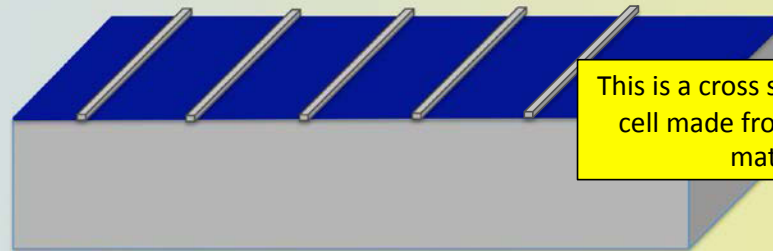
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Adopted from Prof. Buonassisi

High Quality Materials

Solar Cells and Material Quality: A Brief Tutorial

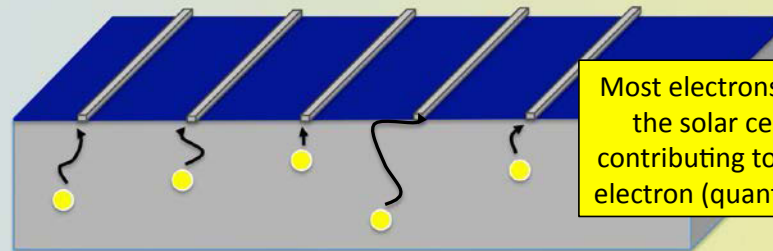
Cross section of solar cell made of high-quality material



This is a cross section of a solar cell made from high-quality material.

Solar Cells and Material Quality: A Brief Tutorial

Cross section of solar cell made of high-quality material



Most electrons diffuse through the solar cell uninhibited, contributing to high photon-to-electron (quantum) efficiencies.

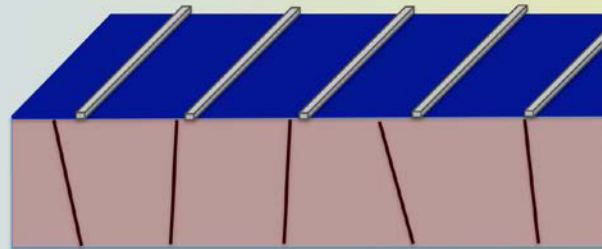
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Low Quality Materials

Solar Cells and Material Quality: A Brief Tutorial

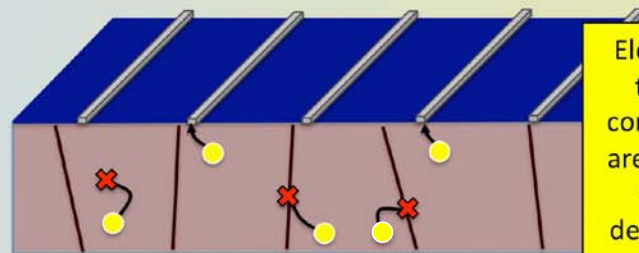
Cross section of solar cell made of defect-ridden material



Here's a cross section of a silicon wafer. Black lines represent structural defects (dislocations and grain boundaries), while red lines represent dangerous impurity species.

Solar Cells and Material Quality: A Brief Tutorial

Cross section of solar cell made of defect-ridden material



Electrons generated closer to the surface make it to the contacts, but those in the bulk are likely to "recombine" (lose their energy, e.g., at bulk defects, and not contribute to the solar cell output current).

Solar Cells and Material Quality: A Brief Tutorial

(1) Materials Optimization

Let's start from the wafer, before even a solar cell device is made.

Solar Cells and Material Quality: A Brief Tutorial

(2) Materials Optimization

First, let's entice as many defects out of the wafer by annealing treatments...

e.g., D. R. Khanal, T. Buonassisi *et al.*, *Appl. Phys. Lett.* **90**, 102110 (2007).

Solar Cells and Material Quality: A Brief Tutorial

(3) Materials Optimization

... and remove them once they're near the surfaces.

Solar Cells and Material Quality: A Brief Tutorial

(4) Materials Optimization

Then, as we process the wafer into a solar cell, we engineer all remaining bulk defects into their least detrimental state(s).

e.g., M. D. Pickett and T. Buonassisi, *Appl. Phys. Lett.* **92**, 122103 (2008).

Solar Cells and Material Quality: A Brief Tutorial

☺ Materials Optimization

Although we started with defect-ridden material, we managed to engineer it into a very usable form.

Solar Cells and Material Quality: A Brief Tutorial

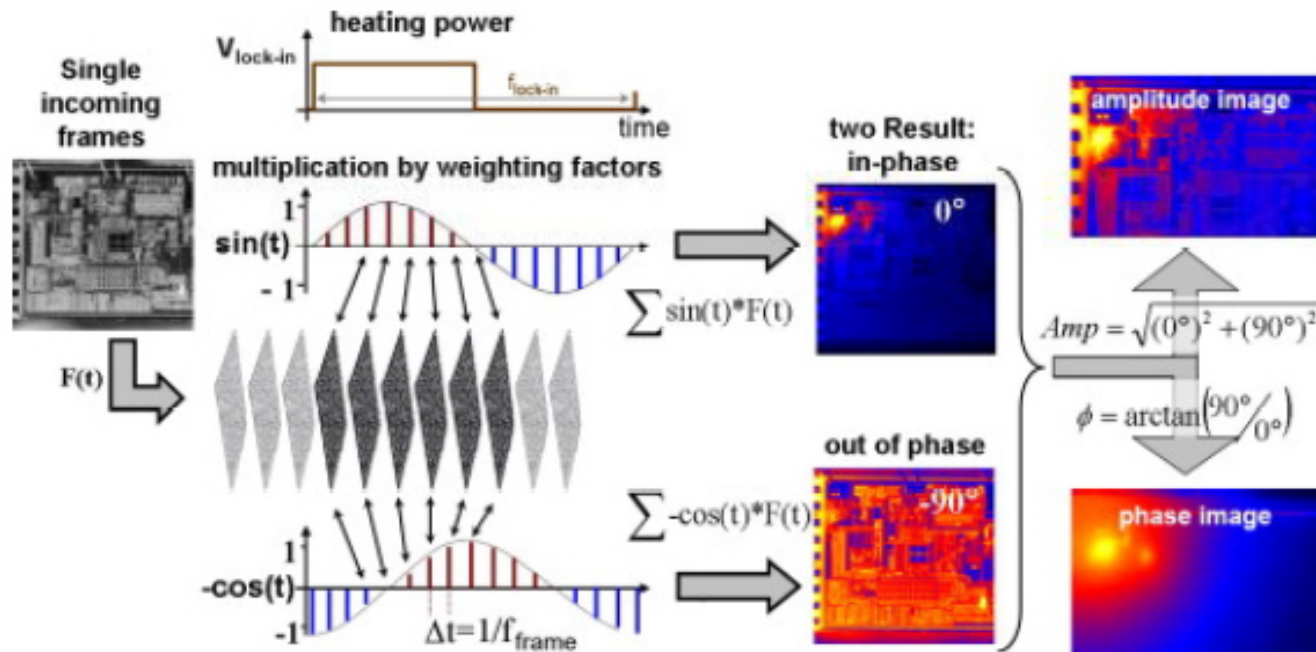
☹ Cross section of solar cell made of defect-ridden material

If we didn't know how to optimize our material, and simply blindly applied a standard cell process, we would've achieved very low efficiencies indeed!

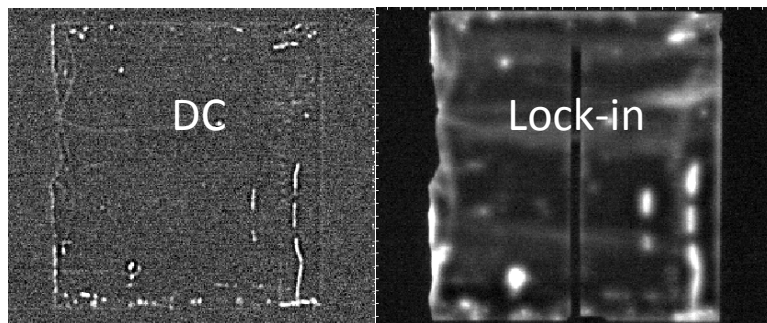
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Lock-in Thermography



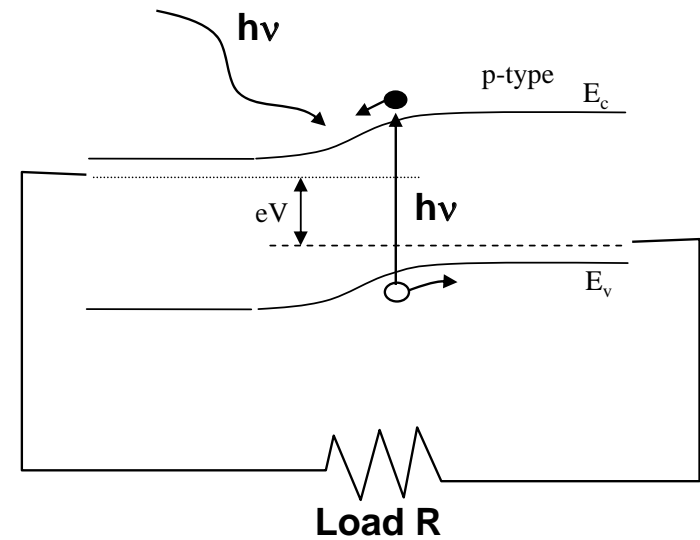
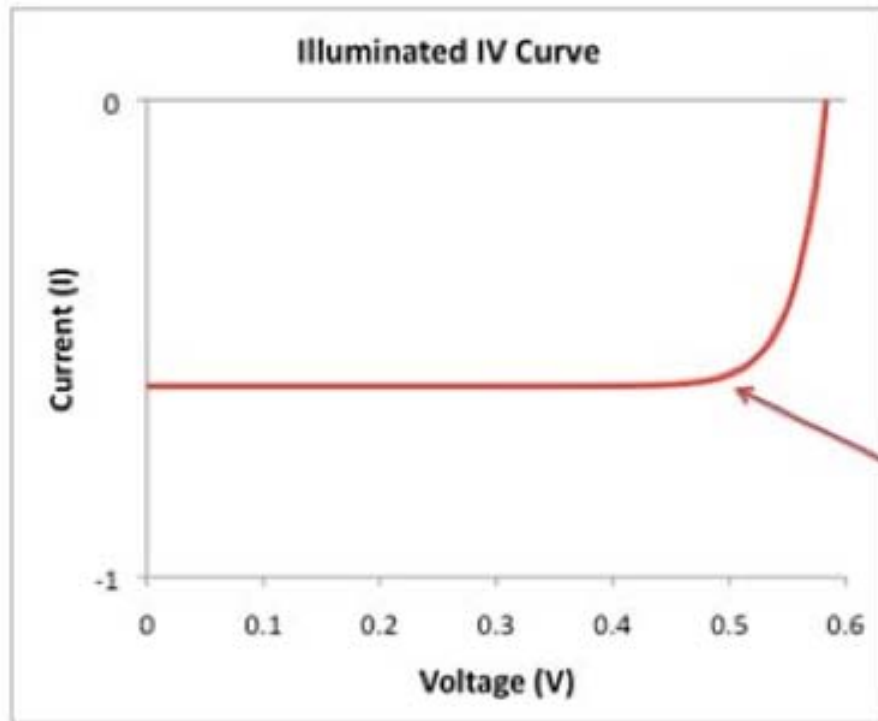
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- Ribbon-Si Device
- 100 Hz lock-in frequency
- 0.6 V bias

Solar Energy
Fabrication
Material Defect
Efficiency

IV Characterization



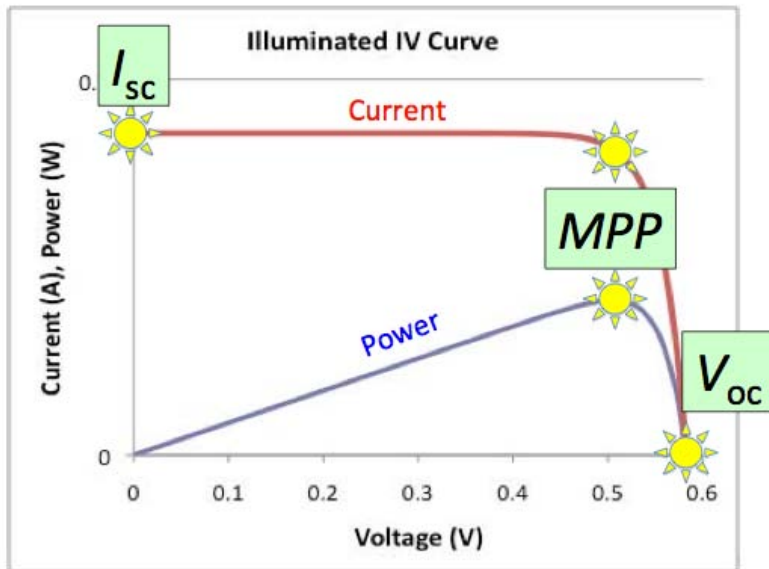
$$I = I_o \left(e^{qV/kT} - 1 \right) - I_L$$

I_L : excitation due to photon short circuit current

Courtesy of Tonio Buonassisi. Used with permission.

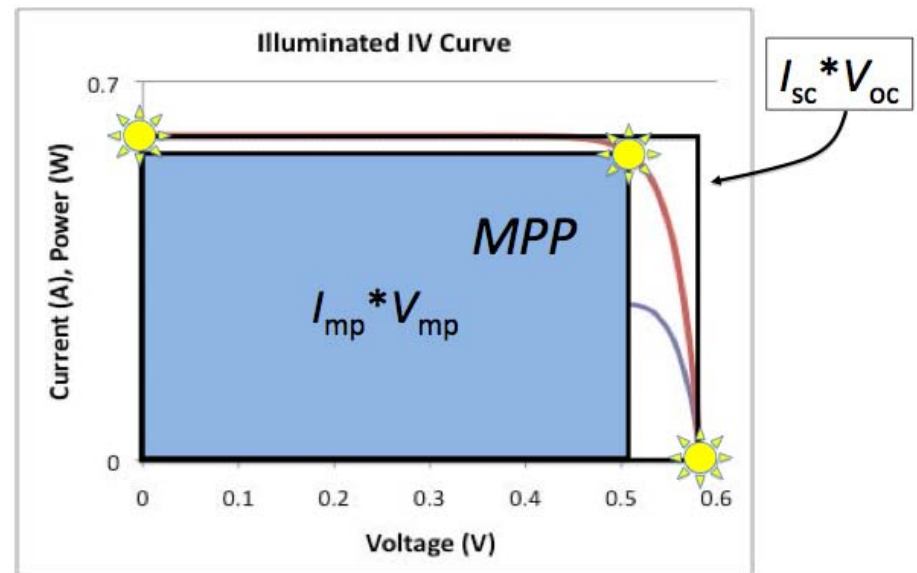
Efficiency

MPP: Maximum Power Point



$$\text{Efficiency} \equiv \eta = \frac{\text{Power Out}}{\text{Power In}} = \frac{V_{mp} \cdot I_{mp}}{\Phi}$$

Quadrant flipped!



$$\text{Fill Factor} \equiv FF = \frac{V_{mp} \cdot I_{mp}}{V_{oc} \cdot I_{sc}}$$

Adopted from Prof. Buonassisi

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$$\text{Efficiency} \equiv \eta = \frac{\text{Power Out}}{\text{Power In}} = \frac{V_{\text{mp}} \cdot I_{\text{mp}}}{\Phi}$$

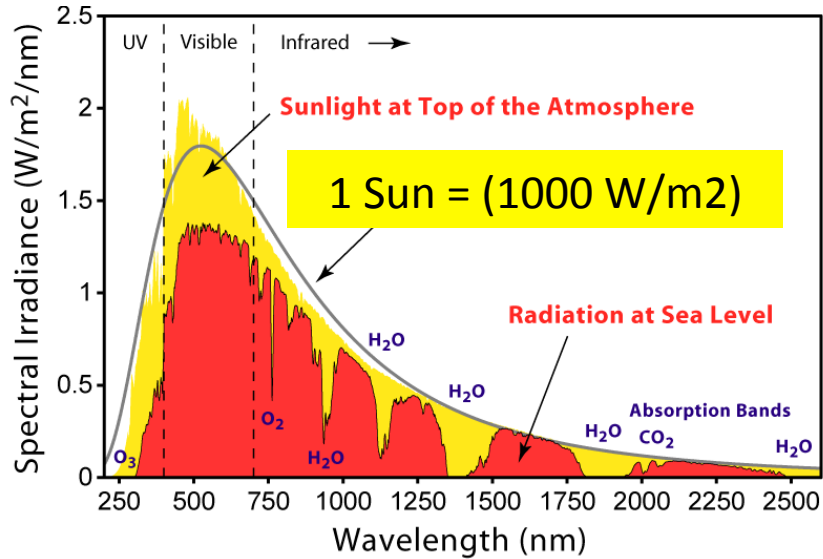
$$\text{Fill Factor} \equiv FF = \frac{V_{\text{mp}} \cdot I_{\text{mp}}}{V_{\text{oc}} \cdot I_{\text{sc}}}$$

$$\text{Efficiency} \equiv \eta = \frac{\text{Power Out}}{\text{Power In}} = \frac{V_{\text{mp}} \cdot I_{\text{mp}}}{\Phi} = \frac{FF \cdot V_{\text{oc}} \cdot I_{\text{sc}}}{\Phi}$$

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Conclusions



Single Crystal



Polycrystalline Crystal

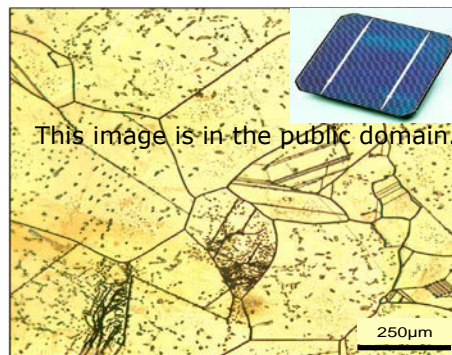


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Metal Impurities
Iron, Titanium, Nickel
Chromium, Copper

Non-Metal Impurities
Oxygen, Nitrogen
Carbon



Dislocations
Edge, Screw, Mixed,
Loops

Grain boundaries
Small-angle, Large-angle

$$\text{Efficiency} \equiv \eta = \frac{\text{Power Out}}{\text{Power In}}$$

$$= \frac{V_{mp} \cdot I_{mp}}{\Phi} = \frac{FF \cdot V_{oc} \cdot I_{sc}}{\Phi}$$

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