Purdue University, Spring 2019

Crystalline Solar Cells

Mark Lundstrom

Electrical and Computer Engineering
Purdue University
West Lafayette, Indiana USA
lundstro at purdue dot edu

Objective

In the previous lecture, we discussed the optical and electrical design of a specific modern, high-efficiency, crystalline silicon solar cell − the PERL cell.

Many general principles were discussed in the context of this specific cell.

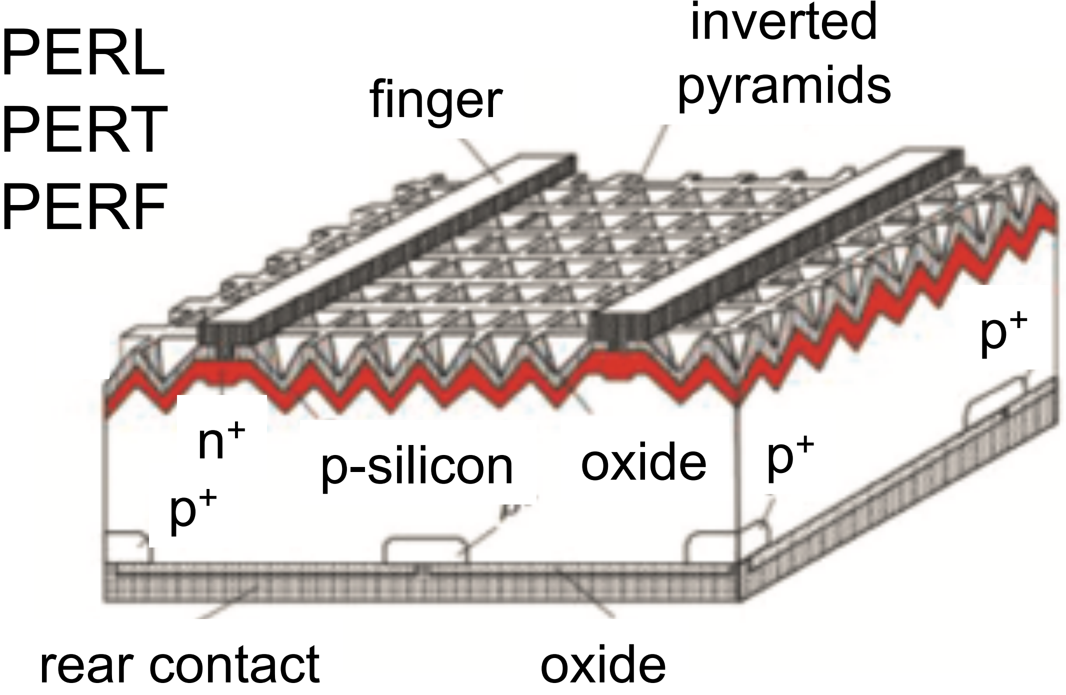
This lecture is a broader survey of crystalline (and multi-crystalline) solar cells.

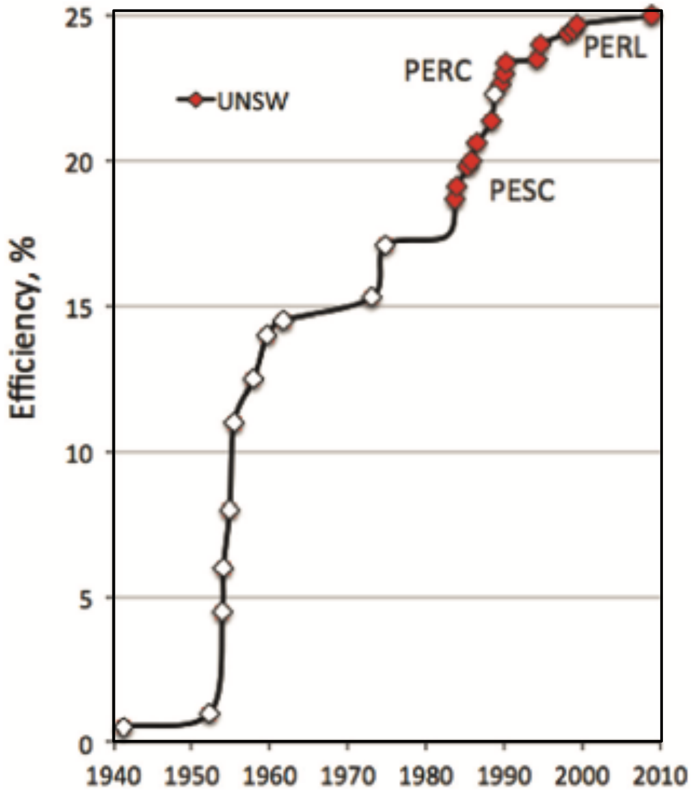
Outline

1) High volume Si and MC Si solar cells
2) IBC solar cells
3) Heterojunctions for solar cells
4) HJ silicon solar cells
5) HJ GaAs solar cells
6) Tandem solar cells
7) Summary

Evolution of Si solar cell efficiency

PERD
PERL
PERT
PERF





M.A. Green, “The Passivated Emitter and Rear Cell: From Conception to Mass Production,” *Solar Energy Materials and Solar Cells*, **143**, 190-197, 2015.

PERC Solar Cells

Key Features

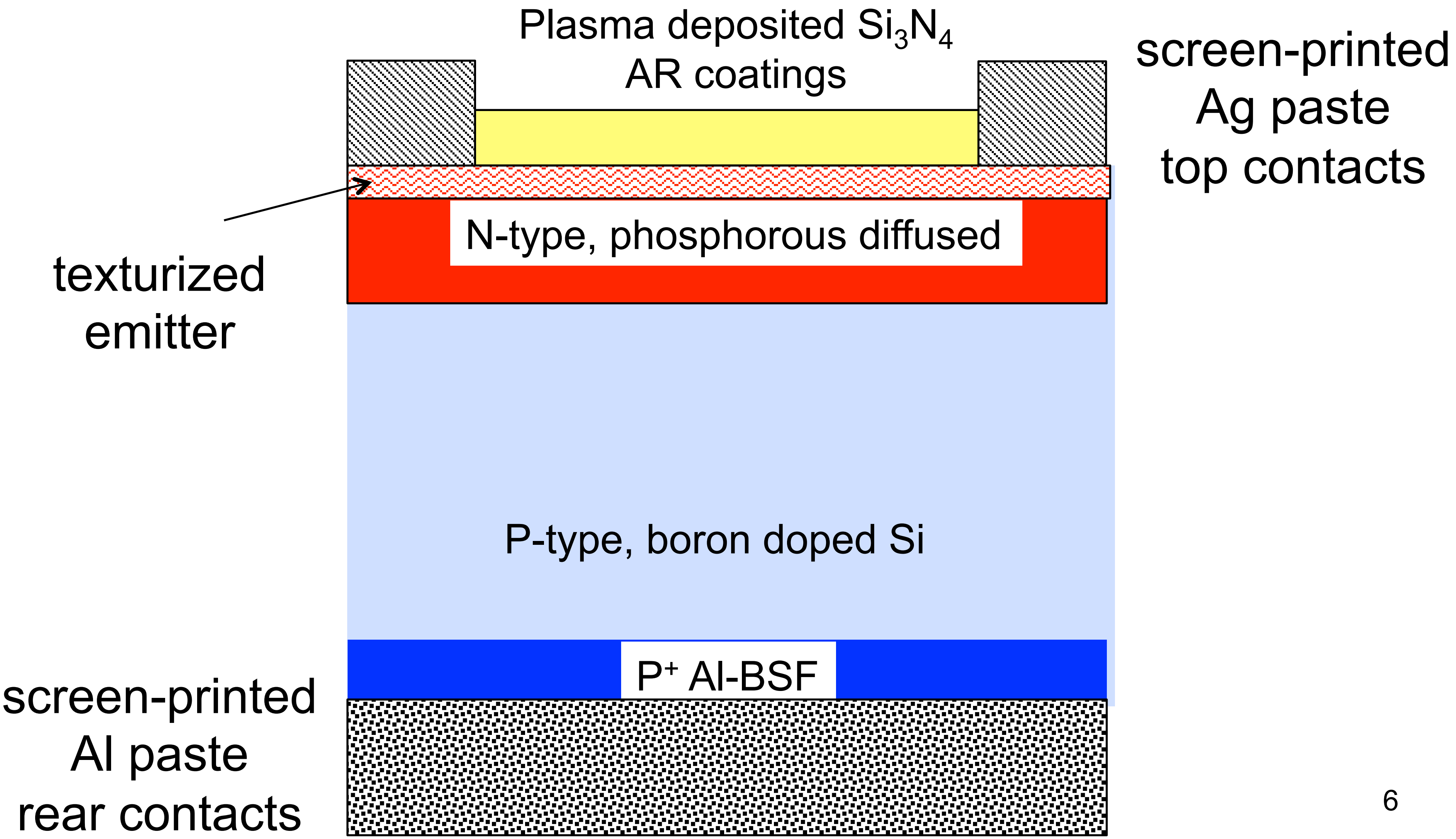
- Passivated emitter and back surface
- Localized contacts
- Highly effective light trapping

Implications

- Very high efficiency
- Expensive to manufacture
- Pointed the way to higher efficiency commercial cells

M.A. Green, "The Passivated Emitter and Rear Cell: From Conception to Mass Production," *Solar Energy Materials and Solar Cells*, **143**, 190-197, 2015.

Commercial Si solar cells: 1980's – 2010's

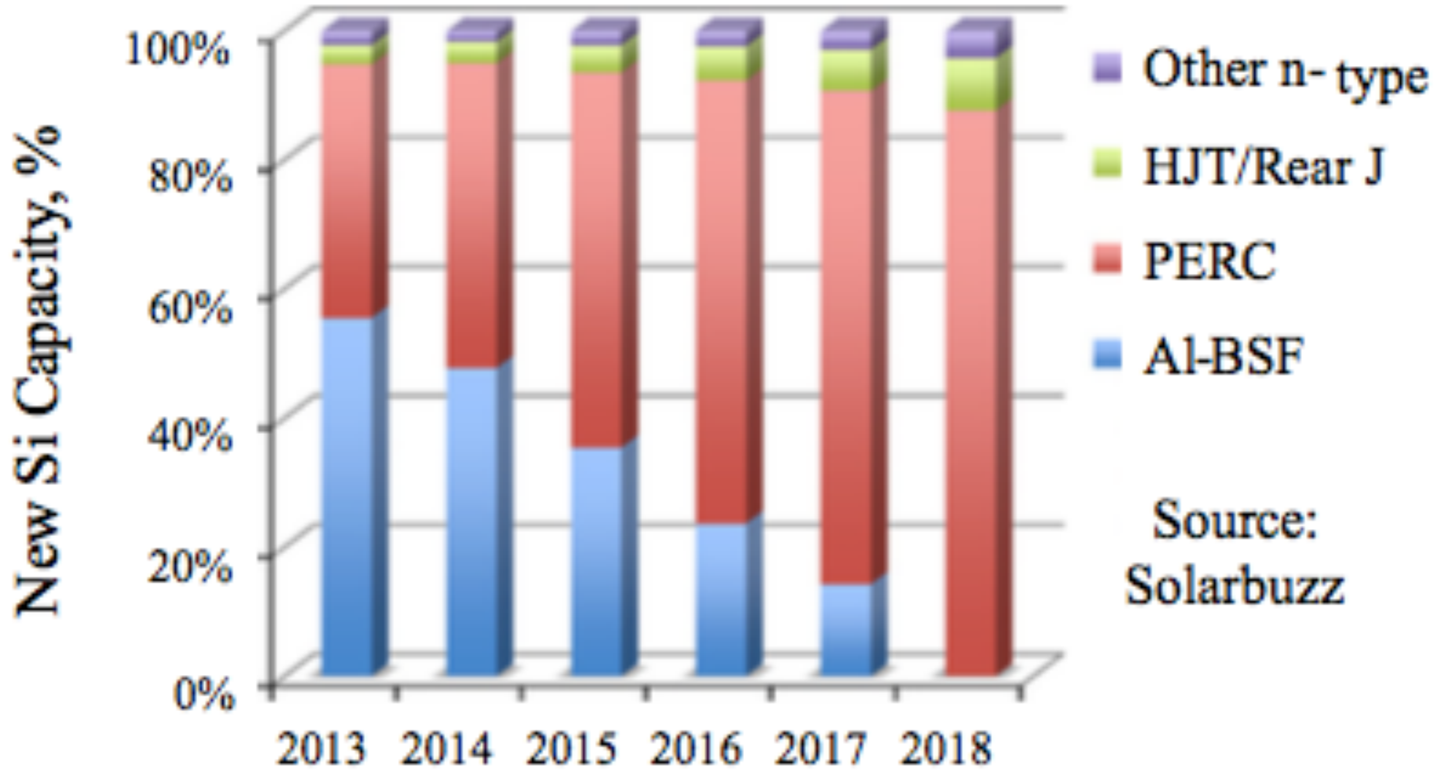


Manufacturing process

1) Wafer etch and texture
2) Phosphorous emitter diffusion and etch
3) Plasma deposit Si_3N_4 ARC
4) Screen and fire contacts
5) Sort and test cells

Simple, inexpensive, and relatively efficient

Al-BSF vs. PERC **new** manufacturing capacity



M.A. Green, “The Passivated Emitter and Rear Cell: From Conception to Mass Production,” *Solar Energy Materials and Solar Cells*, **143**, 190-197, 2015.

Manufacturing processes

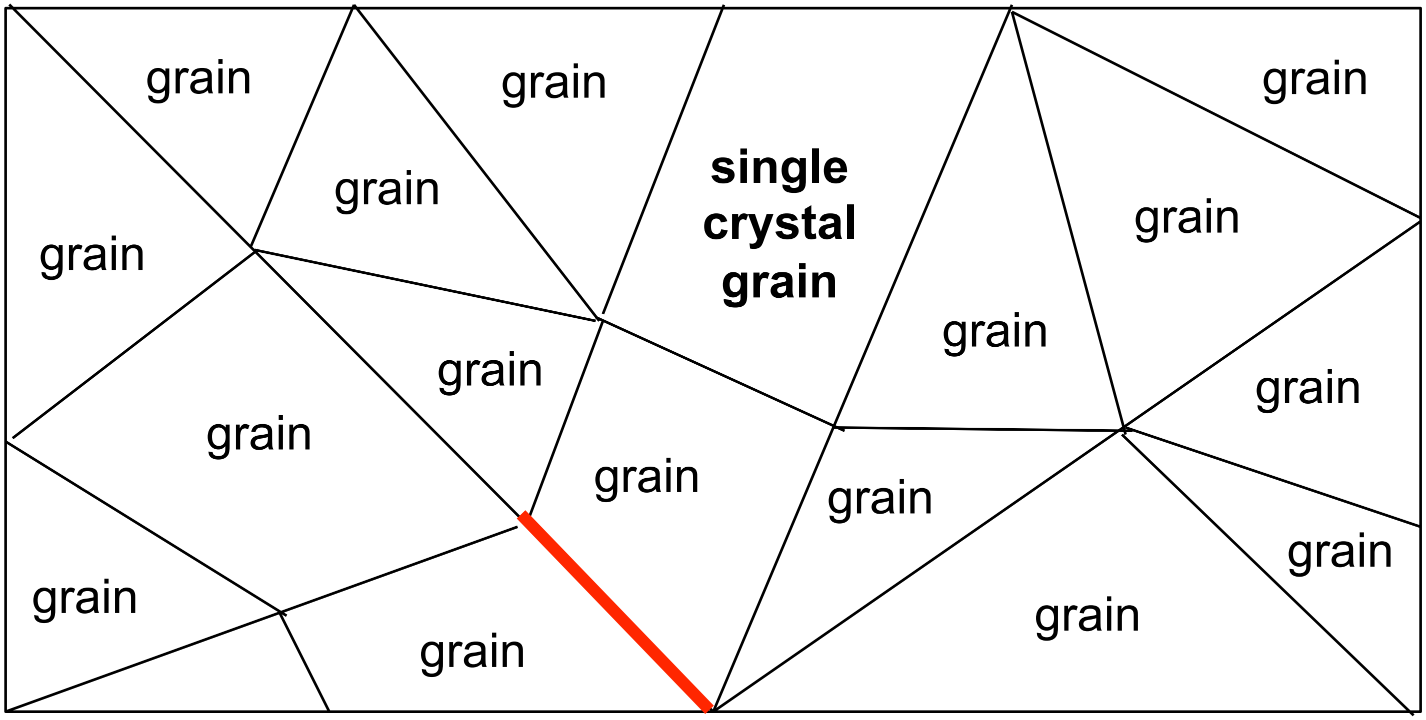
Al-BSF

1) Wafer etch and texture
2) Emitter diffusion and etch
3) Plasma deposit ARC
4) Screen and fire contacts
5) Sort and test cells

PERC

1) Wafer etch and texture
2) Emitter diffusion and etch
3) **Rear side etch**
4) Front **passivation** and ARC
5) **Back passivation/RC**
6) **Laser contact ablation**
7) Screen and fire contacts
8) Sort and test cells

Crystalline vs. poly-crystalline



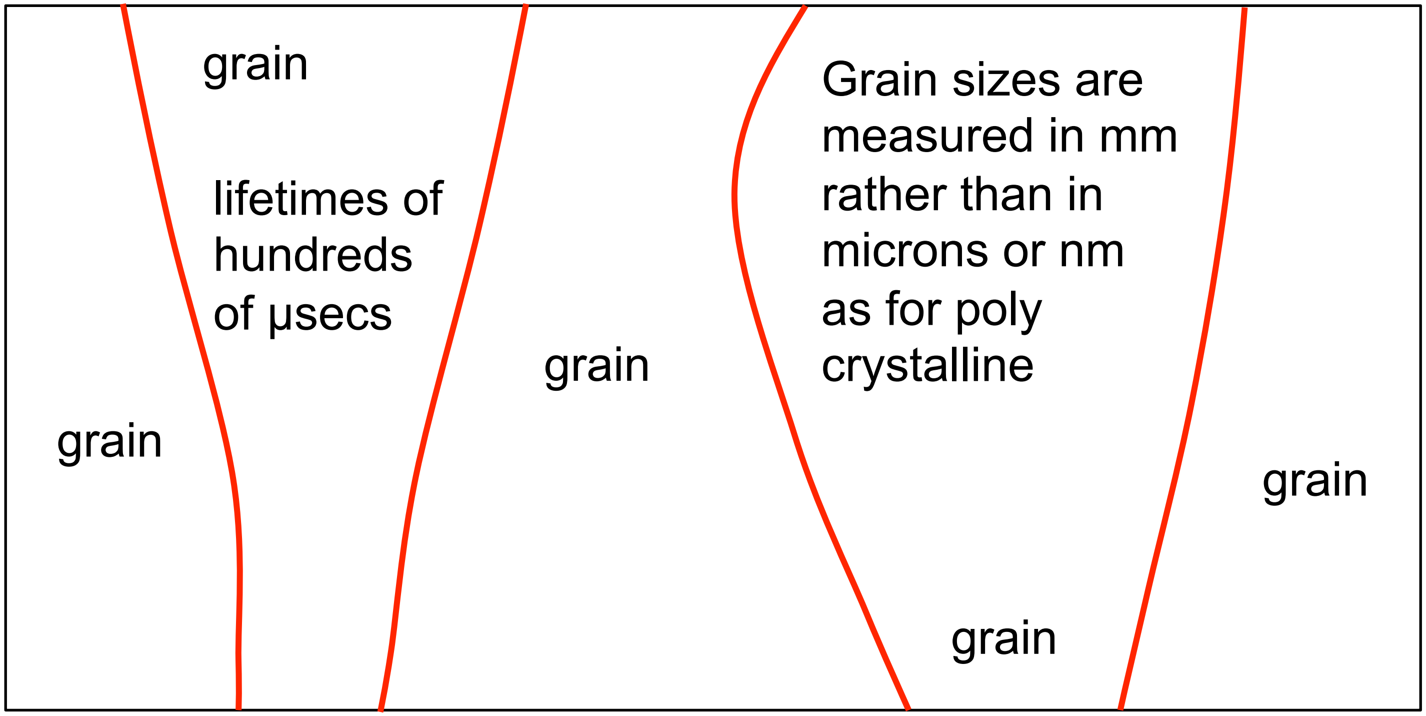
Each grain is crystalline, but the grains are oriented differently.

grain boundary

Increased recombination at grain boundaries

“seed-assisted crystalline”

Multi-crystalline vs. poly-crystalline



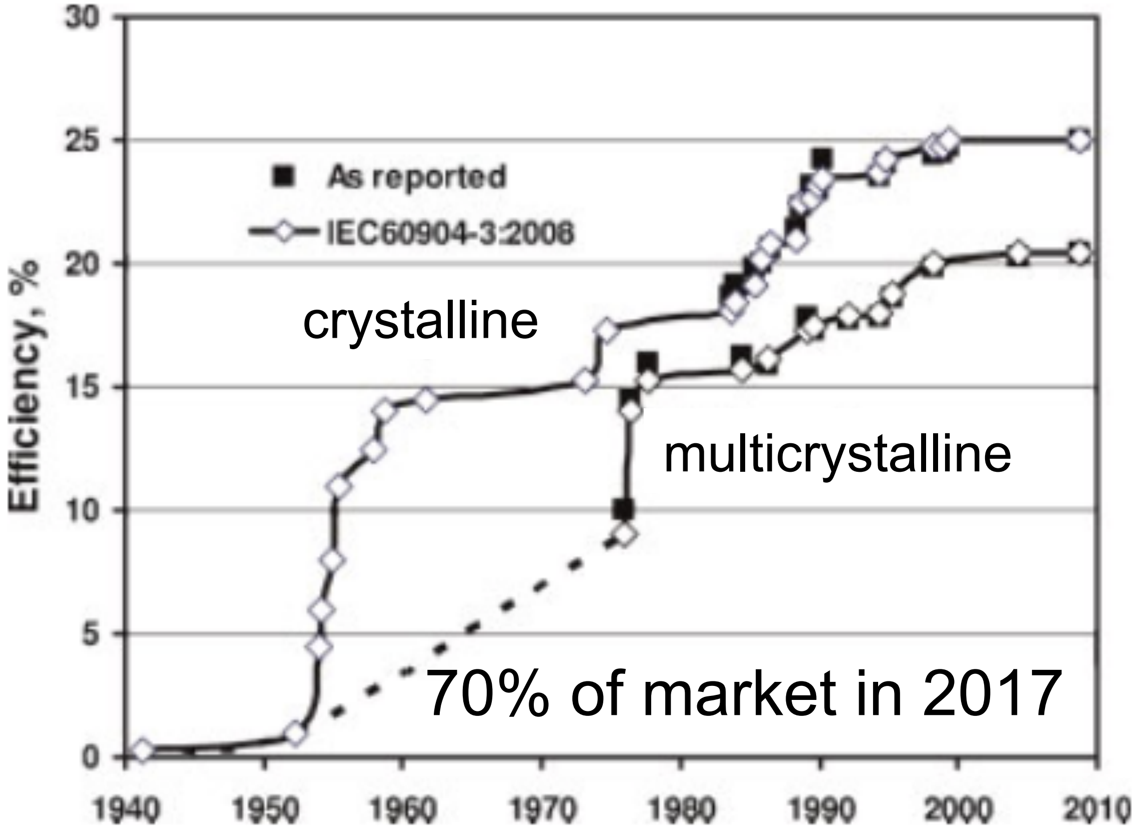
Grain sizes are measured in mm rather than in microns or nm as for poly crystalline

Grain are quite large and vertically oriented

Wafers can be square (better packing efficiency in modules)

Seeded growth crystallization

Multi-crystalline vs. crystalline efficiencies



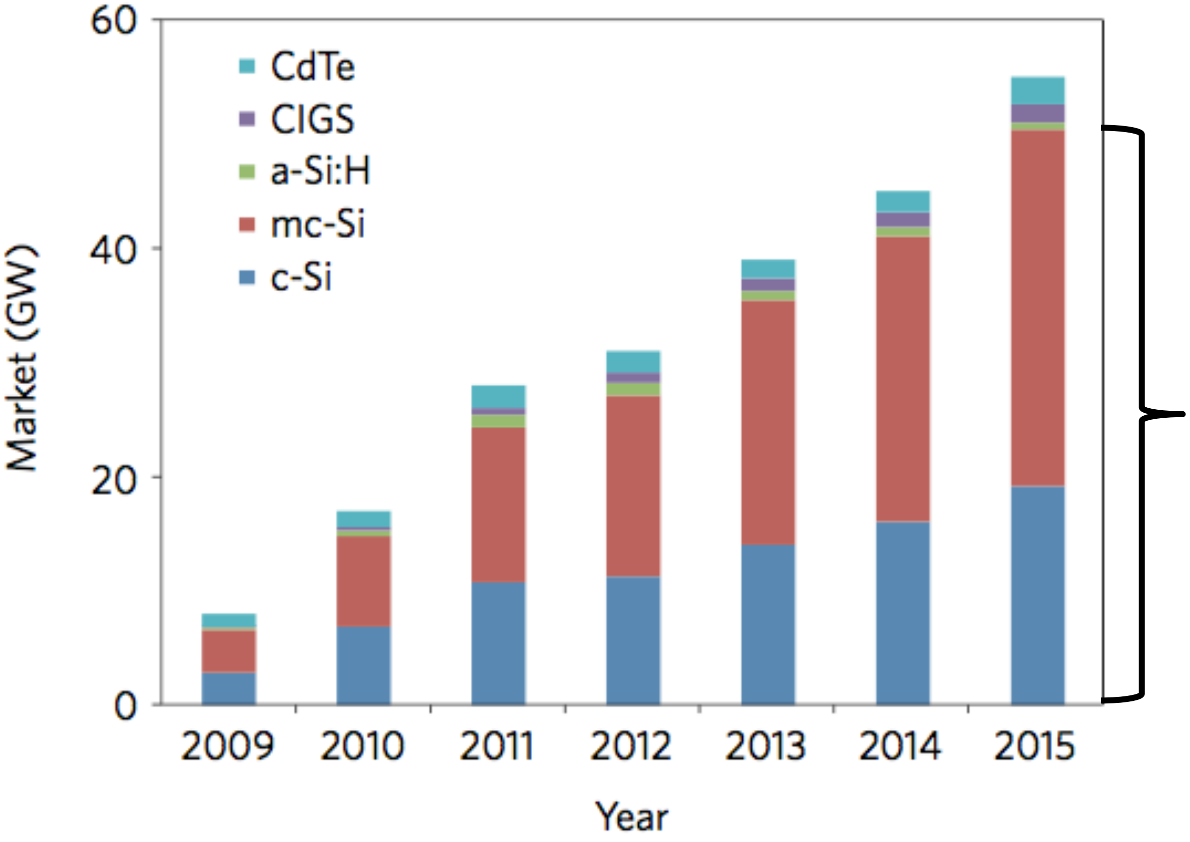
crystalline

multicrystalline

70% of market in 2017

Martin A. Green, “The Path to 25% Silicon Solar Cell Efficiency: History of Silicon Cell Evolution,” *Prog. In Photovoltaics: Research and Applications*, **17**, 183-189, 2009.

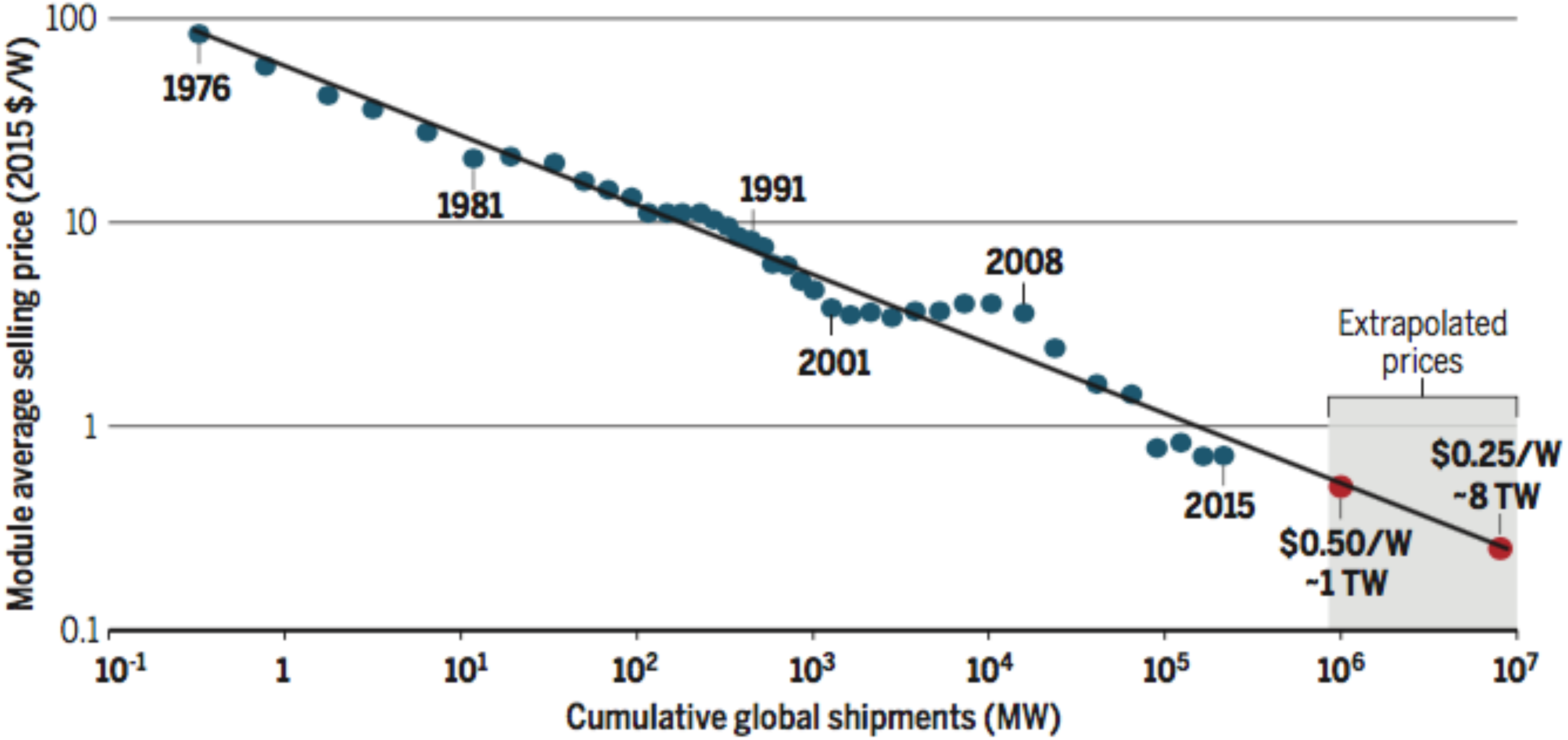
Silicon photovoltaics



Silicon is dominant and increasingly dominant.

Martin Green, “Commercial progress and challenges for photovoltaics,” *Nature Energy*, **1**, 1-4, 2016

The PV “learning curve”



Nancy M. Haegel, et al., “Terwatt-scale photovoltaics,Science, **356**, 141-1143, 2017.

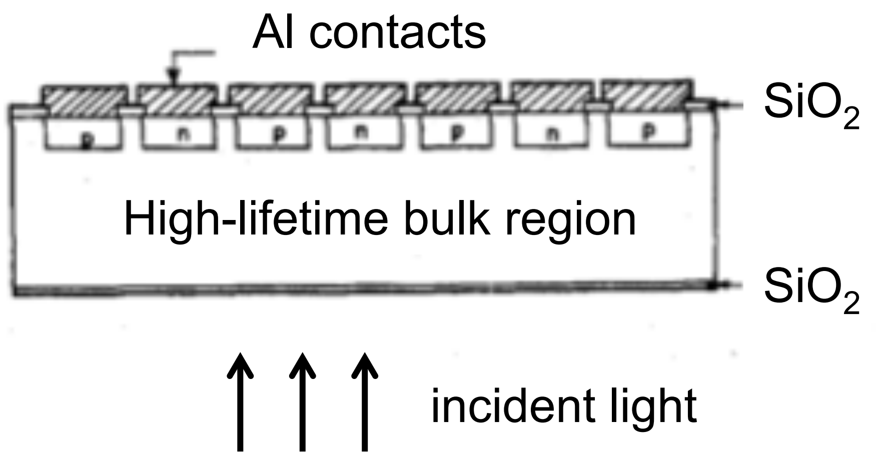
Outline

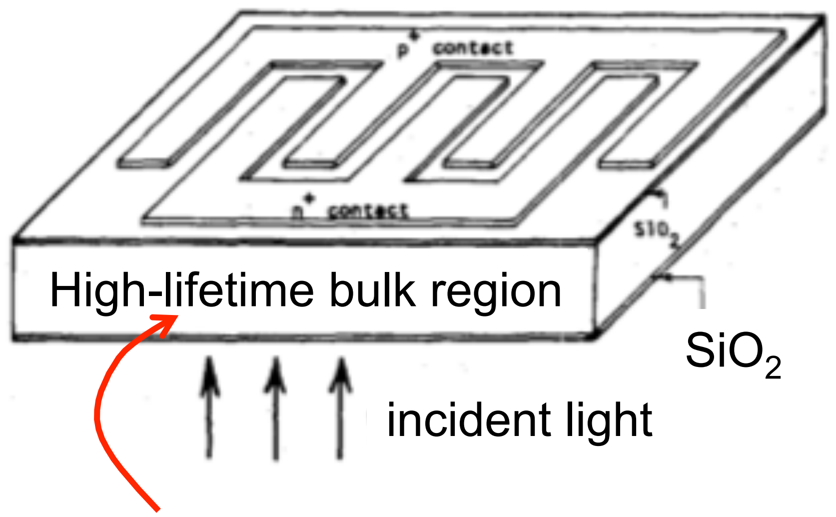
1) High volume Si and MC Si solar cells
2) **IBC solar cells**
3) Heterojunctions for solar cells
4) HJ silicon solar cells
5) HJ GaAs solar cells
6) Tandem solar cells
7) Summary

IBC solar cells

The Interdigitated Back Contact Solar Cell: A Silicon Solar Cell for Use in Concentrated Sunlight

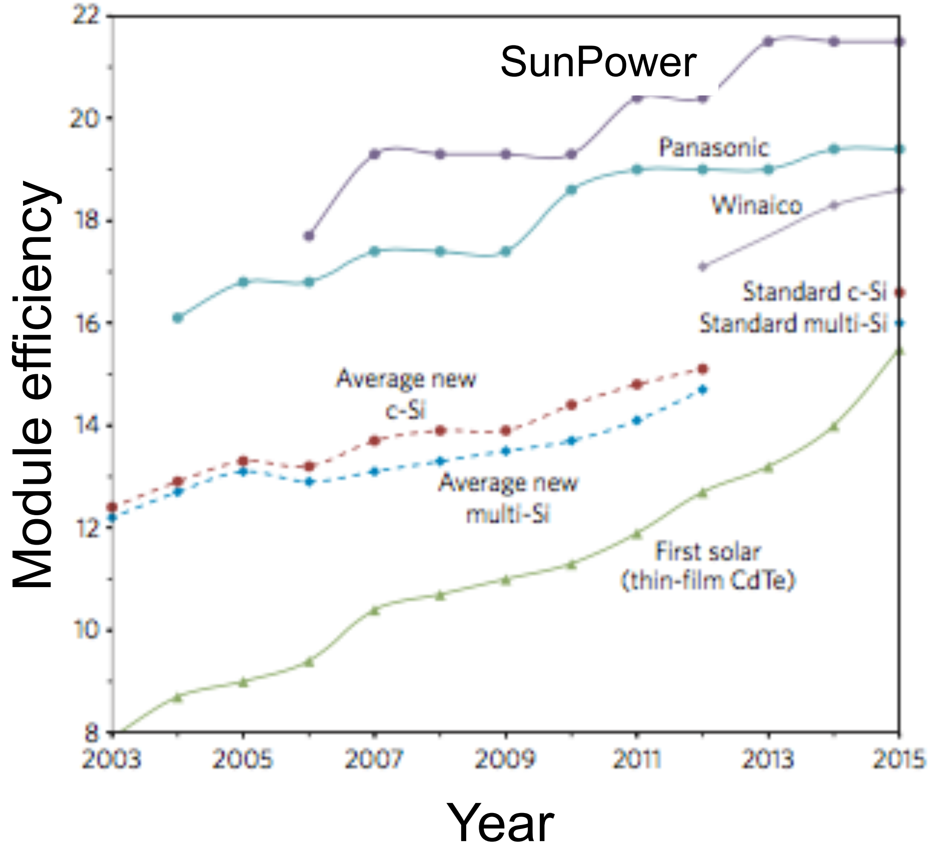
Michael D. Lammert and Richard J. Schwartz
IEEE Transactions on Electron Devices, **24**, 337-342, 1977





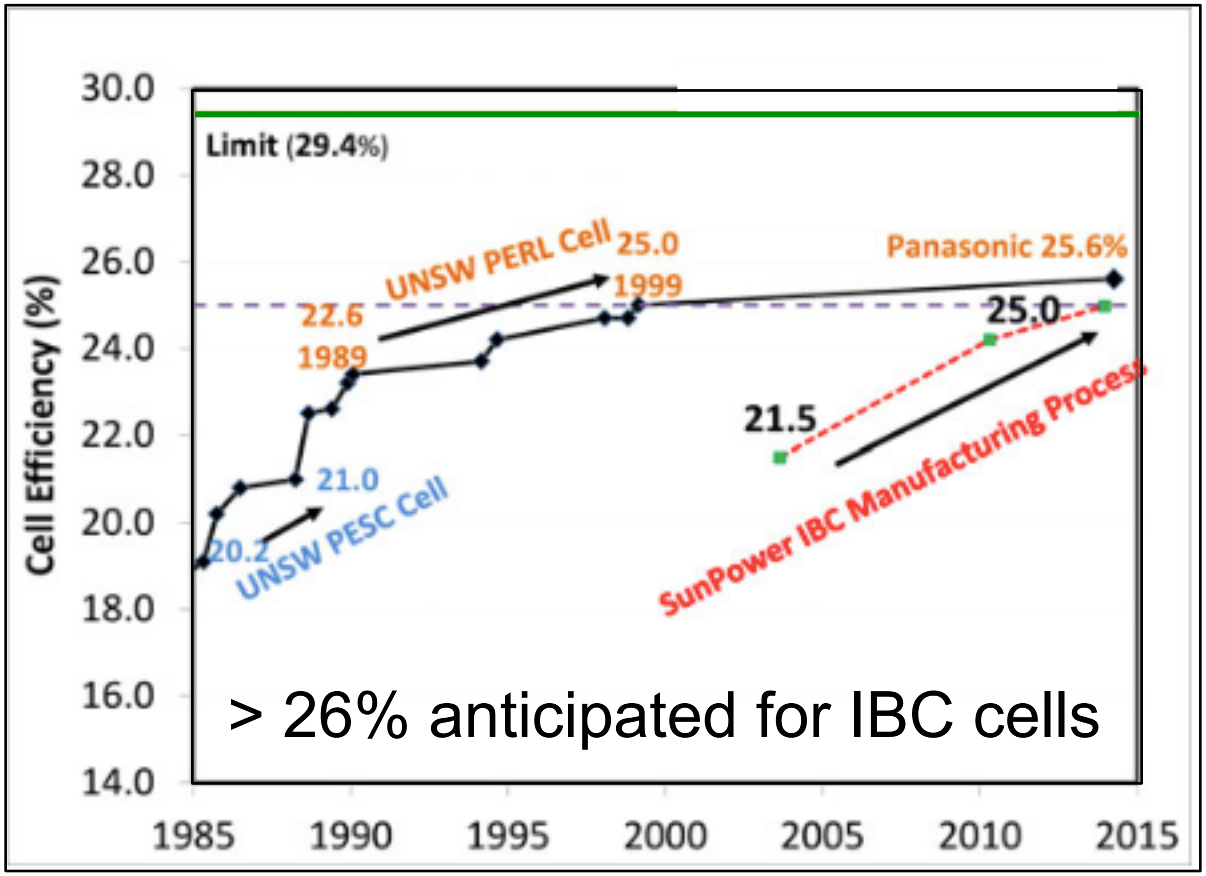
> 10 ms lifetimes!

IBC solar cells



Martin Green, “Commercial progress and challenges for photovoltaics,” *Nature Energy*, **1**, 1-4, 2016

IBC solar cells



> 26% anticipated for IBC cells

David D. Smith, et al., “Towards the practical limits of solar cells,” *IEEE J. Photovoltaics*, **4**, 1465-1469, 2014.

IBC vs. PERL

IBC

$A = 121\ \mathrm{cm}^2$
$t = 145\ \mu\mathrm{m}$
$V_{OC} = 730.3\ \mathrm{mV}$
$J_{SC} = 41.22\ \mathrm{mA/cm}^2$
$FF = 82.96$
$R_s = 0.36\ \Omega\text{-cm}^2$
$\eta = 25.0$

PERL

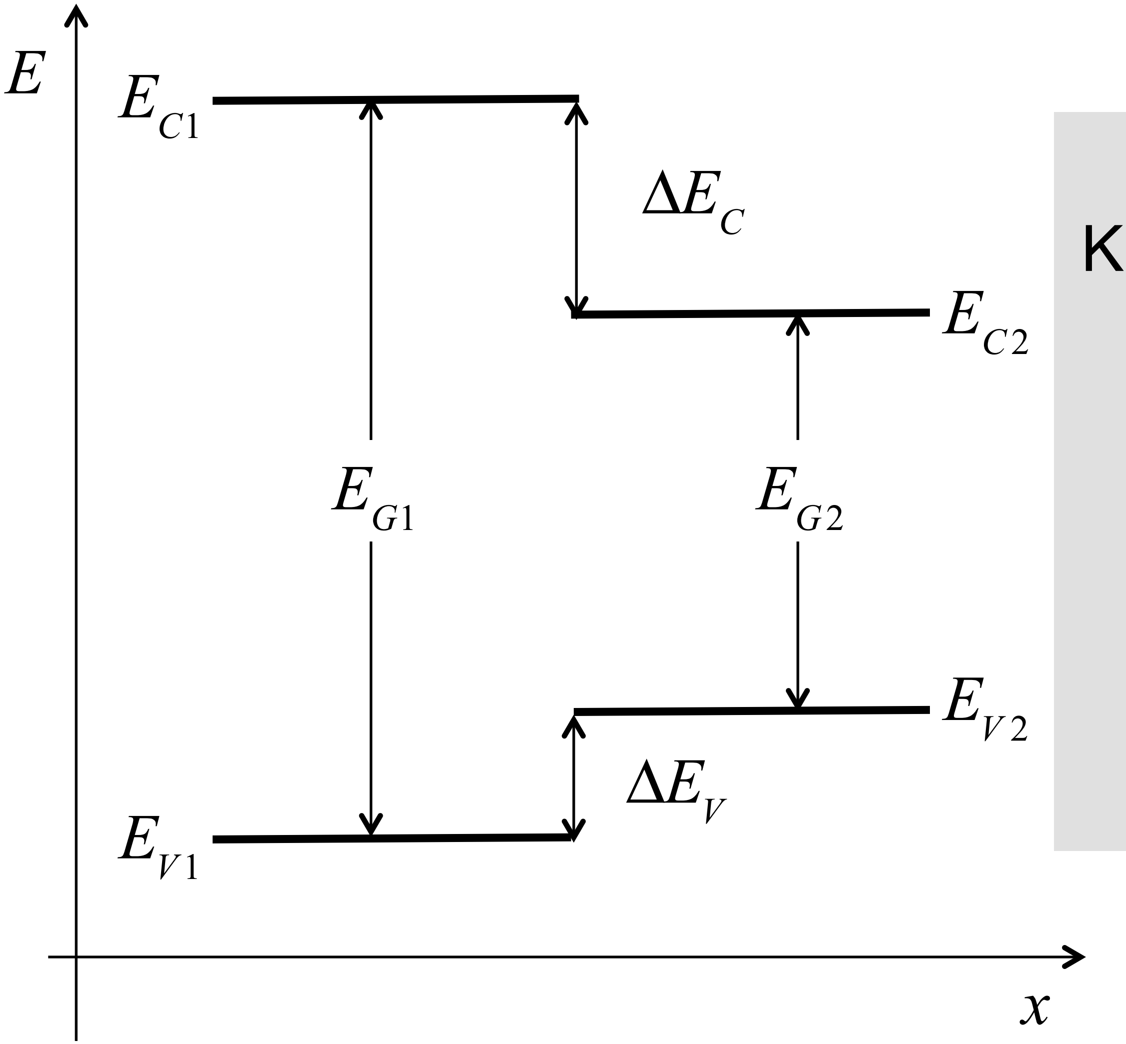
$A = 4\ \mathrm{cm}^2$
$t = 450\ \mu\mathrm{m}$
$V_{OC} = 706.0\ \mathrm{mV}$
$J_{SC} = 42.70\ \mathrm{mA/cm}^2$
$FF = 82.80$
$R_s = 0.50\ \Omega\text{-cm}^2$
$\eta = 25.0$

David D. Smith, et al., “Towards the practical limits of solar cells,” *IEEE J. Photovoltaics*, **4**, 1465-1469, 2014.

Outline

1) High volume Si and MC Si solar cells
2) IBC solar cells
3) **Heterojunctions for solar cells**
4) HJ silicon solar cells
5) HJ GaAs solar cells
6) Tandem solar cells
7) Summary

Heterojuctions



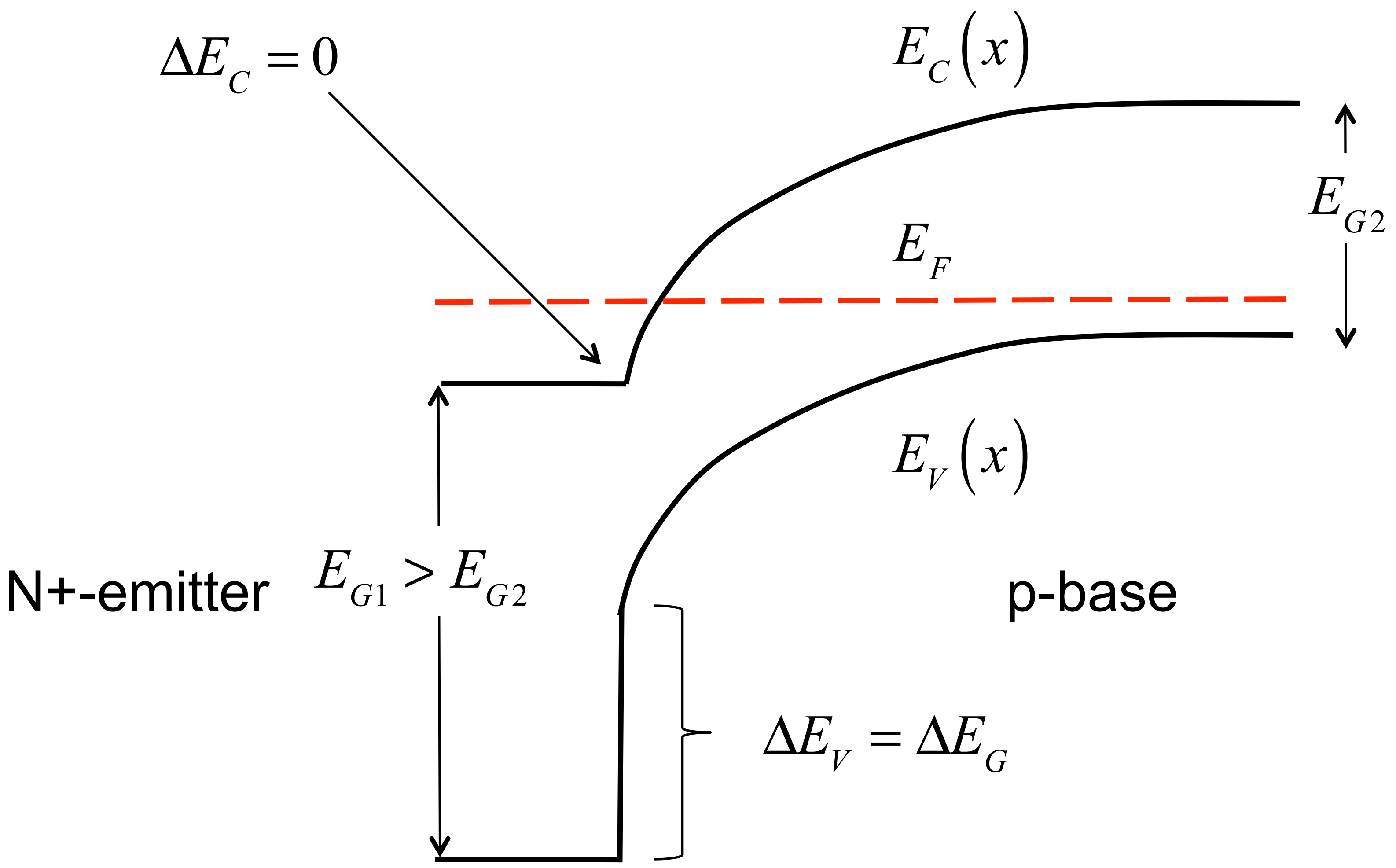
Key parameters for a HJ

$$\Delta E_G = E_{G1} - E_{G2}$$

$$\Delta E_C$$

$$\Delta E_V$$

N⁺p heterojuction



Lundstrom 2019

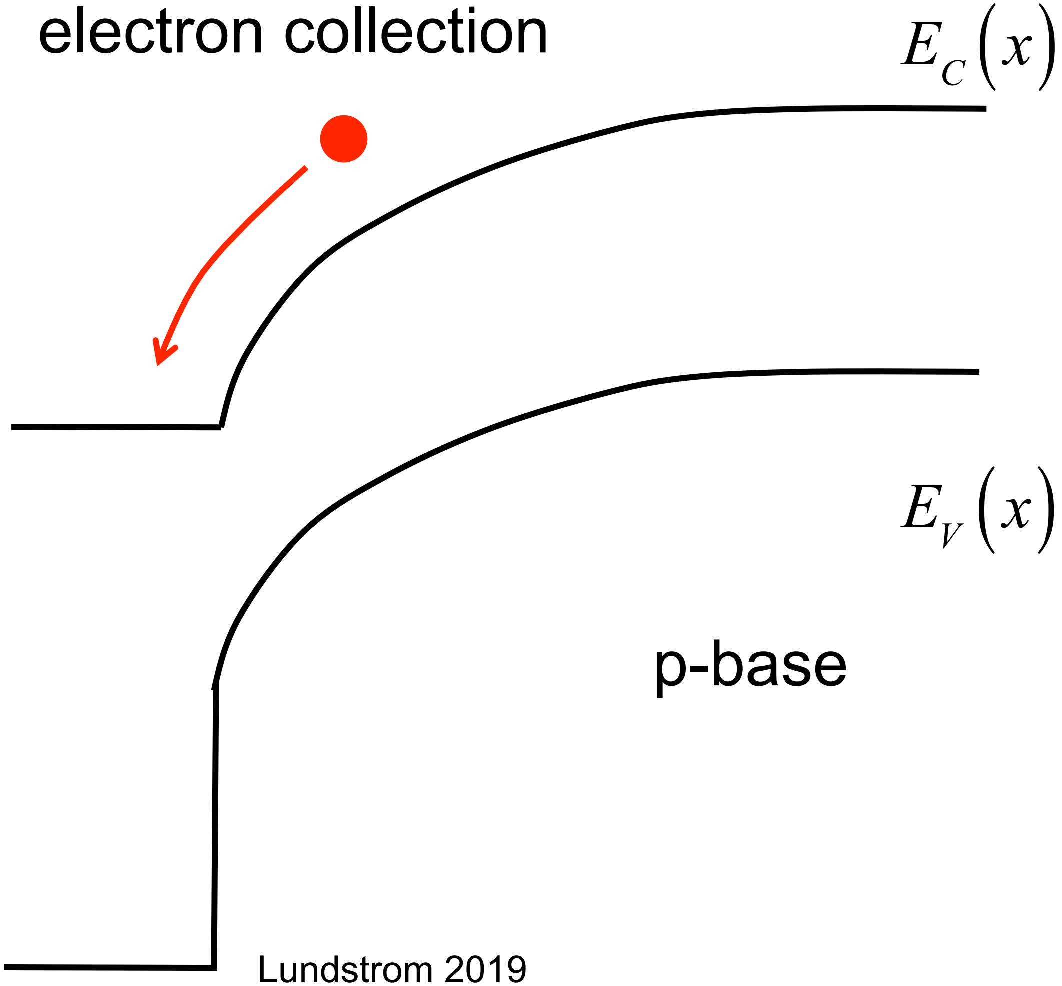
N$^+$p HJ: Short-circuit

N$^+$-emitter

Reduces optical absorption – minimizes surface recombination.

Passivates p-type absorber

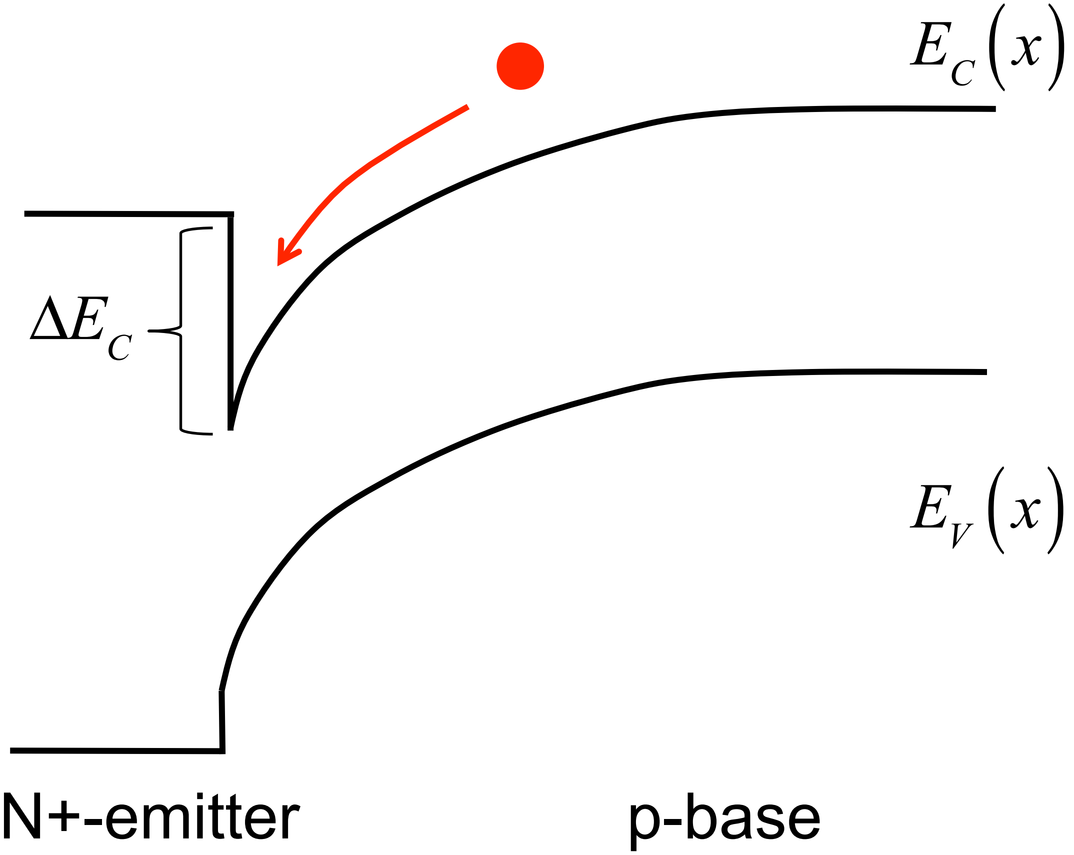
“window layer”



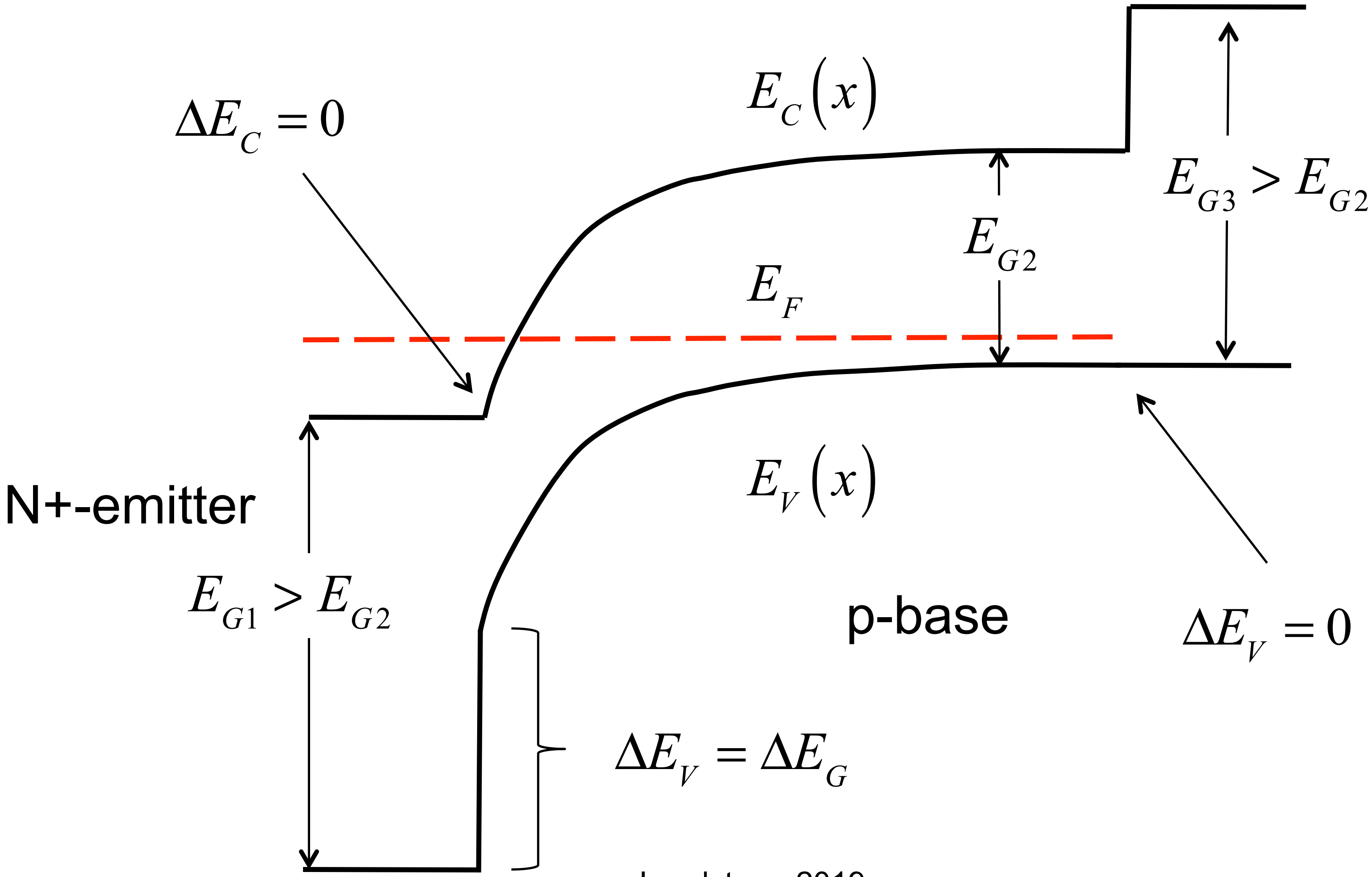
no barrier for electron collection

Problems with band offsets

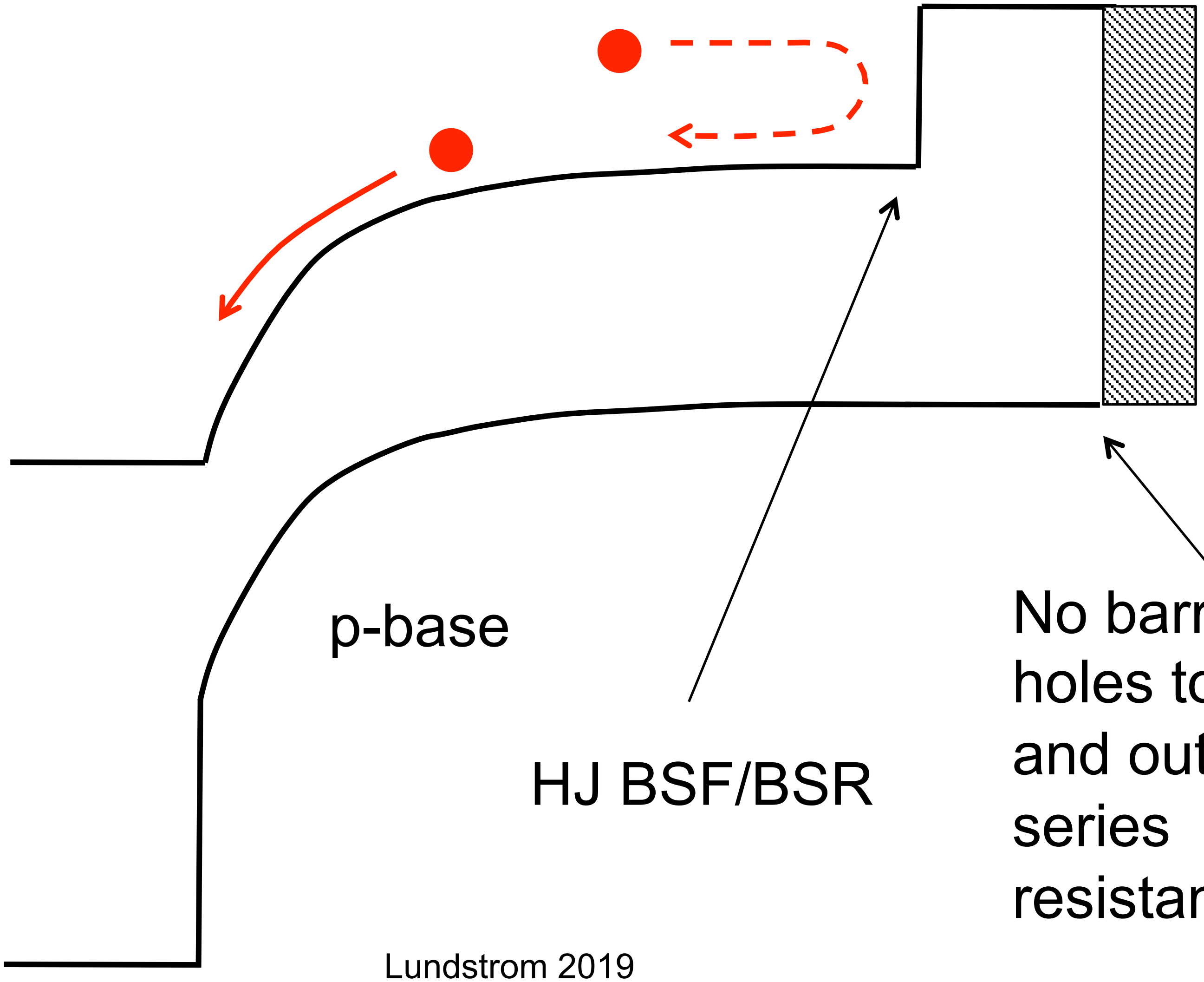
Conduction band "spikes" can impede current collection



N$^+$ p P$^+$ heterojuction



N$^+$ p P$^+$ HJ: Short circuit



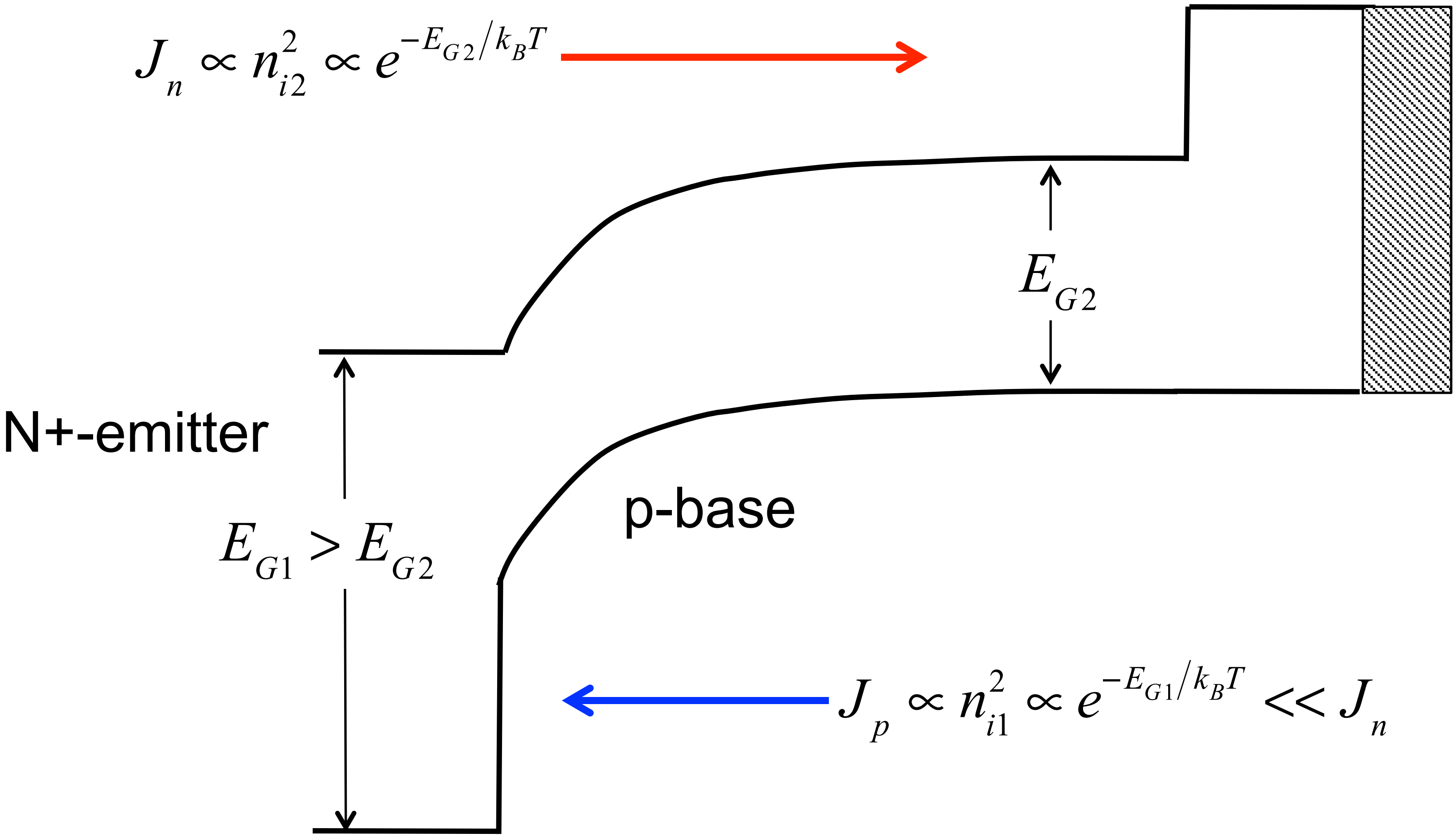
N+-emitter

p-base

HJ BSF/BSR

No barrier for holes to get in and out (low series resistance)

N^+ p P^+ HJ: Dark current



$$J_n \propto n_{i2}^2 \propto e^{-E_{G2}/k_BT}$$

$$J_p \propto n_{i1}^2 \propto e^{-E_{G1}/k_BT} << J_n$$

Outline

1) High volume Si and MC Si solar cells
2) IBC solar cells
3) Heterojunctions for solar cells
4) **HJ silicon solar cells**
5) HJ GaAs solar cells
6) Tandem solar cells
7) Summary

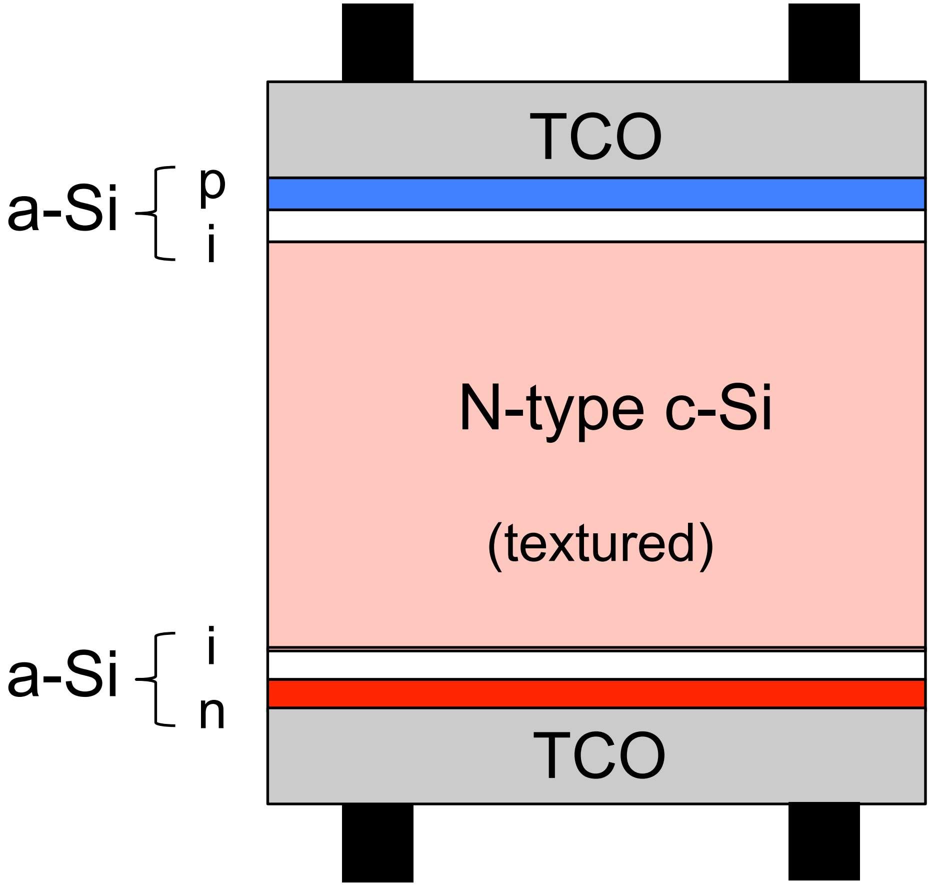
III-V and Si heterojunctions

Historically, the fact that III-V semiconductors provide the ability to grow high-quality HJs has been one of their advantages.

e.g. $Al_{1-x}Ga_xAs$

More recently, it has been discovered that amorphous Si (a-Si) with a bandgap of ~1.7 eV provides a good HJ to crystalline Si (c-Si), which has a bandgap of 1.1 eV.

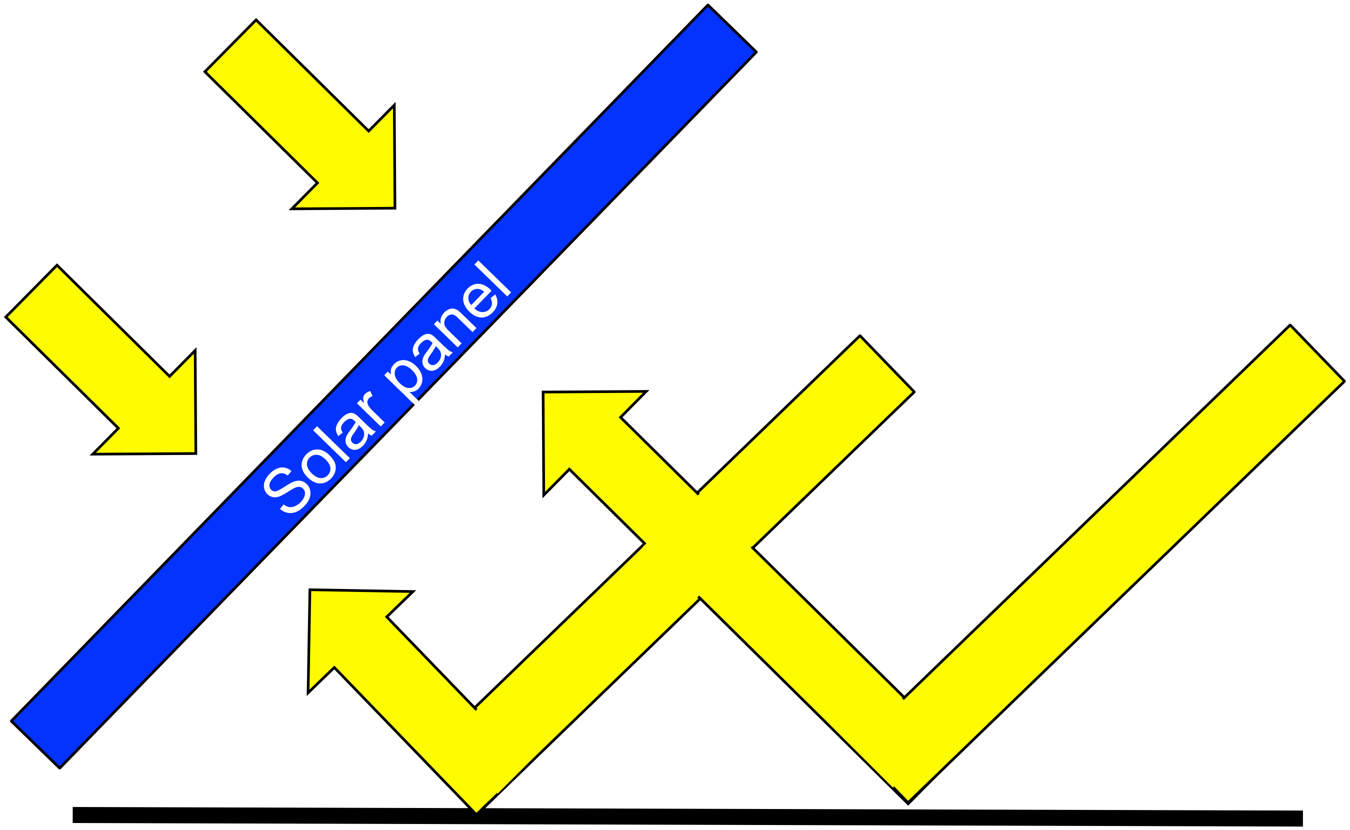
Heterojunction with **I**ntrinsic **T**hin Layer (HIT) cell



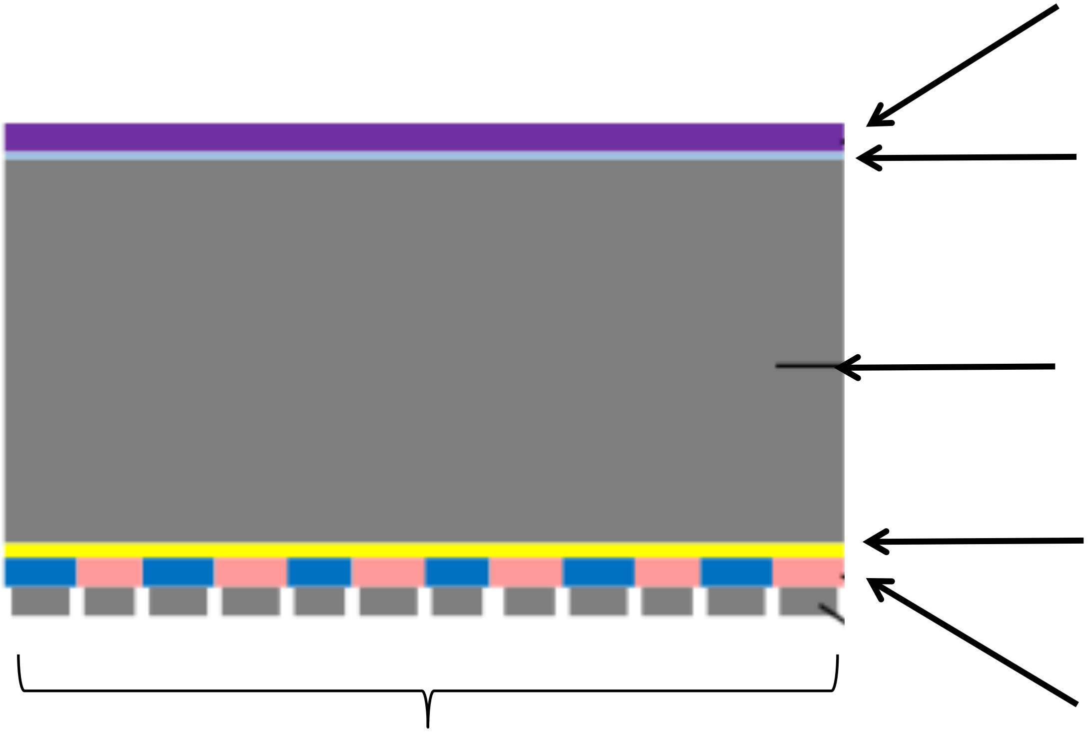
- Low-T processing (<200 C)
- i: a-Si passivates c-Si
- WBG emitter suppresses back injection
- WBG BSF eliminates minority carrier recombination
- Symmetrical (bifacial cell)
- >25% efficiency

M. Taguchi, et al, “HIT Cells- High-Efficiency Crystalline Si Cells with Novel Structure,” *Prog. Photovolt: Res. Appl.*, **8**, 503-513,2000.

Bifacial solar cells



IBC-HIT cell with 26.3% Efficiency



AR layer

i:a-Si passivation

N-c-Si

i:a-Si passivation

p:a-Si / n:a-Si

electrodes

K. Yoshikawa, et al, “Silicon heterojunction solar cell with interdigitated back contacts for a photovoltaic conversion efficiency over 26%,” *Nature Energy*, **2**, 17032,2017.

IBC vs. HJ IBC

IBC

$A = 121\ \text{cm}^2$
$t = 145\ \mu\text{m}$
$V_{OC} = 730.3\ \text{mV}$
$J_{SC} = 41.22\ \text{mA/cm}^2$
$FF = 82.96$
$R_s = 0.36\ \Omega\text{-cm}^2$
$\eta = 25.0$

HJ IBC

$A = 180\ \text{cm}^2$
$t = 150\ \mu\text{m}$
$V_{OC} = 744\ \text{mV}$
$J_{SC} = 42.3\ \text{mA/cm}^2$
$FF = 83.8$
R_s
$\eta = 26.3$

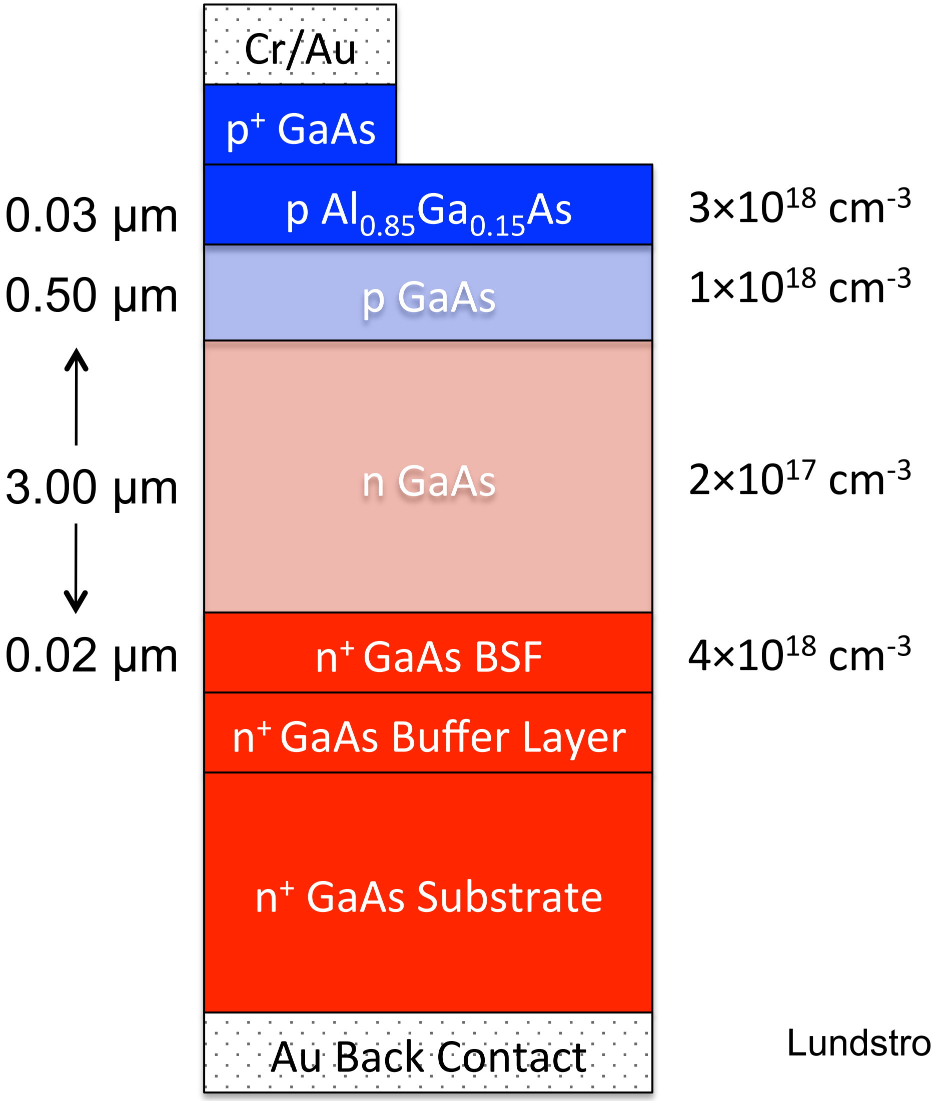
David D. Smith, et al., “Towards the practical limits of solar cells,” *IEEE J. Photovoltaics*, **4**, 1465-1469, 2014.

K. Yoshikawa, et al, “Silicon heterojunction solar cell with interdigitated back contacts for a photovoltaic conversion efficiency over 26%,” *Nature Energy*, **2**, 17032,2017.

Outline

1) High volume Si and MC Si solar cells
2) IBC solar cells
3) Heterojunctions for solar cells
4) HJ silicon solar cells
5) **HJ GaAs solar cells**
6) Tandem solar cells
7) Summary

Conventional GaAs “heteroface” cell



- Direct gap semiconductor
- Radiative recombination dominates

$$J_{SC} \approx 29 \text{ mA/cm}^2$$

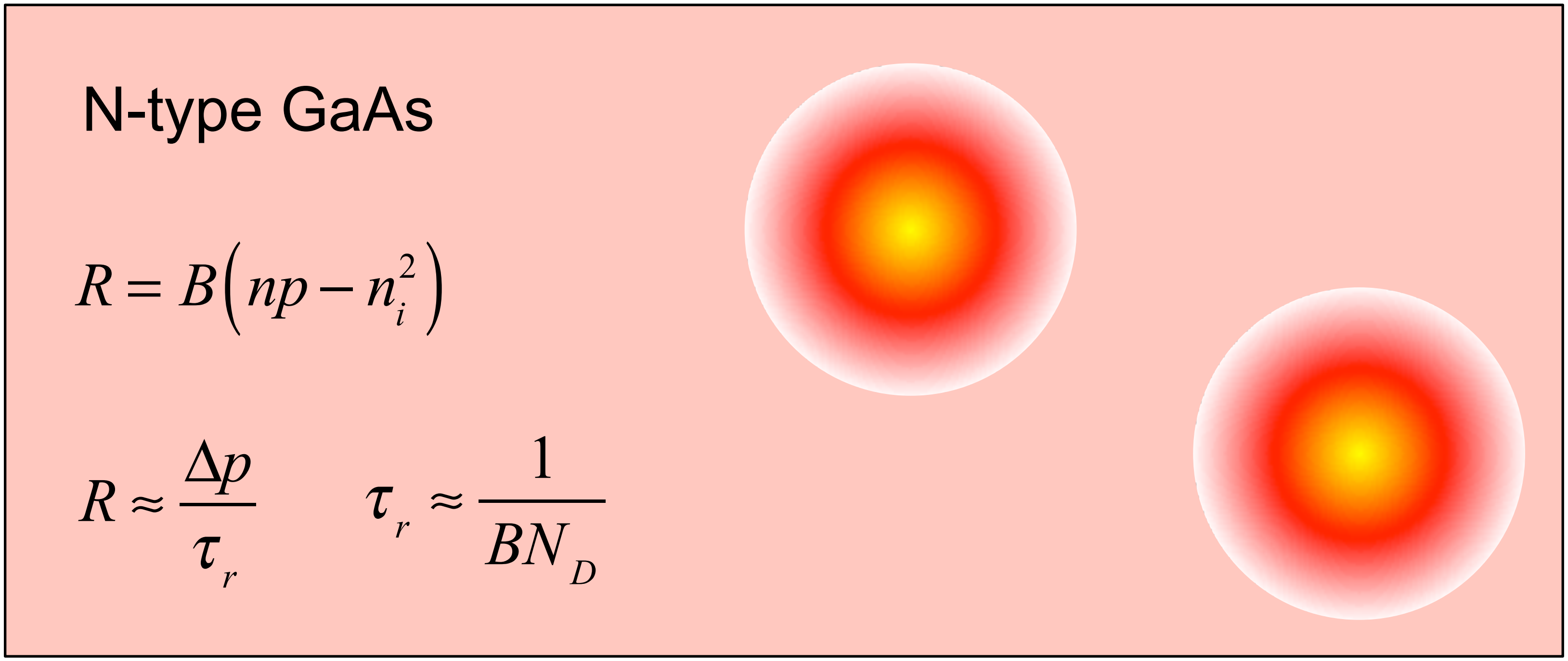
$$V_{OC} \approx 1.04 \text{ V}$$

$$\text{FF} \approx 0.85$$

$$\eta \approx 26\%$$

Lundstrom 2019

Photon re-cycling



N-type GaAs

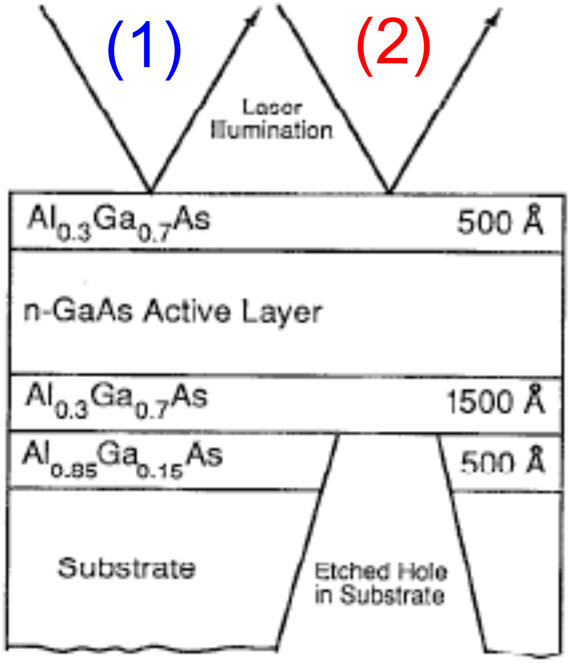
$$R = B\left(np - n_i^2\right)$$

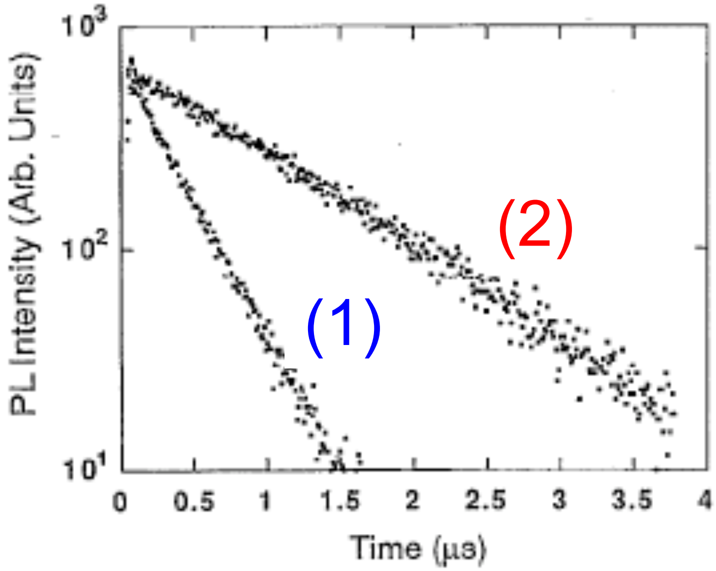
$$R \approx \frac{\Delta p}{\tau_r} \qquad \tau_r \approx \frac{1}{BN_D}$$

Electrons and holes recombine and emit photons
Photons can be re-absorbed, create new e-h pairs.

Lundstrom 2019

Photon re-cycling



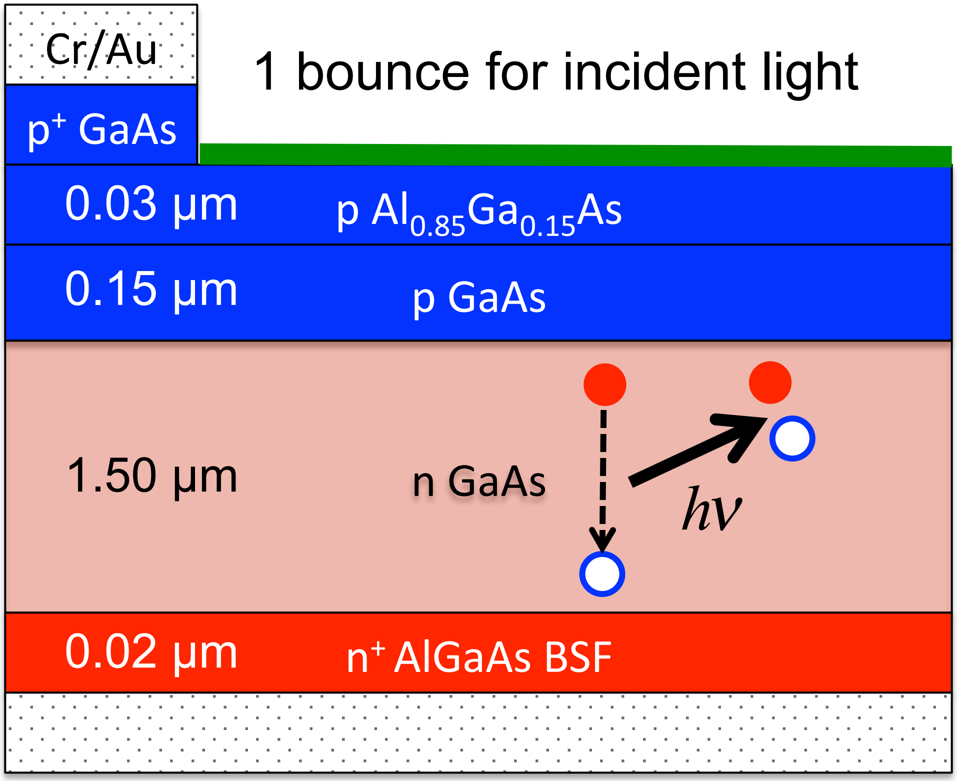


With substrate: liftetime = 10 x radiative lifetime

W/O sunstrate: lifetime > 1 microsecond

G. B. Lush, M. R. Melloch, and M. S. Lundstrom, D. H. Levi and R. K. Ahrenkie H. F. MacMillan, "Microsecond lifetimes and low interface recombination velocities in moderately doped n-GaAs thin films," *App. Phys. Lett.*, **61**, 2440, 1992.

Cell design to exploit photon re-cycling



1 bounce for incident light

highly reflective back contact

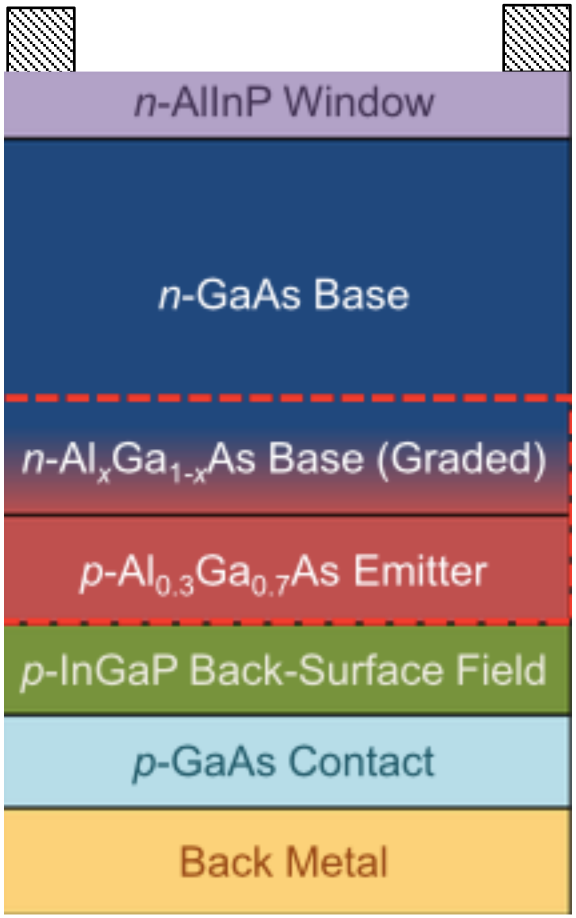
$$\tau_r = \frac{1}{BN_D}$$

$$\tau_r \to \phi\tau_t$$

$$\tau_r = \frac{1}{B_{eff}N_D}$$

The effective B-coefficient for radiative recombination is material ***and*** device-dependent.

Recent example



GaAs	PERL
A = 1 cm^2	A = 4 cm^2
V_{OC} = 1108 mV	V_{OC} = 706.0 mV
J_{SC} = 30.0 mA/cm^2	J_{SC} = 42.70 mA/cm^2
FF = 86.5	FF = 82.80
η = 28.7%	η = 25.0%

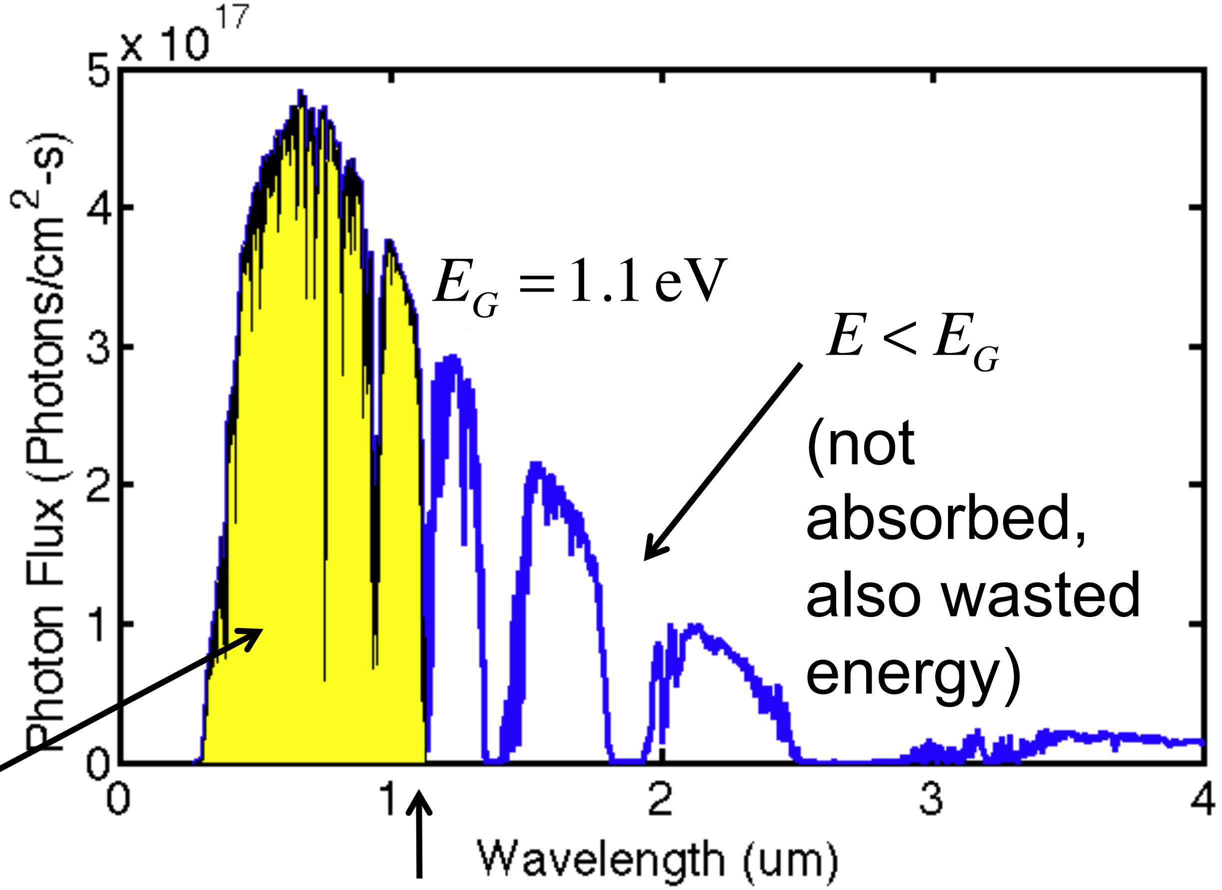
Current record: 28.8% (Alta Devices)

Sun-Tae Hwang, et al., “Bandgap grading and Al$_{0.3}$Ga$_{0.7}$As heterojunction emitter for highly efficient GaAs-based solar cells,” Solar Energy Materials & Solar Cells, **155**, 264–272, (2016)

Outline

1) High volume Si and MC Si solar cells
2) IBC solar cells
3) Heterojunctions for solar cells
4) HJ silicon solar cells
5) HJ GaAs solar cells
6) **Tandem solar cells**
7) Summary

Un-used solar energy



$E_G = 1.1\,\text{eV}$

$E < E_G$

(not absorbed, also wasted energy)

$E > E_G$

(wasted energy)

$\lambda = 1.13\,\mu\text{m}$

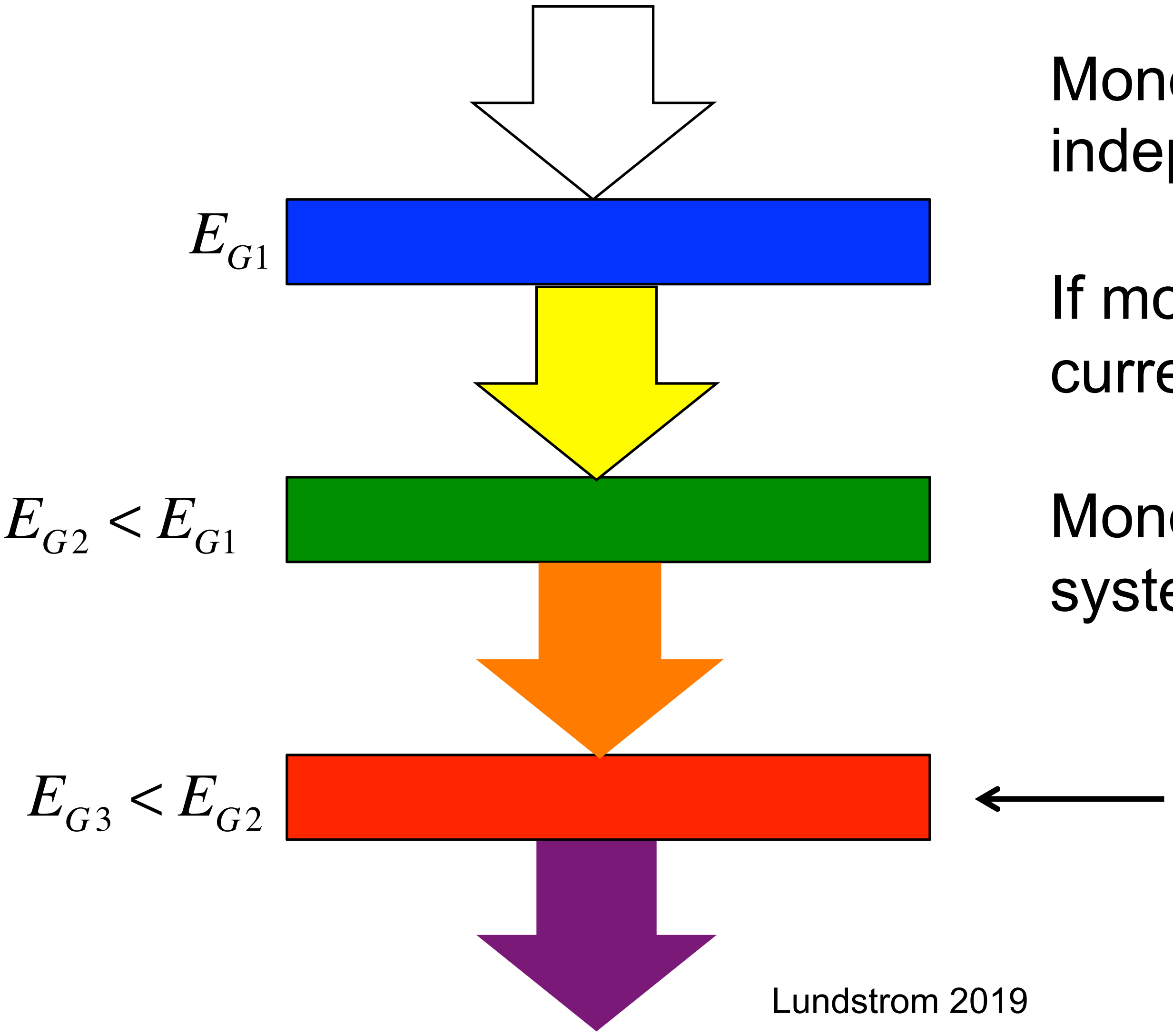
Un-used solar energy

Conclusion: A single semiconductor material cannot efficiently use the solar spectrum

Solution: Use more than one semiconductor with different bandgaps

Trade-off: More efficient, but more expensive

A three junction tandem cell



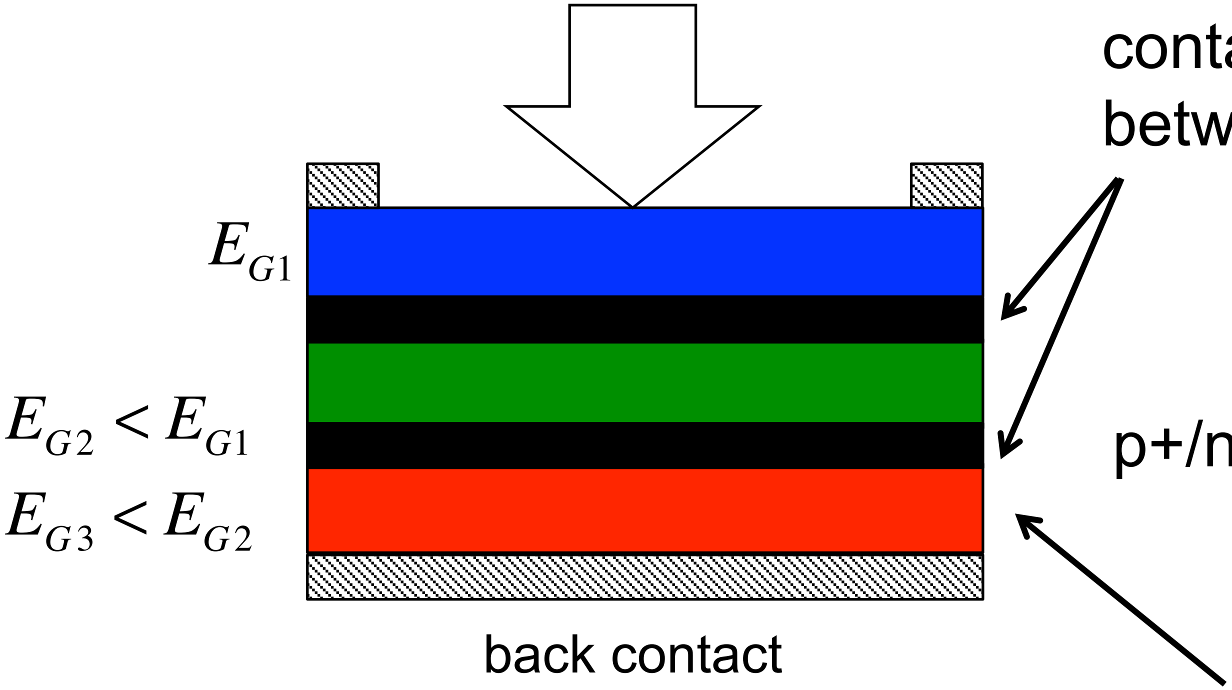
Monolithic or
independent?

If monolithic/series,
currents must be matched

Monolithic is attractive for
systems

Si?

A monolithic three junction tandem cell

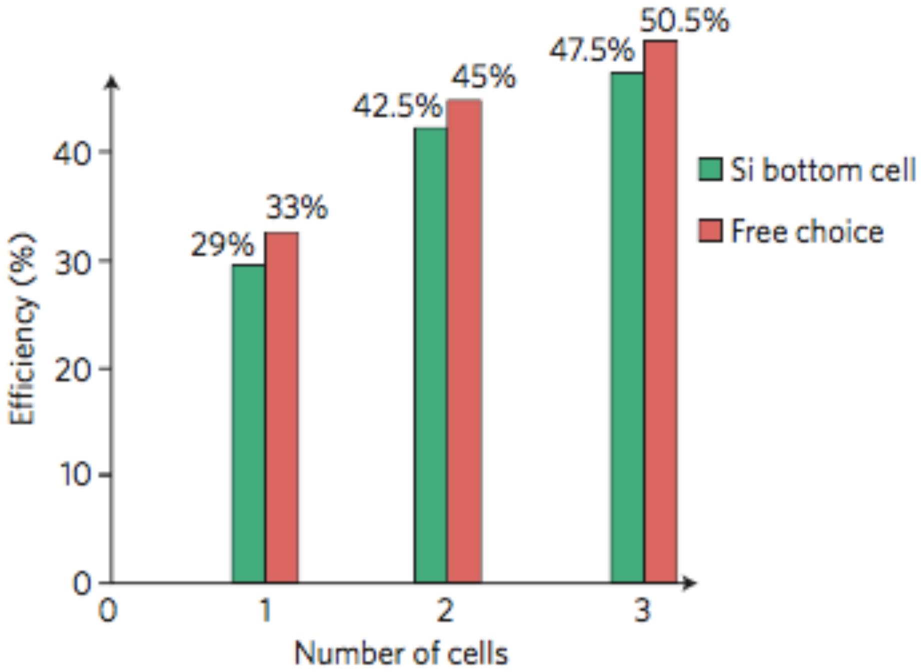


Transparent ohmic contacts are needed between the cells.

p+/n+ tunnel junctions

Si?

Si for the bottom cell?



The Si bandgap is a little too small for a single junction, but a little too big as the bottom cell in a tandem, but...

Si provides an evolutionary path for manufacturers to reach 30-35% module efficiencies by 2030.

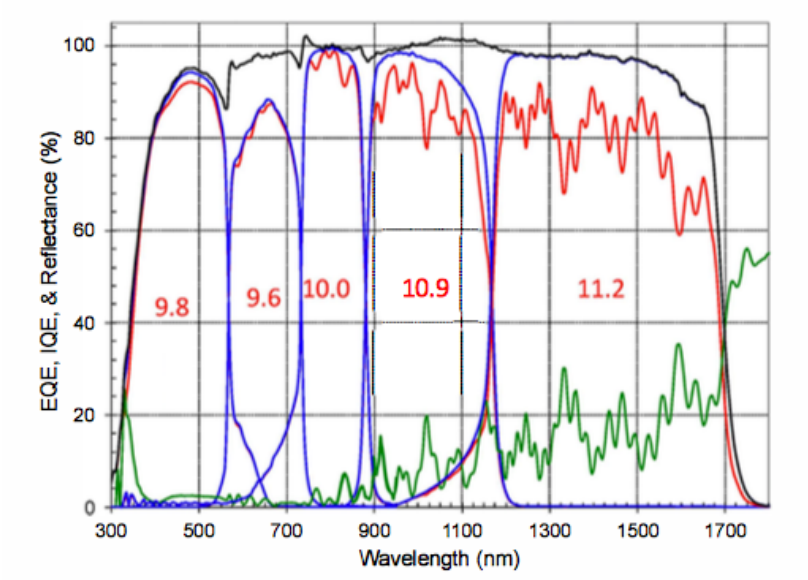
Martin A. Green, "Commercial progress and challenges for photovoltaics," *Nature Energy*, **1**, 1-4, 2016.

5-Junction example

E_G = 2.2, 1.7, 1.4 eV
grown on GaAs

bonded to

E_G = 1.05, 0.73 eV
grown on InP



A = 1 cm^2
V_{OC} = 4.2128 V
J_{SC} = 9.56 mA/cm^2
FF = 85.2%
η = 38.8%

P.T. Chiu, et al., "35.8% space and 38.8% terrestrial 5J direct bonded cells," *Proc. 40th IEEE PVSC*, 11-13, 2014.

Outline

1) High volume Si and MC Si solar cells
2) IBC solar cells
3) Heterojunctions for solar cells
4) HJ silicon solar cells
5) HJ GaAs solar cells
6) Tandem solar cells
7) **Summary**

Summary

1) **Efficiency is the key.**

Balance of systems (BOS) costs (such as the cost of installation, land needed, power electronics required, etc.) exceed the cost of modules.

High module efficiency reduces the number of modules needed and, therefore the BOS costs.

Summary

1) Efficiency is the key.

2) Si cell efficiency has increased by about 60% beginning about 1980, when cell efficiencies had plateaued.

3) Production cells and modules continue increase in efficiency.

4) Longer term, module efficiencies of > 30% will be achieved with Si-based tandem cells

5) Si will continue to be dominate, with new materials adding to Si-based tandems.

Questions

1) High volume Si and MC Si solar cells
2) IBC solar cells
3) Heterojunctions for solar cells
4) HJ silicon solar cells
5) HJ GaAs solar cells
6) Tandem solar cells
7) Summary