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Design of Silicon Solar Cells

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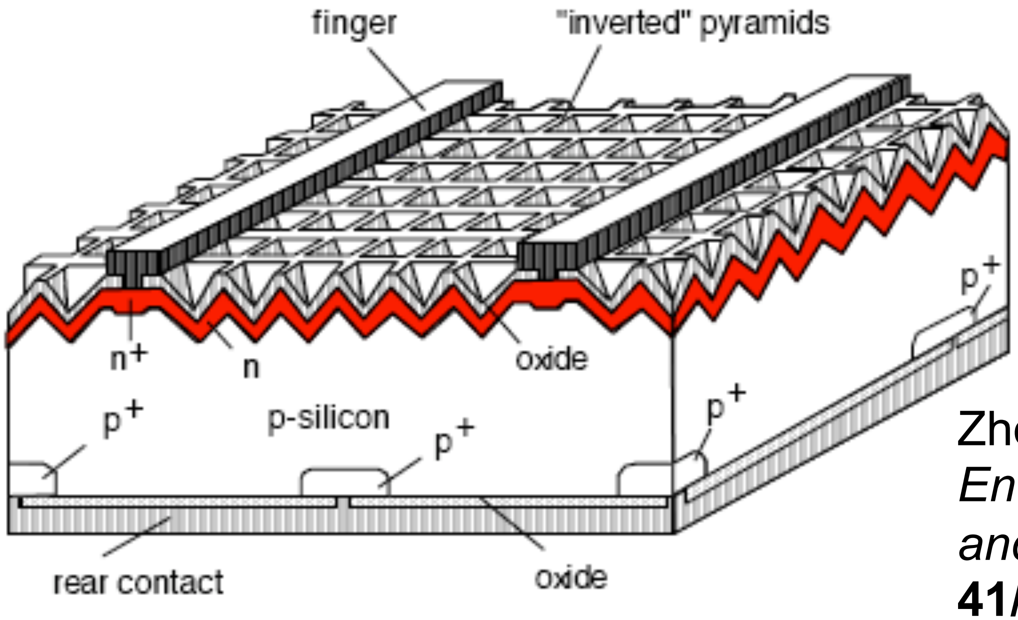
Objective

In this lecture, we will consider the optical and electrical design of a modern, high-efficiency, crystalline silicon solar cell.

The general principles discussed here are broadly applicable, but for thin-film, polycrystalline solar cells, there are some special considerations (which will be discussed later).

The PERL cell

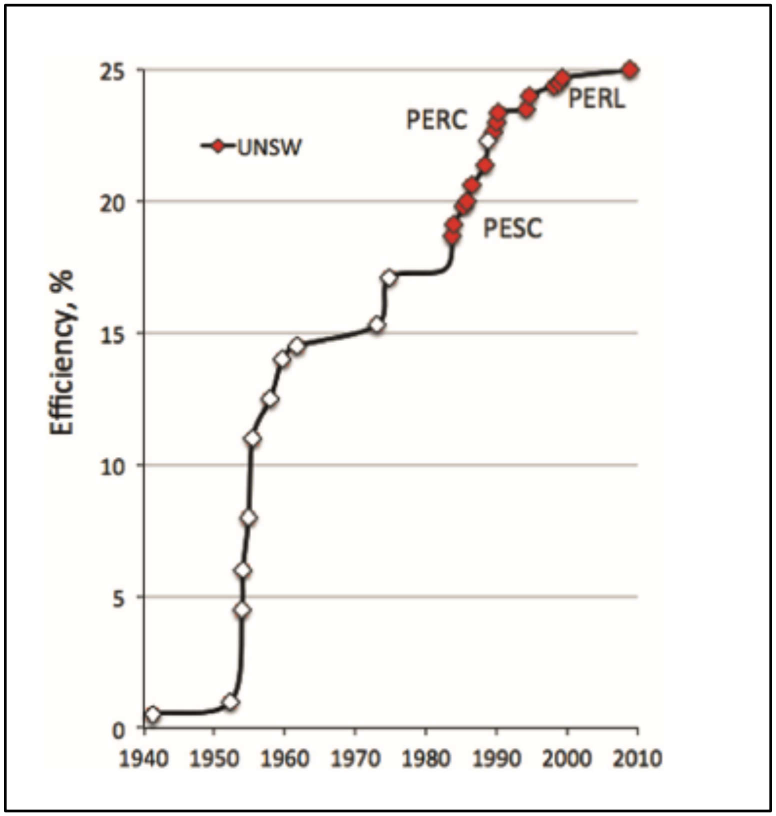


Zhou, et al., *Solar Energy Materials and Solar Cells*, **41/42**,87-99, 1996.

"**P**assivated **E**miitter **R**ear **L**ocally diffused"

Martin Green Group, University of New South Wales

Evolution of Si solar cells



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.

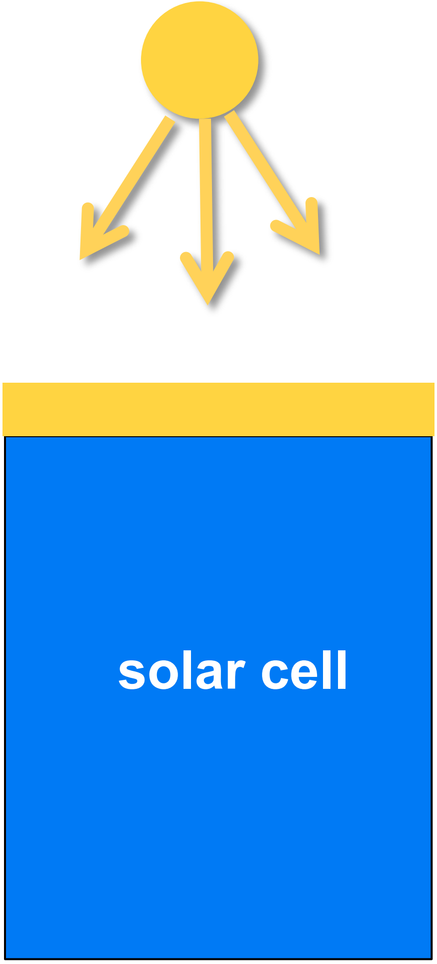
Outline

1) Introduction
2) **Optical design**
3) Principles of electrical design
4) Electrical design of the PERL cell
5) Series resistance
6) Discussion
7) Summary

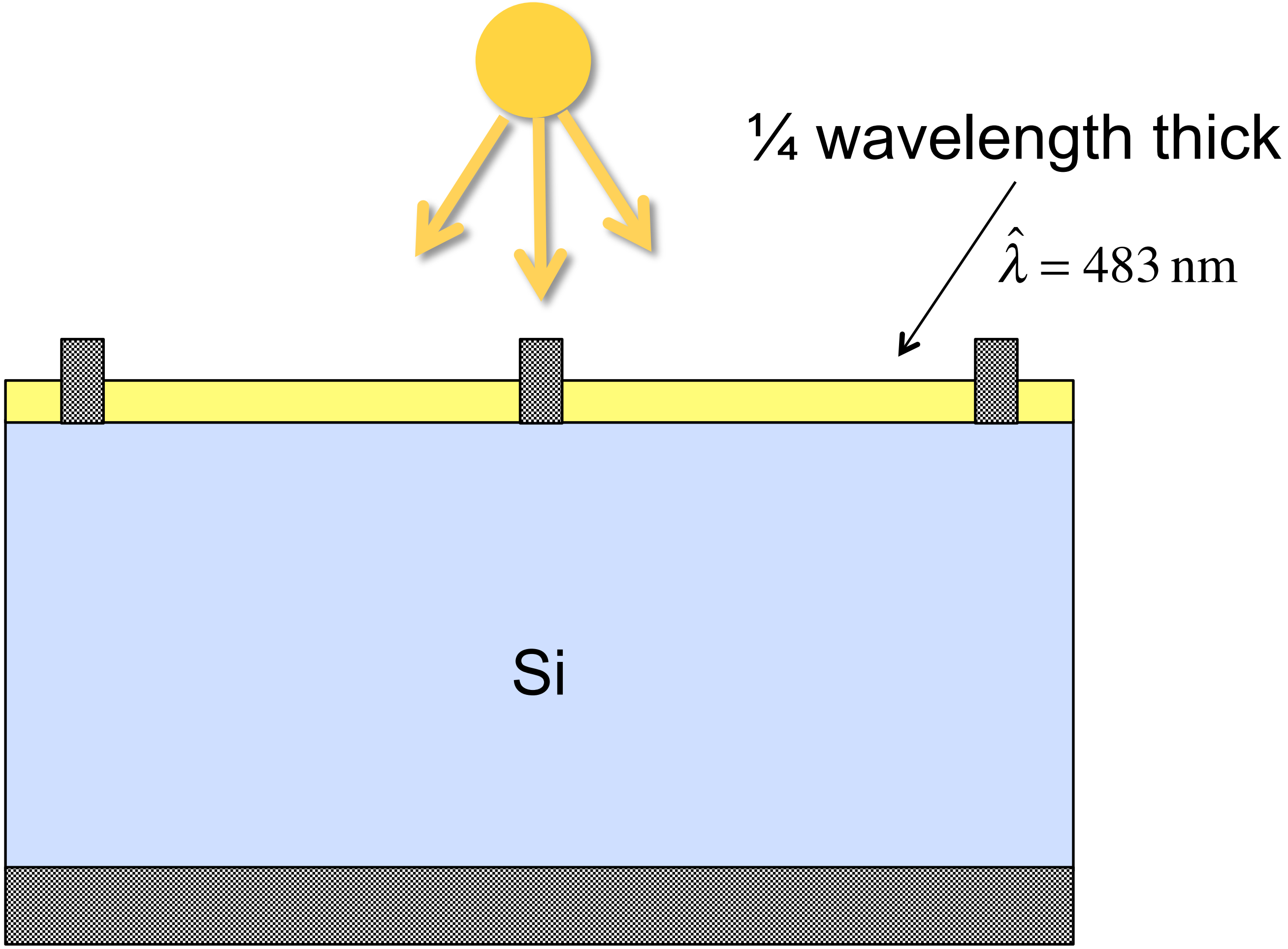
Maximizing light absorption / generation

1) Maximize the number of phonons that get into the solar cell (AR coating, texturizing).

2) Maximize the "effective" thickness of the absorber (light trapping).



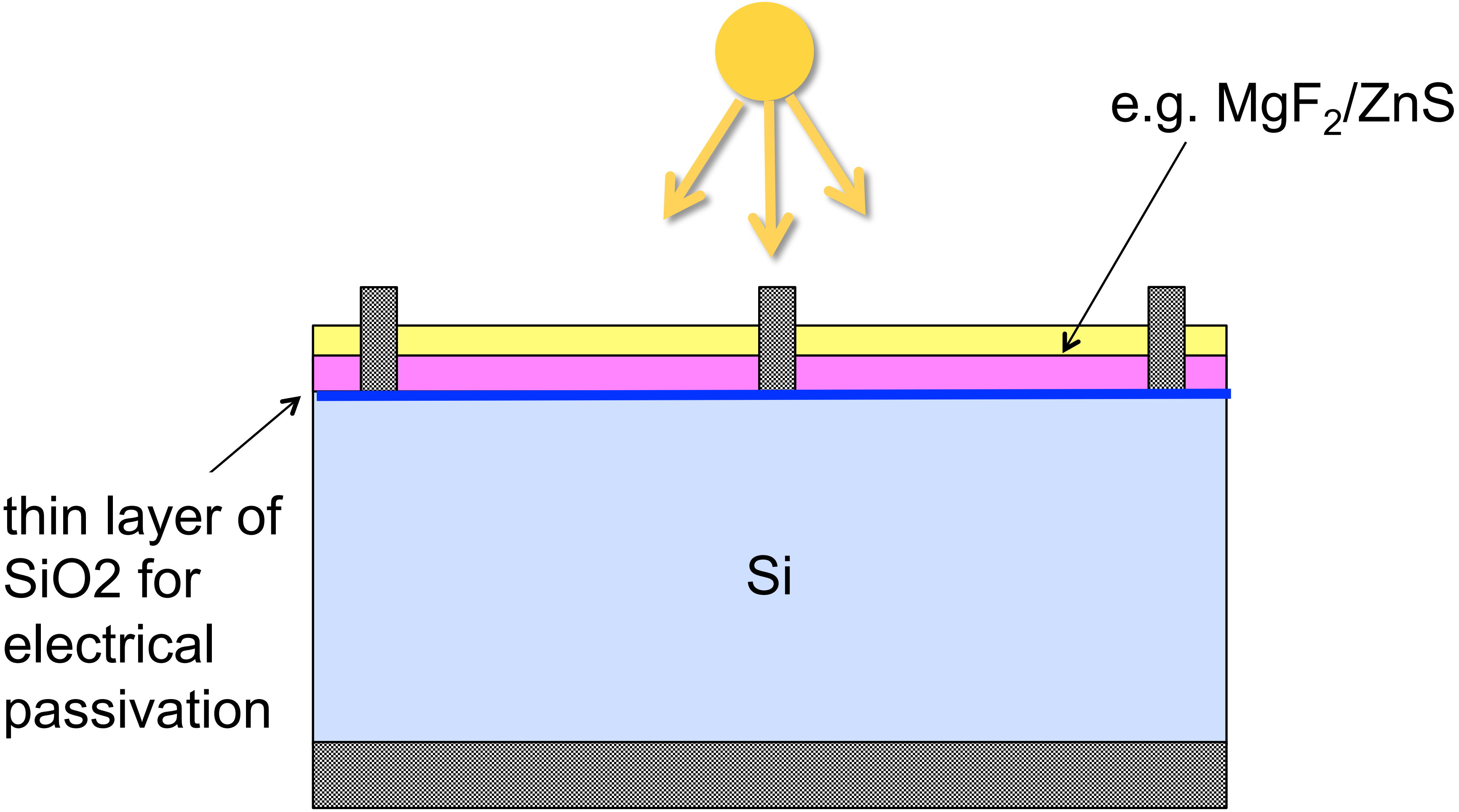
Anti-reflection coatings



¼ wavelength thick

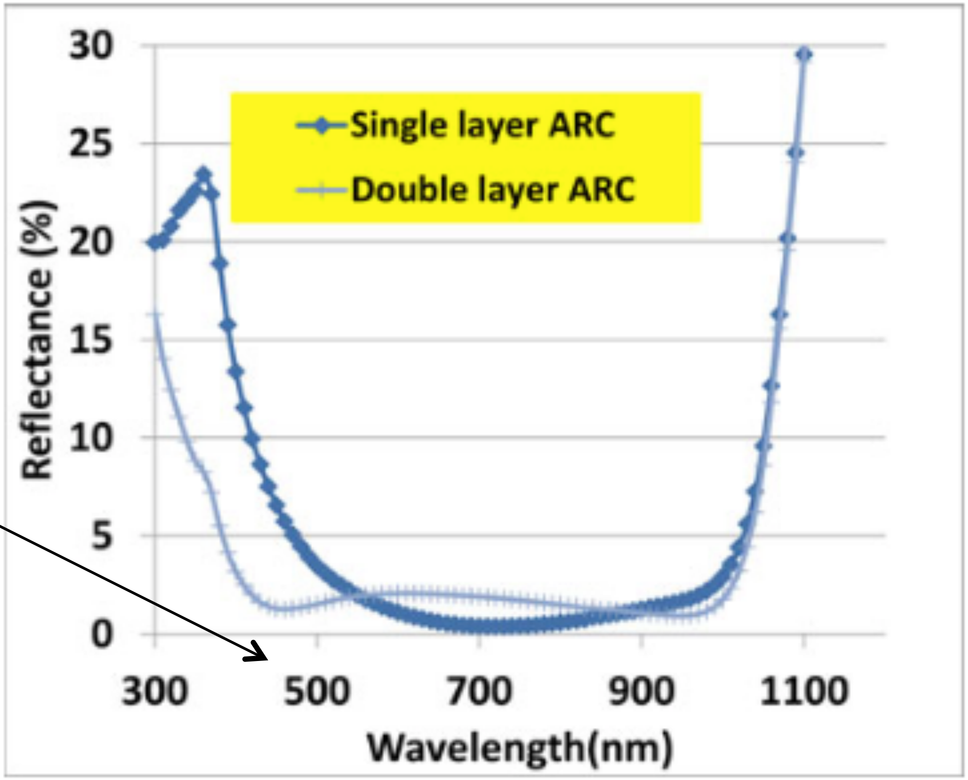
$\hat{\lambda} = 483\ \mathrm{nm}$

Dual-level AR coatings (DLAR)



https://www.pveducation.org/pvcdrom/design-of-silicon-cells/double-layer-anti-reflection-coatings

Dual-level AR coatings (DLAR)

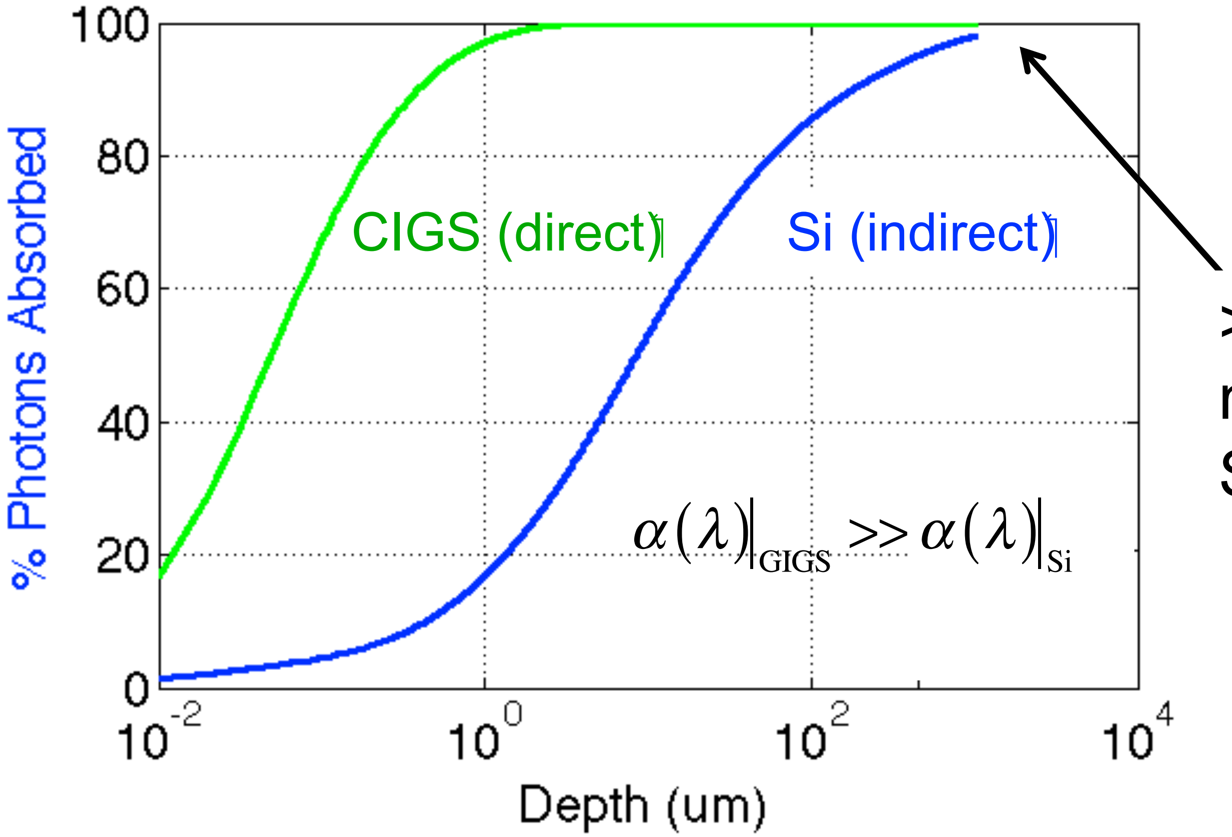


approximate
peak of solar
spectrum

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

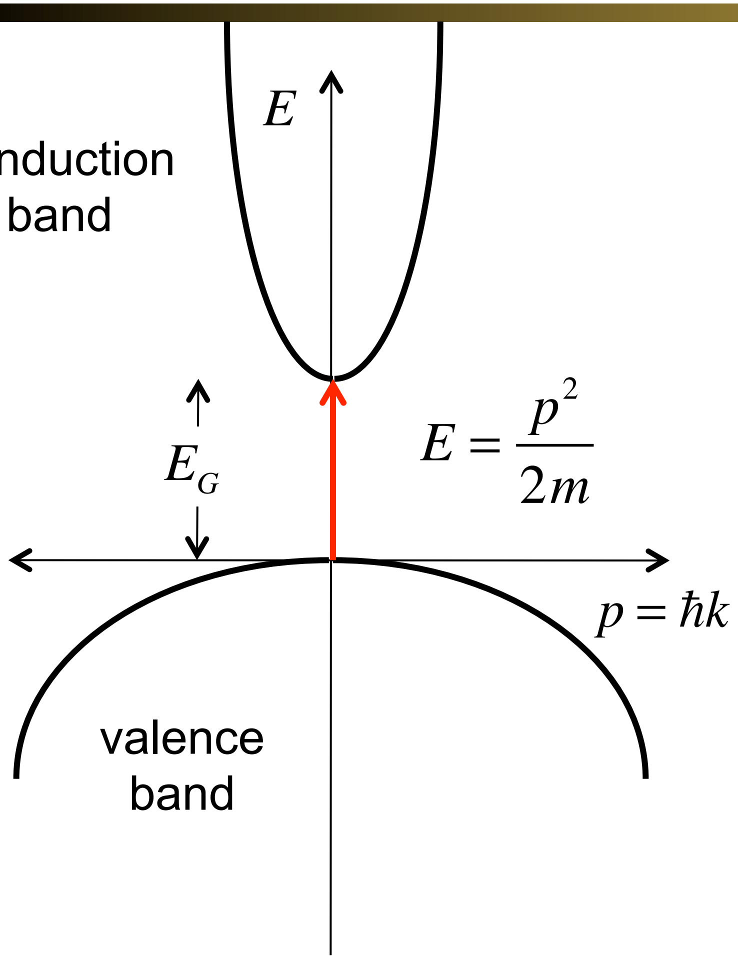
Light absorption vs. semiconductor thickness

The direct bandgap of CIGS allows it to absorb light much faster than Silicon. A layer of silicon must be thousands of microns thick to absorb ~100% of the light, while CIGS need only be about 2 microns thick.

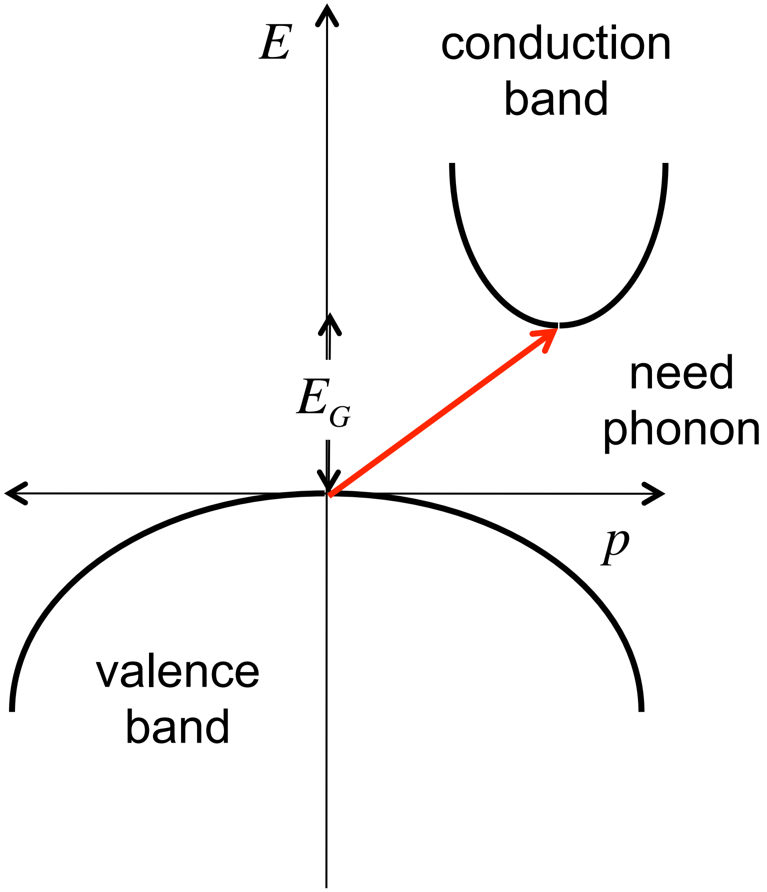


> 1000 microns of Si needed

What determines alpha?



Direct gap: strong absorption (high alpha)

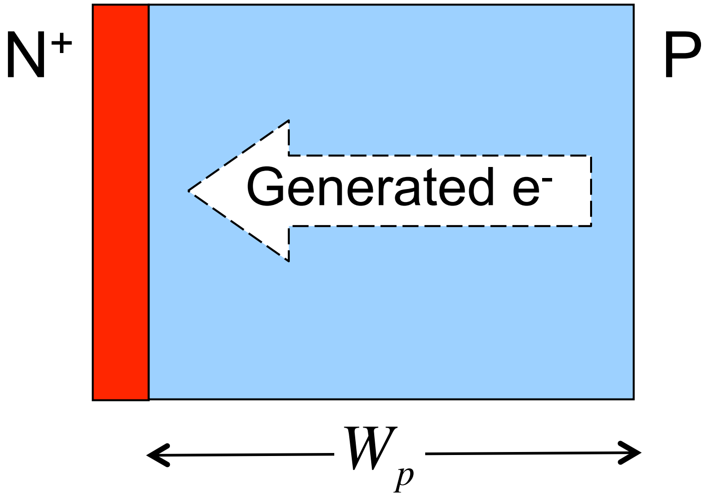


Indirect gap: weaker absorption lower alpha)

Current collection

Generated carriers are only useful if they are collected before they recombine.

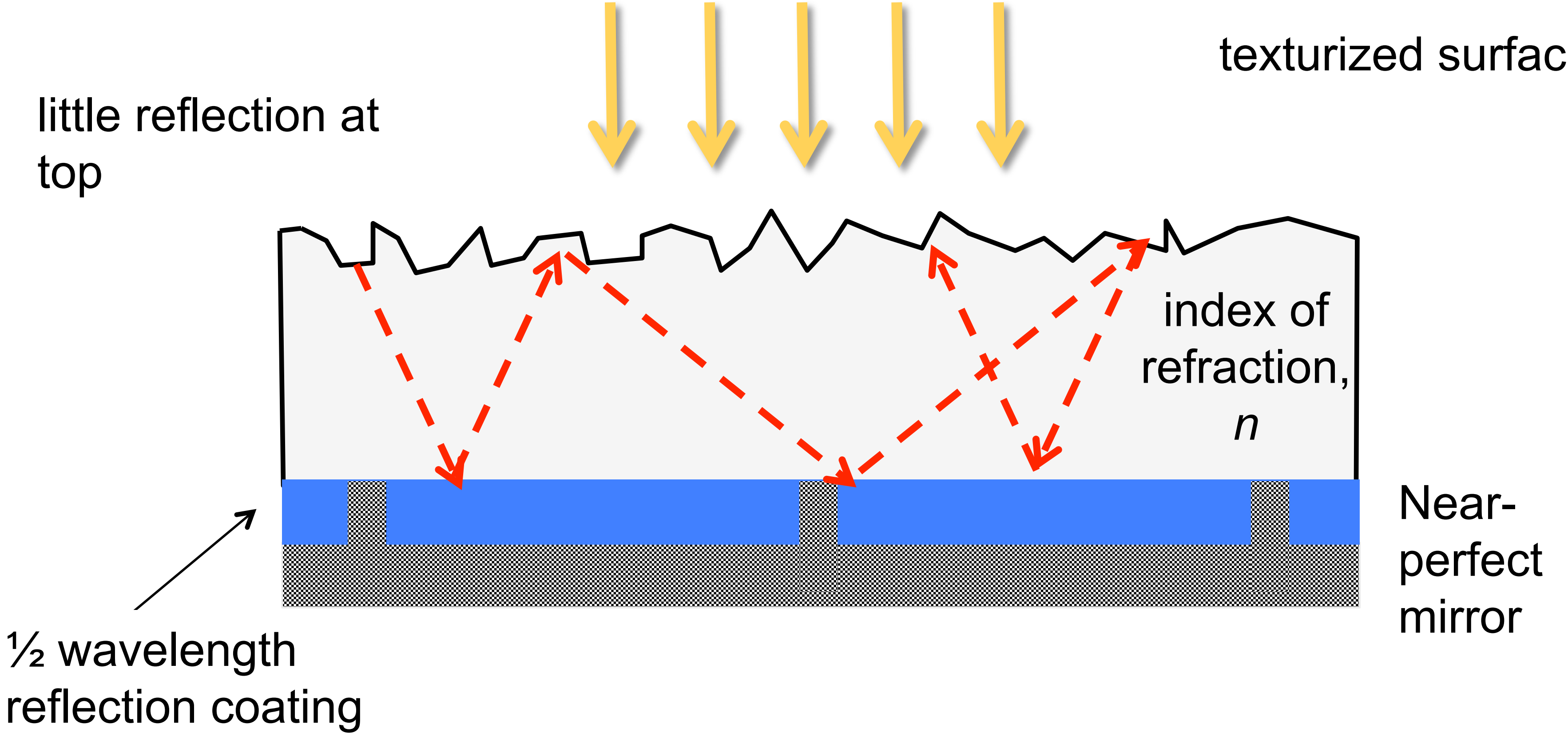
Electron diffusion length: $L_n = \sqrt{D_n \tau_n}$



$W_p << L_n$

The absorbing layer must be **electrically thin**, $W_p << L_n$, and **optically thick**, $W_p >> 1/\alpha$

Light trapping



texturized surface

little reflection at top

index of refraction, *n*

Near-perfect mirror

½ wavelength reflection coating

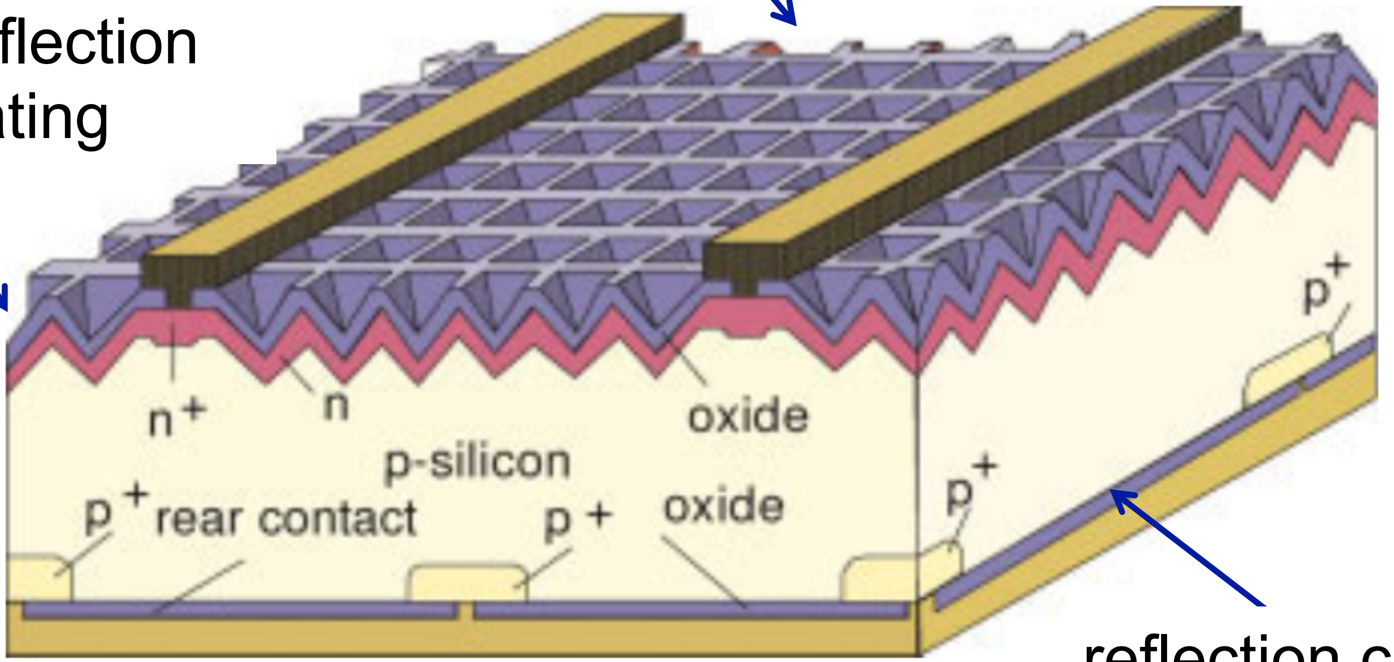
Probability of escaping from top surface = $1/4n^2$ (~2%)

Random vs. patterned sufaces

1) Absorption enhanced by $4n^2$ (Yablonovitch limit)
   E. Yablonovitch, "Statistical ray optics," *J. Opt. Soc. Am. A*, **72**, 899-907 (1982).

2) Similar enhancements possible with patterned surfaces.
   P. Campbell, M.A. Green, "Light trapping properties of pyramidally textured surfaces," *J. Appl. Phys*. **62**, 243-249 (1987).

PERL cell optical design



patterned top surface

front metal contact

anti-reflection coating

back metal contact

reflection coating

(111) planes are exposed by anisotropic etching

M. A. Green, *Prog. In Photovoltaics: Research and Applications*, **17**, 183-189, 2009.

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The semiconductor equations

$$\nabla \bullet \vec{D} = \rho$$

$$\nabla \bullet \left(\vec{J}_n / -q\right) = \left(G - R\right)$$

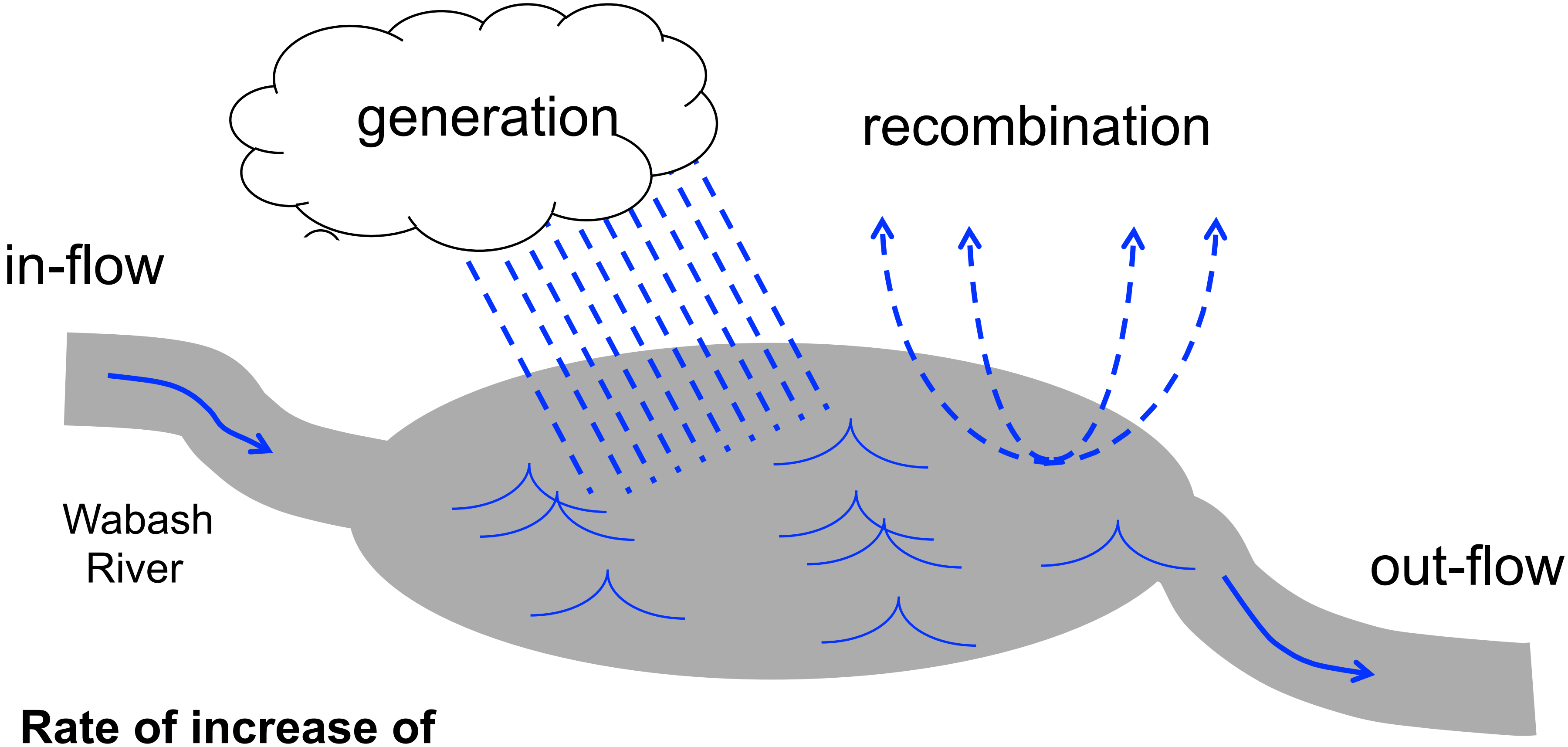
$$\nabla \bullet \left(\vec{J}_p / \; q\right) = \left(G - R\right)$$

steady-state

3 coupled, nonlinear, second order PDE’s for the 3 unknowns:

$$\psi(\vec{r}) \quad n(\vec{r}) \quad p(\vec{r})$$

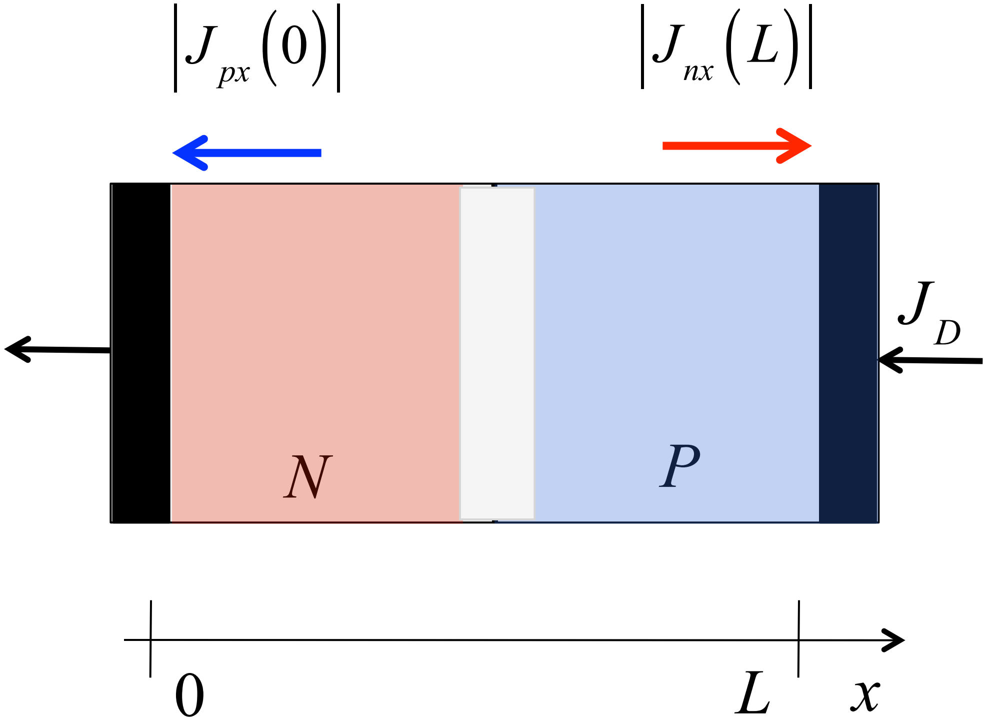
A continuity equation



Rate of increase of water level in lake **= (in flow - outflow) + rain - evaporation**

$$\frac{\partial p}{\partial t} = -\nabla \bullet \left(\vec{J}_p / q \right) + G - R$$

Solar cells and recombination-generation



By integrating the continuity equations, we can relate the diode current to R and G. (see Appendix 1)

$$J_D(V_D) = q\left(R_{TOT}(V_D) - G_{TOT}\right)$$

$$R_{TOT} = \int_0^L R(x)dx + R_F + R_B$$

$$R_F = \left|J_{px}(0)\right|$$

$$R_B = \left|J_{nx}(L)\right|$$

$$G_{TOT} = \int_0^L G_{op}(x)dx$$

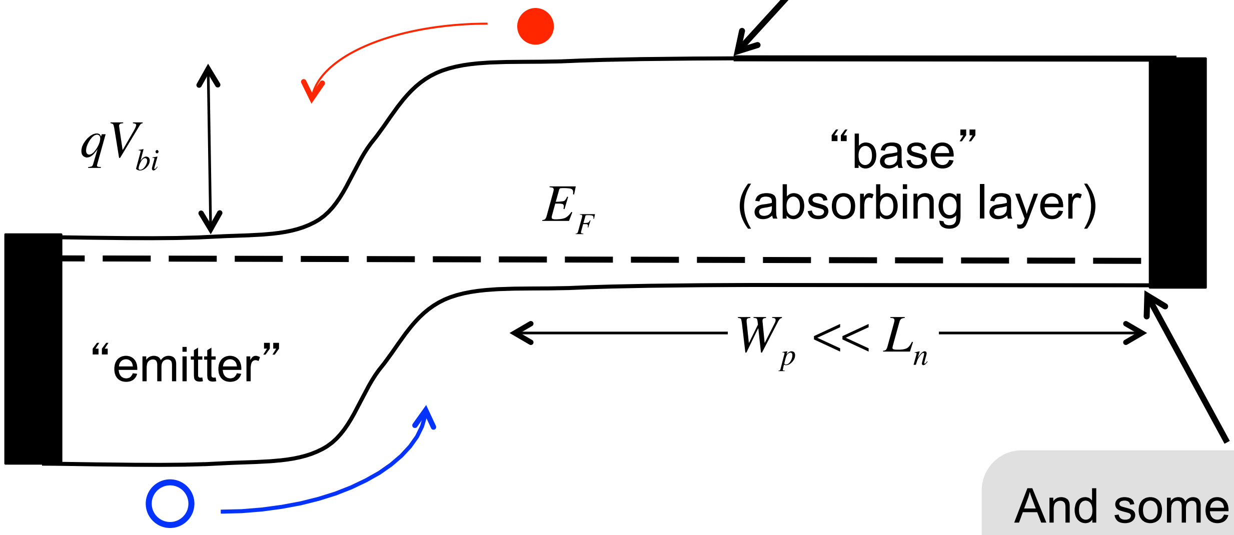
Solar cell design

- The goal is to **maximize optical generation** and **minimize minority carrier recombination**.
- Recombination lowers the short-circuit current (i.e. the collection efficiency) and reduces the open-circuit voltage.
- To optimize solar cell performance, we need a clear understanding where minority carriers are recombining.

Short-circuit current

Photo-generated carriers should diffuse to the junction and be collected.

Some may recombine in the base.

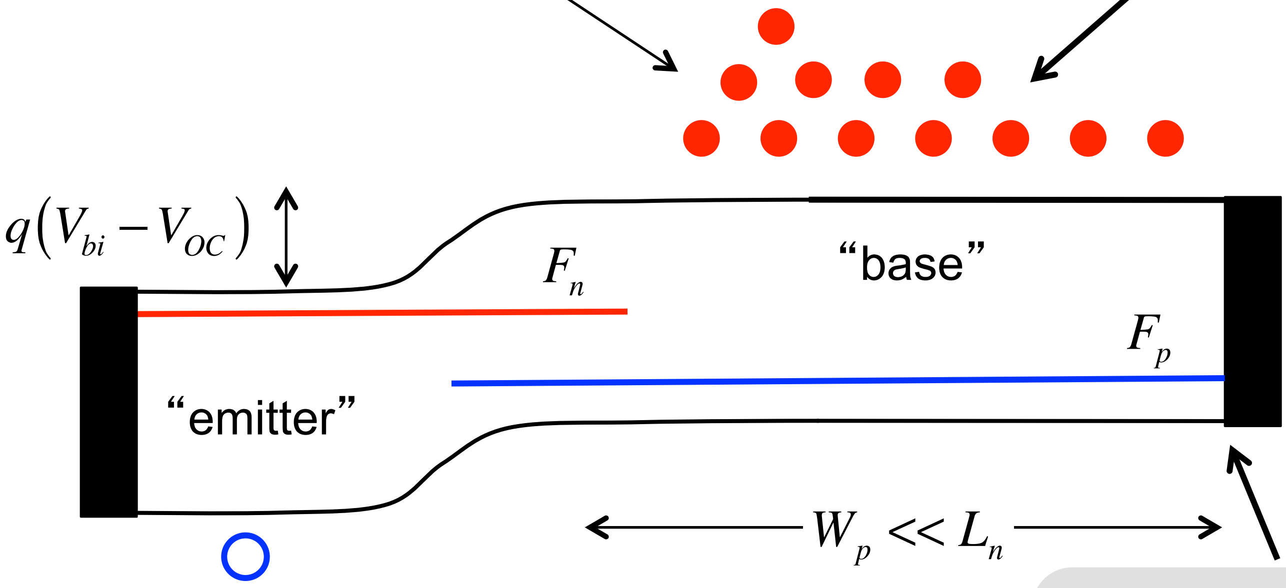


And some may diffuse to the contact and recombine.

$$CE \equiv \frac{J_{SC}}{qG_{TOT}}$$

"collection efficiency"

Open-circuit voltage



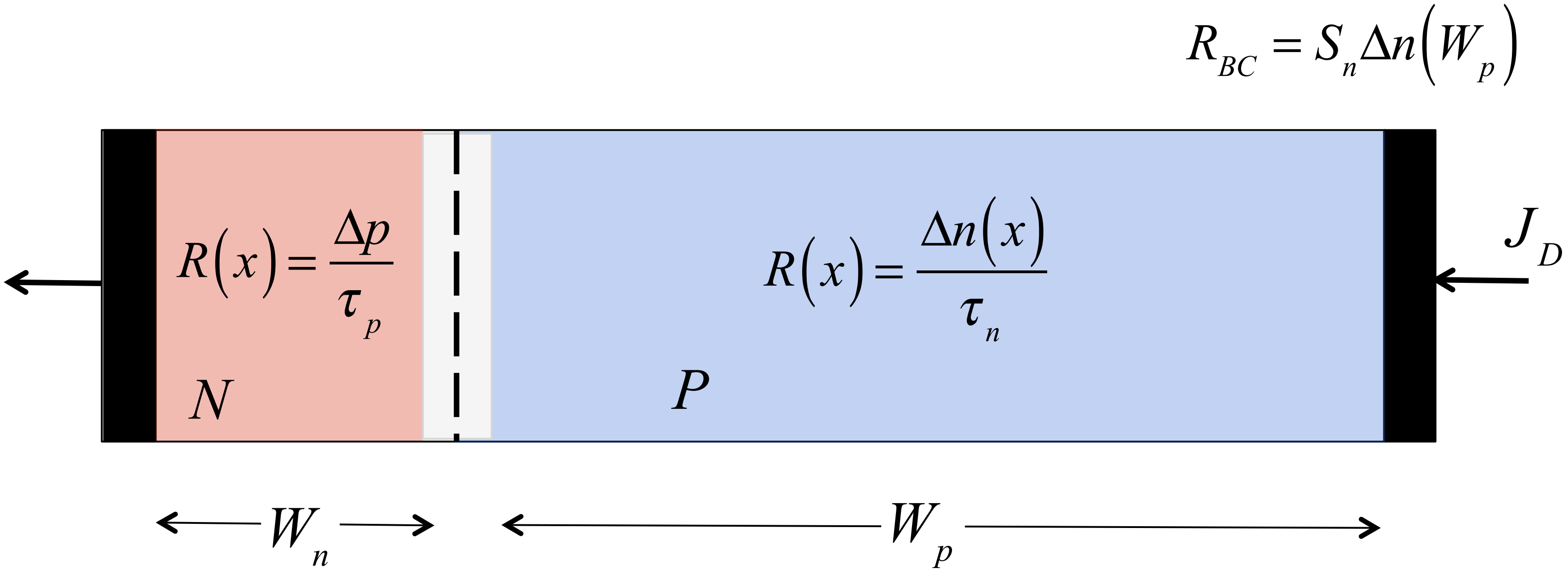
injected minority electron profile, n(x)

Some may recombine in the base.

And some may diffuse to the contact and recombine.

The same thing occurs on the P-side.

Minority carrier profiles



What are the minority carrier profiles in the quasi-neutral N and P regions?

$$\Delta p(x) = p(x) - p_0 \qquad \Delta n(x) = n(x) - p_0$$

MCDE

To answer this question, we must solve the minority carrier diffusion equation (MCDE), a simplification of the general continuity equation (see Appendix 2).

On the P-side:

$$\boxed{\frac{d^2\Delta n}{dx^2}=0}$$

$$\Delta n(x)=n(x)-p_0$$

(assumes little recombination in the P-region)

$$W_p << L_n$$

Solution:

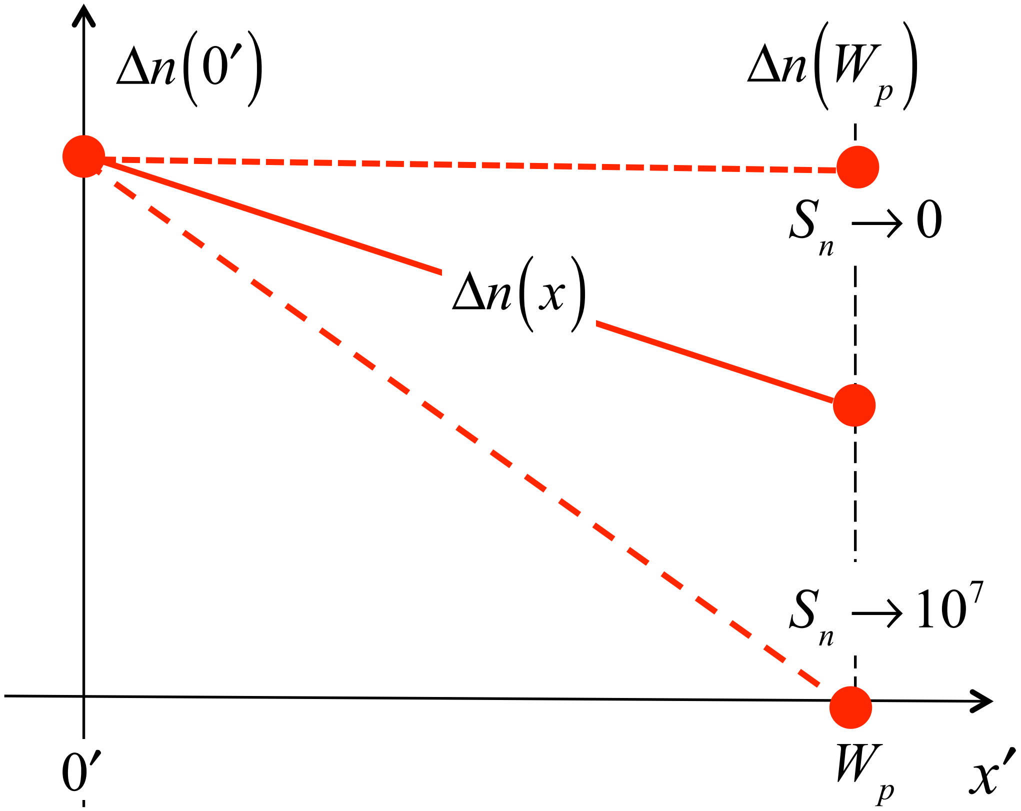
$$\Delta n(x)=Ax+B$$

FB N$^+$P diode in the dark

$$\Delta n(0') = \frac{n_i^2}{N_A}\left(e^{qV_D/k_BT} - 1\right)$$

$$\Delta n(W_p) = \frac{\Delta n(0')}{1 + S_n W_p / D_n}$$

$$0 < S_n < 10^7 \text{ cm/s}$$



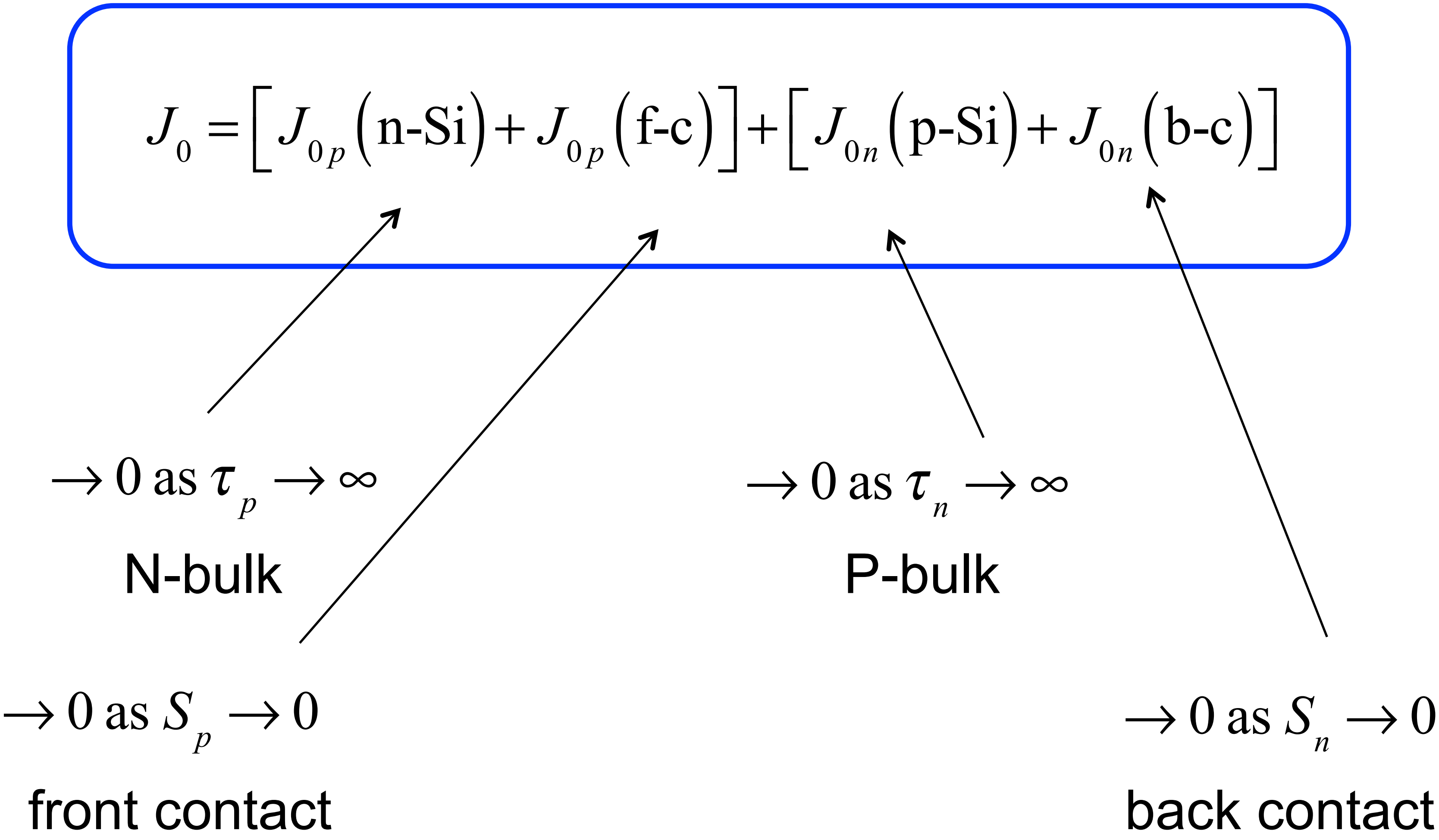
Minority carrier electrons recombine in the **P-base** or at the **back contact**. (Same for holes in the N-emitter and front contact.)

FB N$^+$P diode in the dark

$$J_n = \underbrace{\frac{qW_p}{2\tau_n}\left[\Delta n(0') + \Delta n(W_p)\right]}_{\substack{\text{recombination}\\ \text{in the P-layer}}} + \underbrace{\frac{qD_n}{W_p}\left[\Delta n(0') - \Delta n(W_p)\right]}_{\substack{\text{recombination}\\ \text{at the back}\\ \text{contact}}}$$

$$\boxed{\begin{gathered} J_D = J_0\left(e^{qV_D/k_BT} - 1\right) \\ J_0 = \left[J_{0n}(\text{p-Si}) + J_{0n}(\text{b-c})\right] + \left[J_{0p}(\text{n-Si}) + J_{0p}(\text{f-c})\right] \end{gathered}}$$

Dark current components



$$J_0 = \left[J_{0p}(\text{n-Si}) + J_{0p}(\text{f-c}) \right] + \left[J_{0n}(\text{p-Si}) + J_{0n}(\text{b-c}) \right]$$

$\rightarrow 0 \text{ as } \tau_p \rightarrow \infty$

N-bulk

$\rightarrow 0 \text{ as } \tau_n \rightarrow \infty$

P-bulk

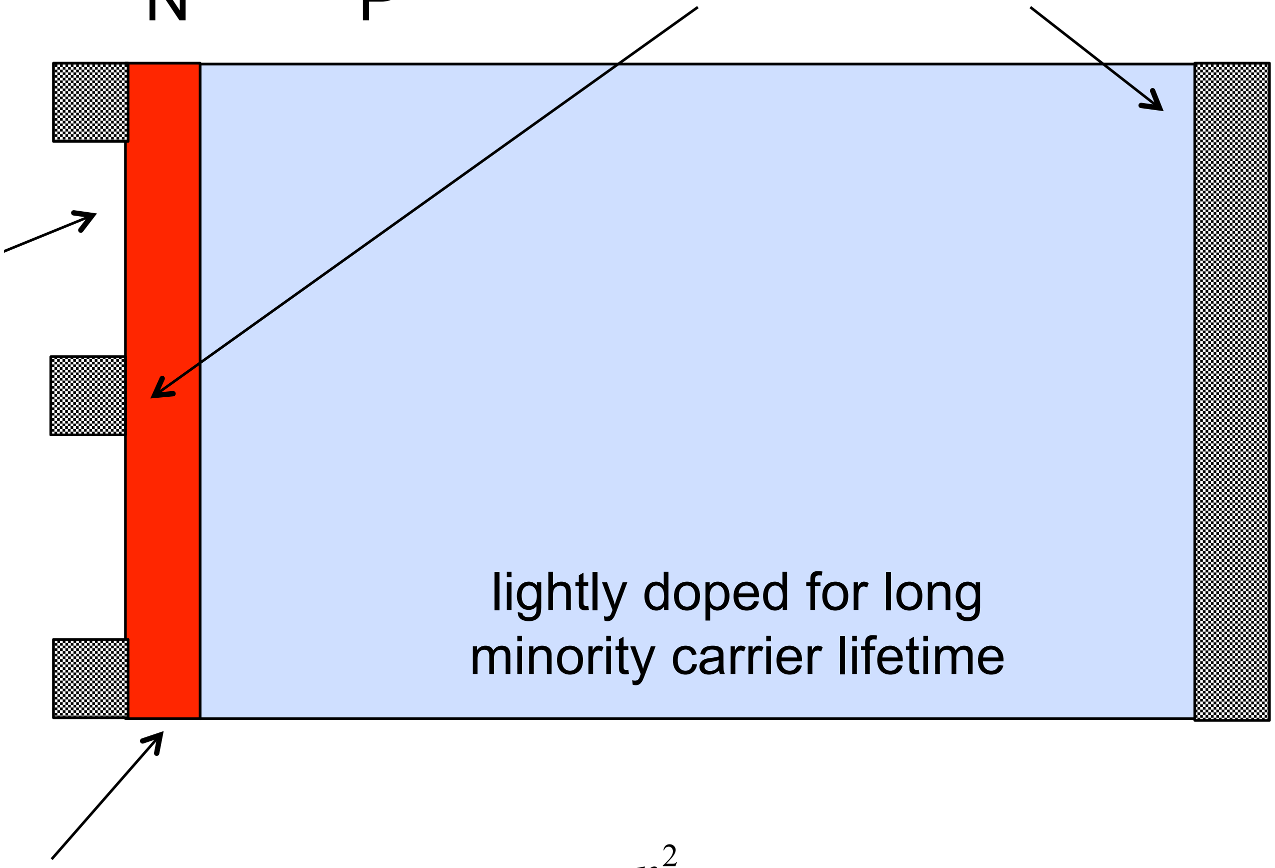
$\rightarrow 0 \text{ as } S_p \rightarrow 0$

front contact

$\rightarrow 0 \text{ as } S_n \rightarrow 0$

back contact

Model NP solar cell



MS contact $S_n \approx 10^7$ cm/s

N^+

P

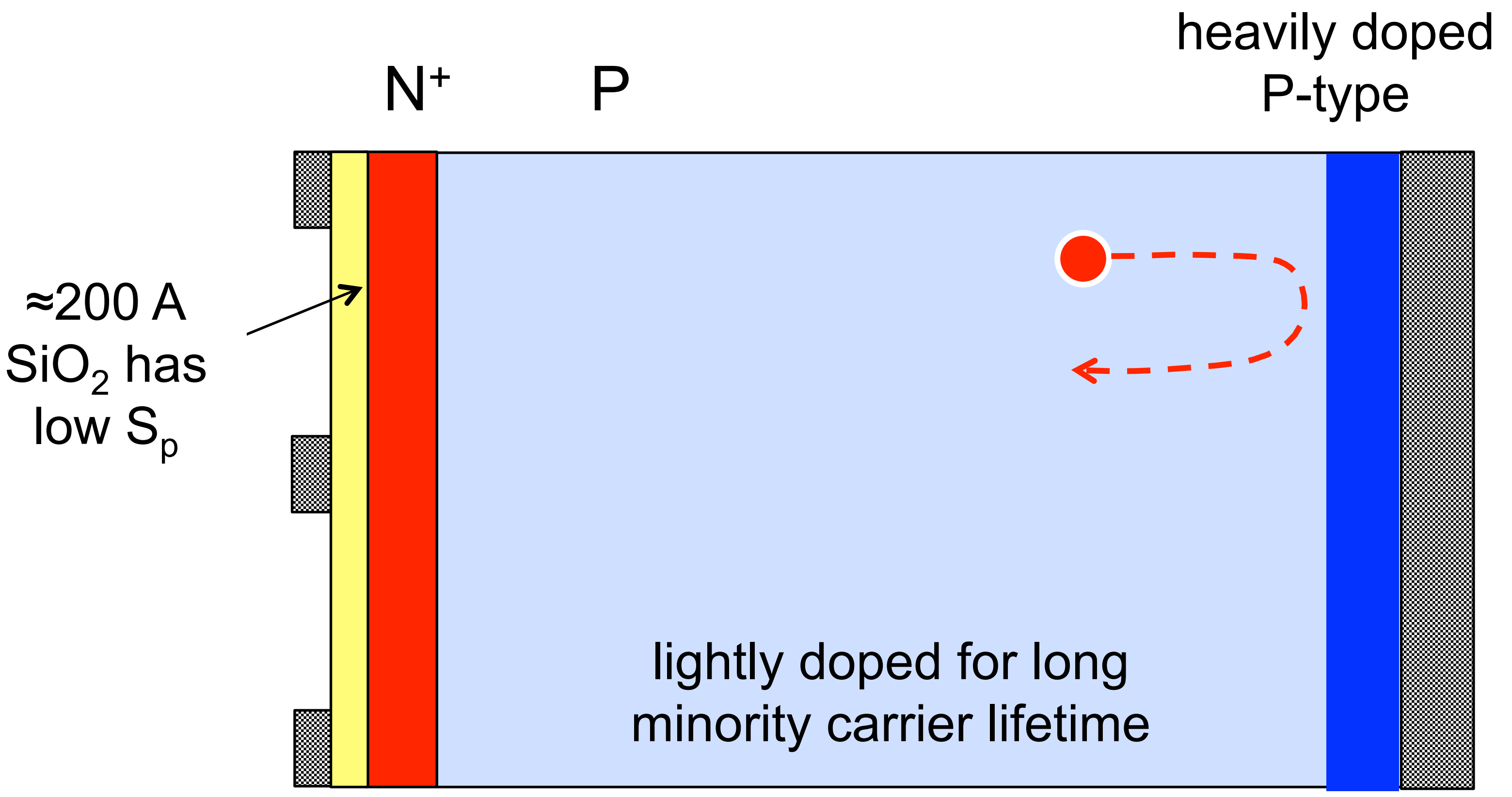
bare
surface
has high
S_p

lightly doped for long
minority carrier lifetime

more heavily doped to
suppress hole injection

$$\Delta p(0) = \frac{n_i^2}{N_D}\left(e^{qV_D/k_BT} - 1\right)$$

Minimizing the dark current



“emitter”

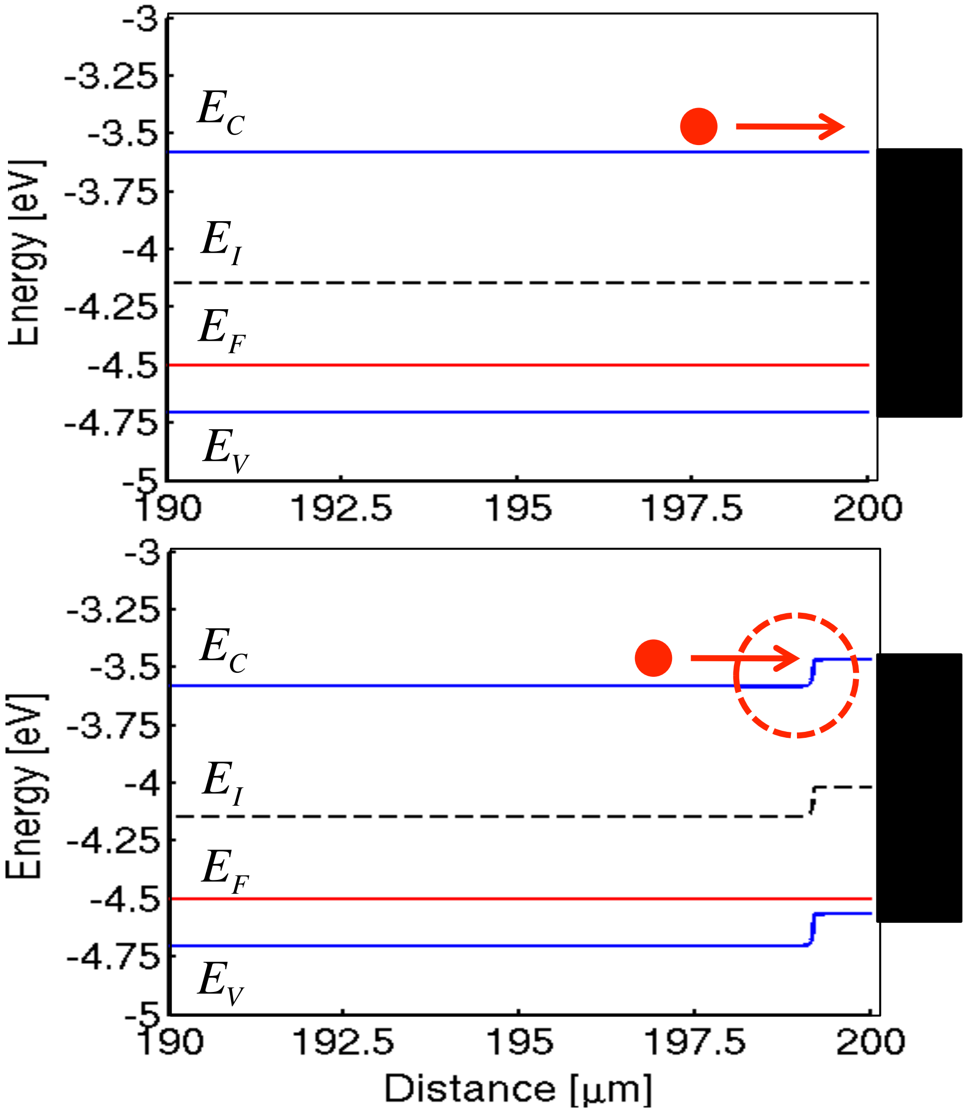
“base”

“back surface field” BSF

passivated front surface

“minority carrier mirror”

Back surface field (BSF)



$$S_n \approx \upsilon_{th}$$
$$\simeq 1\times 10^7 \text{ cm/s}$$

$$S_n \approx \upsilon_{th} e^{-\Delta E/k_B T}$$
$$< 1\times 10^7 \text{ cm/s}$$

$$\Delta E = k_B T \ln\left(\frac{N_A^{++}}{N_A}\right)$$

$$S_n \approx \upsilon_{th} e^{-\Delta E/k_B T}$$
$$\simeq 0.5\times 10^7 \text{ cm/s}$$

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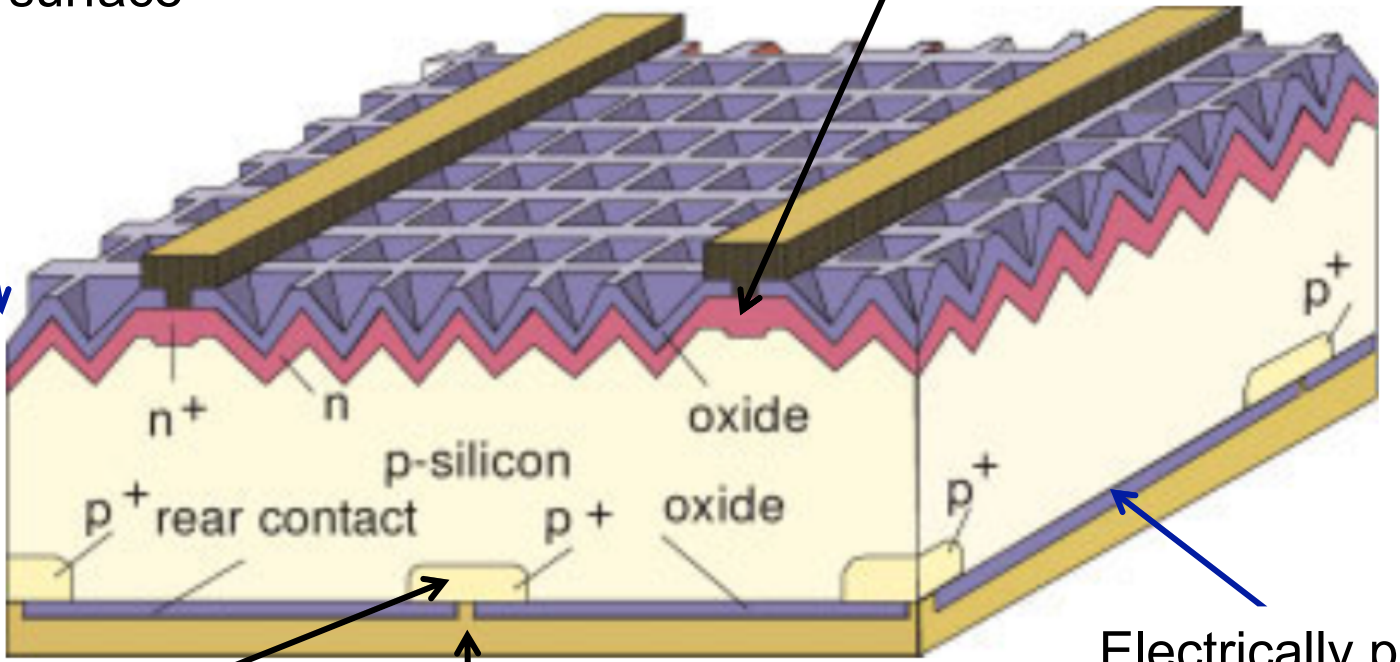
PERL cell electrical design



Electrically passivated front surface

Reduced contact area and FSF

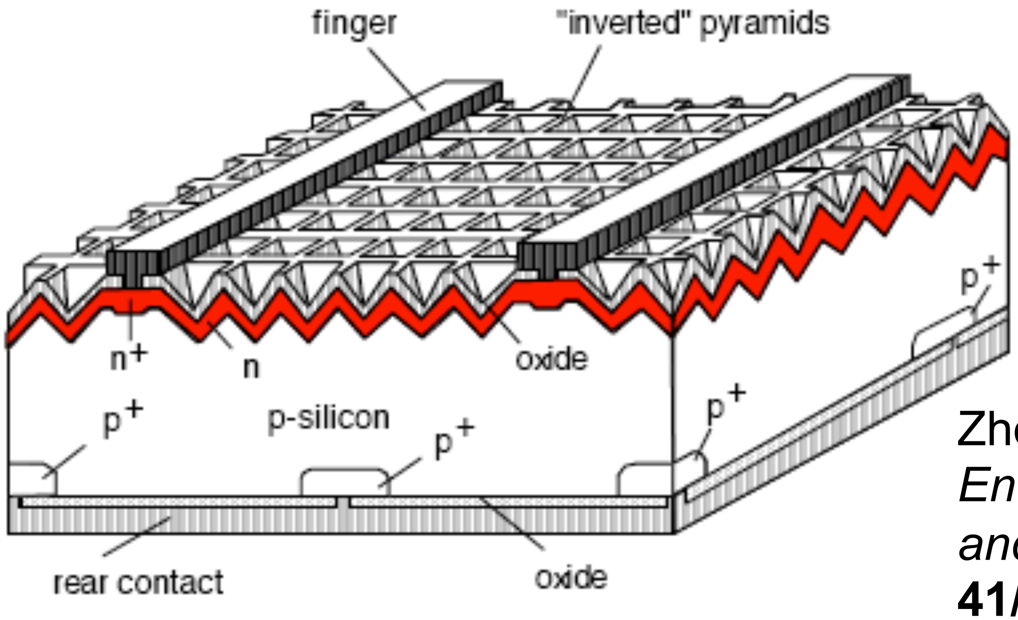
Electrically passivated back surface

BSF

Reduced M-Si contact area

M. A. Green, *Prog. In Photovoltaics: Research and Applications*, **17**, 183-189, 2009.

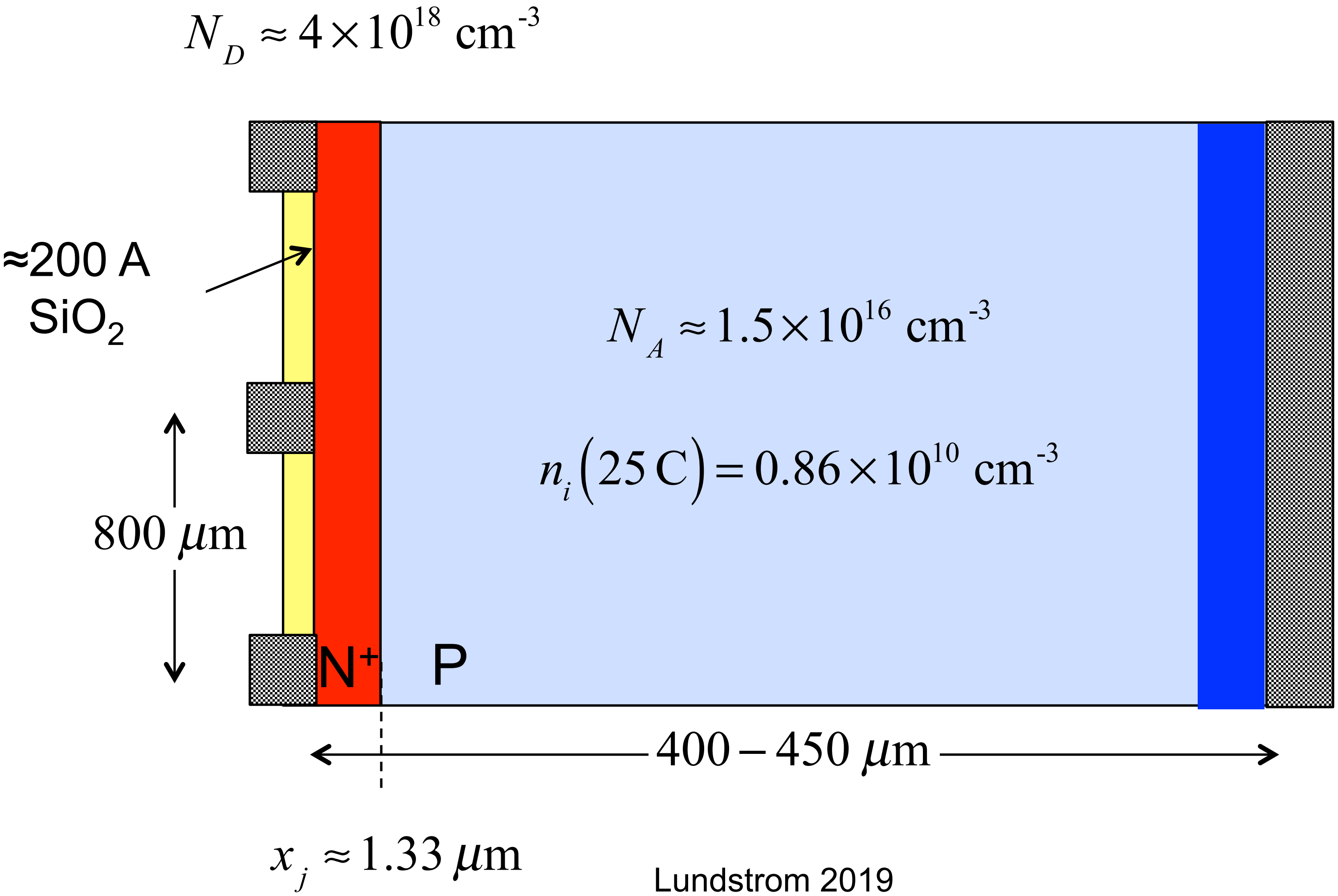
Passivated Emiitter Rear Locally diffused



Zhou, et al., *Solar Energy Materials and Solar Cells*, **41/42**,87-99, 1996.

Martin Green Group, University of New South Wales

Typical PERL device parameters



$N_D \approx 4 \times 10^{18}\ \text{cm}^{-3}$

≈200 A SiO$_2$

$N_A \approx 1.5 \times 10^{16}\ \text{cm}^{-3}$

$n_i(25\,\text{C}) = 0.86 \times 10^{10}\ \text{cm}^{-3}$

$800\ \mu\text{m}$

N$^+$ P

$400 - 450\ \mu\text{m}$

$x_j \approx 1.33\ \mu\text{m}$

Best PERL cell parameters

$$J_{SC} = 42.7 \text{ mA/cm}^2$$

$$V_{OC} = 706 \text{ mV}$$

$$FF = 82.8\ \%$$

$$\eta = 25.0\ \%$$

$$J_{\max} = 44.8 \text{ mA/cm}^2$$

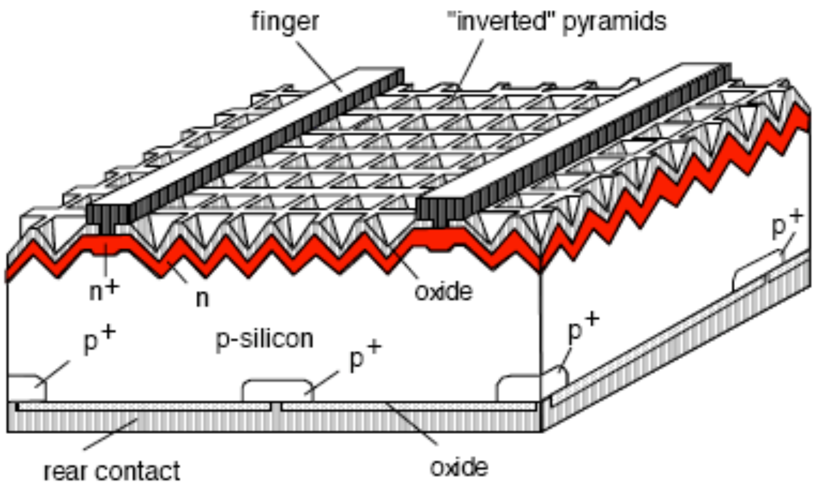
$$J_{SC} / J_{\max} = 95.3\ \%$$

(3.5% shadowing, + reflection/ absorption, ~100% CE)

$$qV_{OC} = E_G - 0.4 \text{ eV}$$

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.

PERL: Dark current components



Zhou, et al., *Solar Energy Materials and Solar Cells*, **41/42**,87-99, 1996.

$$J_D = J_0\left(e^{qV_D/k_BT} - 1\right)$$

$$J_0 = 50\ \text{fA}/\text{cm}^2$$

$$J_0 = \left[J_{0n}(\text{p-Si}) + J_{0n}(\text{b-c})\right] + \left[J_{0p}(\text{n-Si}) + J_{0p}(\text{f-c})\right]$$

$$J_{0p}(\text{n-Si}) + J_{0p}(\text{f-c}) = 15\ \text{fA}/\text{cm}^2$$

Martin A. Green, "The Passivated Emitter and Rear Cell (PERC): From Conception to mass production," *Solar Energy Materials and Solar Cells,* **143**, 190-197, 2015.

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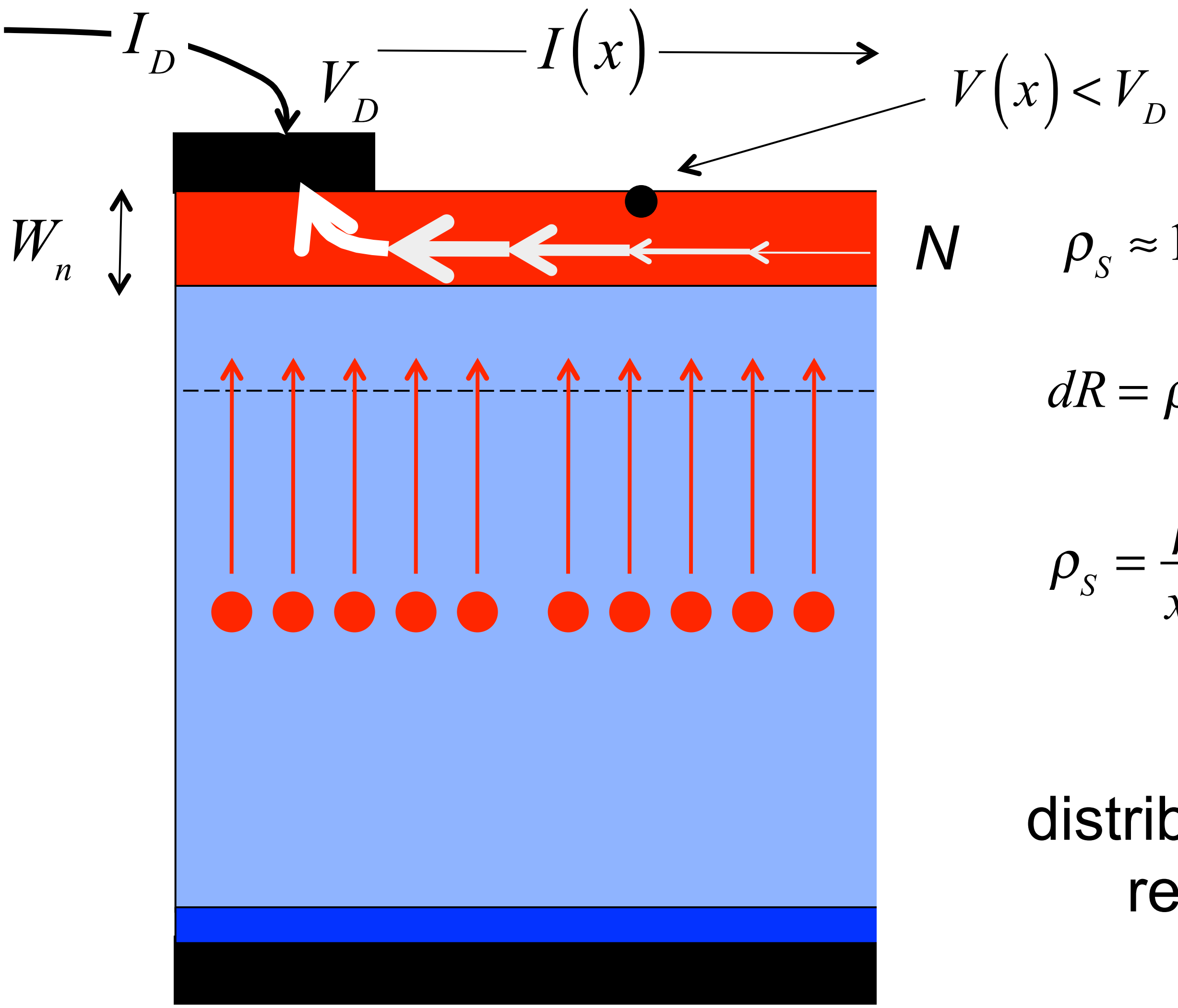
2D effects



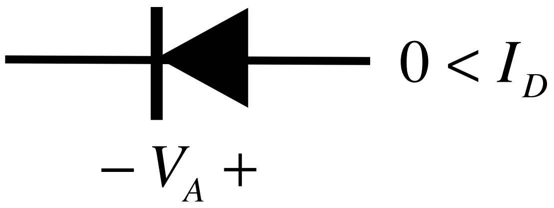
$\rho_S \approx 150\,\Omega/\square$ (PERL)

$$dR = \rho_S \frac{dx}{W_n}$$

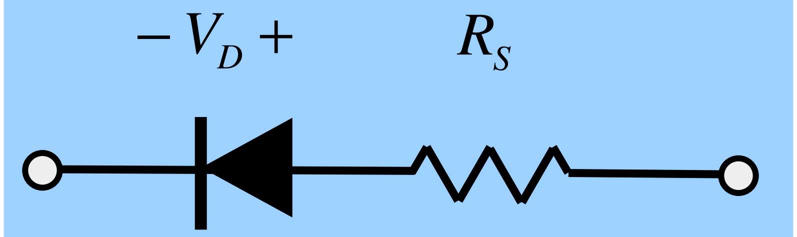
$$\rho_S = \frac{\rho}{x_j} = \frac{1}{N_D q \mu_n x_j}$$

distributed series resistance

Series resistance



$$I_D = I_0\left(e^{qV_D/k_BT} - 1\right)$$

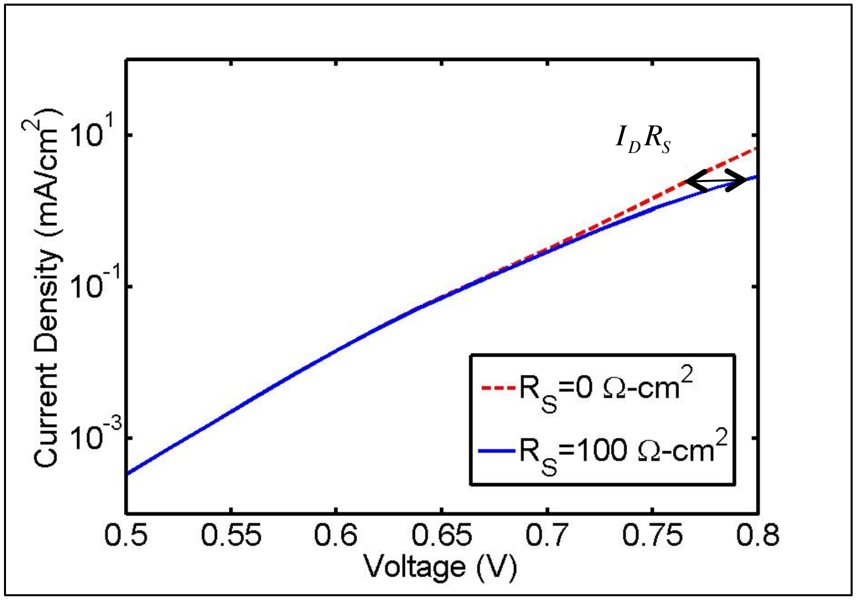


$$\leftarrow \quad V_D' = V_D + I_D R_S \quad —$$

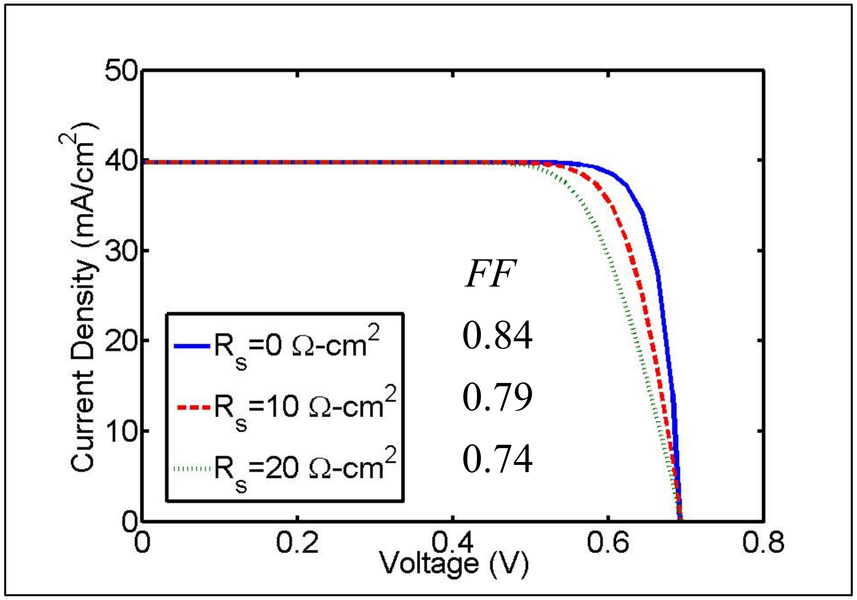
$$I_D = I_0\left(e^{q(V_D' - I_D R_S)/k_BT} - 1\right)$$

Effect on dark and illuminated IV

dark



illuminated



Larger V_D to reach the same current

Fill Factor is reduced

$R_S \approx 0.5\,\Omega\text{-cm}^2$ PERL

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Limits

The solar spectrum and bandgap set the upper limit for the short-circuit current.

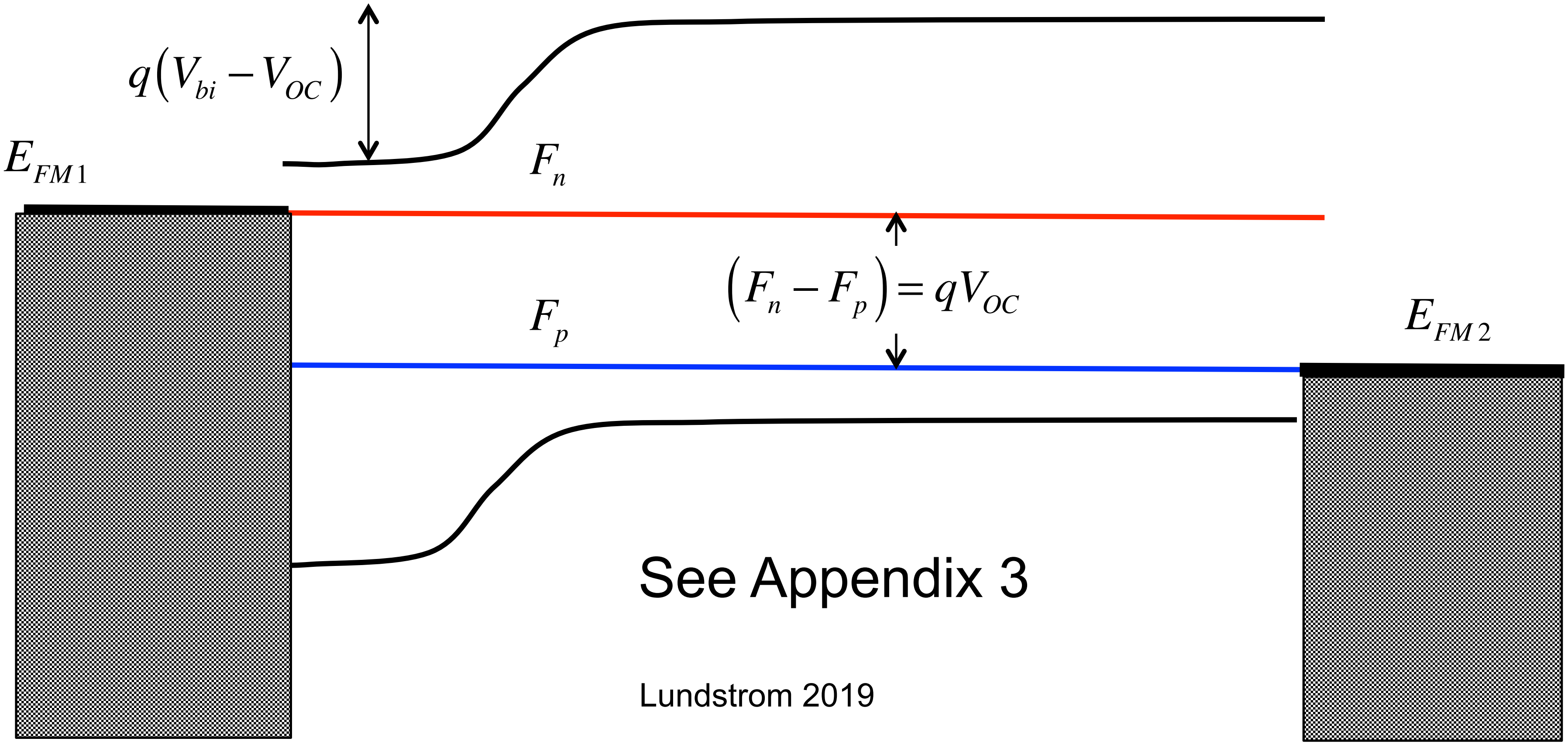
What sets the limit for the open-circuit voltage?

$$V_{OC} < E_G / q$$

Why?

Voc and QFLs

$$\boxed{E_{FM1} - E_{FM2} = qV_{OC} = F_n - F_p}$$



See Appendix 3

What determines F_n - F_p?

$$np = n_i^2 e^{\left(F_n - F_p\right)/k_B T}$$

$$\Delta n N_A = n_i^2 e^{\left(F_n - F_p\right)/k_B T}$$

$$\boxed{\left(F_n - F_p\right) = \frac{k_B T}{q} \ln\left(\frac{\Delta n}{n_{p0}}\right)}$$

$$\left(F_n - F_p\right) = \frac{k_B T}{q} \ln \frac{\Delta n}{\left(n_i^2 / N_A\right)} = \frac{k_B T}{q} \ln \frac{\Delta n}{n_{p0}}$$

What determines Δn?

$$R\left(V_{OC}\right)=G_{TOT}\approx J_{SC}/q$$

$$R\left(V_{OC}\right)=\frac{\Delta n\left(V_{OC}\right)W_p}{t_n}$$

$$\boxed{\Delta n\left(V_{OC}\right)=\frac{\left(J_{SC}/q\right)}{W_p}t_n}$$

$$R\left(V_{OC}\right)=G_{TOT}\rightarrow\Delta n\left(V_{OC}\right)$$

Higher lifetime gives higher Δn, which give more QFL splitting and a higher V_{OC}

What determines the lifetime?

In practice

- Defects at the surfaces
- Contacts
- Defects in the p-bulk
- Defects in the n-bulk

Fundamental

Band-to-band radiative recombination (Shockley-Queisser)

But for Si, Auger recombination

V_{OC} and bandgap

$$qV_{OC} = \left(F_n - F_p\right)$$

$$\left(F_n - F_p\right) = \frac{k_B T}{q}\ln\left(\frac{\Delta n}{n_{p0}}\right)$$

$$\Delta n\left(V_{OC}\right) = \frac{\left(J_{SC}/q\right)}{W_p}t_n$$

$$n_{p0} = n_i^2/N_A$$

$$n_i^2 = N_C N_V e^{-E_G/k_B T}$$

$$\boxed{V_{OC} = E_G - \frac{k_B T}{q}\ln\left(\frac{W_p N_C N_V/N_A}{\left(J_{SC}/q\right)t_n}\right)}$$

$$V_{OC} = E_G - \left(0.3 - 0.4\right)\text{eV}$$

Estimating the efficiency of a solar cell

1) Maximum J_{SC} from the bandgap

2) $V_{OC} = \frac{E_G}{q} - (0.3 - 0.4)$

3) FF assuming low series resistance: $FF \approx \frac{V_{OC}/(k_B T/q)}{4.7 + V_{OC}/(k_B T/q)}$

4) Efficiency $\eta = \frac{J_{SC} V_{OC} FF}{P_{in}}$

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Summary

1) Optical design should ensure that all phonons with energies above the bandgap are absorbed. For indirect gap semiconductors, light-trapping makes physically thin layers optically thick.

2) Recombination must be minimized to maximize the collection efficiency (J_{SC}) and open-circuit voltage (V_{OC}).

3) Series resistance lowers the fill factor (FF).

4) The short-circuit current can be close to the maximum possible, but the open-circuit voltage is still significantly less than the bandgap.

Questions

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