NCN Summer School: July 2011

Notes on the Fundamental of Solar Cell

What is Different about Thin-Film PV

M. A. Alam and S. Dongaonkar

alam@purdue.edu

Electrical and Computer Engineering

Purdue University

West Lafayette, IN USA

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The lecture series on solar cells

- Introduction to Solar cells
- Physics of Crystalline Solar cells
- Simulating Solar Cells
- What is different about thin film solar cell
- Organic photovoltaics

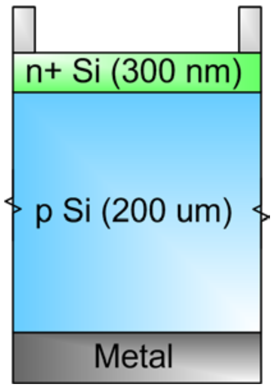
superposition and recombination

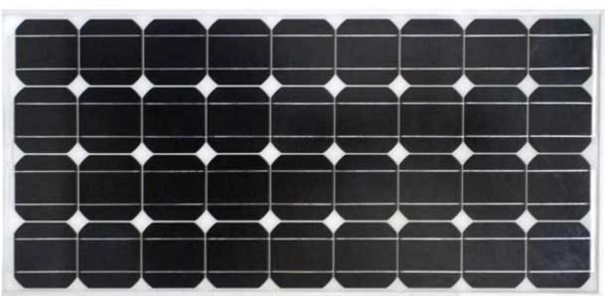
Outline of the lecture

1) Background information about thin film solar cells
2) Photo current from the transmission perspective
3) Dark current, shunt conduction, and weak diodes
4) Variability, reliability, and lifetime of solar cells
5) Conclusions

Different types of solar cells

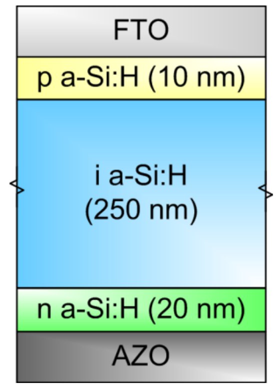
p-n





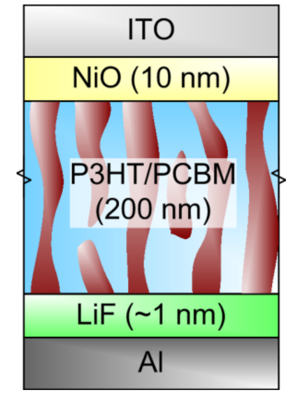
Crystalline Silicon

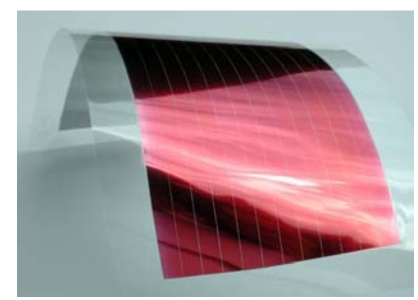
p-i-n



Amorphous silicon

m-i-m





Flexible organic

Si too thick and expensive …

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*Google Images

Economics of solar cells

	C-Si	CdTe	a-Si	CIGS	OPV
Material/m²	207	50-60	64	100-125	37
Process/m²	123	86	73	130	23-37
Total/m²	350	130	138	230	50-80
Cost/W	1.75	0.94 -1.2	0.9-1.4	1.63	1-1.36

c-Si installation, labor, etc. $3.75/W
Others … $1.00-1.50/W

…. but thin film solar cell has their own problems !

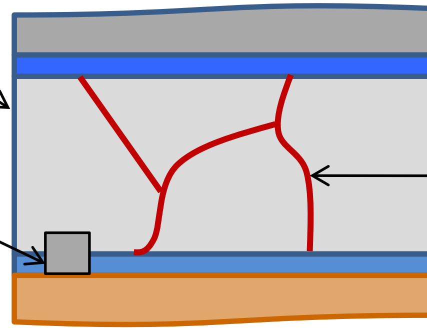
- All costs are approximate

(J. Kalowekamo/E. Baker, Solar Energy, 2009. Goodrich, PVSC Tutorial, 2011.

Features of thin film solar cells

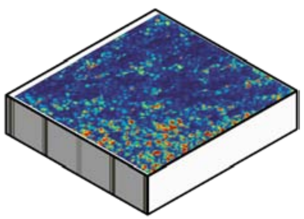
(1) Thin absorption layer

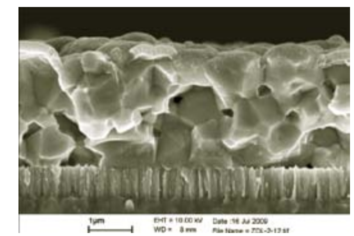
(2) Thin doped region

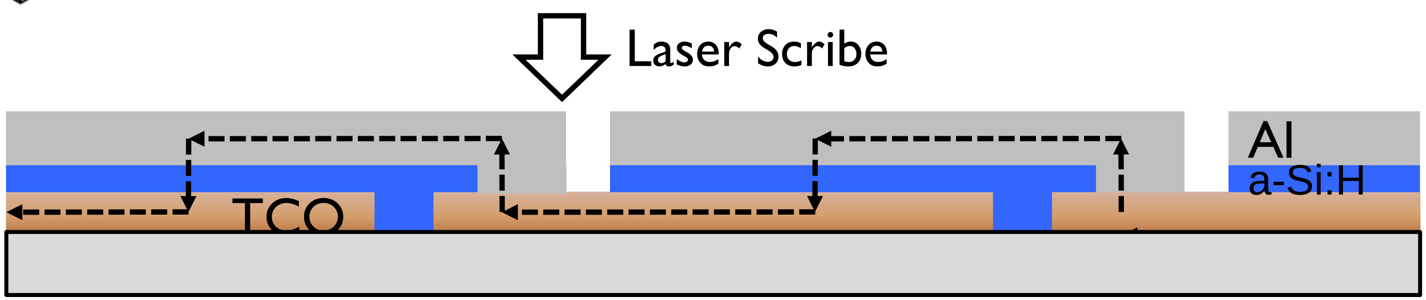


(3) Contact diffusion

(4) Grain boundaries







(5) Series connection

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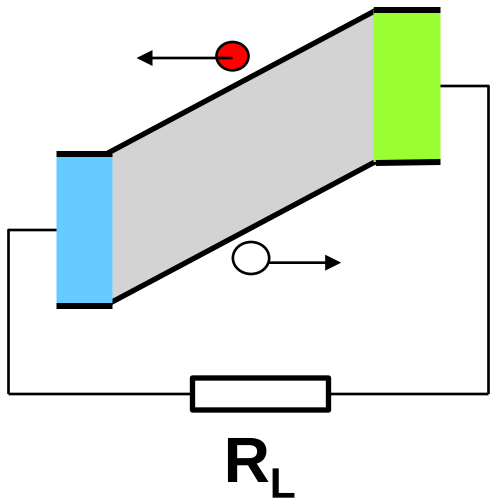
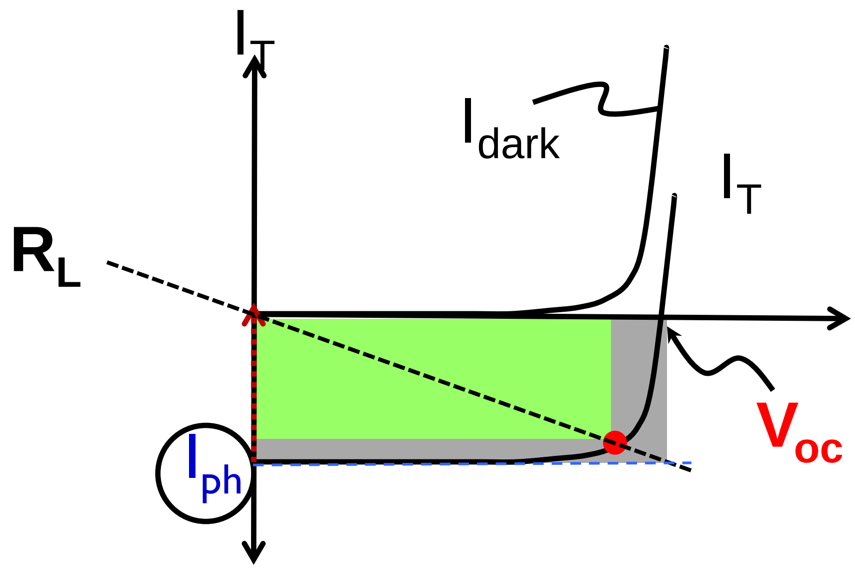
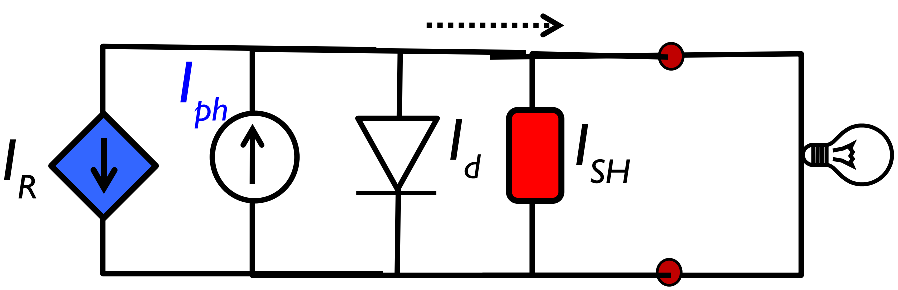
Equivalent circuit of thin film solar cells







$$P_{max} = I_{ph} \times V_{oc} \times FF$$

$$I = I_{ph} - I_0\left(e^{qV/k_BT} - 1\right)$$

$$\Rightarrow V_{OC} = \left(kT/q\right)\ln\left(1 + I_{ph}/I_0\right)$$

Superposition does not hold …

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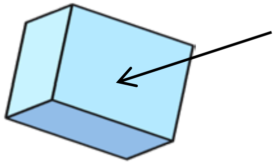
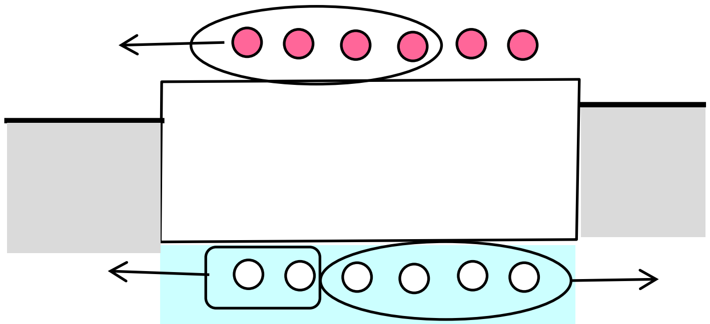


Basics of current flow

Wrong contact loss



$$J_n \neq J_n^L = 4q\upsilon_0$$

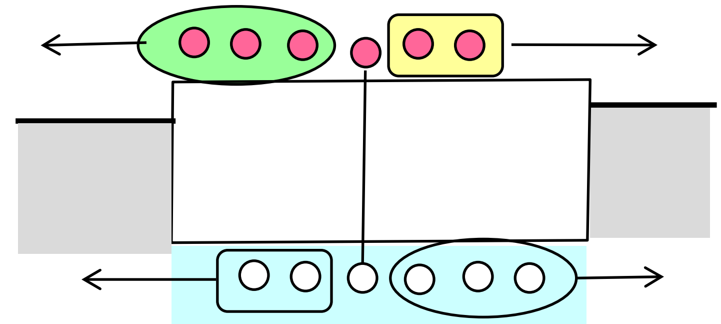
$$J = J_n^L - J_p^L = J_n^L - J_n^R$$

$$= 4q\upsilon_0 - 2q\upsilon_0$$

$$= 6q \times \frac{4}{6}\upsilon_0 - 6q \times \frac{2}{6}\upsilon_0$$

$$= qG \times \frac{\gamma_{L,n}}{\gamma_{L,n} + \gamma_{R,n}} - qG \times \frac{\gamma_{L,p}}{\gamma_{L,p} + \gamma_{R,p}}$$

+Recombination loss

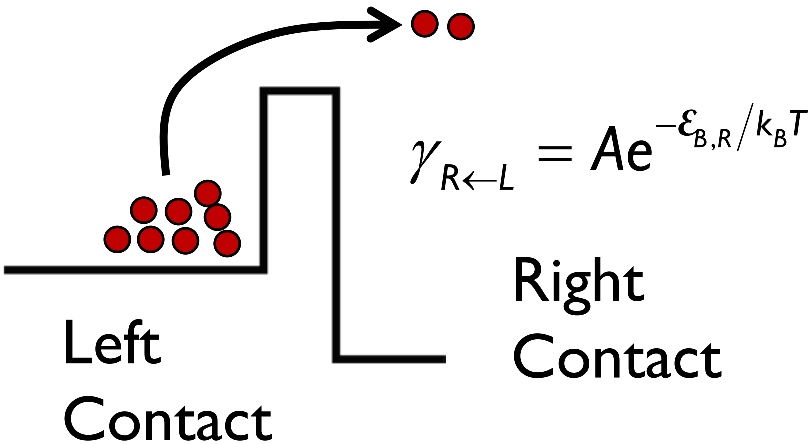


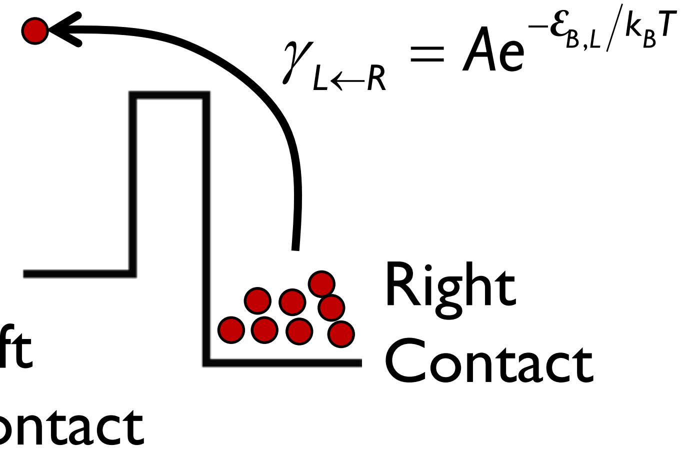
$$J_n = J_n^L - J_p^L = 3q\upsilon_0 - 2q\upsilon_0$$

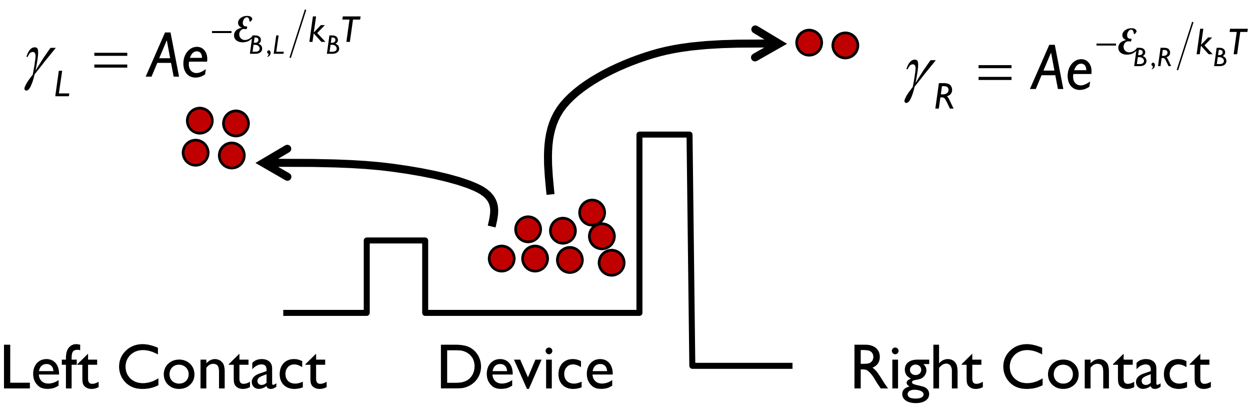
$$= 6q \times \left[\frac{3}{6}\upsilon_0 - \frac{2}{6}\upsilon_0\right]$$

$$= qG \times \left[\frac{\gamma_{L,n}}{\gamma_{L,n} + \gamma_{R,n} + \gamma_{rec}} - \frac{\gamma_{L,p}}{\gamma_{L,p} + \gamma_{R,p} + \gamma_{rec}}\right]$$

Basics of transmission over a barrier







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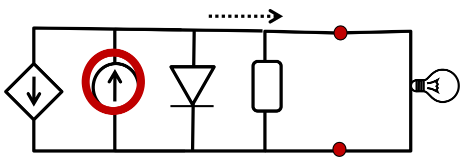
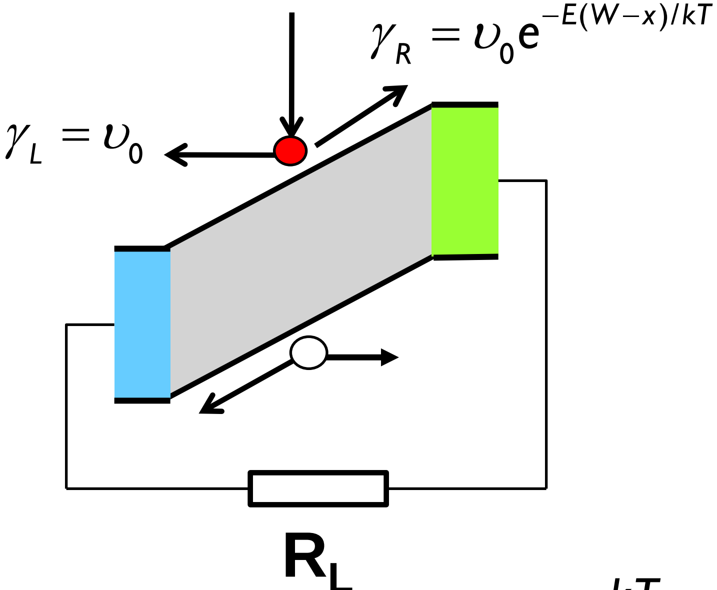
Photocurrent without recombination





$$L_D \equiv \frac{kT}{E}$$

$$\frac{J_{ph}}{qG} = \int_0^W dx \left[\frac{\gamma_{L,n}}{\gamma_{L,n} + \gamma_{R,n}} - \frac{\gamma_{L,p}}{\gamma_{L,p} + \gamma_{R,p}} \right]$$

$$= \int_0^W dx \left[\frac{\gamma_{L,n}}{\gamma_{L,n} + \gamma_{R,n}} - \frac{\gamma_{R,n}}{\gamma_{L,n} + \gamma_{R,n}} \right]$$

$$= \int_0^W dx \left[\frac{\upsilon_0}{\upsilon_0 + \upsilon_0 e^{-E(W-x)/kT}} - \frac{\upsilon_0 e^{-E(W-x)/kT}}{\upsilon_0 + \upsilon_0 e^{-E(W-x)/kT}} \right]$$

$$= W \times \frac{2L_D}{W} \log\cosh\frac{W}{2L_D} \cong W \left[\frac{2L_D}{W} - \coth\frac{W}{2L_D} \right]$$

‘Price length’ and point of no return ….

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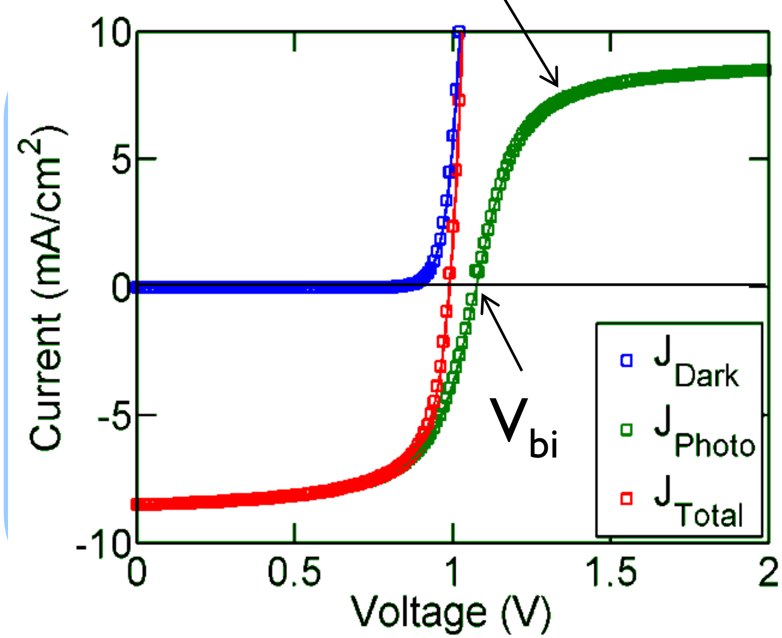
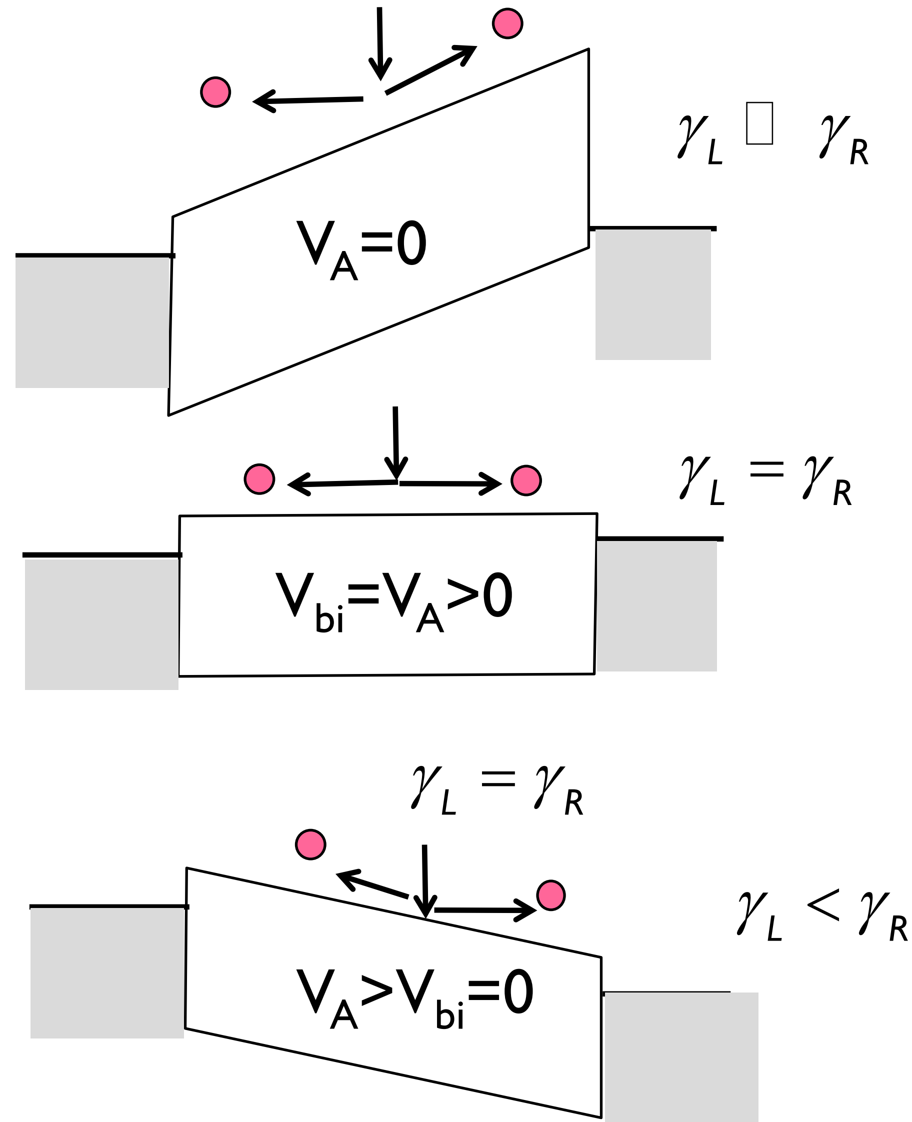
Properties of 'Sokel' photo-current

Sokel and Hughes, JAP, 53(11), 1982.

$$\frac{J_{ph}}{qG} = W \times \frac{2L_D}{W} \log\cosh\frac{W}{2L_D}$$

$$\cong W\left[\frac{2L_D}{W} - \coth\frac{W}{2L_D}\right]$$



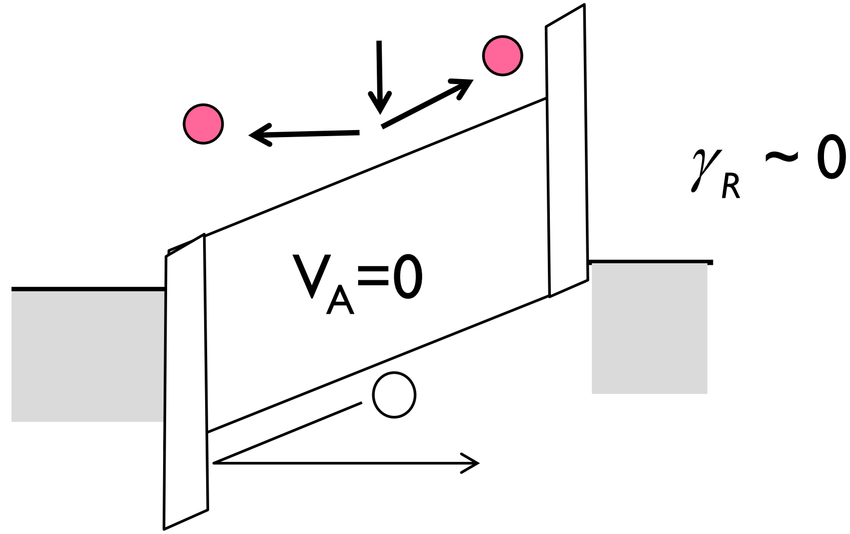


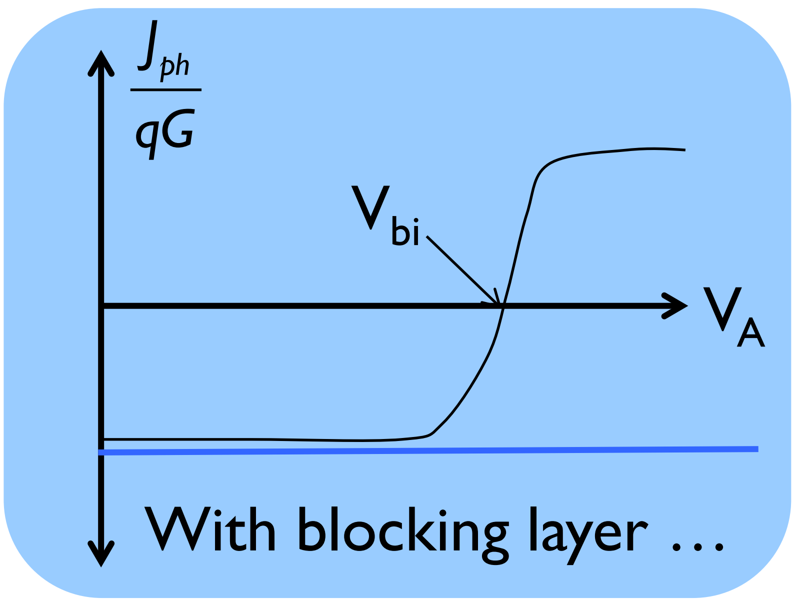
Voltage dependent photocurrent, different from Si p-n junction …

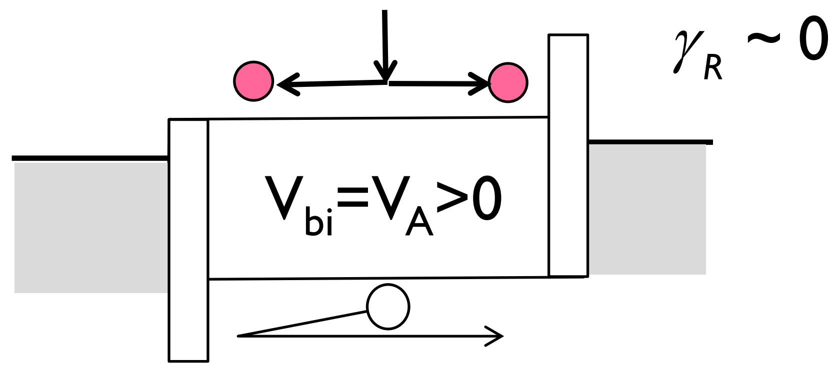
Blocking layer and photocurrent

$$\frac{J_{ph}}{qG} = \int_0^W dx \left[\frac{\gamma_{L,n}}{\gamma_{L,n} + \cancel{\gamma_{R,n}}} - \frac{\cancel{\gamma_{R,n}}}{\gamma_{L,n} + \cancel{\gamma_{R,n}}} \right]$$

$$J_{ph} = qGW$$



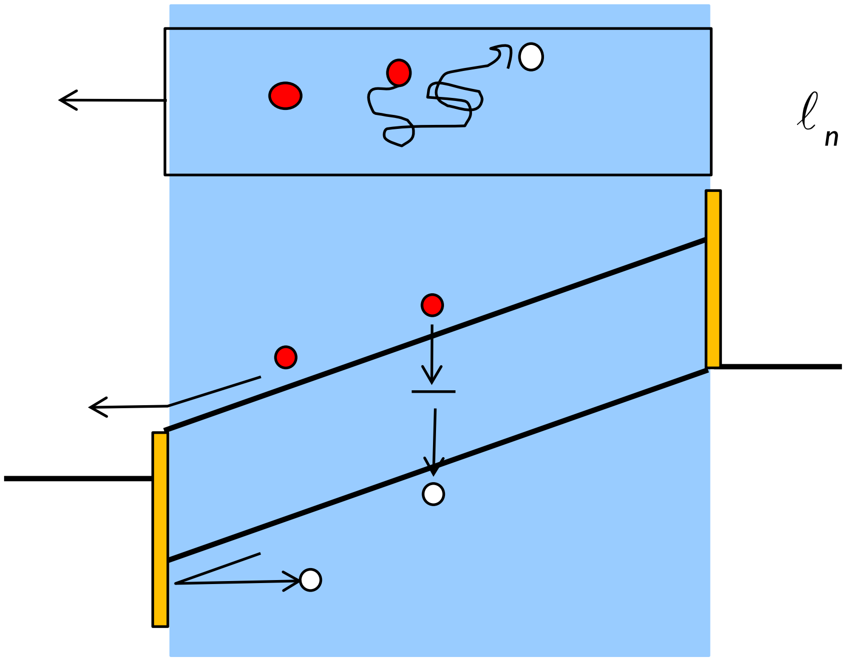




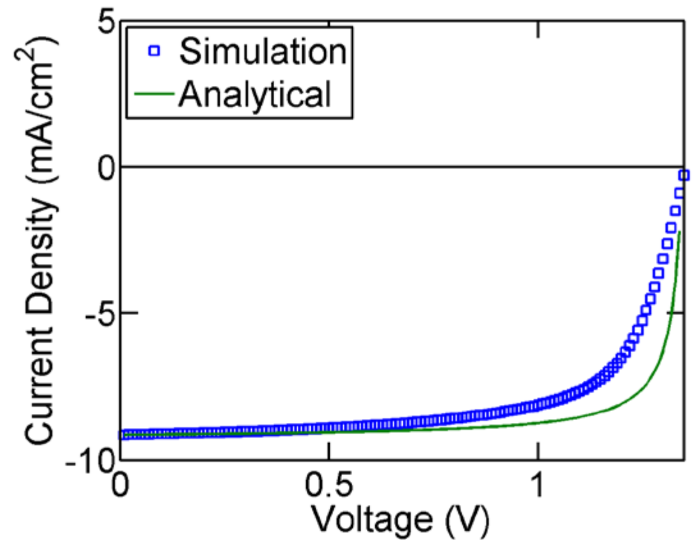
Blocking is essential for many types of thin film PV ….

Photocurrent with recombination

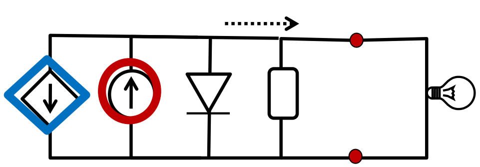
Crandall, JAP, 54(12), 19823



$$\ell_n \equiv \upsilon_0 \times \tau_n = \mu_n \times E \times \tau_n$$

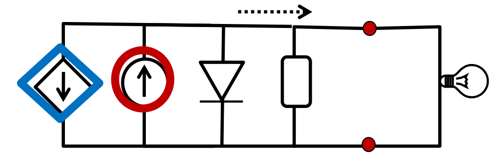


$$\frac{J_{ph}}{qG} = \int_0^W dx \left[\frac{\gamma_{L,n}}{\gamma_{L,n} + \cancel{\gamma_{R,n}} + \gamma_{rec}} - \frac{\cancel{\gamma_{L,p}}}{\cancel{\gamma_{L,p}} + \gamma_{R,p} + \gamma_{rec}} \right] = \int_0^W dx \left[e^{-x/\ell_c} \right] = \ell_c \left[1 - e^{-W/\ell_c} \right]$$

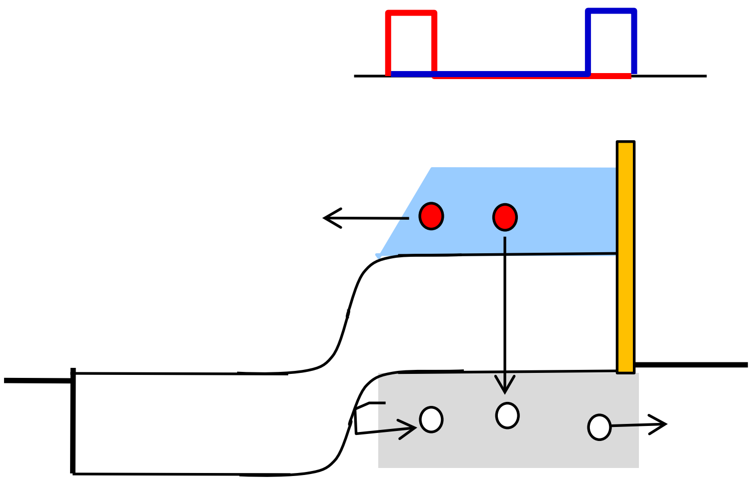


$$\frac{J_{ph}}{qG} = W - \left\{ W - \ell_n \left[1 - e^{-W/\ell_n} \right] \right\}$$

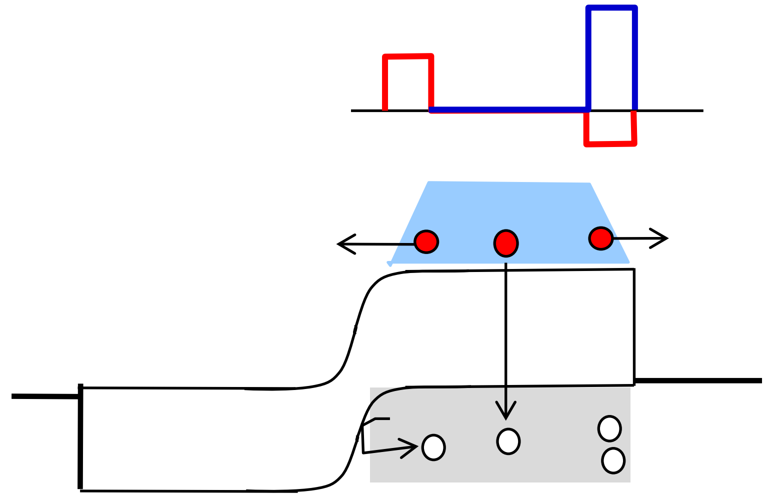
Photo-current in crystalline cells



with electron mirror



without electron mirror



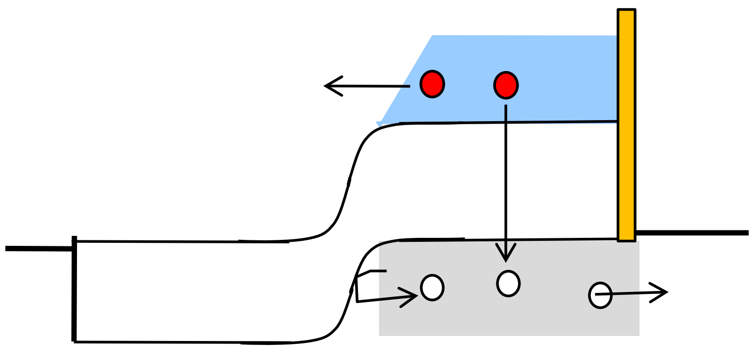
$$\frac{J_{ph}}{qG} = \frac{J_{L,n}}{qG} - \cancel{\frac{J_{L,p}}{qG}} = \ell_n \left[1 - e^{-W/\ell_n} \right] \sim \ell_n \qquad \ell_n \equiv \sqrt{D_n \tau_n} \ll W$$

Voltage independent photocurrent is unaffected by electron mirrors

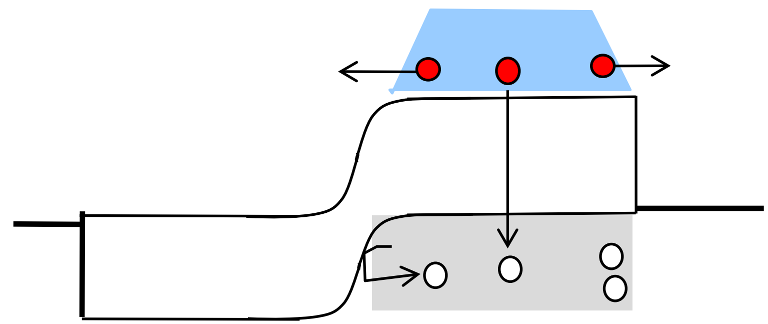
Electron blocking layer does suppress dark current, increases Voc.

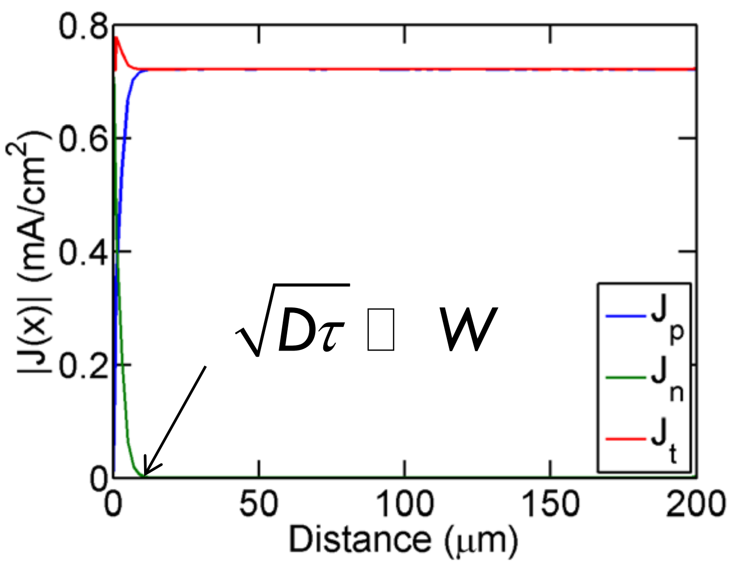
Numerical validation: Effect of blocking layer

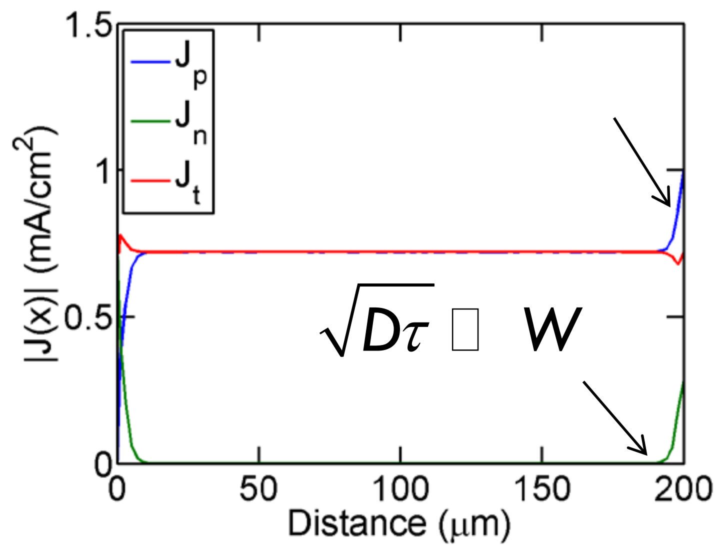
With blocking



Without blocking





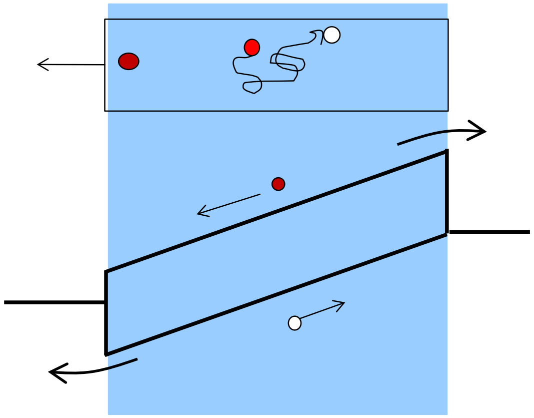


For low quality Si PV, blocking is not essential

Photocurrent with field/recombination

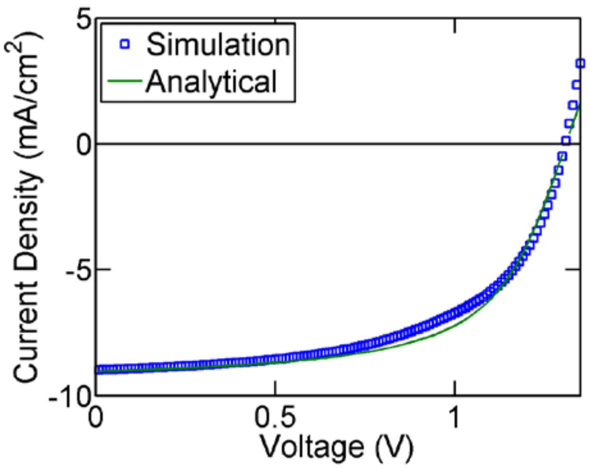
$$\frac{J_{ph}}{qG} = \int_0^W dx \left[\frac{\upsilon_0 e^{-x/\ell_n} - \upsilon_0 e^{-(W-x)/\ell_k} e^{-(W-x)/\ell_n}}{\upsilon_0 + \upsilon_0 e^{-(W-x)/\ell_k}} \right]$$

$$= \int_0^W dx \left[\frac{e^{-x/\ell_n} - e^{-(W-x)/\ell_k} e^{-(W-x)/\ell_n}}{1 + e^{-(W-x)/\ell_k}} \right]$$



$$\frac{J_{ph}}{qG} \cong W \left[\frac{2L_D}{W} - \coth \frac{W}{2L_D} \right]$$

$$L_D \equiv \frac{n_{ph} kT}{E}$$



Matches with numerical simulation very well …

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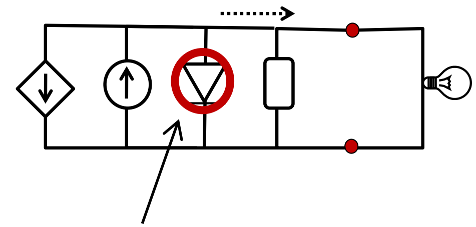
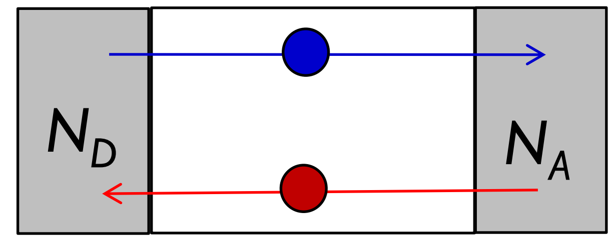
Dark current without recombination



$$J_n = q n_L \upsilon_0 \frac{\gamma_L}{\gamma_L + \gamma_R} - q n_R \upsilon_0 \frac{\gamma_R}{\gamma_L + \gamma_R}$$



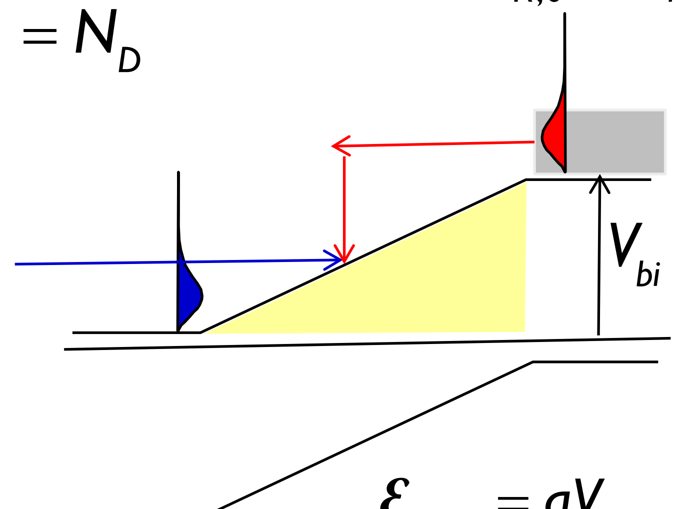
$$n_{L,0} / n_{R,0} = \gamma_{R,0} / \gamma_{L,0}$$

$$\gamma_{L,0} = A e^{-E_{B,0}/k_B T} = A e^{-qV_{bi}/k_B T}$$

$$\gamma_{R,0} = A \times 1 \Rightarrow \gamma_{L,0} / \gamma_{R,0} = e^{-qV_{bi}/k_B T}$$

$$n_{R,0} = n_i^2 / N_A$$

$$n_{L,0} = N_D$$



$$n_{L,0} = n_{R,0} e^{+qV_{bi}/k_B T}$$

$$n_{R,0} = n_i^2 / N_A \qquad n_{L,0} = \frac{n_i^2}{N_A} e^{-qV_{bi}/k_B T}$$

$$\mathcal{E}_{R \leftarrow L} = qV_{bi}$$

$$\mathcal{E}_{L \leftarrow R} = 0$$

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Calculating dark current without recombination

$$\gamma_L = Ae^{-q(V_{bi}-V)/k_BT}$$

$$\gamma_R = A \times 1$$

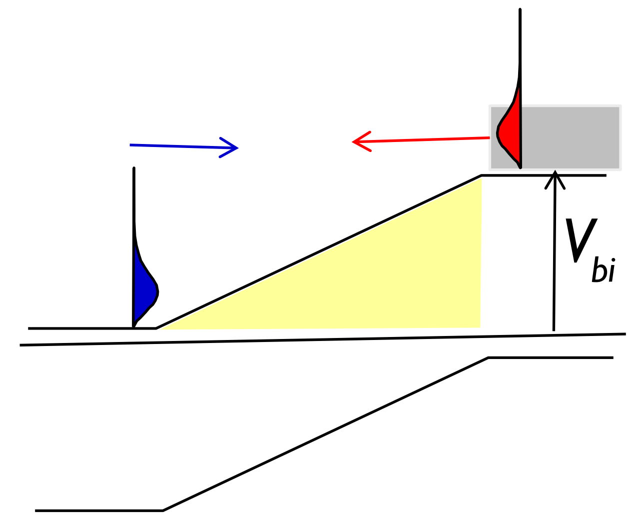
$$n_{L,0} = \frac{n_i^2}{N_A} e^{+qV_{bi}/k_BT}$$

$$J_n = q n_{L,0} \upsilon_0 \frac{\gamma_L}{\gamma_L + \gamma_R} - q n_{R,0} \upsilon_0 \frac{\gamma_R}{\gamma_L + \gamma_R}$$

$$J_n = \frac{q\upsilon_0}{\gamma_L + \gamma_R}\left(n_{L,0}\gamma_L - n_{R,0}\gamma_R\right)$$

$$= \frac{q\upsilon_0}{e^{-q(V_{bi}-V)/k_BT} + 1} \frac{n_i^2}{N_A}\left[e^{qV_{bi}/k_BT} e^{-q(V_{bi}-V)/k_BT} - 1\right]$$

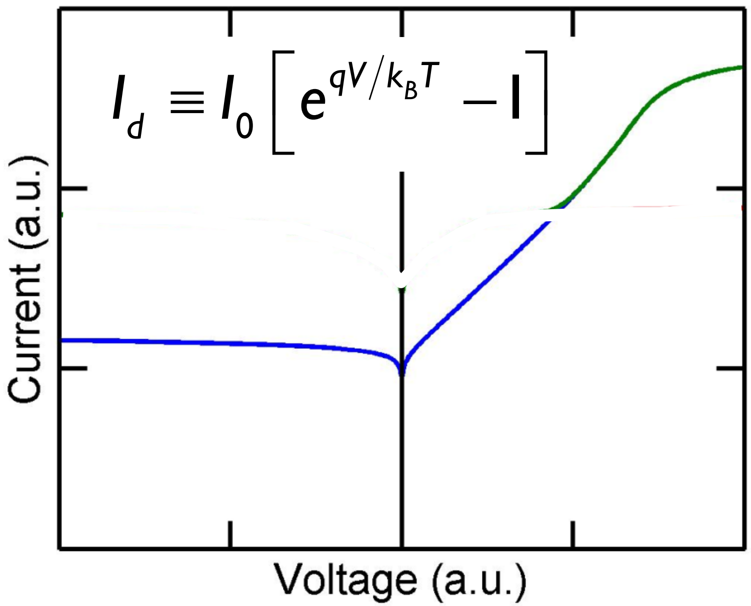
$$= q\frac{n_i^2}{N_A}\left[\frac{\mu_n (V - V_{bi})/d}{e^{+q(V-V_{bi})/k_BT} + 1}\right]\left[e^{qV_b/k_BT} - 1\right]$$



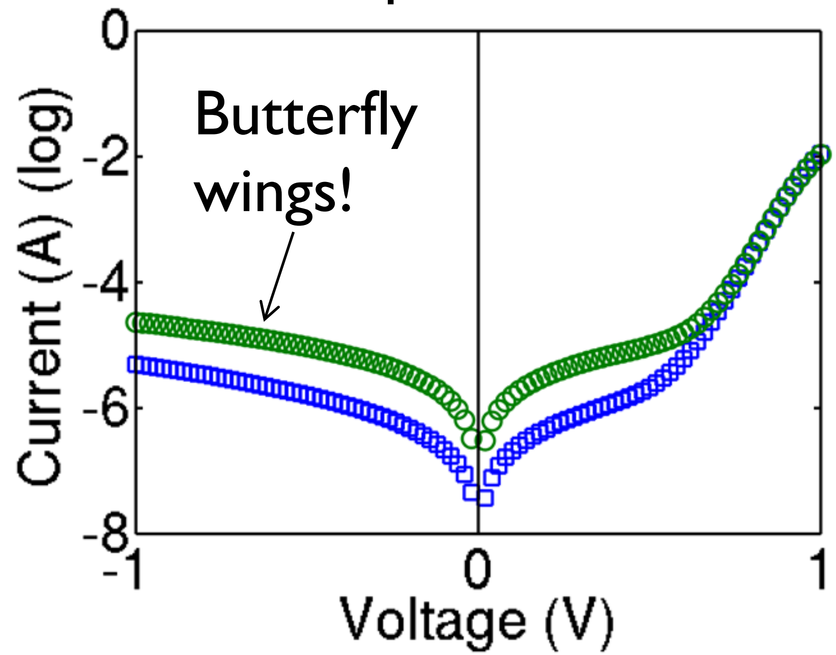
$$J_d = J_n + J_p = q\left[\frac{n_i^2}{N_A} + \frac{n_i^2}{N_D}\right]\left[\frac{\mu_n (V - V_{bi})/d}{e^{+q(V-V_{bi})/k_BT} + 1}\right]\left[e^{qV/k_BT} - 1\right] \equiv I_0\left[e^{qV/k_BT} - 1\right]$$

Theory and practice of thin film dark IV

Theory



Experiment



A real solar cell IV seldom looks like textbook IV!
These wings helped create many complicated models.

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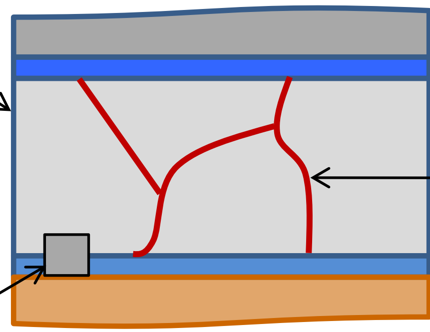
Contact diffusion and shunt conduction

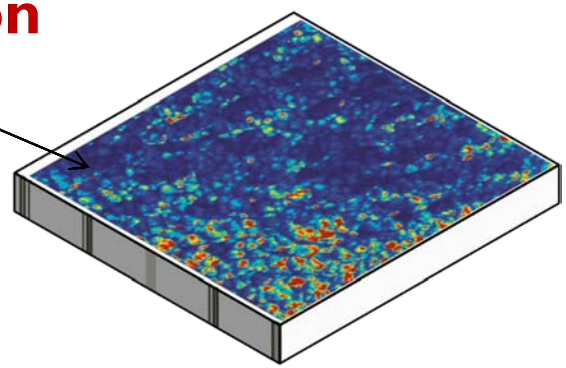
(1) Thin absorption layer

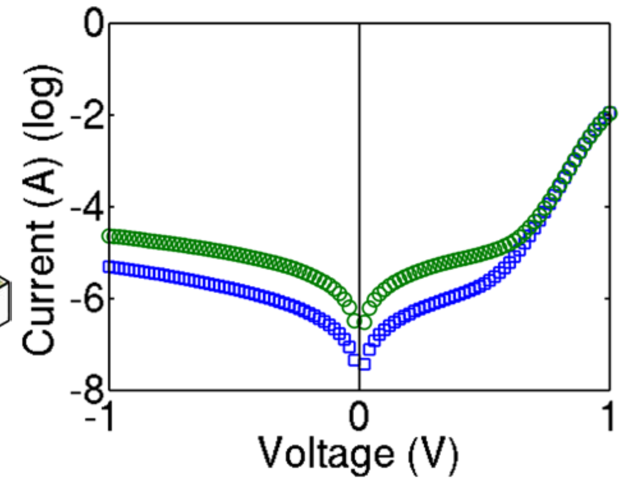
(2) Thin doped region



(4) Grain boundaries

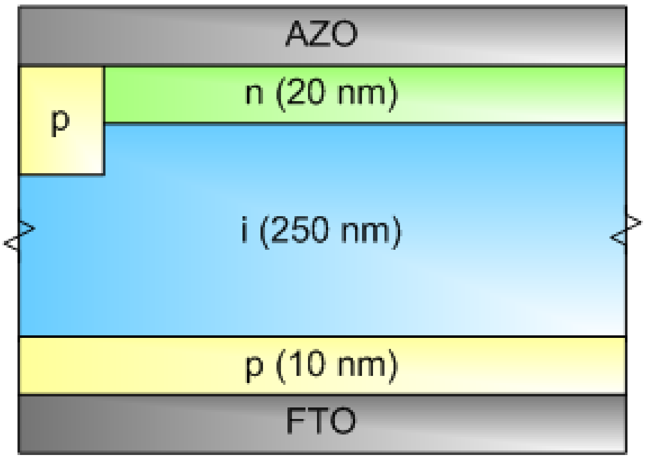
(3) Contact diffusion



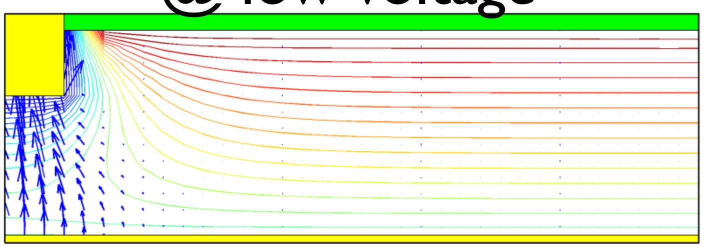


A real solar cell IV seldom looks like textbook IV

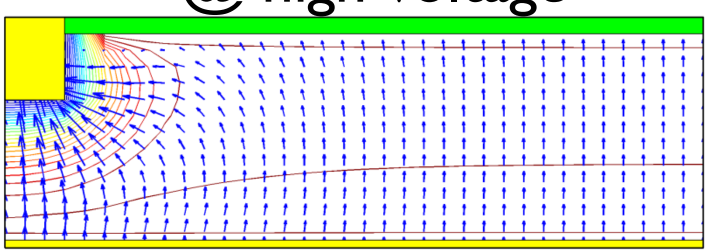
Parasitic shunt leakage

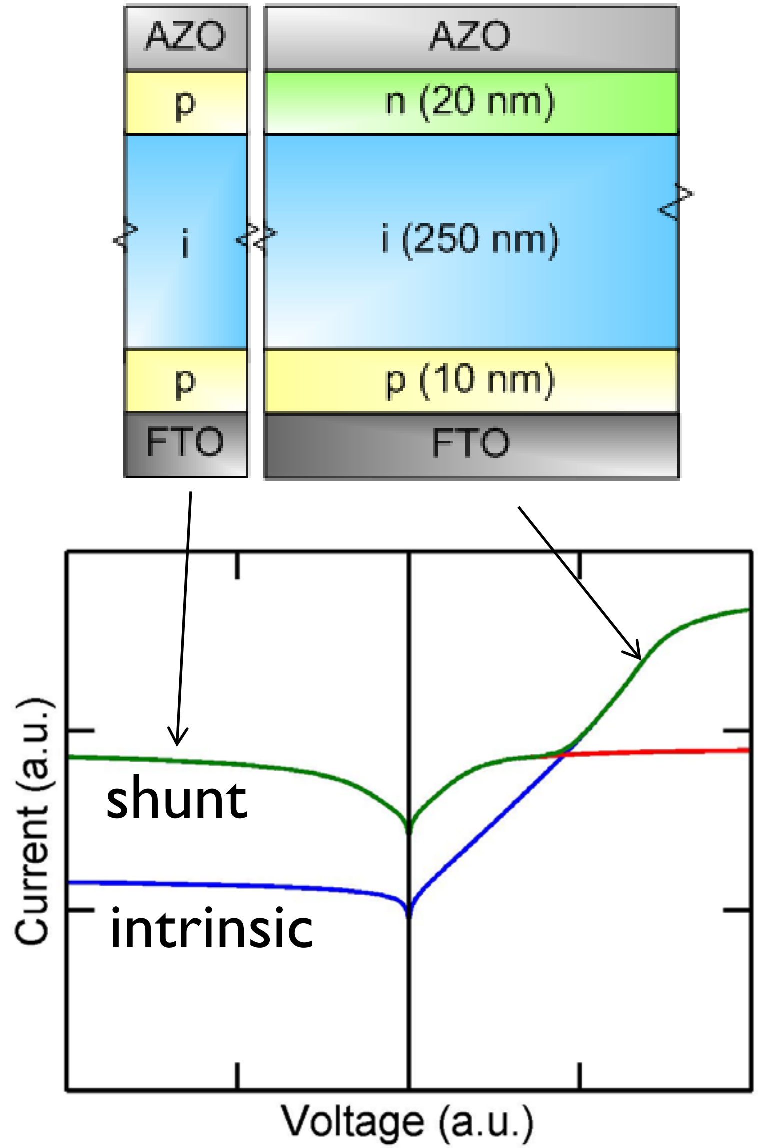


@ low voltage



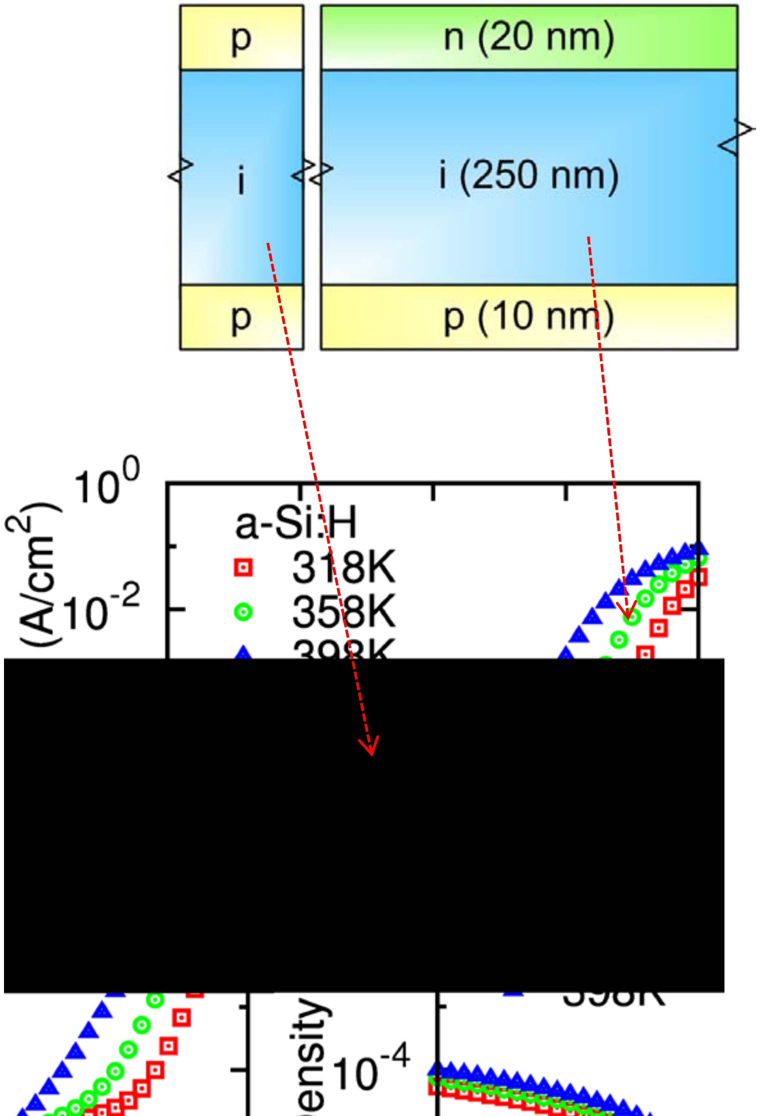
@ high voltage

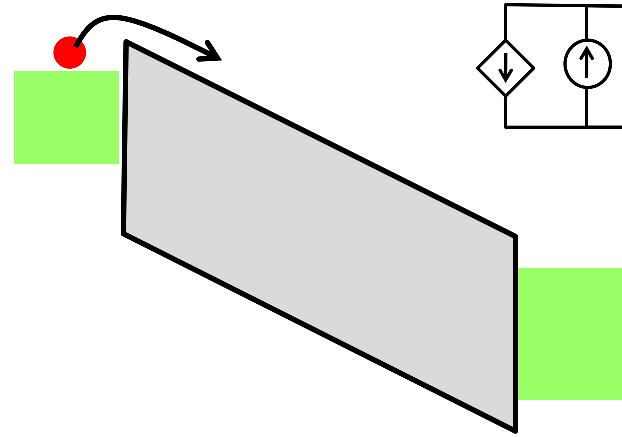


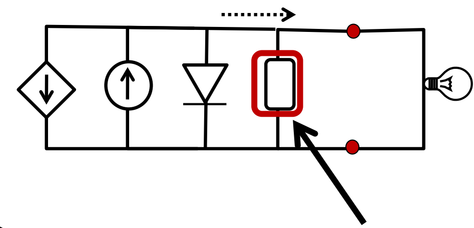


Dongaonkar and Alam JAP, 2010

Interpretation of ‘shunt’ leakage







$$J_n = qn\mu_n\mathcal{E}$$

$$\frac{d\mathcal{E}}{dx} = \frac{qn}{\kappa\varepsilon_0}$$

$$V_a = \frac{2}{3}\sqrt{\frac{2J}{\varepsilon\mu_n}}L^{3/2}$$

$$J(V_a) = \frac{9\varepsilon\mu_n}{8L^3}V_a^2$$

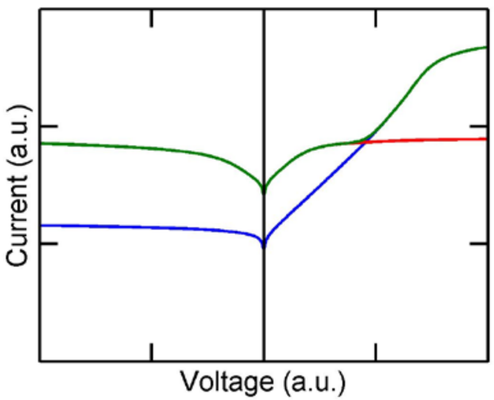
$$I_{shunt} = A\mu\frac{V^{\delta+1}}{L^{2\delta+1}}\,^*$$

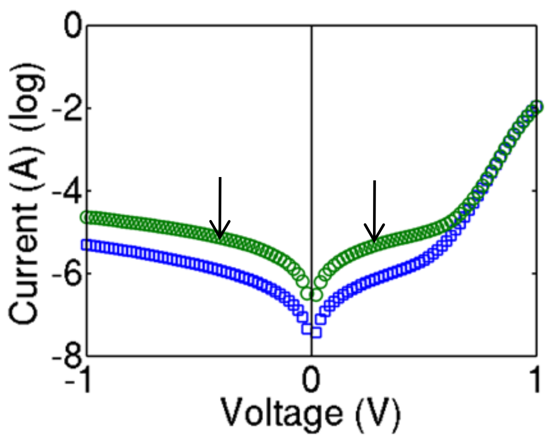
$$\gamma = \frac{E_A}{kT}$$

* G. Paasch et al., JAP 106, 084502 (2009)

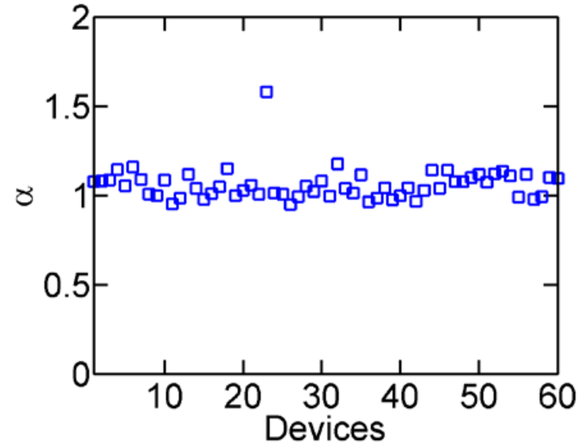
Features of shunt leakage

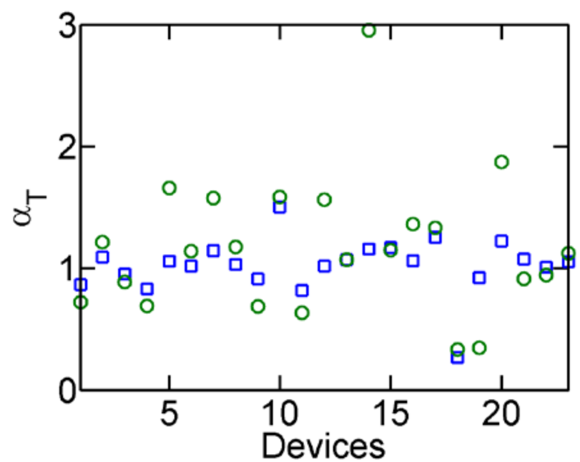
$$I_{shunt} = A\mu \frac{V^{\delta+1}}{L^{2\delta+1}}$$



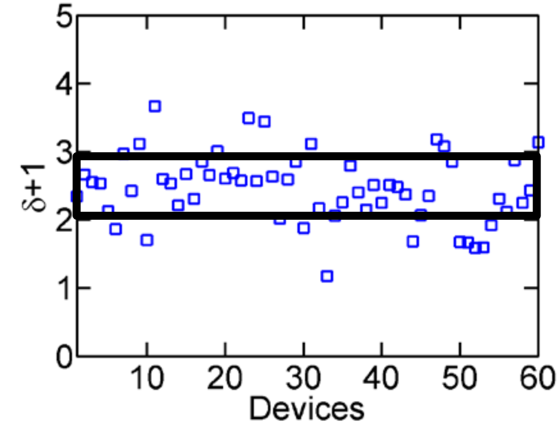


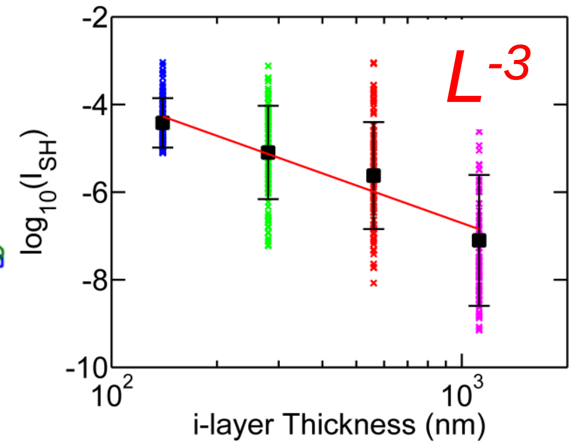
Symmetry





Exponents





Dongaonkar and Alam, EDL, 2010

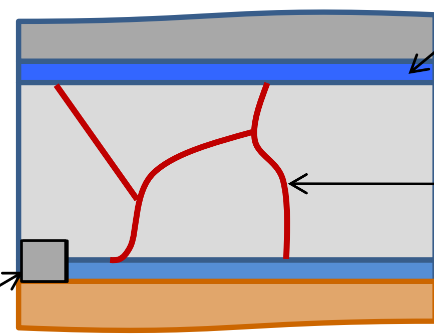
Outline of the lecture

1) Background information about thin film solar
2) Photo current from transmission perspective
3) Dark current, shunt conduction, and weak diodes
4) Variability, reliability, and lifetime of solar cells
5) Conclusions

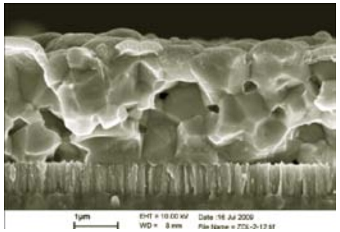
Contact diffusion and shunt conduction

(1) Thin absorption layer

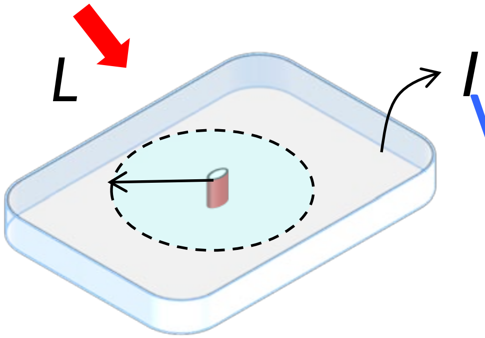
(2) Thin doped region



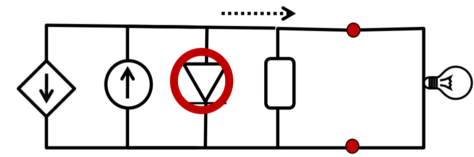
(3) Grain boundaries

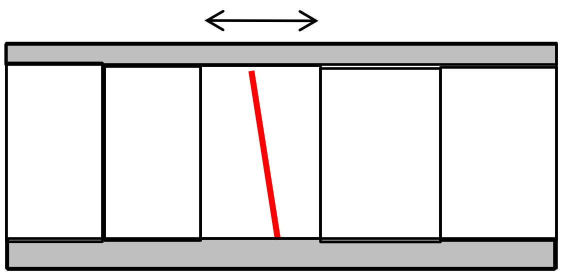


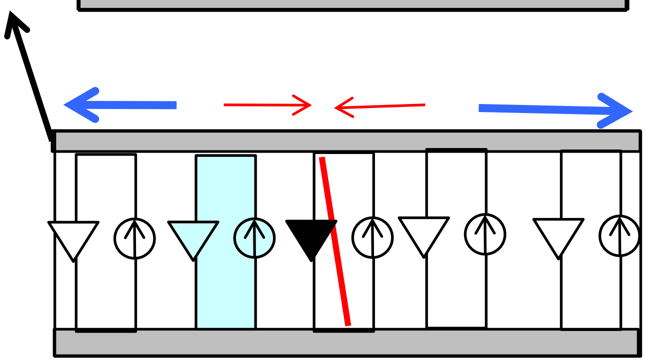
(4) Contact diffusion



Variability and weak diodes







$$I_0 \approx I_{ph}(V_{oc})\, e^{-qV_{oc}/kT}$$

$$I = I_{ph}(V_{oc})(e^{q(V-V_{oc})/kT} - 1)$$

$$l^2 \times n \times I_{ph}(V_{oc1})(e^{q(V-V_{oc1})/kT} - 1)$$
$$= I_{ph}(V_{oc2})(e^{q(V-V_{oc2})/kT} - 1)$$

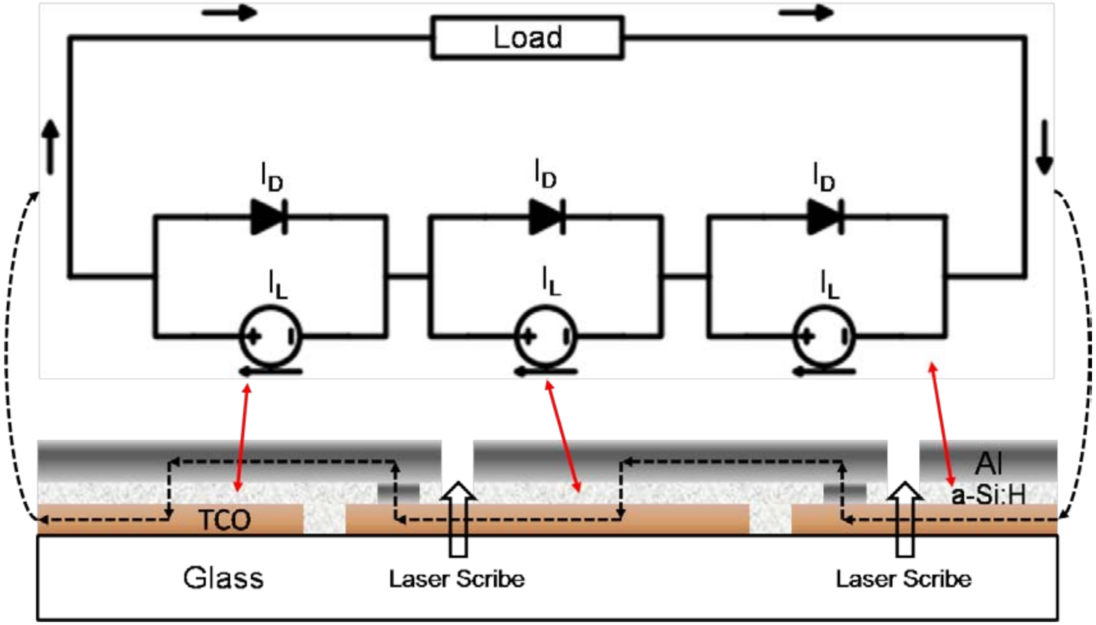
$$n = L^2 / l^2 \approx e^{q(V_{oc1}-V_{oc2})/kT}!$$

$$I = I_0(e^{qV/kT} - 1) - I_{ph}(V)$$
$$I_0(e^{qV_{oc}/kT} - 1) = I_{ph}(V_{oc})$$
$$V_{oc} = k_B T \times \ln(1 + I_{ph}/I_0)$$

Like an impact crater, a single um-sized weak diode can drain away 1-10 mm region !!

(karpov, PRB 69, 045325, 2004.)

(5) Series connection, shadow degradation, and a very weak diode



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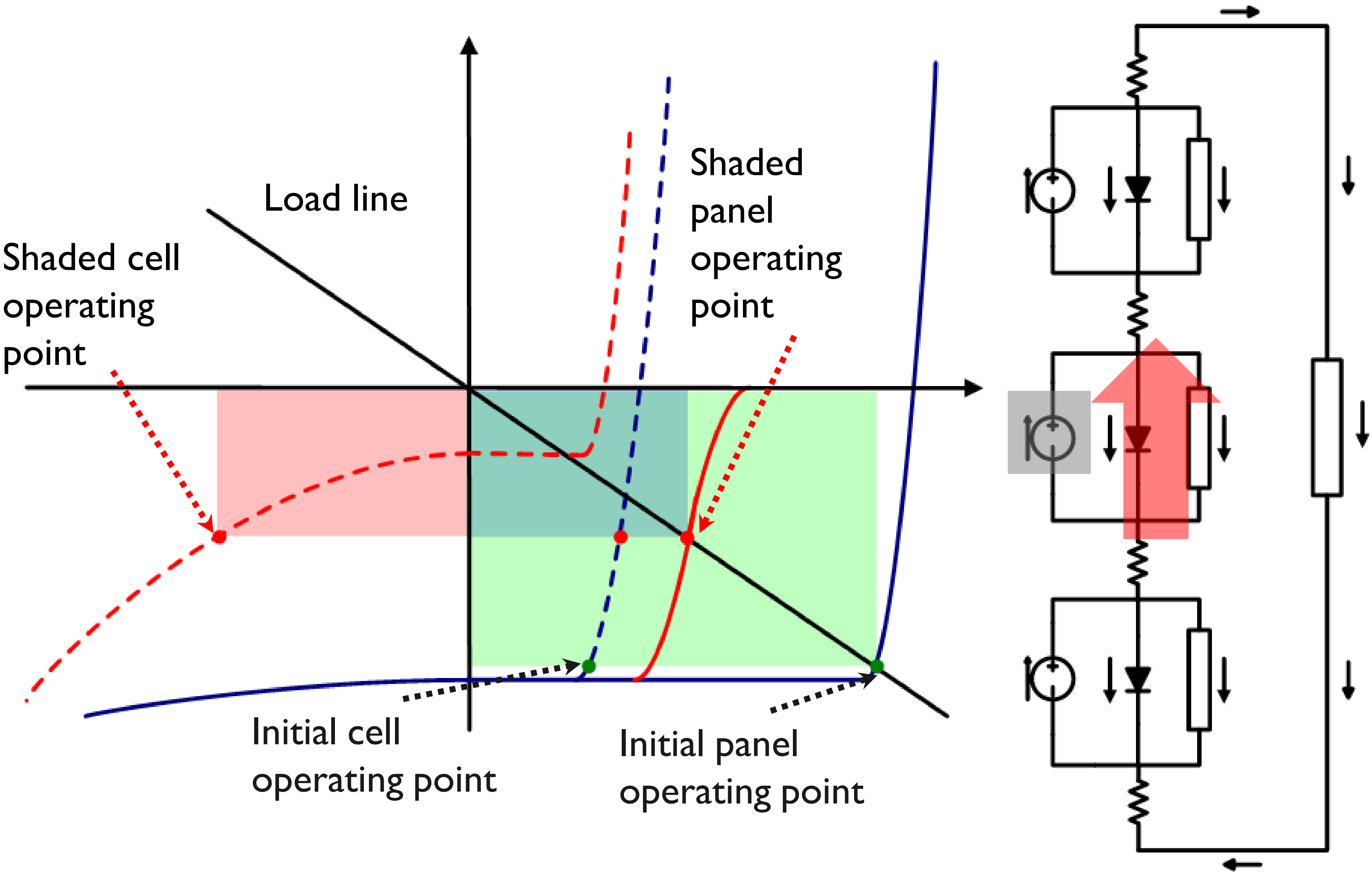
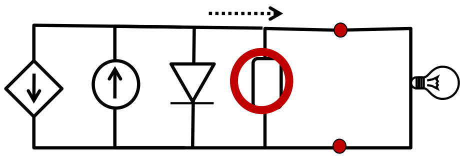
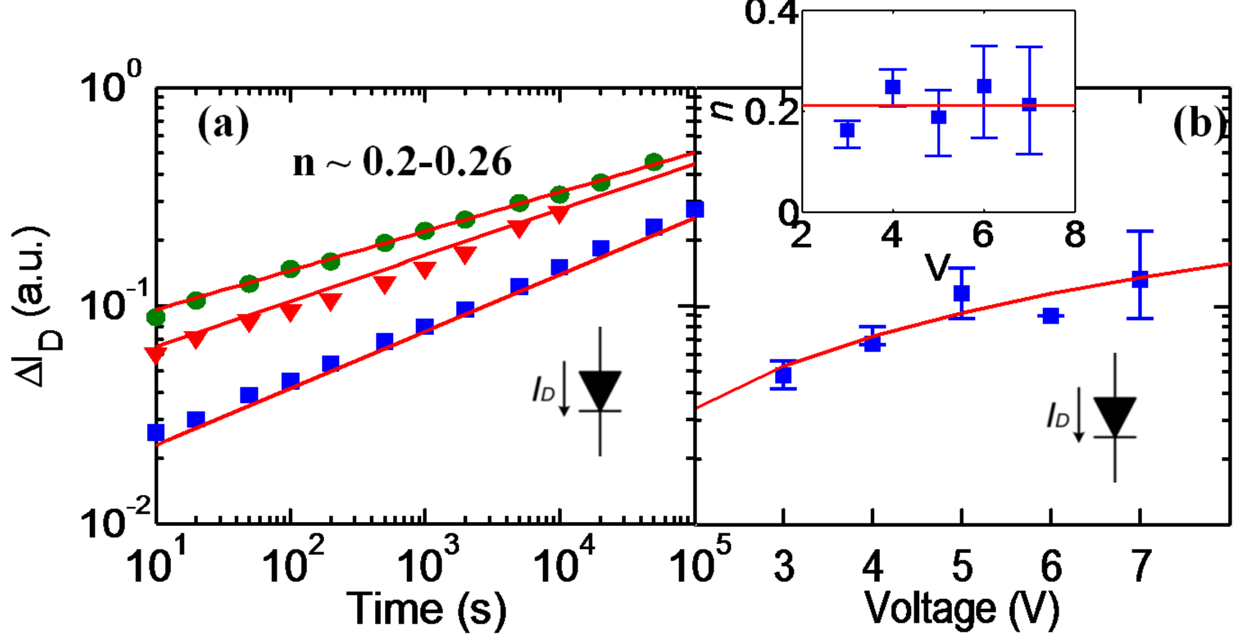
Being in shadow stresses the device



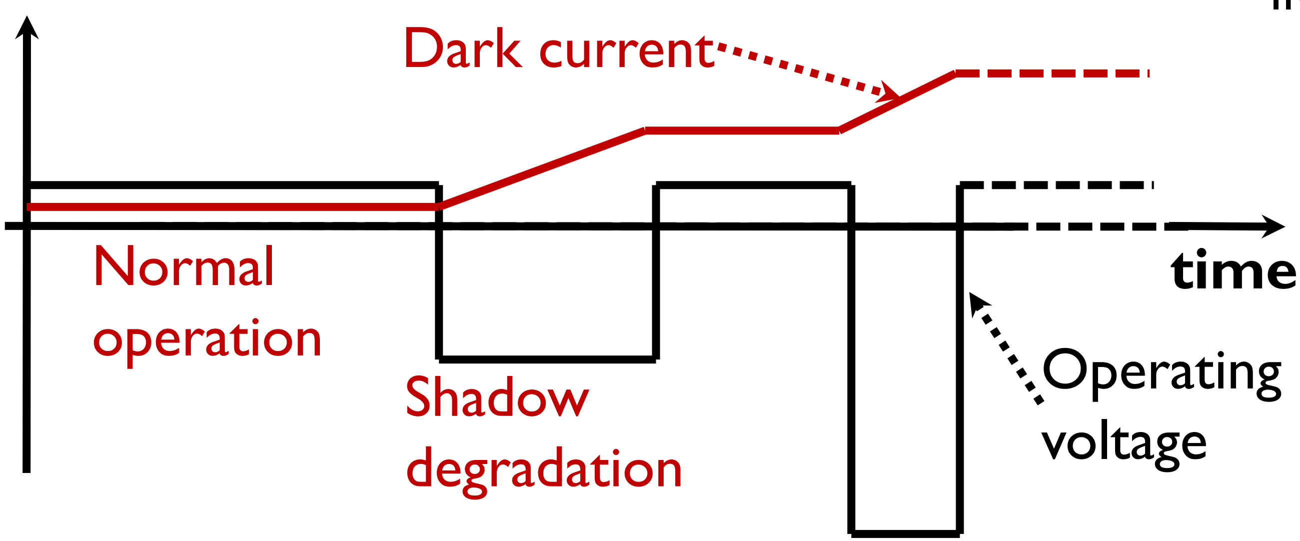
Shaded cells can get reverse biased!

Shadow degradation

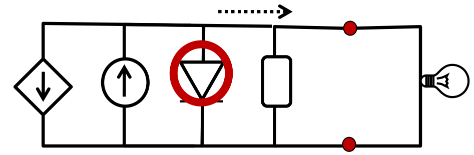


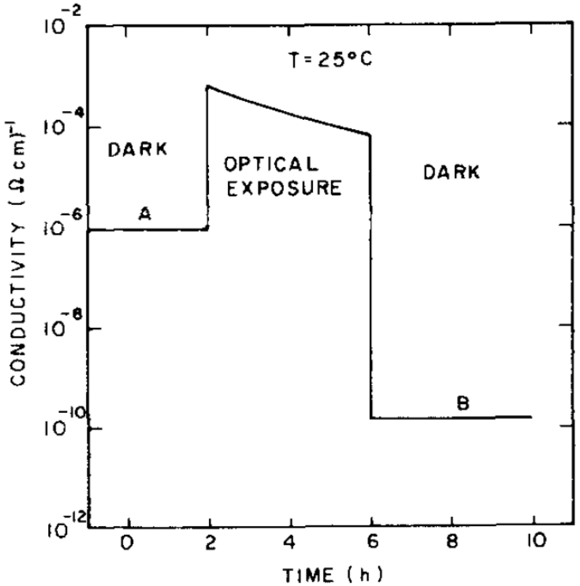


Dongaonkar et al.
IRPS 2011



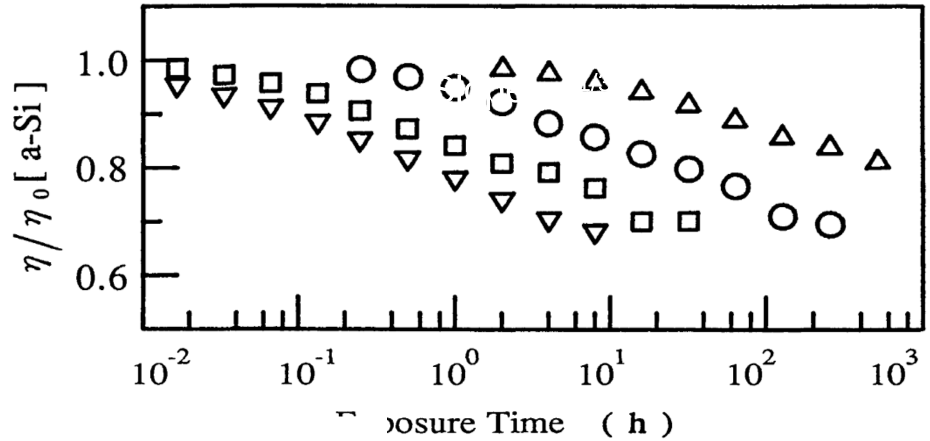
Light induced degradation



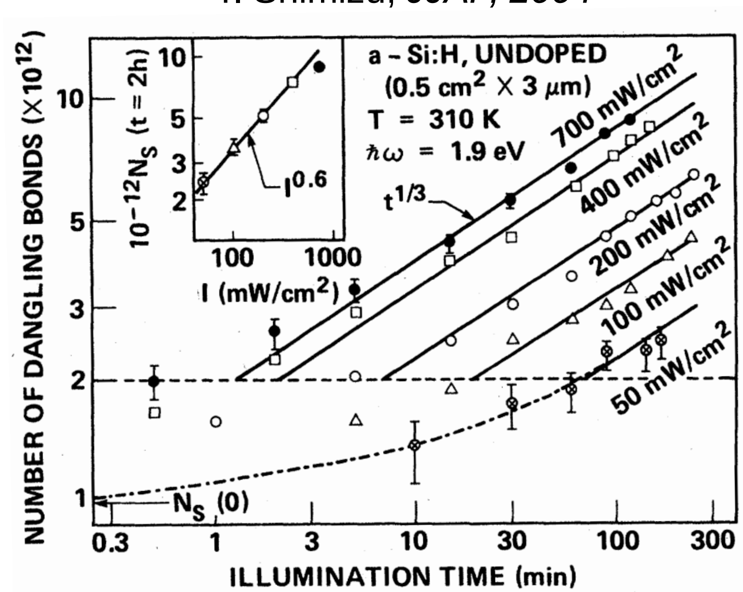


D. L. Staebler, *et al., APL, 1977.*

Y. Nakata, *et al., JJAP, 1992*



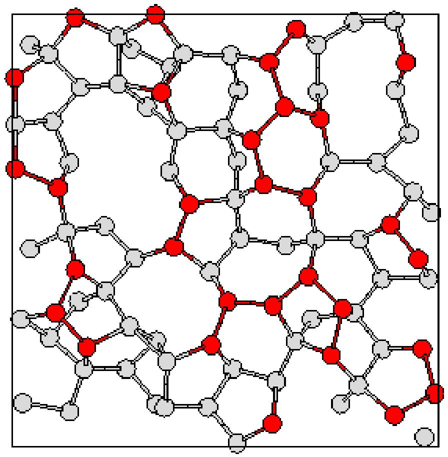
T. Shimizu, *JJAP, 2004*

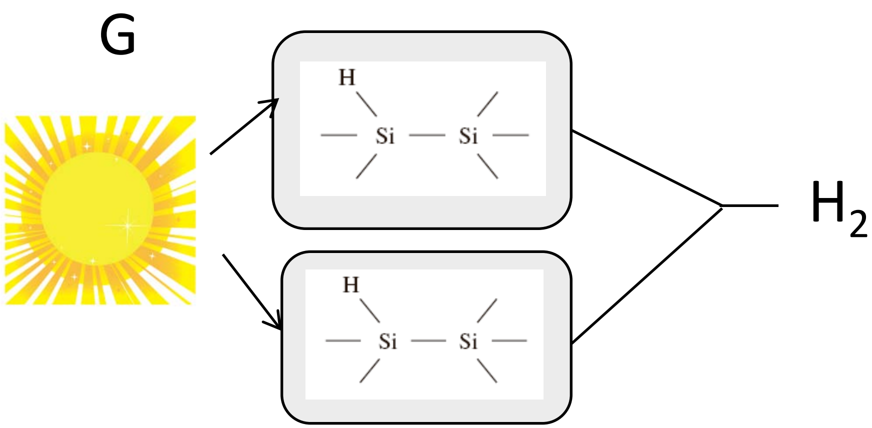


M. Stutzmann, *et al., PRB, 1985*

Ongoing discussion about exponent n~1/3

Reaction-Diffusion Model for LID





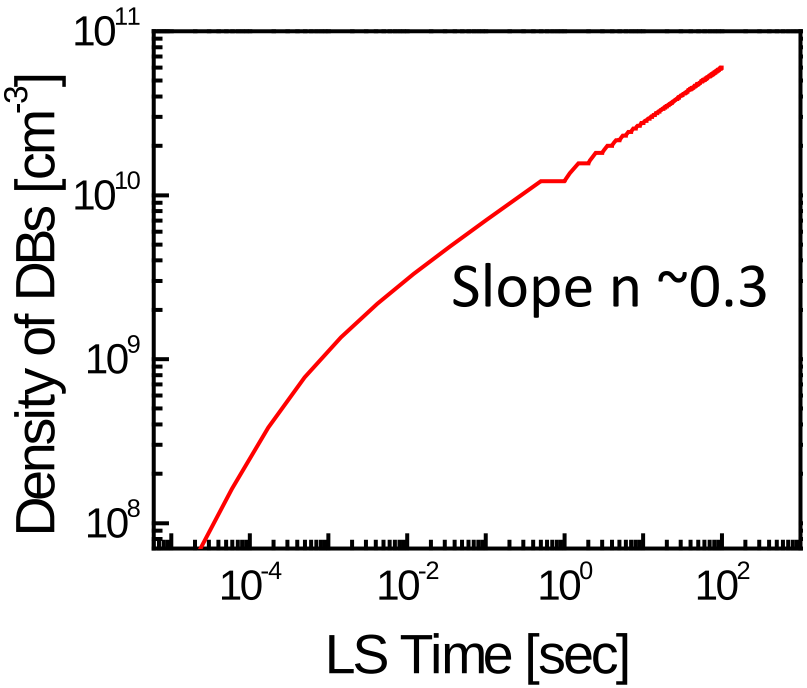
Reaction:

$$\frac{dN_{DB}}{dt} = k_F N_0 G - k_R N_{DB} N_H \sim 0$$

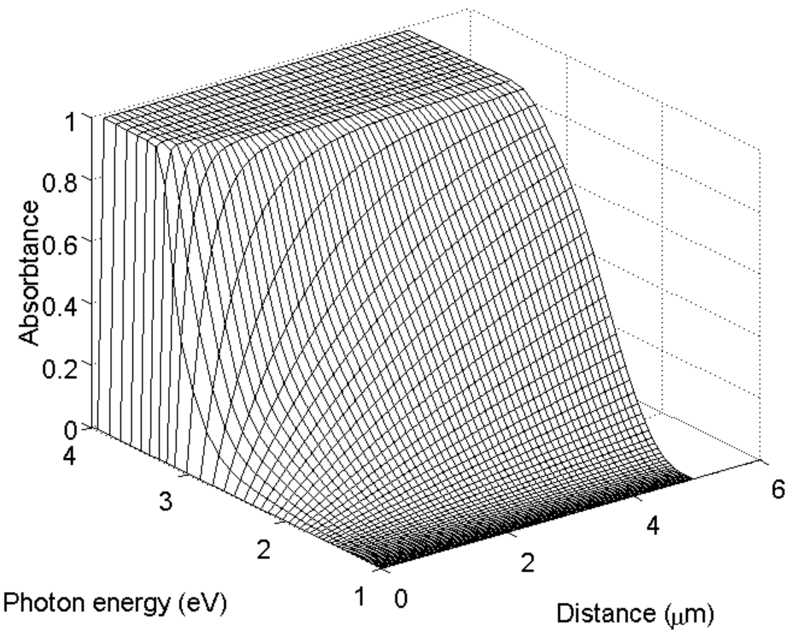
Free H Generation:

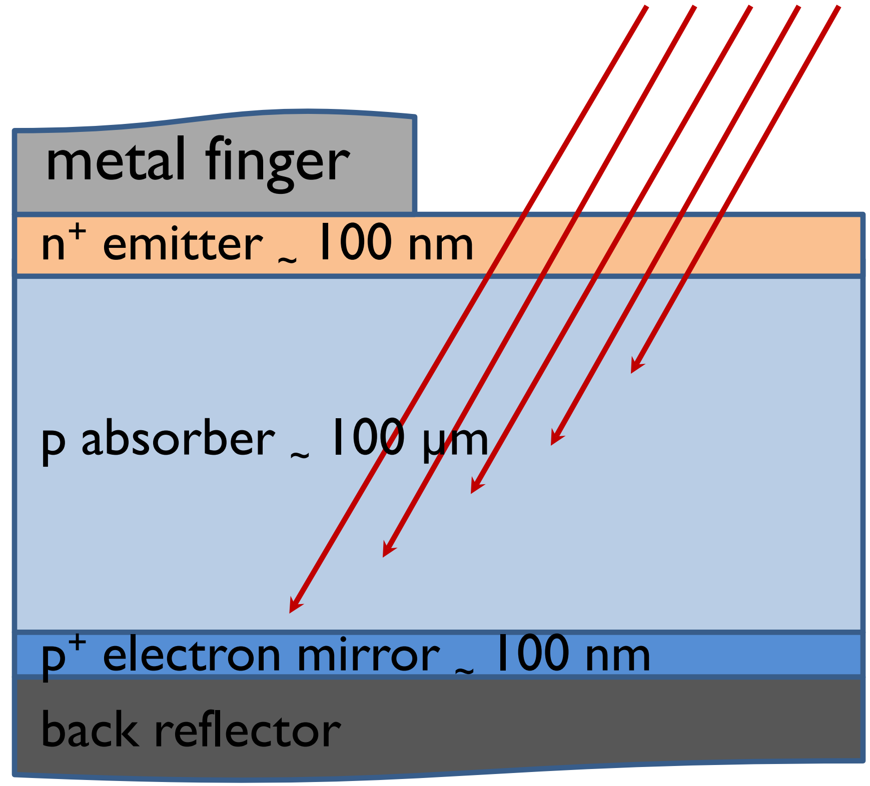
$$\frac{dN_H}{dt} = \frac{dN_{DB}}{dt} - k_H N_H^{\ 2}$$

$$N_{DB} \propto \left(3k_H\right)^{1/3} \left(\frac{k_f N_0 G}{k_r}\right)^{2/3} t^{1/3}$$



Light induced degradation in crystalline PV





Boron-doped Czochralski (Cz) crystalline PV equally susceptible to LID. Float-zone and/or Ga doping better.

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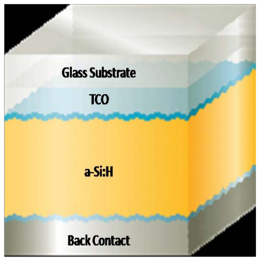
Extrinsic and Intrinsic Solar Cell Reliability



Intrinsic

- Light Induced Degradation
- Hot spot breakdown
- Shunt leakage
- Shadow degradation
- Weak diodes

Extrinsic

- Electrochemical corrosion
- Moisture Ingress
- Glass fracture
- Inverters reliability
- Delamination
- Improper insulation
- Bypass diode failure

Source - www.nrel.gov/pv/performance_reliability/pdfs/failure_references.pdf

conclusions

- Economic incentive to develop thin film solar cell.
- The unique features of thin film PV make photo-current voltage dependent, increases probability of formation of weak diodes and shunts.
- In addition to the extrinsic reliability issues, we need to worry about shadow degradation, light induced degradation, etc.
- The reliability/variability are key concerns – making modules less efficient than individual cells.

Reference for images

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