Theory and Practice of Solar Cells: A Cell to System Perspective

Current-voltage characteristics of thin-film solar cells

M. A. Alam

alam@purdue.edu
Electrical and Computer Engineering
Purdue University
West Lafayette, IN USA

Outline of the lecture

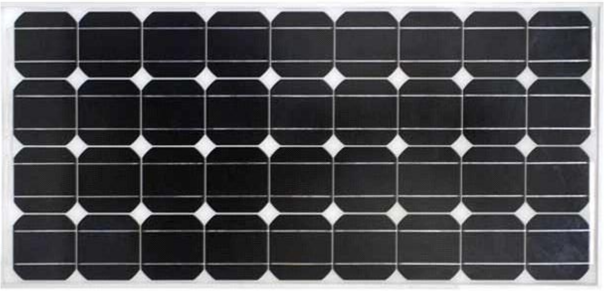
1) Background:
2) Photo current from the transmission perspective
3) Dark current, shunt conduction, and weak diodes
4) Variability, reliability, and lifetime of solar cells
5) Conclusions

Ultimate solar cell

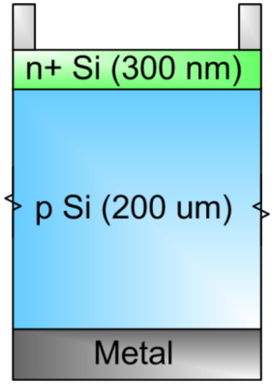
Lightweight, tandem cells, direct and diffused light, recyclable, storage

Different types of solar cells

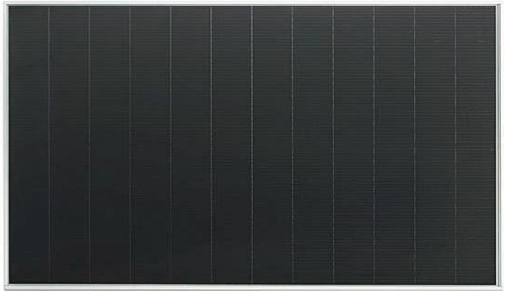
Crystalline Silicon



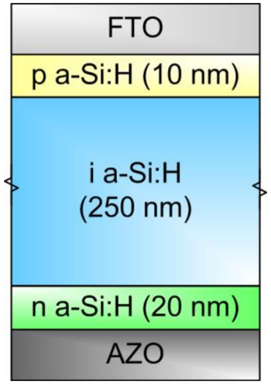
p-n



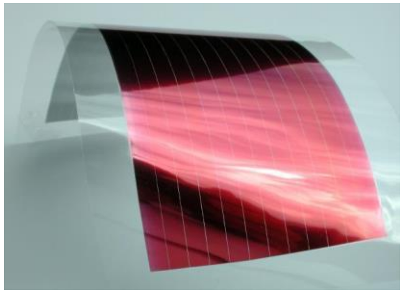
Amorphous silicon



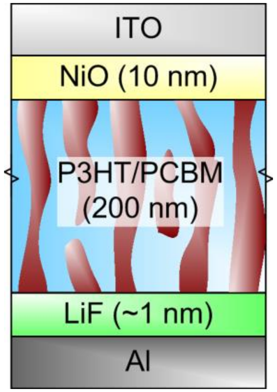
p-i-n



Flexible organic

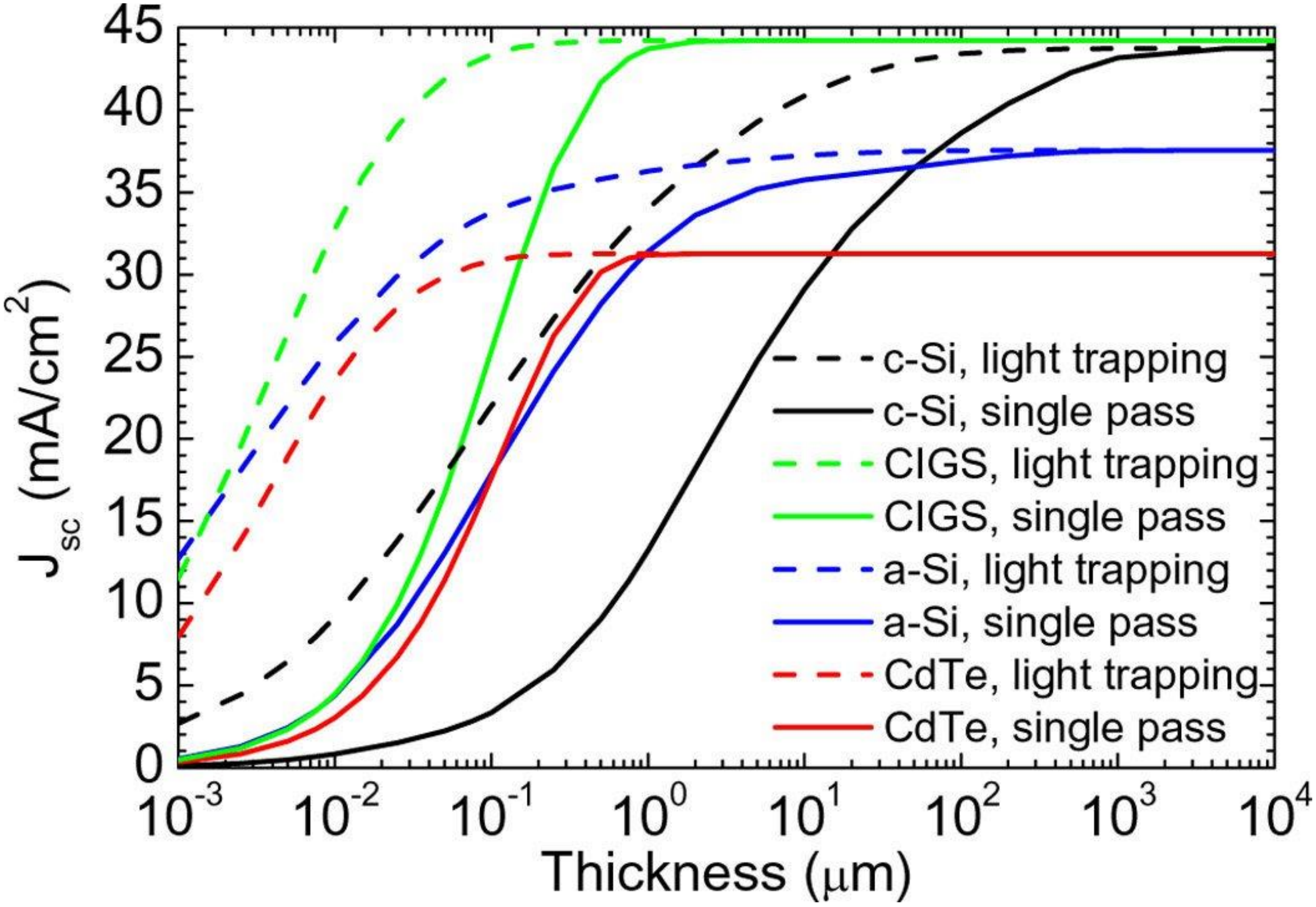


m-i-m



*Google Images

Thin-film solar cells are really thin



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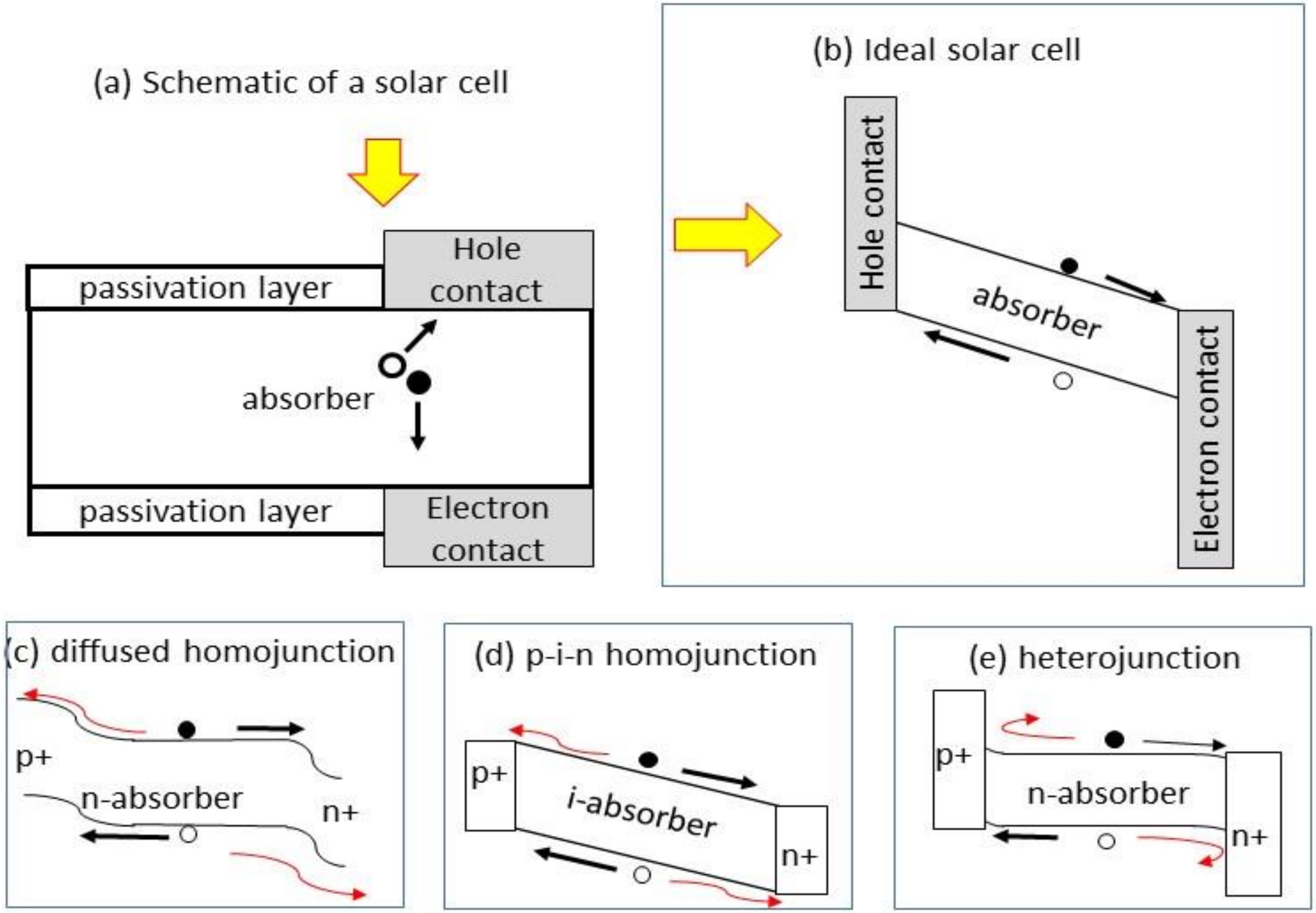
Ideal vs. practical solar cells

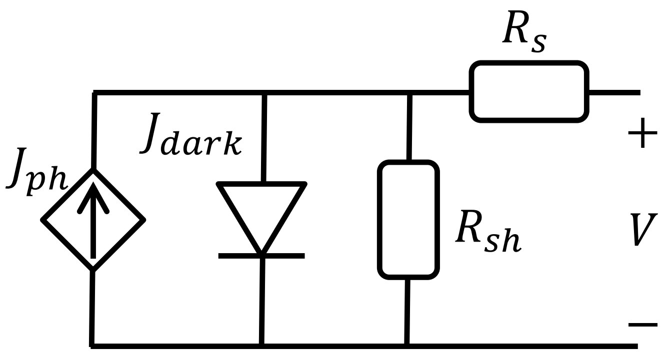


Compact Model: Superposition

Exact I-V characteristics …Self-consistent

$$I(S_0,V) \; = \; I_{ph}\,(S_0,V) - I_{dark}\,(V,I)$$

Voltage-dependent superposition (thin-film)



$$I(S_0,V) \simeq \; I_{ph}\,(S_0,V) - \; I_{dark}\left(V, I_{ph} = 0\right)$$

Voltage-independent superposition (c-Si)

$$I(S_0,V) \simeq \; I_{ph}\,(S_0,V = 0) - \; I_{dark}\left(V, J_{ph} = 0\right)$$

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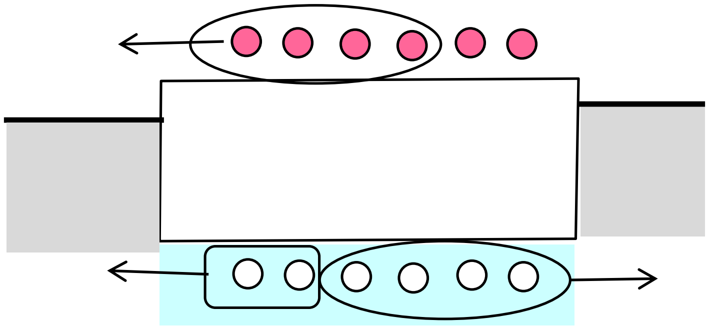
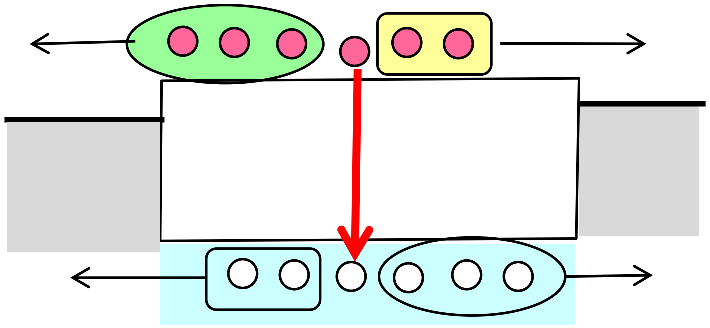
Basics of current flow

Wrong contact loss



+Recombination loss



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

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

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

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

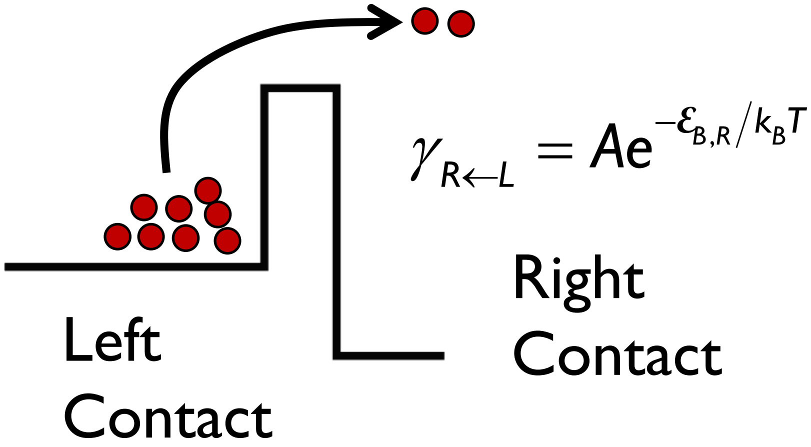
$$= qG \times \frac{\gamma_{L,n}}{\gamma_{L,n} + \gamma_{R,n}} - qG \times \frac{\gamma_{L,p}}{\gamma_{L,p} + \gamma_{R,p}}$$

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

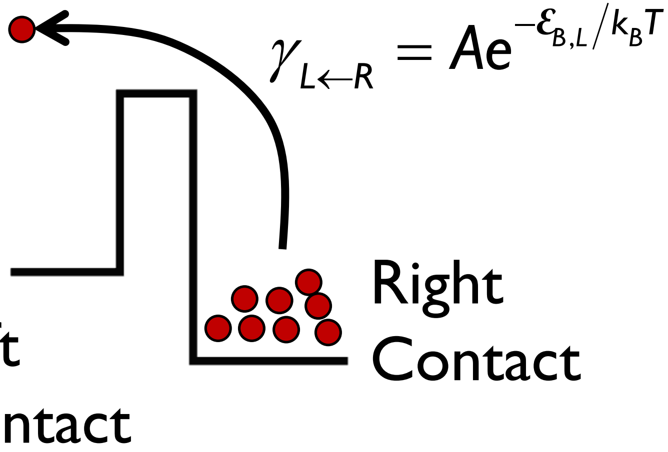
$$= 6q \times \left[\frac{3}{6}\upsilon_0 - \frac{2}{6}\upsilon_0\right]$$

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

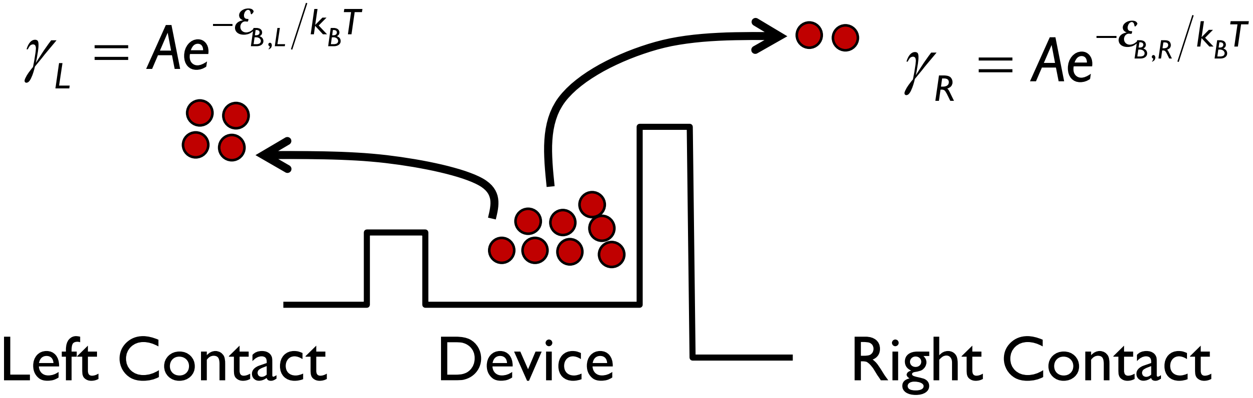
Basics of transmission over a barrier



$$\gamma_{R\leftarrow L} = Ae^{-\mathcal{E}_{B,R}/k_B T}$$



$$\gamma_{L\leftarrow R} = Ae^{-\mathcal{E}_{B,L}/k_B T}$$



$$\gamma_{L} = Ae^{-\mathcal{E}_{B,L}/k_B T}$$

$$\gamma_{R} = Ae^{-\mathcal{E}_{B,R}/k_B T}$$

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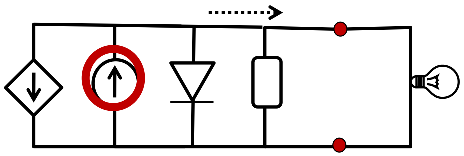
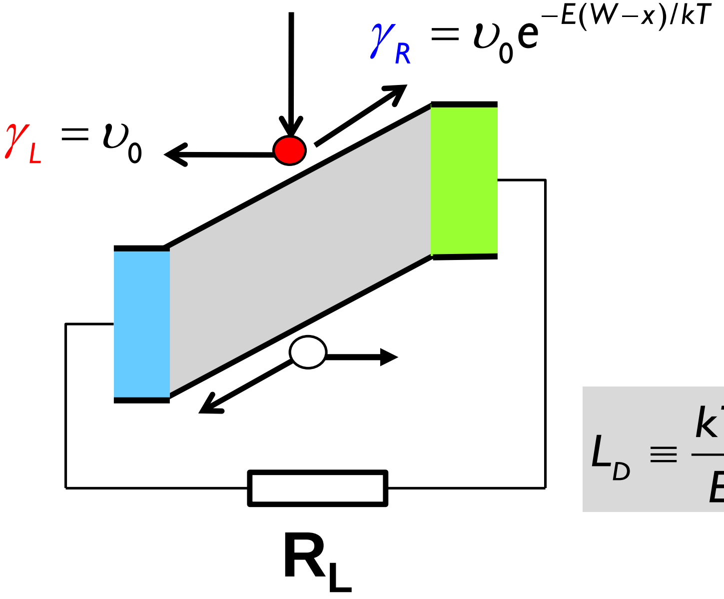
Photocurrent without recombination





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

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

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

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

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

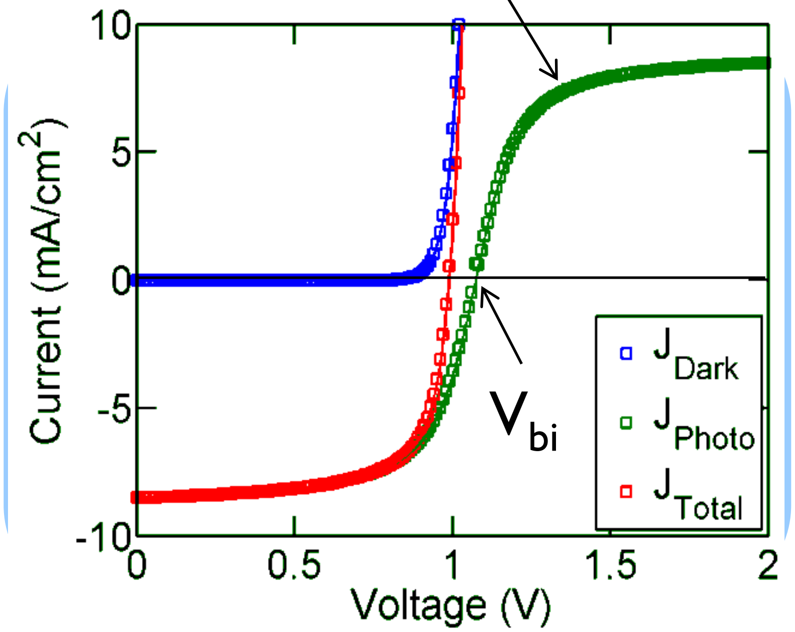
‘Price length’ and point of no return ….

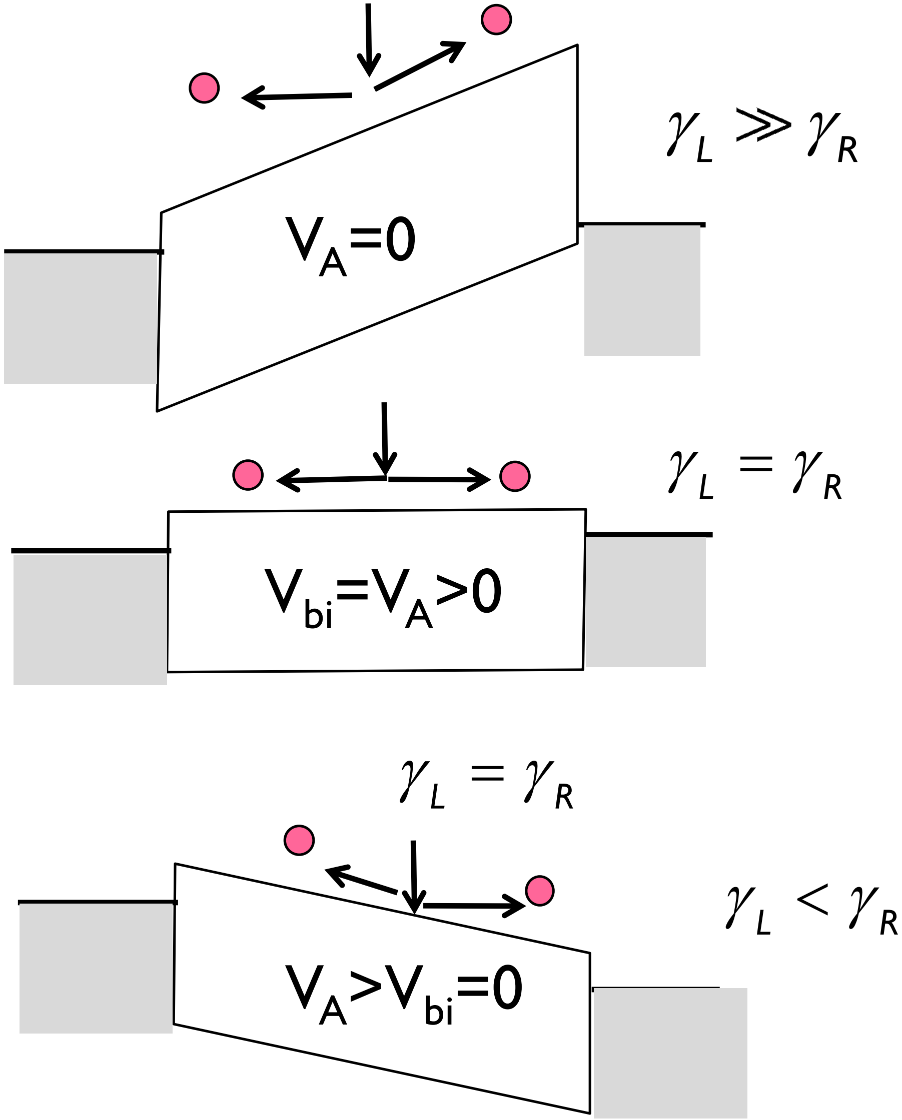
Properties of ‘Sokel’ photo-current

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

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

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



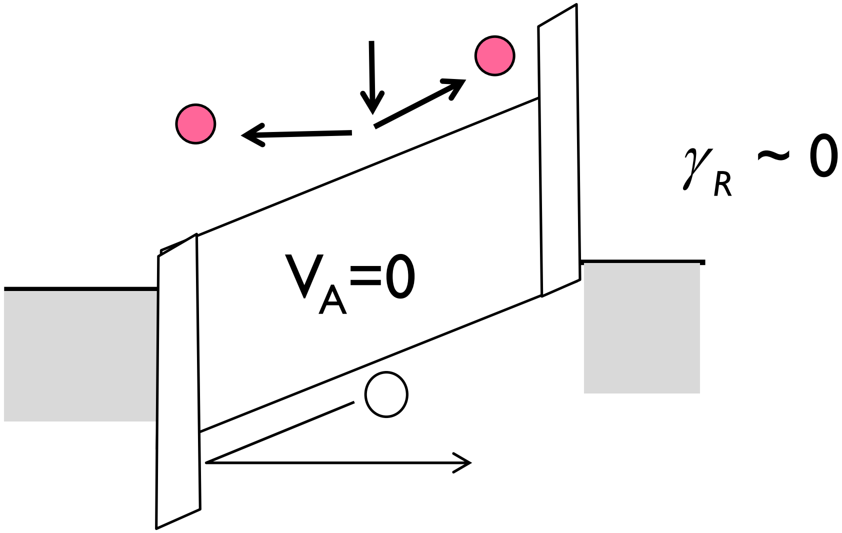


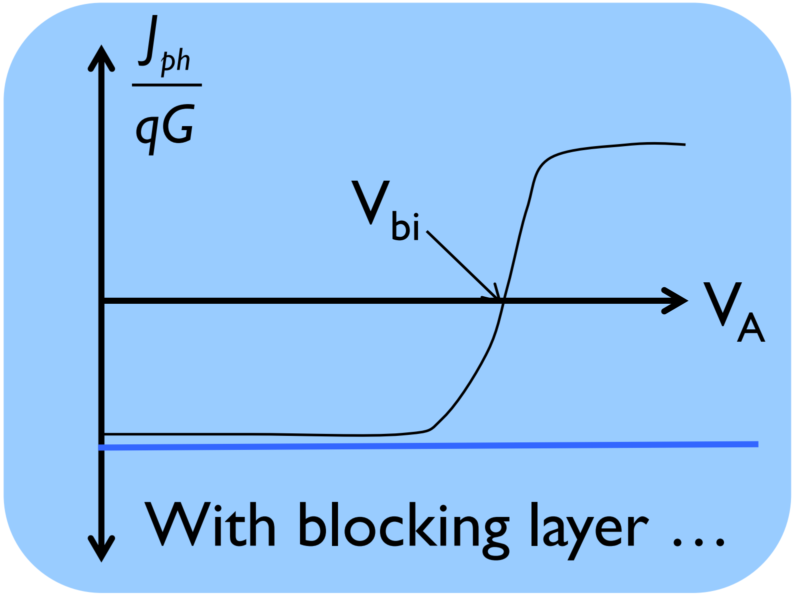
Voltage dependent photocurrent, different from Si p-n junction …

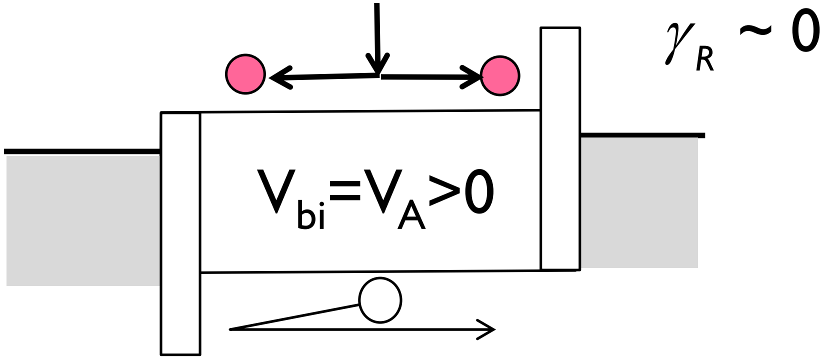
Blocking layer and photocurrent

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

$$J_{ph} = qGW$$



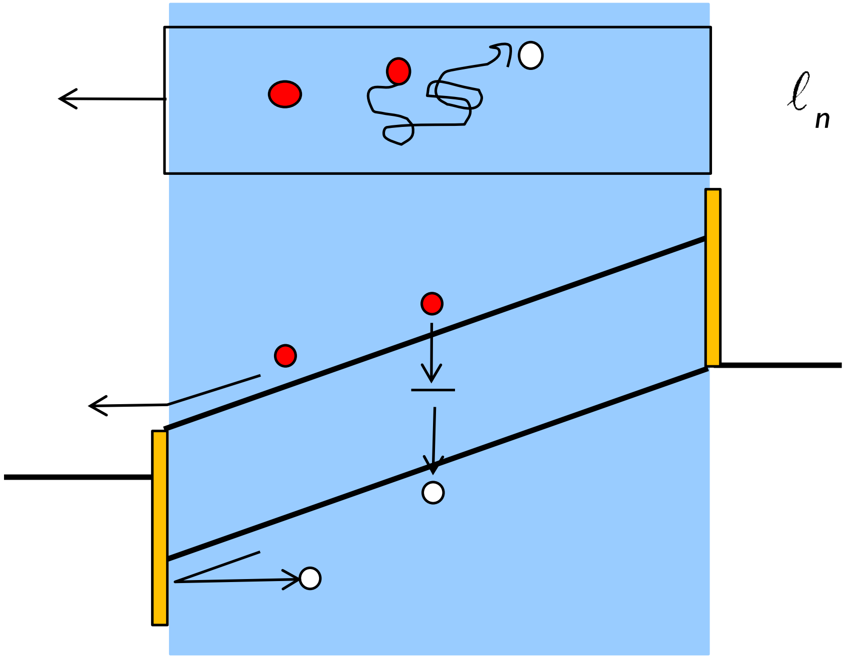




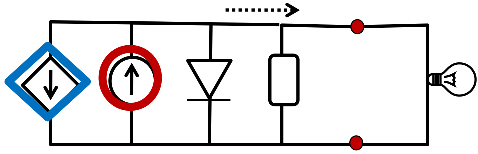
Blocking is essential for many types of thin film PV ….

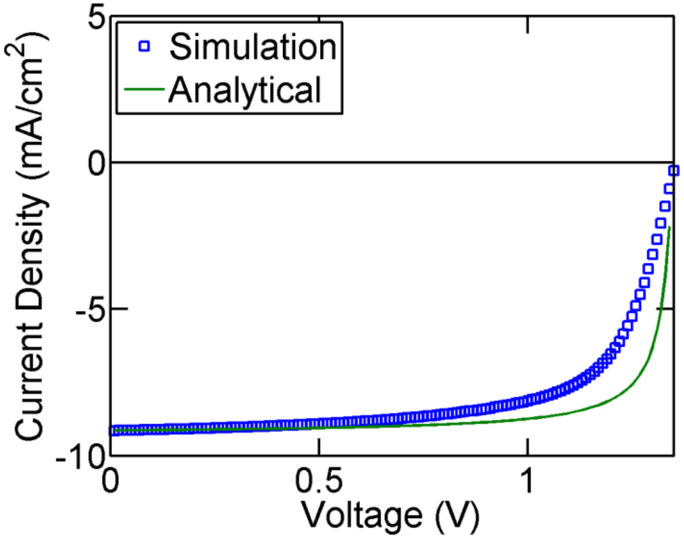
Photocurrent with recombination

Crandall, JAP, 54(12), 1982



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





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

$$= \int_0^W dx\left[e^{-x/\ell_c}\right] = \ell_c\left[1-e^{-W/\ell_c}\right]$$

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

Dark current without recombination

$$\gamma_L = Ae^{-q(V_{bi}-V)/k_BT} \qquad \gamma_R = A\times 1$$

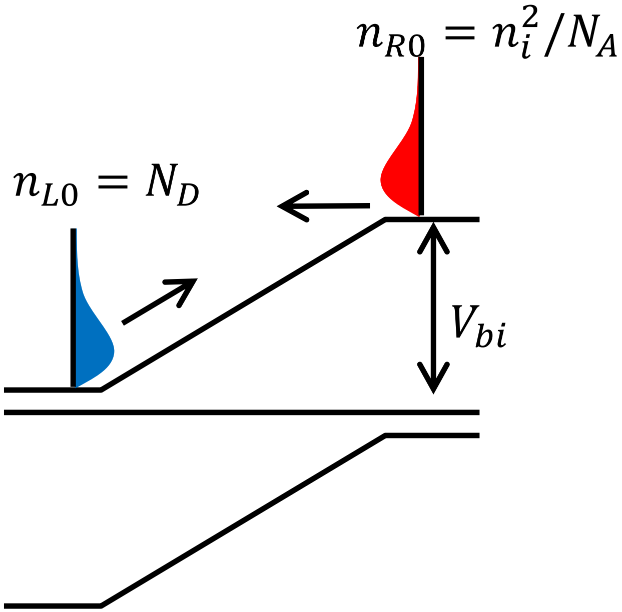
$$n_{L,0} = \left(n_i^2/N_A\right)e^{+qV_{bi}/k_BT}$$

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

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

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

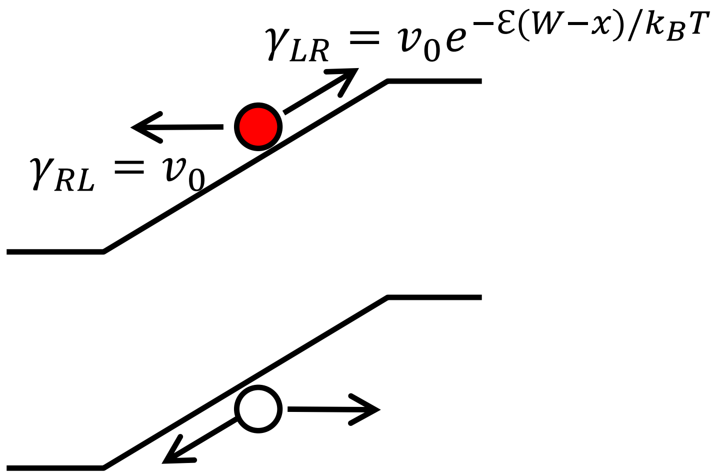
$$= q\frac{n_i^2}{N_A}\left[\frac{\mu_n(V-V_{bi})/d}{e^{+q(V-V_{bi})/k_BT}+1}\right]\left[e^{qV_b/k_BT}-1\right]$$

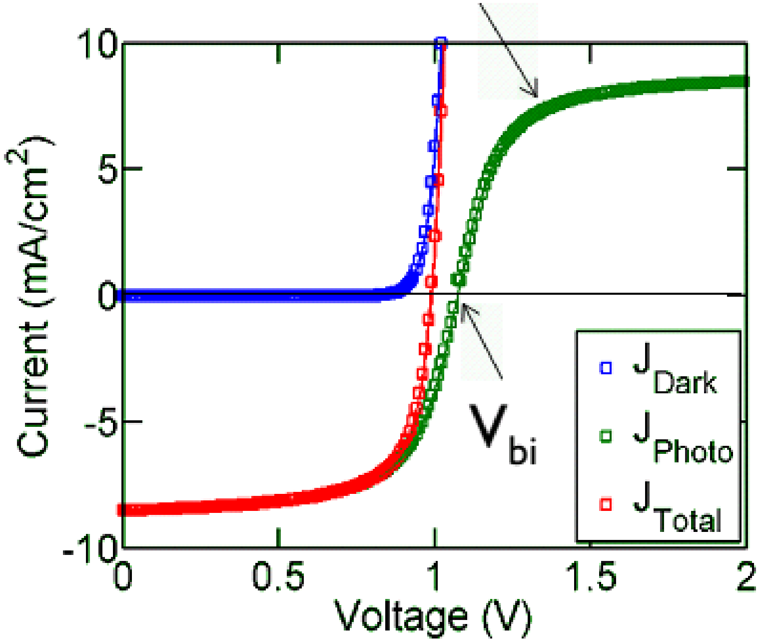


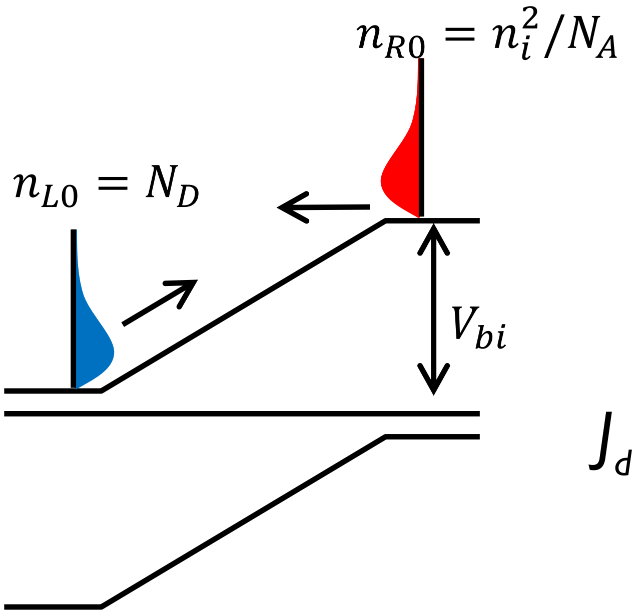
$$J_d = J_n + J_p = q\left[\frac{n_i^2}{N_A}+\frac{n_i^2}{N_D}\right]\left[\frac{\mu_n(V-V_{bi})/d}{e^{+q(V-V_{bi})/k_BT}+1}\right]\left[e^{qV/k_BT}-1\right] \equiv I_0\left[e^{qV/k_BT}-1\right]$$

PIN Compact model Summary

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







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

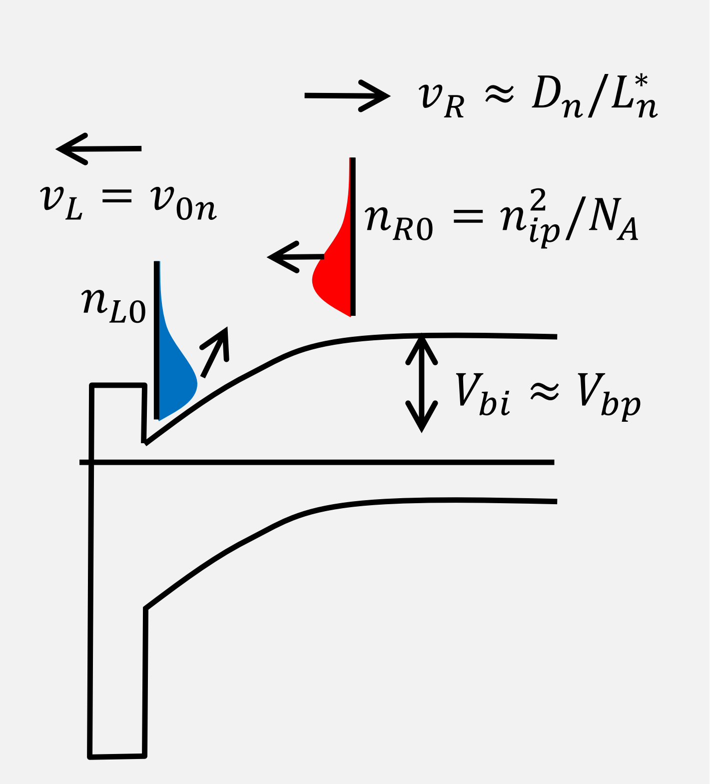
Dark current in Heterojunction cells

$$J_n = q\, n_{L,0}\, v_L \frac{\gamma_{LR}}{\gamma_{RL} + \gamma_{LR}} - q\, n_{R,0}\, v_R \frac{\gamma_{RL}}{\gamma_{RL} + \gamma_{LR}}$$

$$\gamma_{LR} = v_R\, e^{-\frac{q(V_{bi}-V)}{k_B T}}$$

$$(v_R \equiv D_n/L_n)$$

$$\gamma_{RL} = v_L = v_0 e^{-\frac{\Delta}{k_B T}}$$



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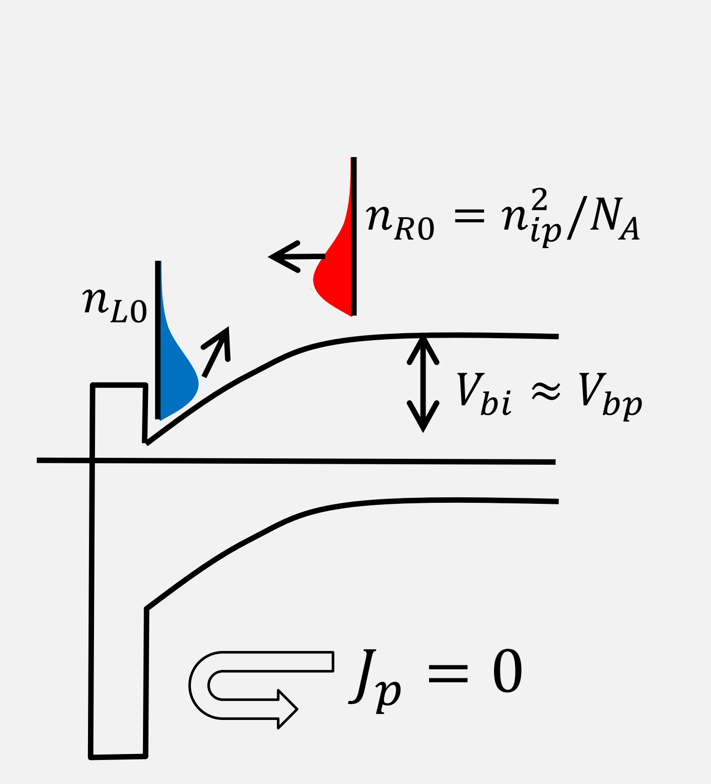
Dark current in heterojunction cell



At equilibrium, $J_n = 0$,

therefore, $n_{L,0} = n_{R,0}\, e^{+\frac{qV_{bi}-\Delta}{k_BT}}$

$$J_n = q\, n_{R,0} \frac{v_L v_R e^{-\frac{\Delta}{kT}}}{\gamma_{LR} + \gamma_{RL}} \left(e^{\frac{qV}{kT}} - 1\right)$$

$$J_n = q\, n_{R,0} v_{eff} \left(e^{-\frac{q(V_{bi}-V)}{k_BT}} - 1\right)$$

$$v_{eff}^{-1} \equiv \left(\frac{D_n}{L_n^*}\right)^{-1} + \left(v_0 e^{q(V_{bi}-V-\Delta)/(\mathrm{k_B}T)}\right)^{-1}$$

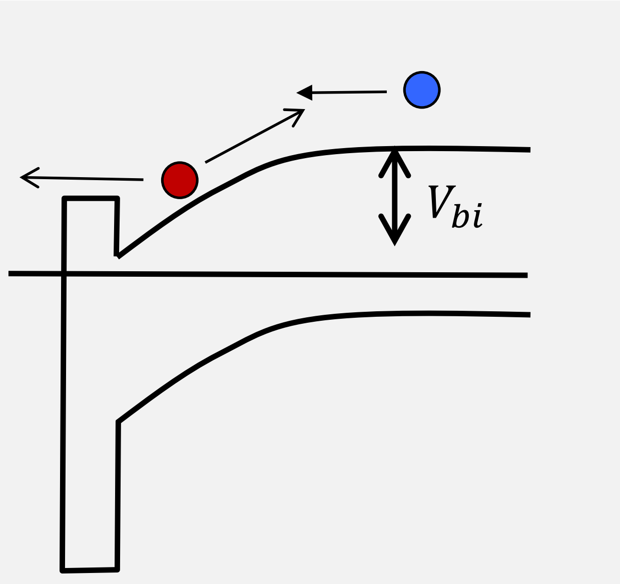
$$J_{dark} = J_n + J_p = J_n$$

Photo-current in HJ cells

$$J_{ph} =$$

$$q\int_0^{x_p} G(x)\left(\frac{\gamma_{LR}}{\gamma_{RL}+\gamma_{LR}}-\frac{\gamma_{RL}}{\gamma_{RL}+\gamma_{LR}}\right)dx$$

$$+q\int_{x_p}^{W} G(x)e^{-(x-x_p)/L_n}$$



$$\gamma_{RL} = v_0 \exp\left(-\frac{\Delta}{k_B\,T}\right)$$

$$G(x) = G_0\, e^{-\frac{x}{\lambda}}$$

$$\gamma_{LR} = \left(\frac{D_n}{L_n}\right)\exp\left(-E\,\frac{x_p - x}{k_B T}\right)$$

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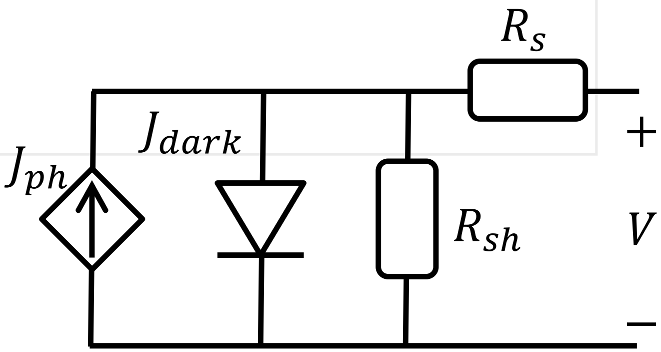
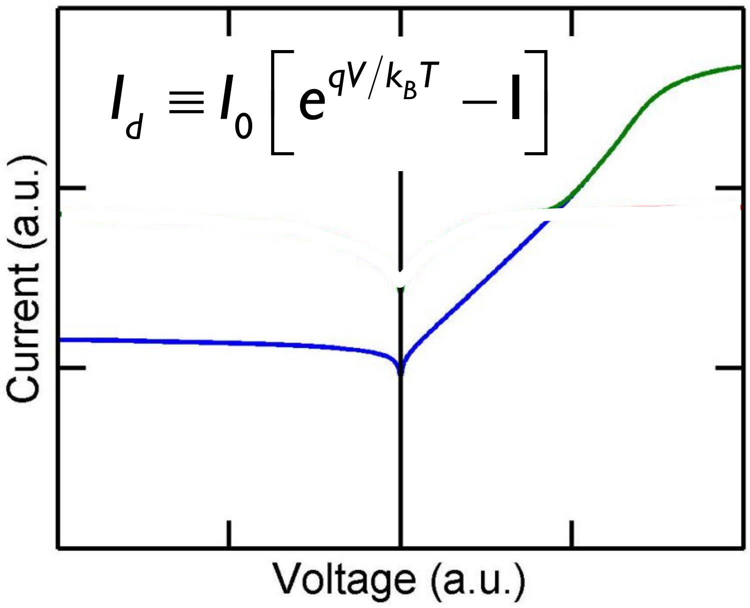


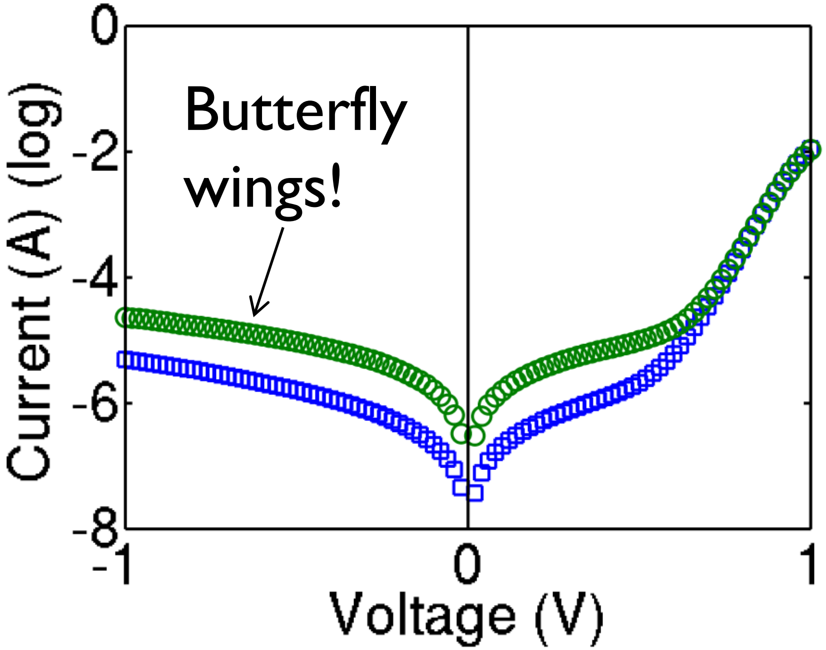
Theory and practice of thin film dark IV

Theory



$$I_d \equiv I_0\left[e^{qV/k_BT} - 1\right]$$

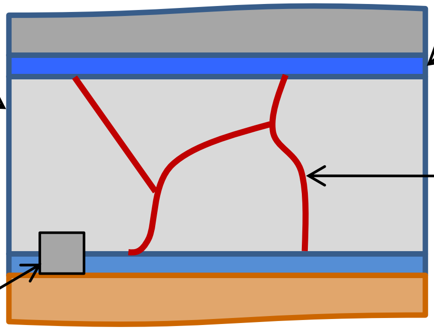
Experiment



Butterfly wings!

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

Contact diffusion and shunt conduction

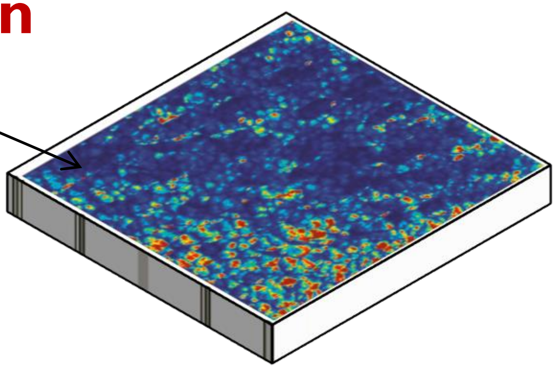


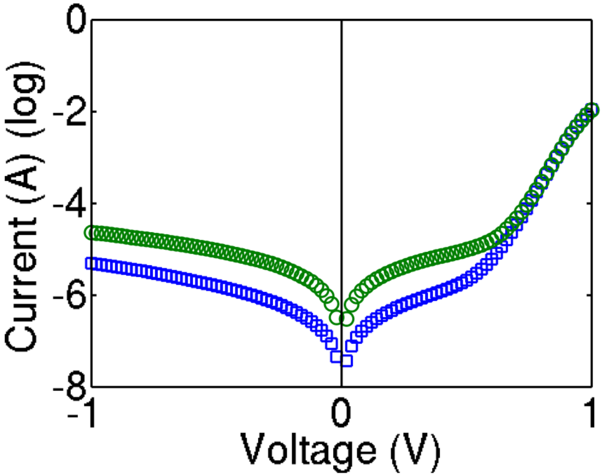
(1) Thin absorption layer

(2) Thin doped region

(4) Grain boundaries

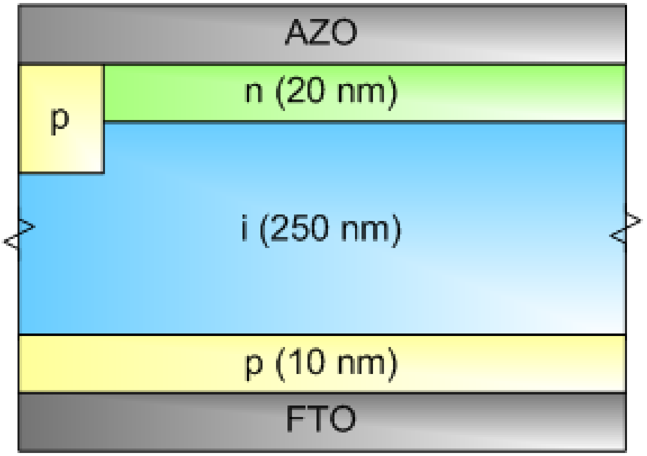
(3) Contact diffusion



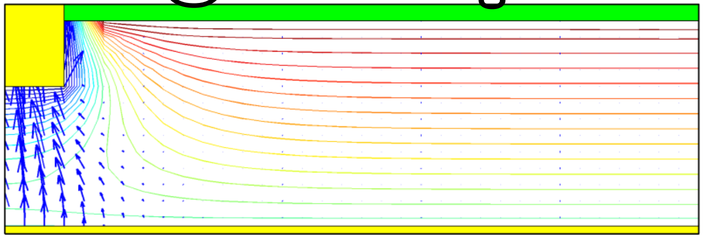


A real solar cell IV seldom looks like textbook IV

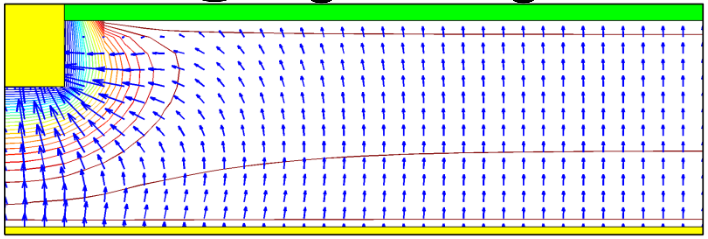
Parasitic shunt leakage

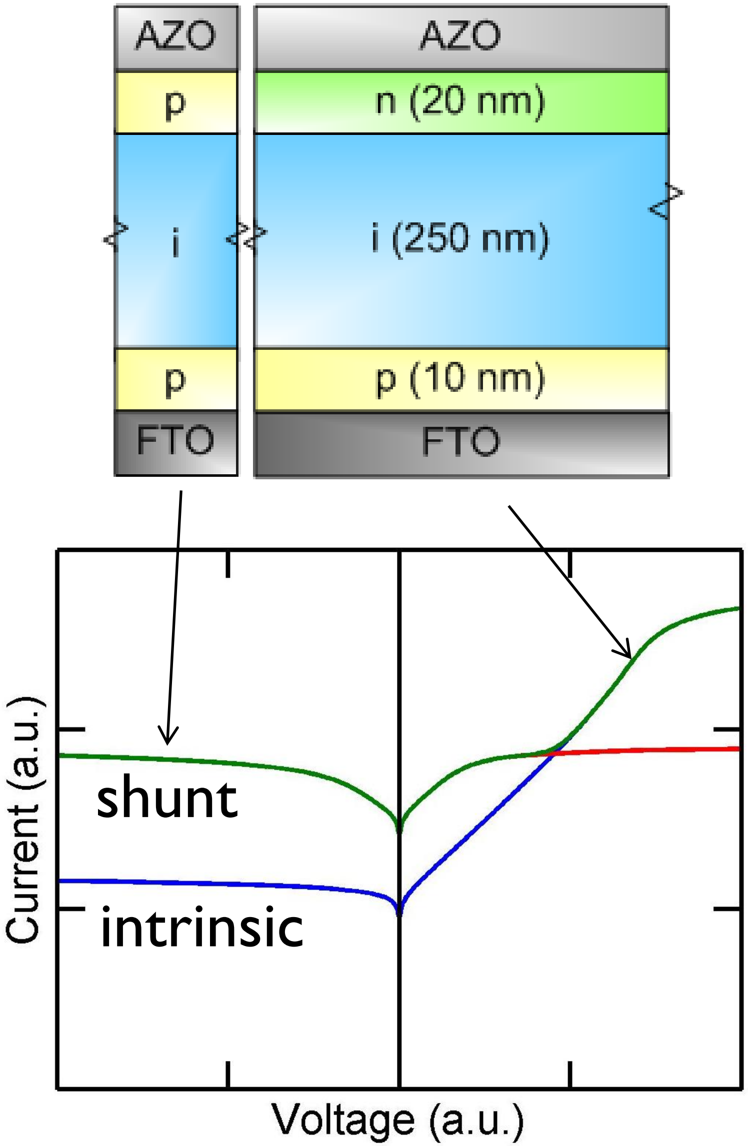


@ low voltage



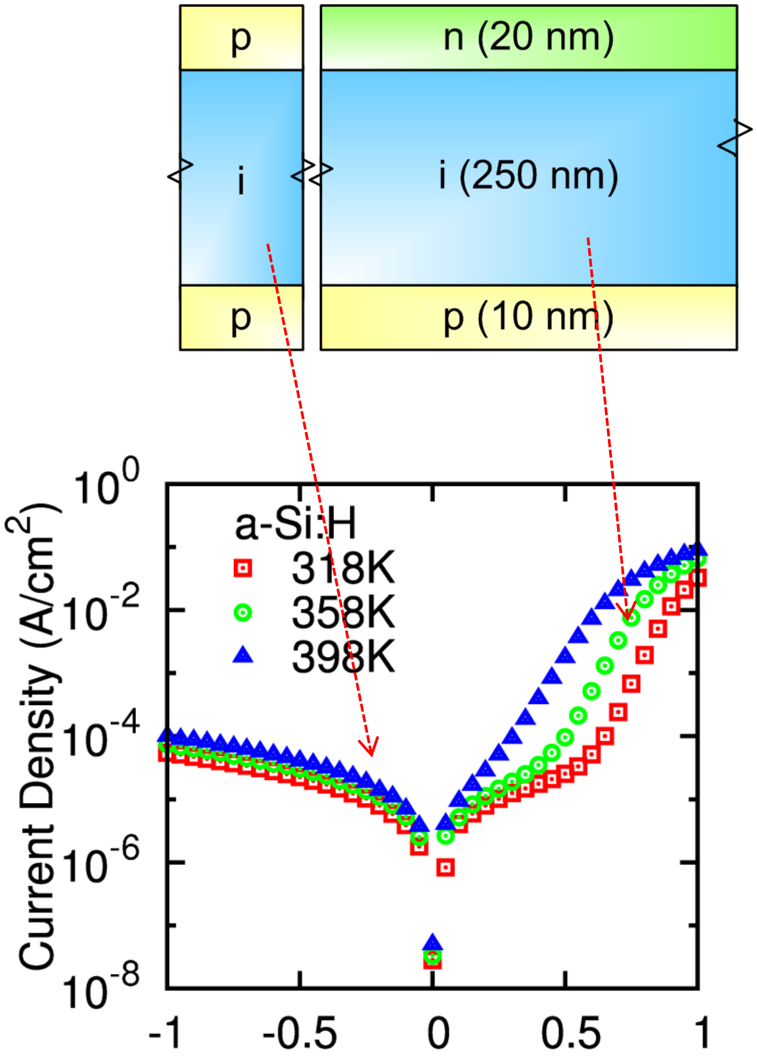
@ high voltage

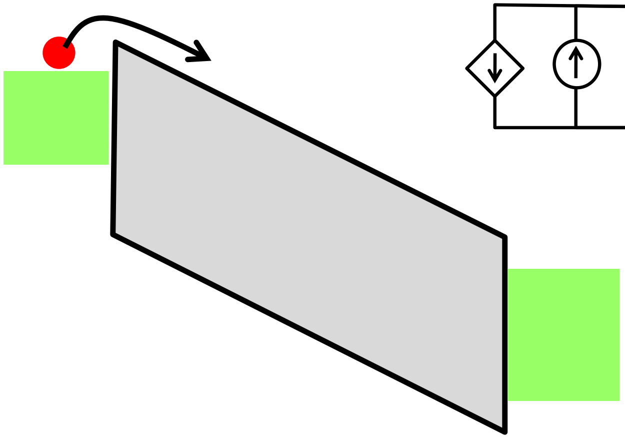


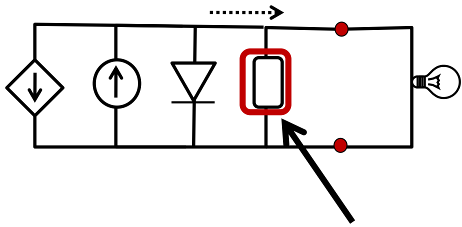


Dongaonkar and Alam JAP, 2010

Interpretation of ‘shunt’ leakage







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

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

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

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

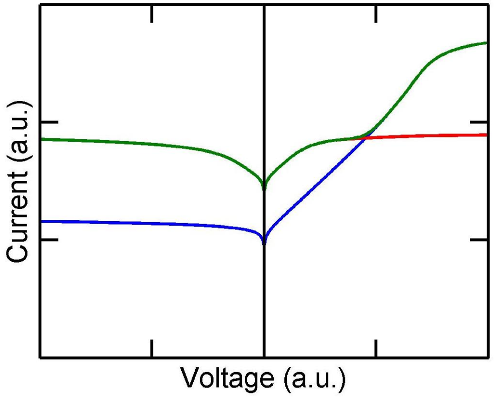
$$I_{shunt} = A\mu\frac{V^{\delta+1}}{L^{2\delta+1}}\,*$$

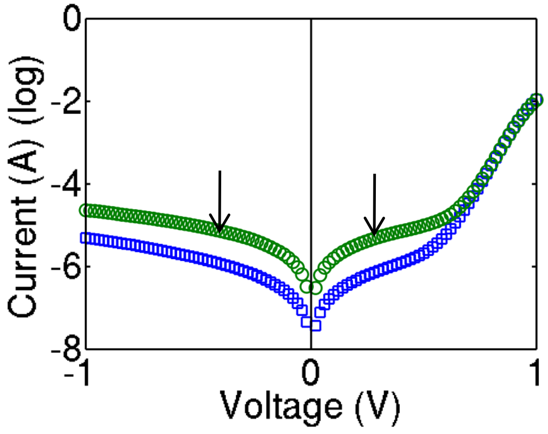
$$\gamma = \frac{E_A}{kT}$$

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

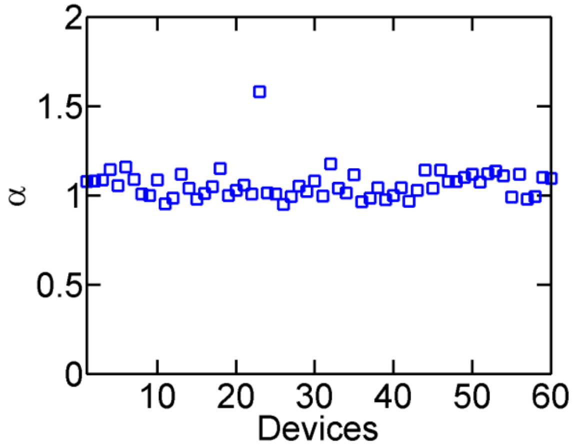
Features of shunt leakage

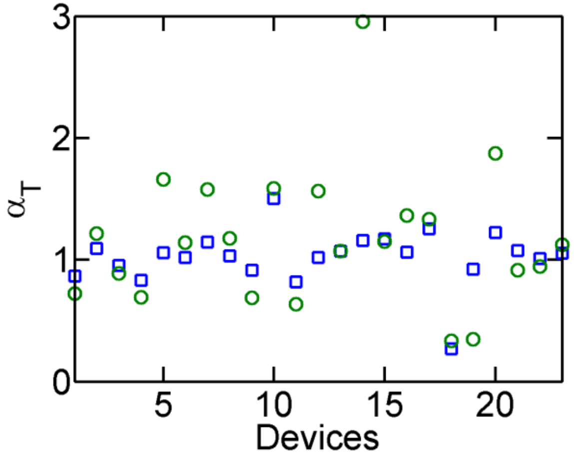
$$I_{shunt} = A\mu \frac{V^{\delta+1}}{L^{2\delta+1}}$$



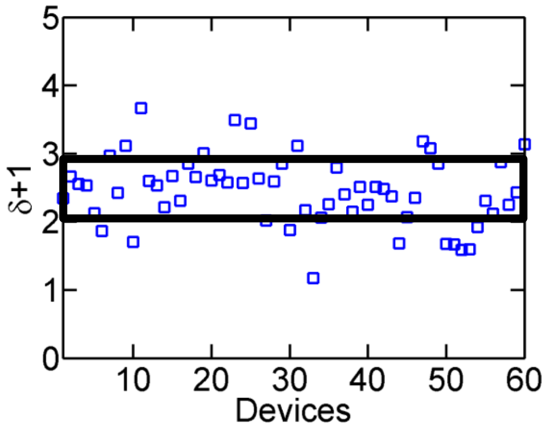


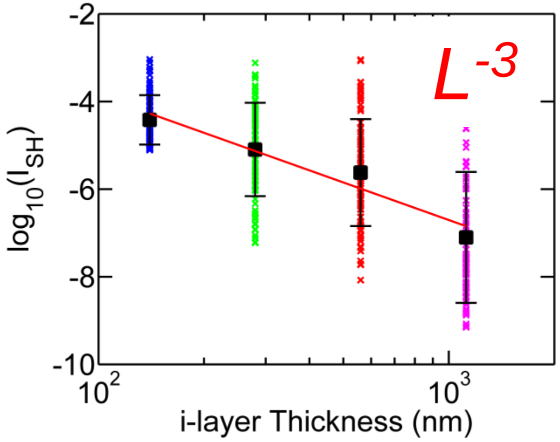
Symmetry





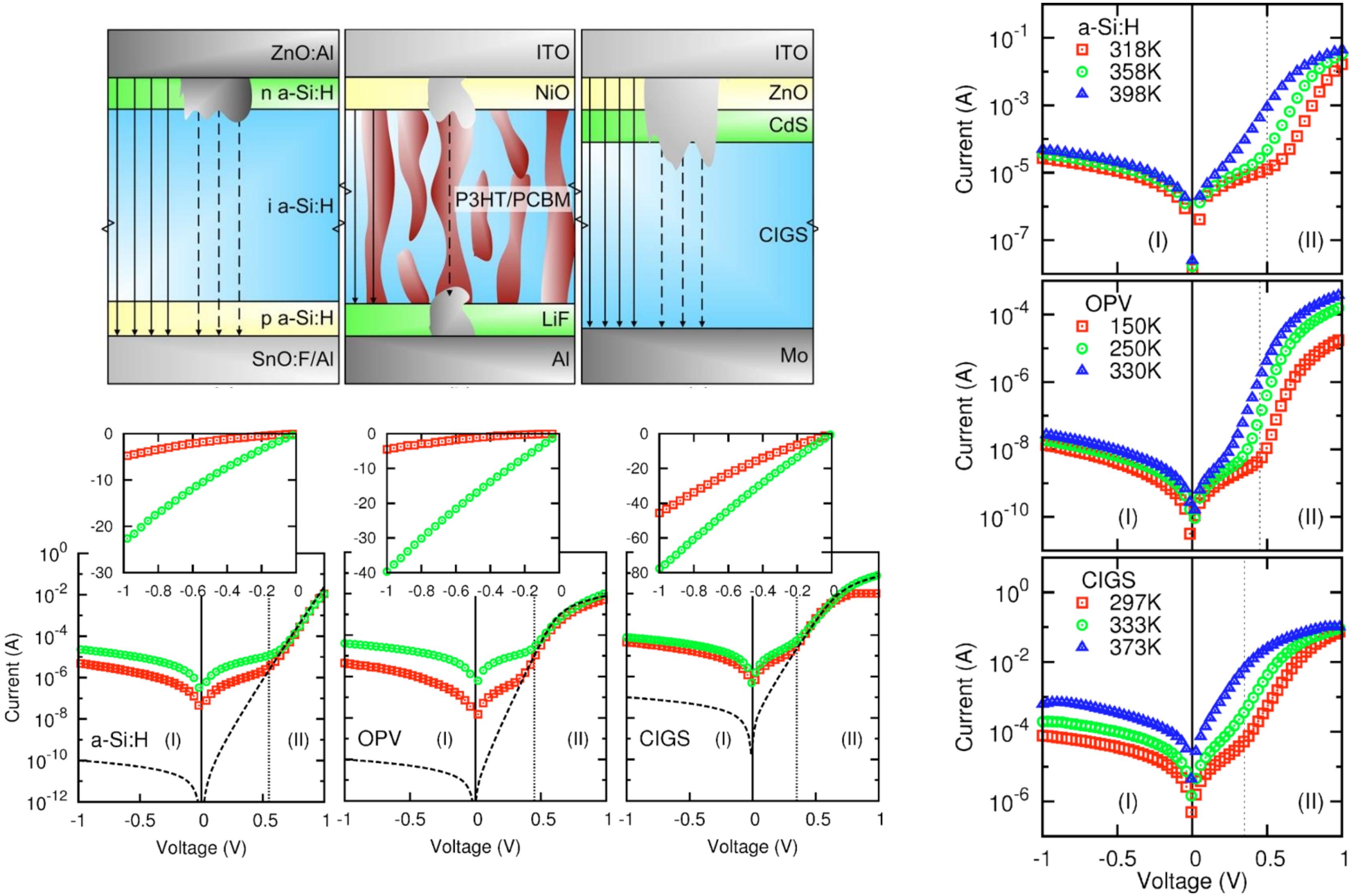
Exponents





Dongaonkar and Alam, EDL, 2010; JAP 2011, JPV 2012

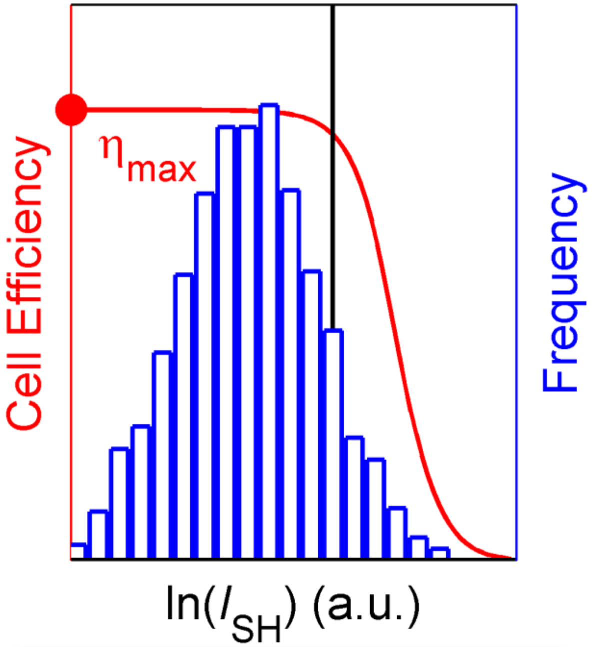
Universality of Electrical Conduction

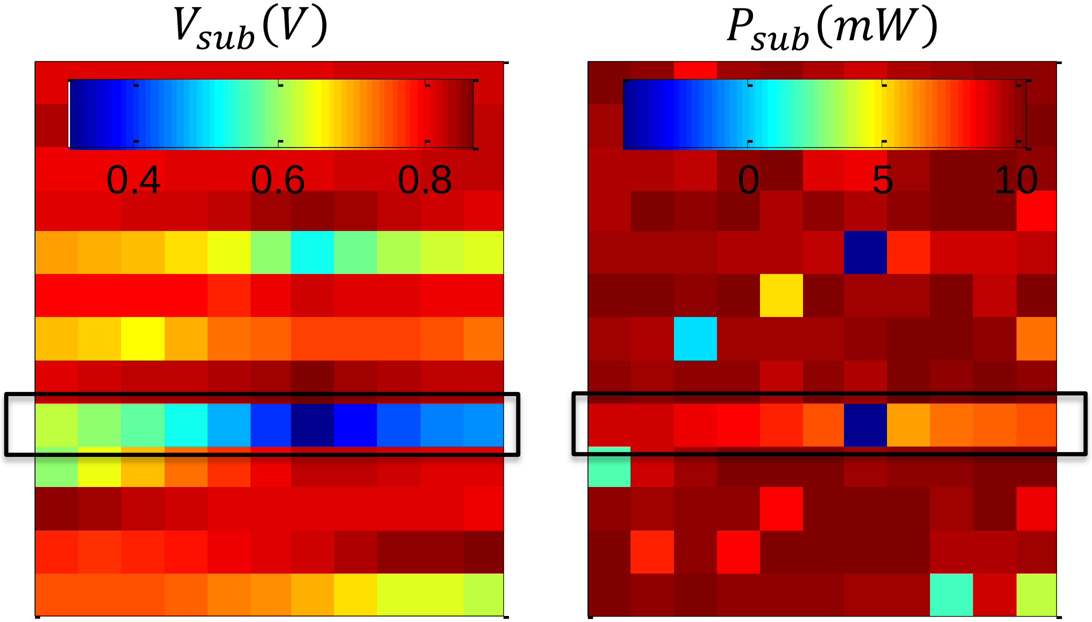


M. A. Alam, PV Lecture Notes

Dongaonkar and Alam, JAP, 2011

Impact of heavy tailed shunt distribution





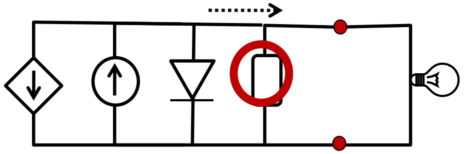
Heavy tail of shunt distribution determines the number of low efficiency shunted cells

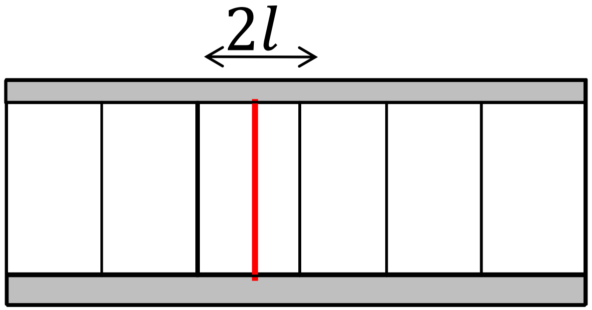
Shunted cells modify the bias of entire row, affecting the power output of their neighbors

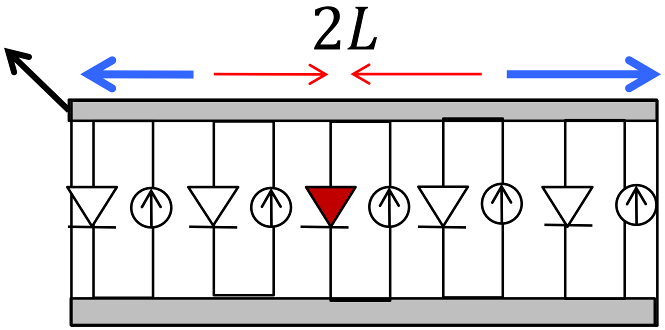
Shunted cells drain the power output of neighbors, with disproportionate impact on module output

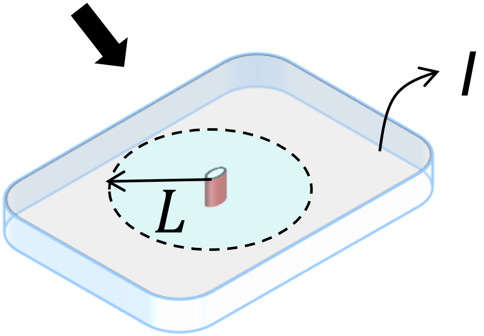
Long range interaction between sub-cells determines module performance loss

Hotspot degradation









(Karpov, PRB 69, 045325, 2004.)

$$I = I_0(e^{qV/kT} - 1) - I_{ph}(V)$$

$$I_0(e^{qV_{oc}/kT} - 1) = I_{ph}(V_{oc})$$

$$V_{oc} = k_B T \times \ln(1 + I_{ph}/I_0)$$

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

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

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

$$= I_{ph}(V_{oc2})(e^{q(V-V_{oc2})/kT} - 1)$$

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

A single um-sized weak diode drains away 1-10 mm region!!

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.

Self-test questions

- Name a few key thin-film technologies being pursued in industry and academia.
- Most of the thin-film technologies are direct bandgap materials. Why?
- Thin-film solar cell may not follow superposition principle. Explain.
- How is the thickness of a thin-film solar cell constrained by light absorption and carrier collection?
- What is the origin of hot-spots? Why is it so detrimental to PV performance?
- Why is shunt-resistance nonlinear? What type of distribution does shunt-resistance follow?