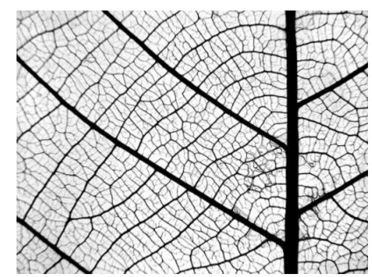
Theory and Practice of Solar Cells: A Cell to System Perspective

How a Module gets its Stripes: c-Si

M. A. Alam

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



Network for Photovoltaic Technology

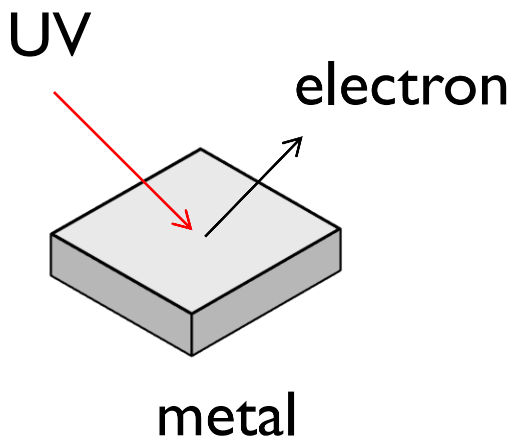
nanoHUB.org

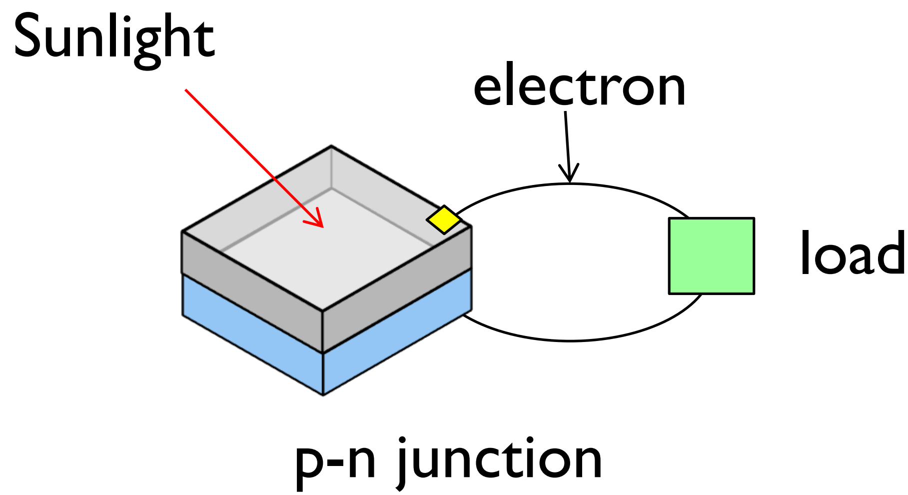
PURDUE UNIVERSITY

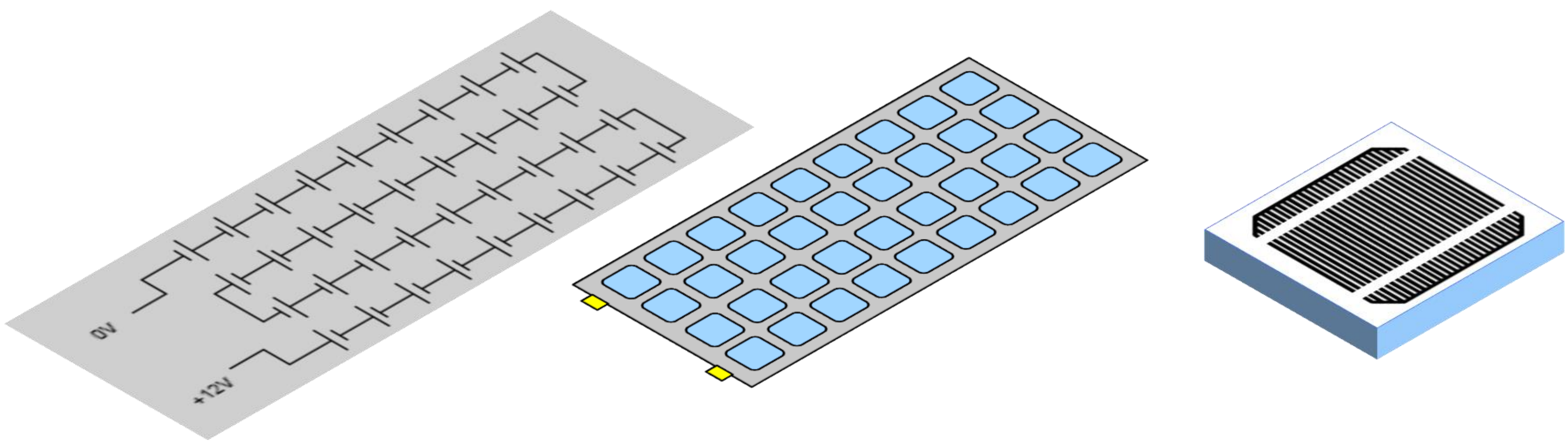
Outline

1) Three types of c-Si gridding
2) Physics of standard c-Si cell gridding
3) Physics of bifacial cell design
4) Inter-digitated back-contact design
5) Conclusion

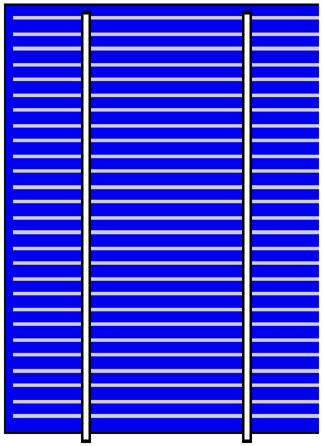
Photoelectric effect and solar cells

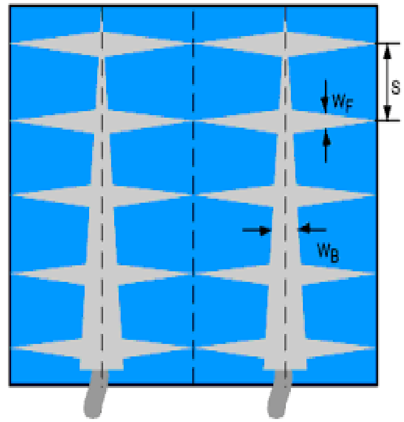


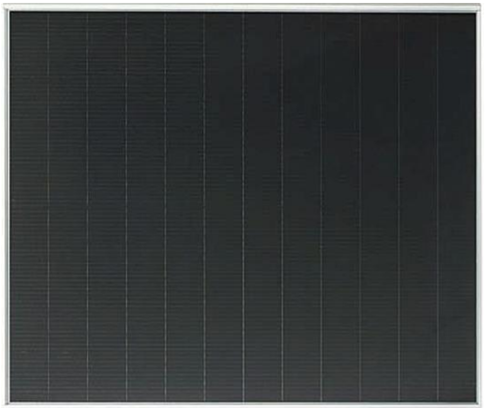


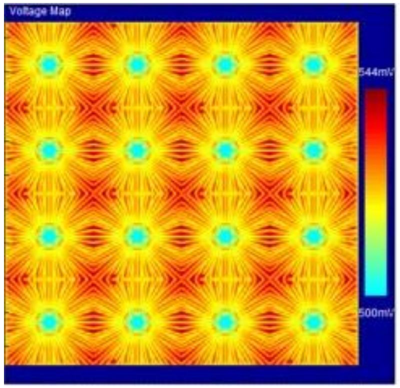


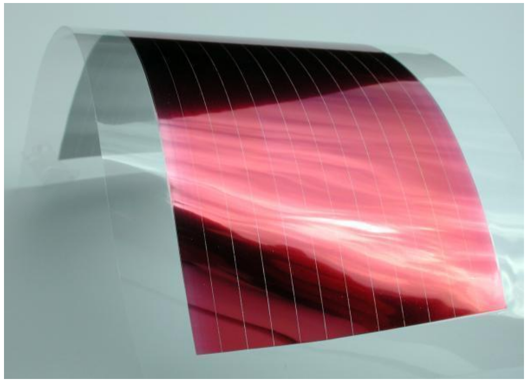
The Puzzle of Striping



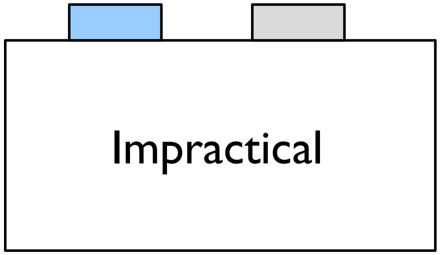




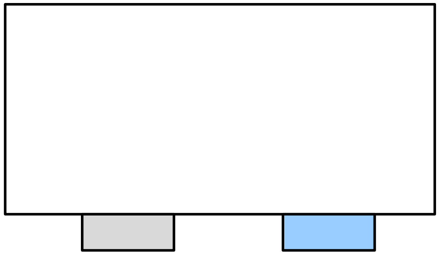




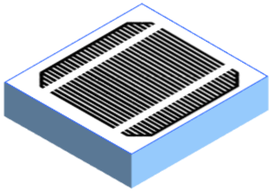
Grid arrangement of c-Si

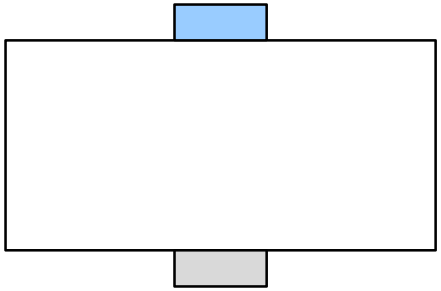


IBC

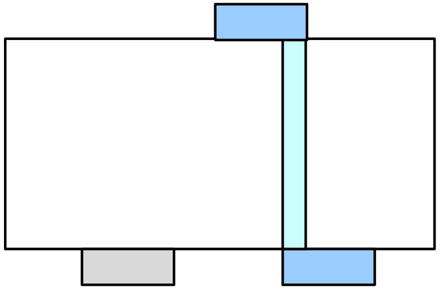


PE-BSF, PERC,
PERL, HIT

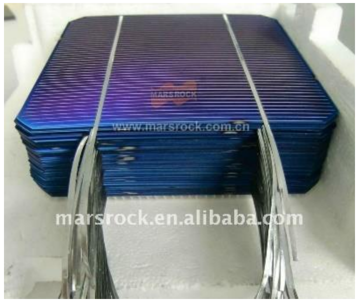


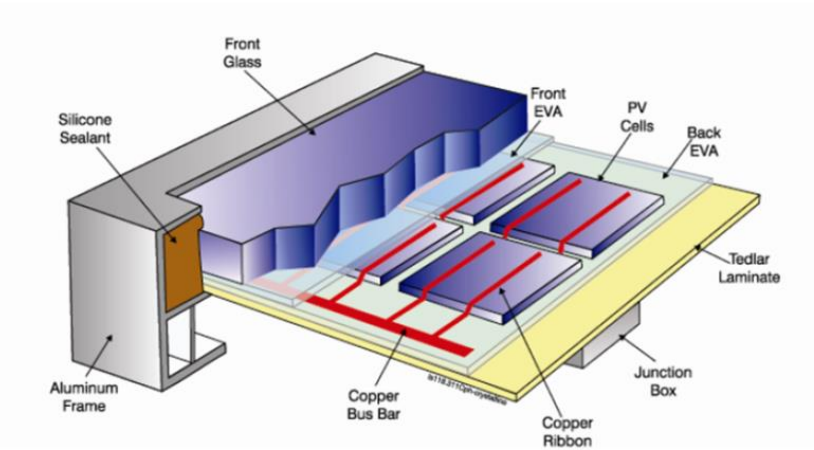


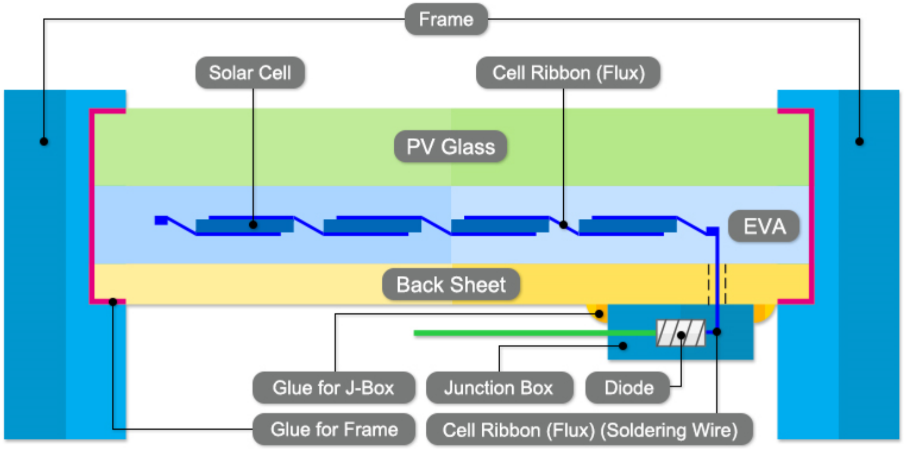
Emitter Wrap through
Metal Wrap through



A module consists of many cells







M. A. Alam, PV Lecture Notes

Outline

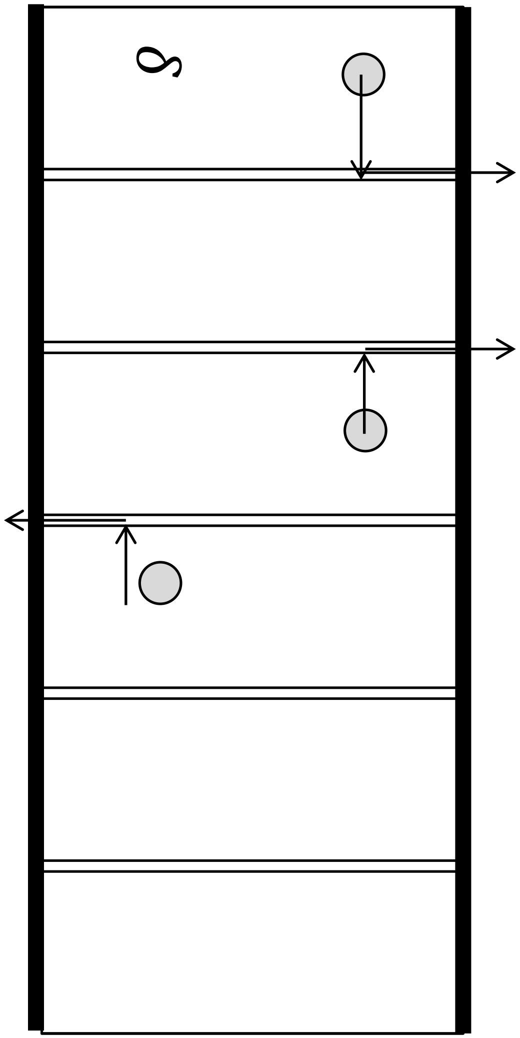
1) Three types of c-Si gridding
2) Physics of standard c-Si cell gridding
3) Physics of bifacial cell design
4) Normal grid vs. percolation grid
5) Conclusion

What about c-Si?

$$\frac{N_{opt,1}}{N_{opt,2}} = \left(\frac{J_{0,1}/\eta_1}{J_{0,2}/\eta_2}\right)^{\frac{2}{3}} = \left(\frac{W_2}{W_1}\right)$$

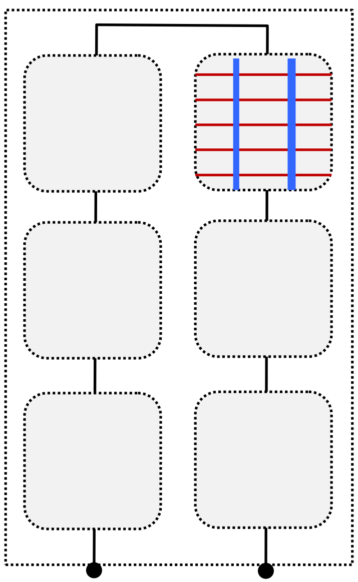
$$W^{c-Si} = W^{\alpha-Si}\left(\frac{J_0^{a-Si}/\eta_1}{J_0^{c-Si}/\eta_2}\right)$$

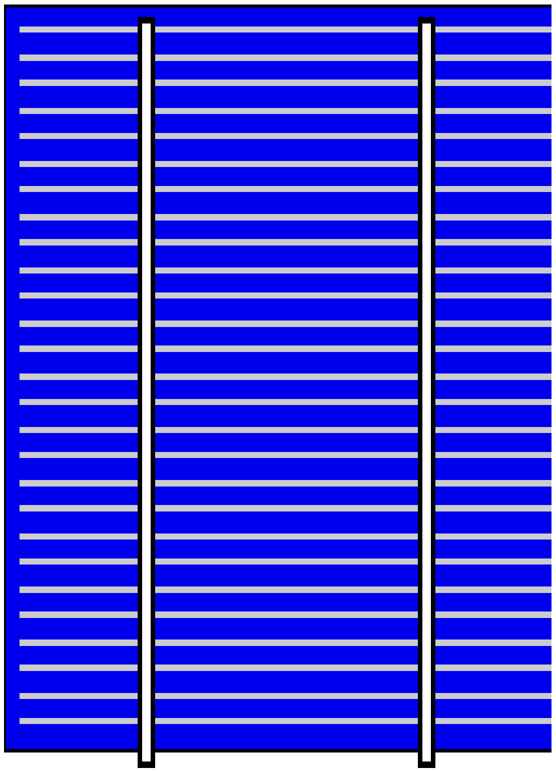
$$\sim\left(\frac{16}{40}\right)^{\frac{2}{3}}\sim 0.52\ cm$$

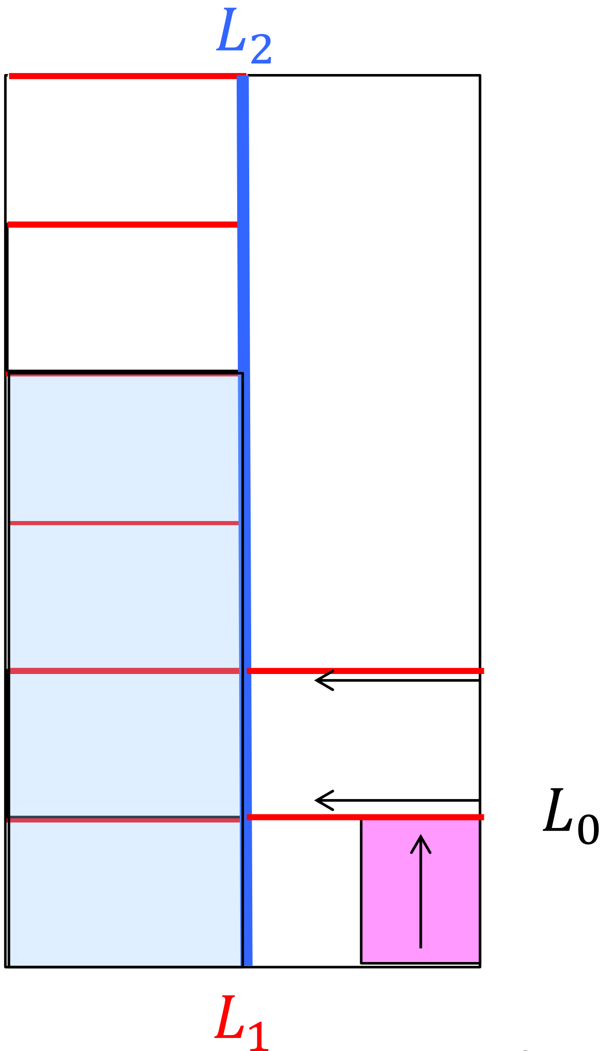


Scribing through 200 μm Si is difficult.

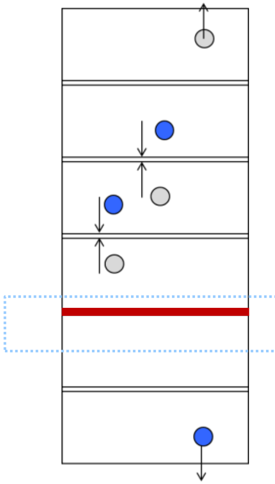
Power dissipation in hierarchical grids







Thin film solar cells: the case for rectangular cells



$$P_1 = \int_0^{L_1} dx \frac{\rho_1}{a_1 h_1} I^2(x)$$

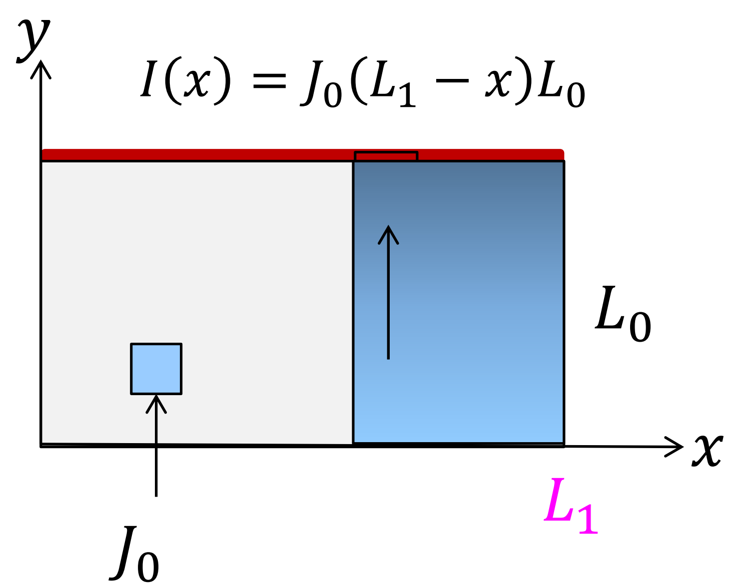
cross-section

$$P_1 = \int_0^{L_1} dx \frac{\rho_1}{a_1 h_1} J_0^2 (L_1 - x)^2 L_0^2$$

Shape factor

$$P_1 = \frac{1}{3} \frac{\rho_1 L_1}{a_1 h_1} J_0^2 L_1^2 L_0^2 = \frac{1}{3} R_{s,1} J_0^2 A_1^2$$

$$P_i = \frac{1}{3} \frac{\rho_i L_i}{a_i h_i} J_0^2 L_i^2 L_{i-1}^2 = \frac{1}{3} R_{s,i} J_0^2 A_i^2$$



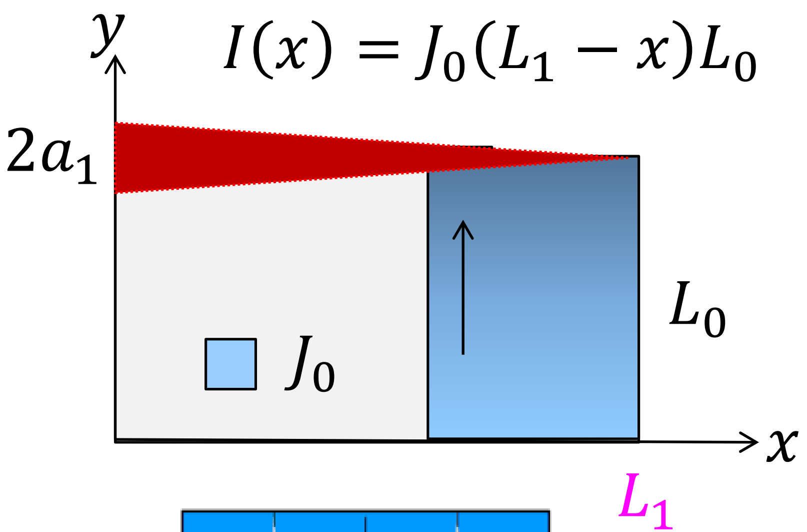
Homework: Other wire shapes may reduce power dissipation further

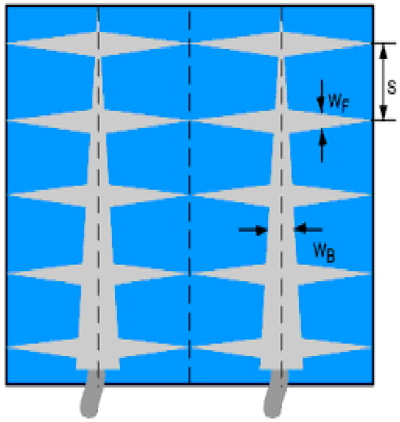
$$P_1 = \int_0^{L_1} dx \frac{\rho_1}{\frac{2a_1(L_1 - x)}{L_1} h_1} I^2(x)$$

$$P_1 = \frac{1}{4}\frac{\rho_1 L_1}{a_1 h_1} J_0^2 L_1^2 L_0^2 = \frac{1}{4} R_{s,1} J_0^2 A_1^2$$

$$P_i = \frac{1}{4}\frac{\rho_i L_i}{a_i h_i} J_0^2 L_1^2 L_0^2$$

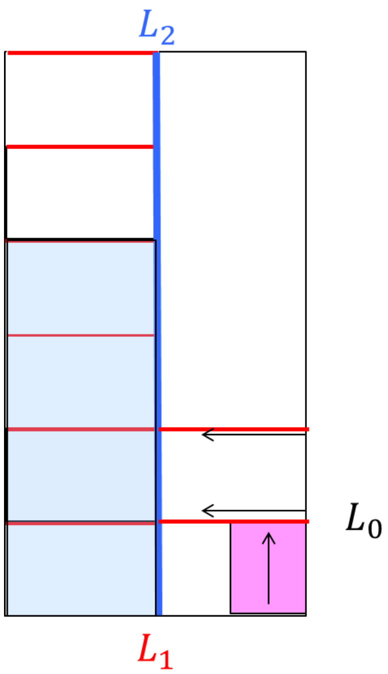
$$R_s = \int_0^{L_1} dx \frac{\rho_1}{\frac{2a_1(L_1 - x)}{L_1} h_1} \to \infty$$





Hierarchical Design Rules

$$P_i = \frac{1}{3}\frac{\rho_i L_i}{a_i h_i} J_0^2 L_i^2 L_{i-1}^2 = \frac{1}{3} R_{s,i} J_0^2 A_i^2$$



Constant dissipation

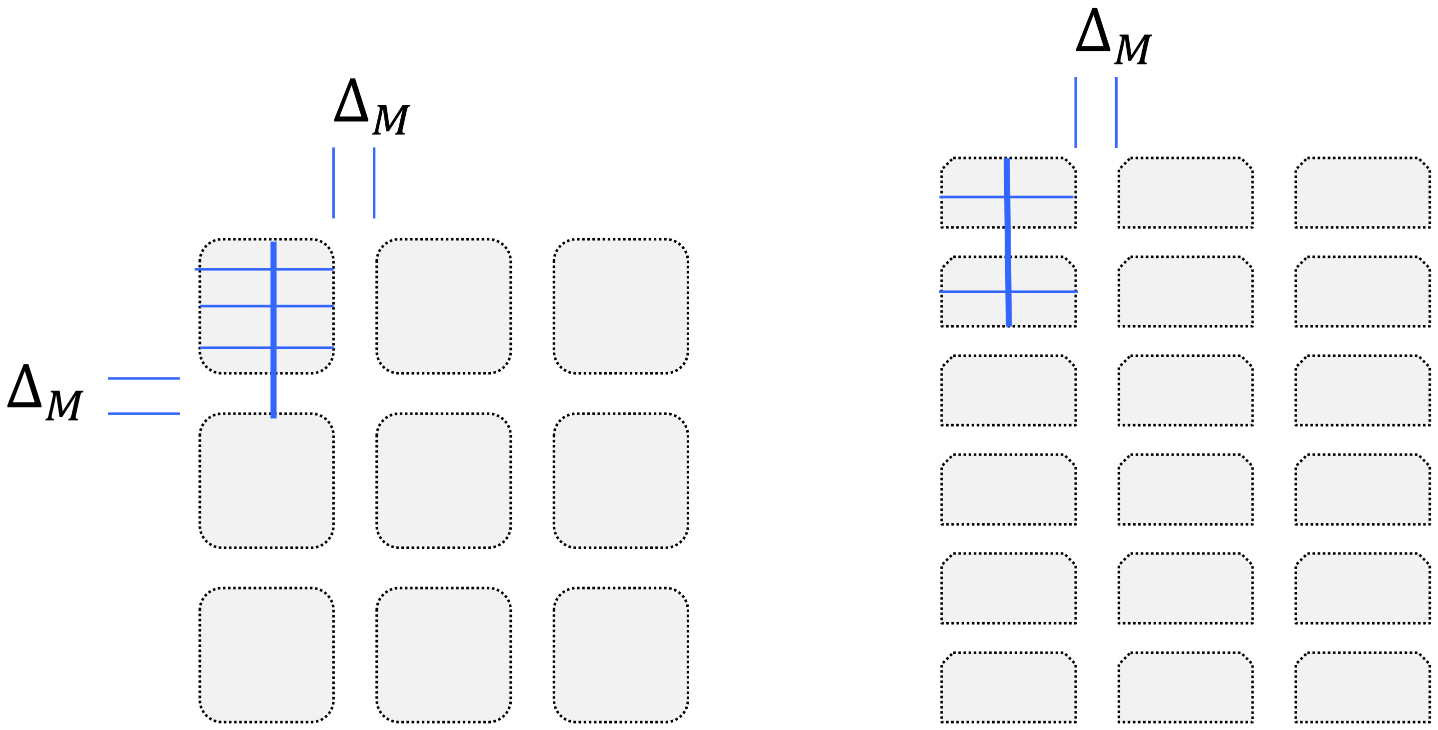
$$P_{i+1} = N_i P_i = \frac{L_{i+1}}{L_i} P_i$$

$$\frac{L_{i+1}}{L_i} \times \frac{1}{3}\frac{\rho_i L_i}{a_i h_i} J_0^2 L_i^2 L_{i-1}^2 = \frac{1}{3}\frac{\rho_{i+1} L_{i+1}}{a_{i+1} h_{i+1}} J_0^2 L_{i+1}^2 L_i^2$$

$$\frac{a_{i+1}}{a_i} = \left(\frac{L_{i+1}}{L_{i-1}}\right)^2$$

$\sum_i^n a_i L_i =$ const shading.

Physics of Half-Cells

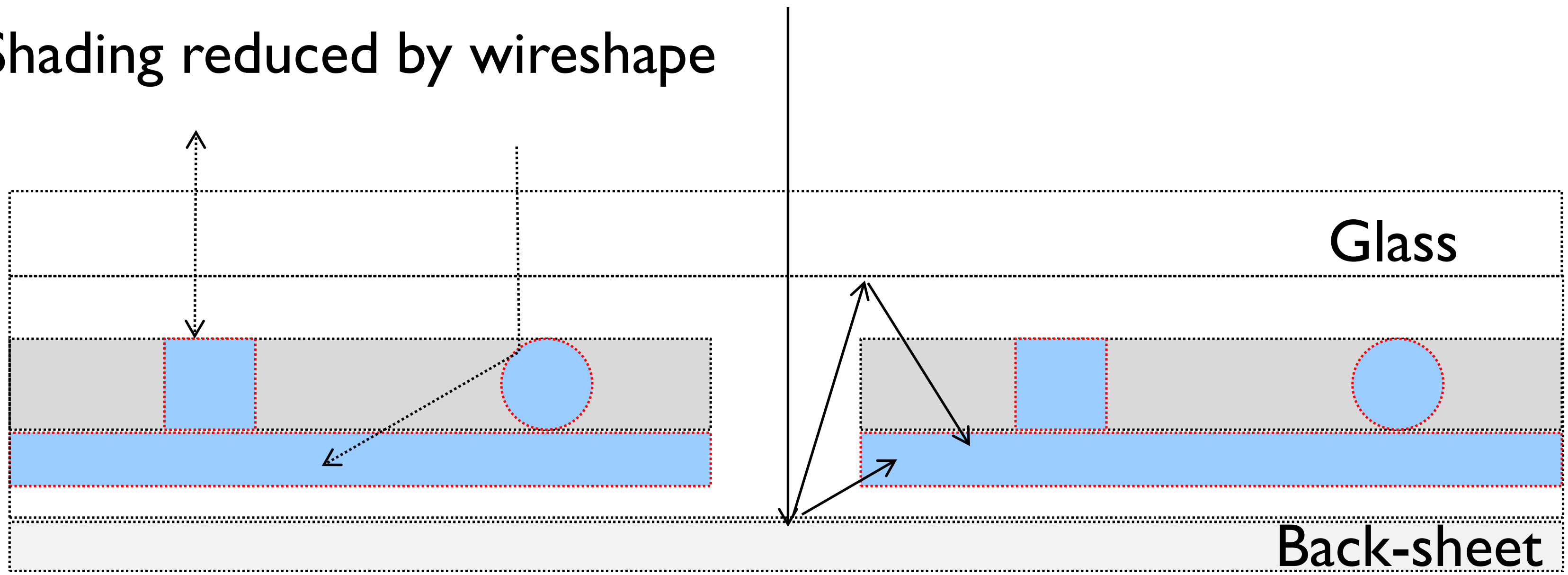


Mimicking thin-film PV

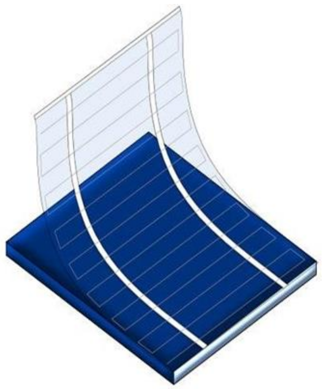
Excess resistance loss cut in half, but increased dead area.

Not as bad as it seems?

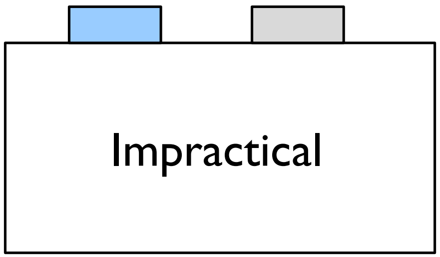
Shading reduced by wireshape



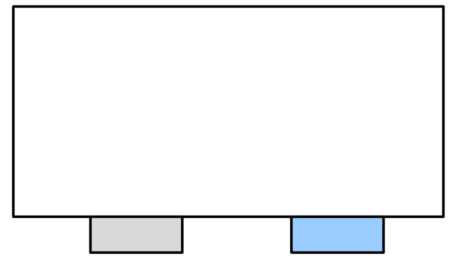
Internal reflection



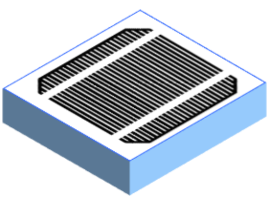
Grid arrangement of c-Si

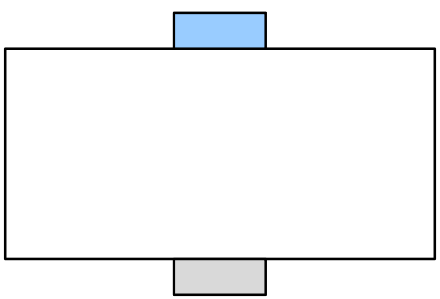


IBC

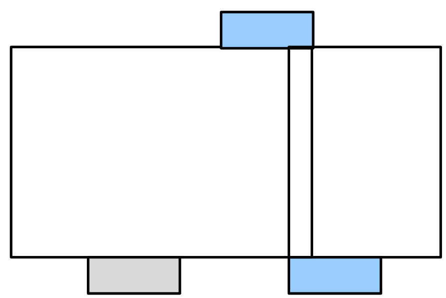


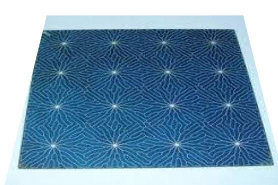
PE-BSF, PERC,
PERL, HIT



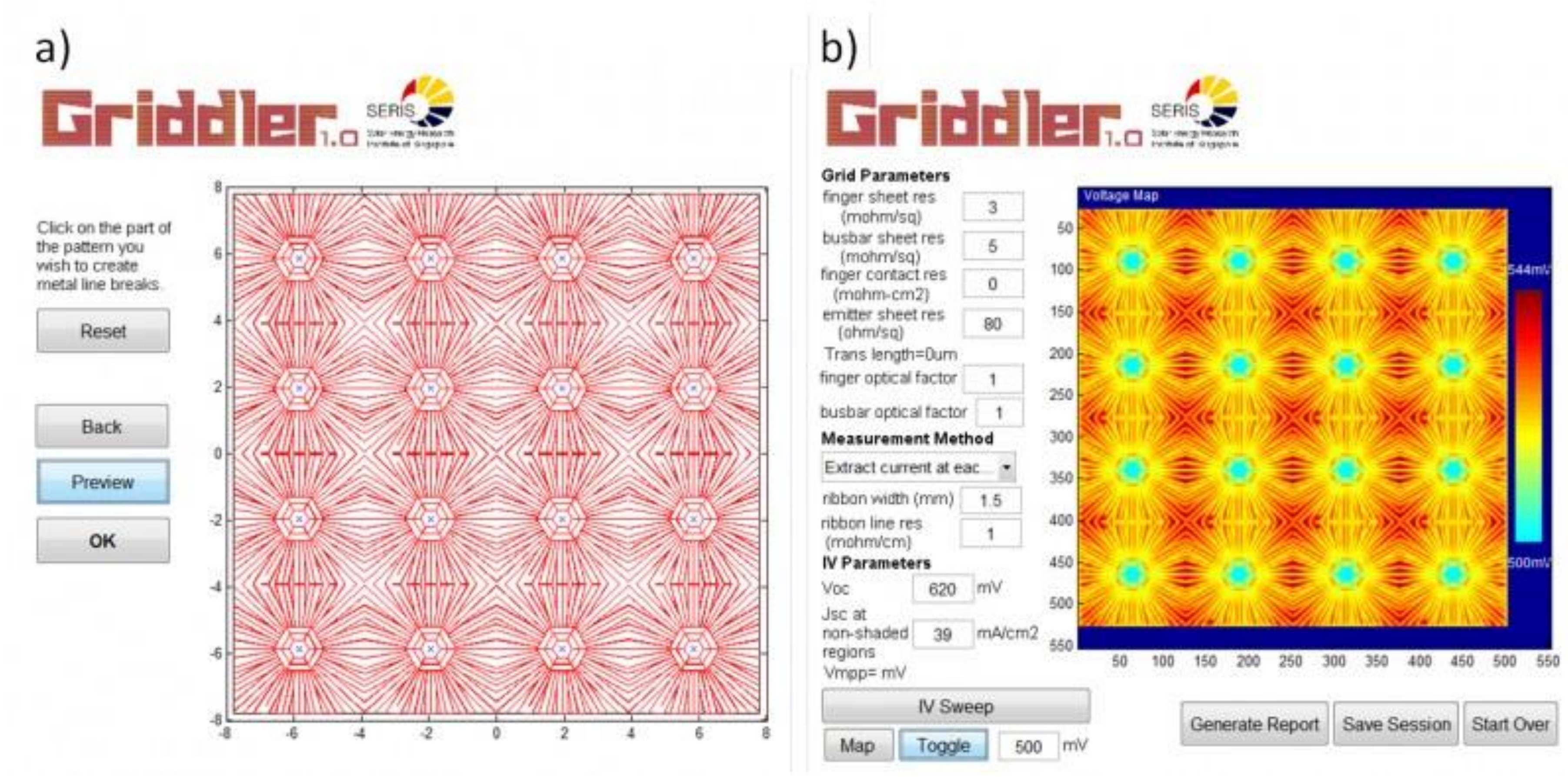


Emitter Wrap through
Metal Wrap through



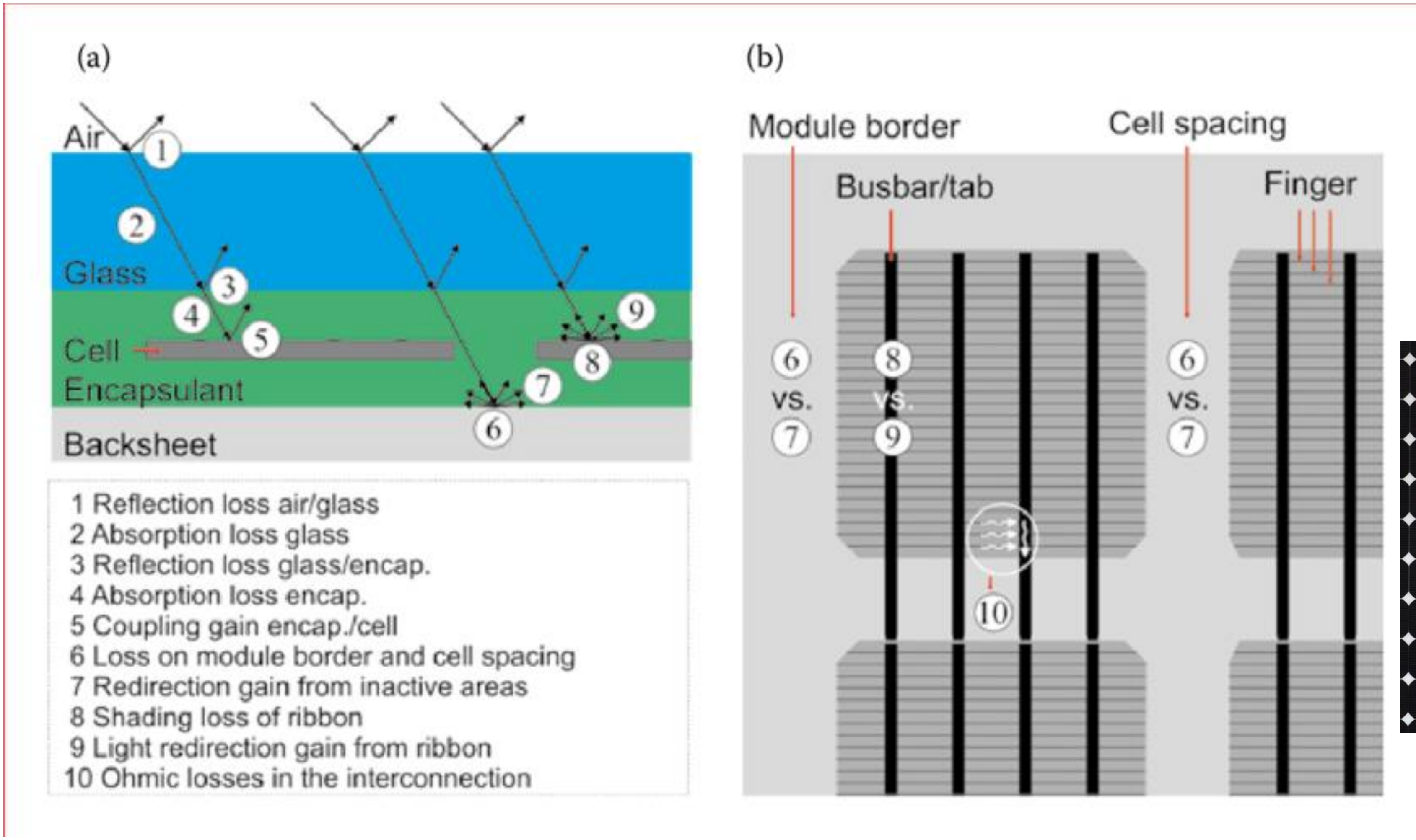


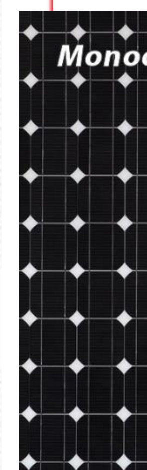
Simulation Tools: Griddler



Simulation is not an issue; the question is what to simulate?

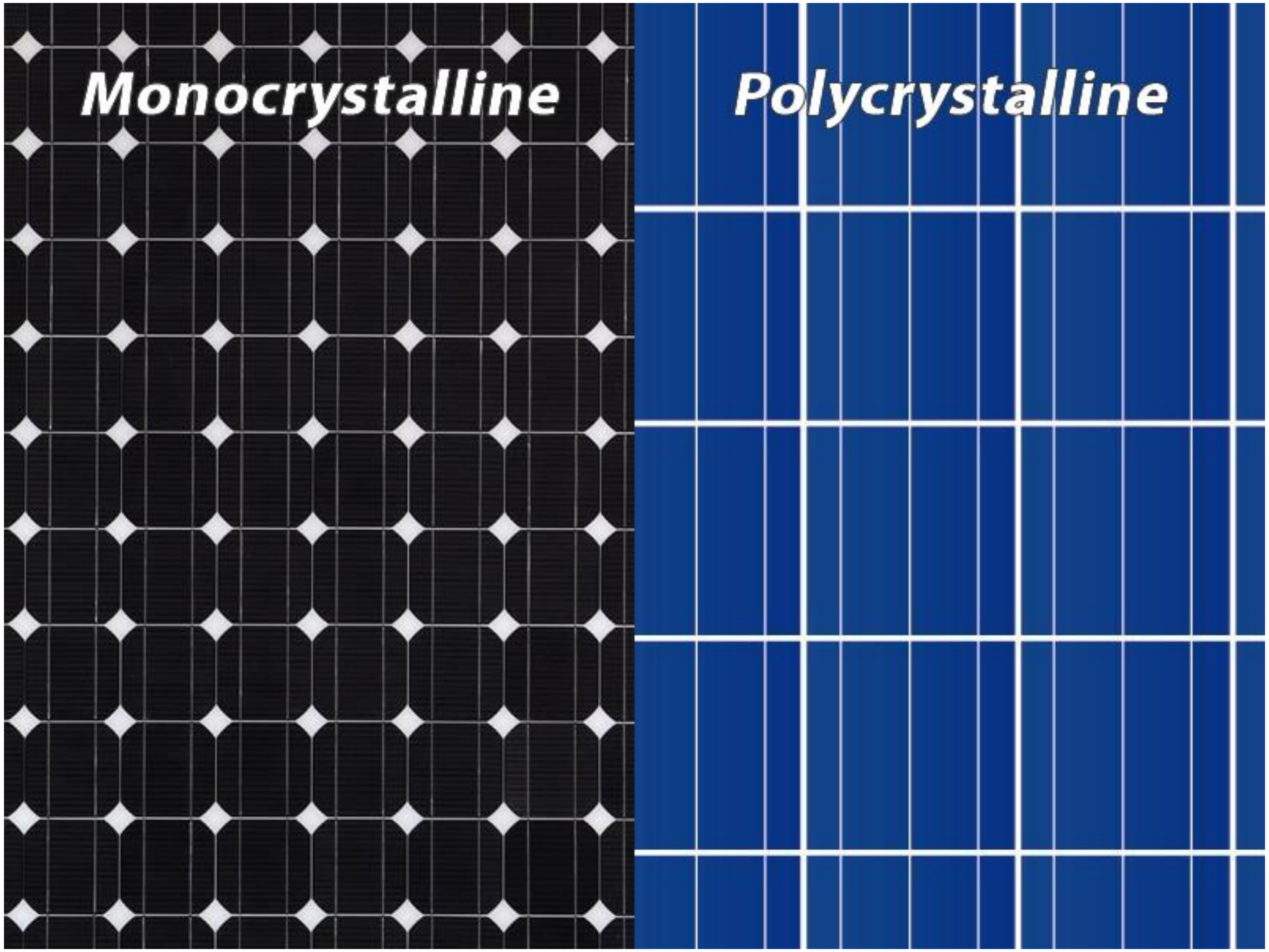
Module optical design





M. A. Alam, PV Lecture Notes

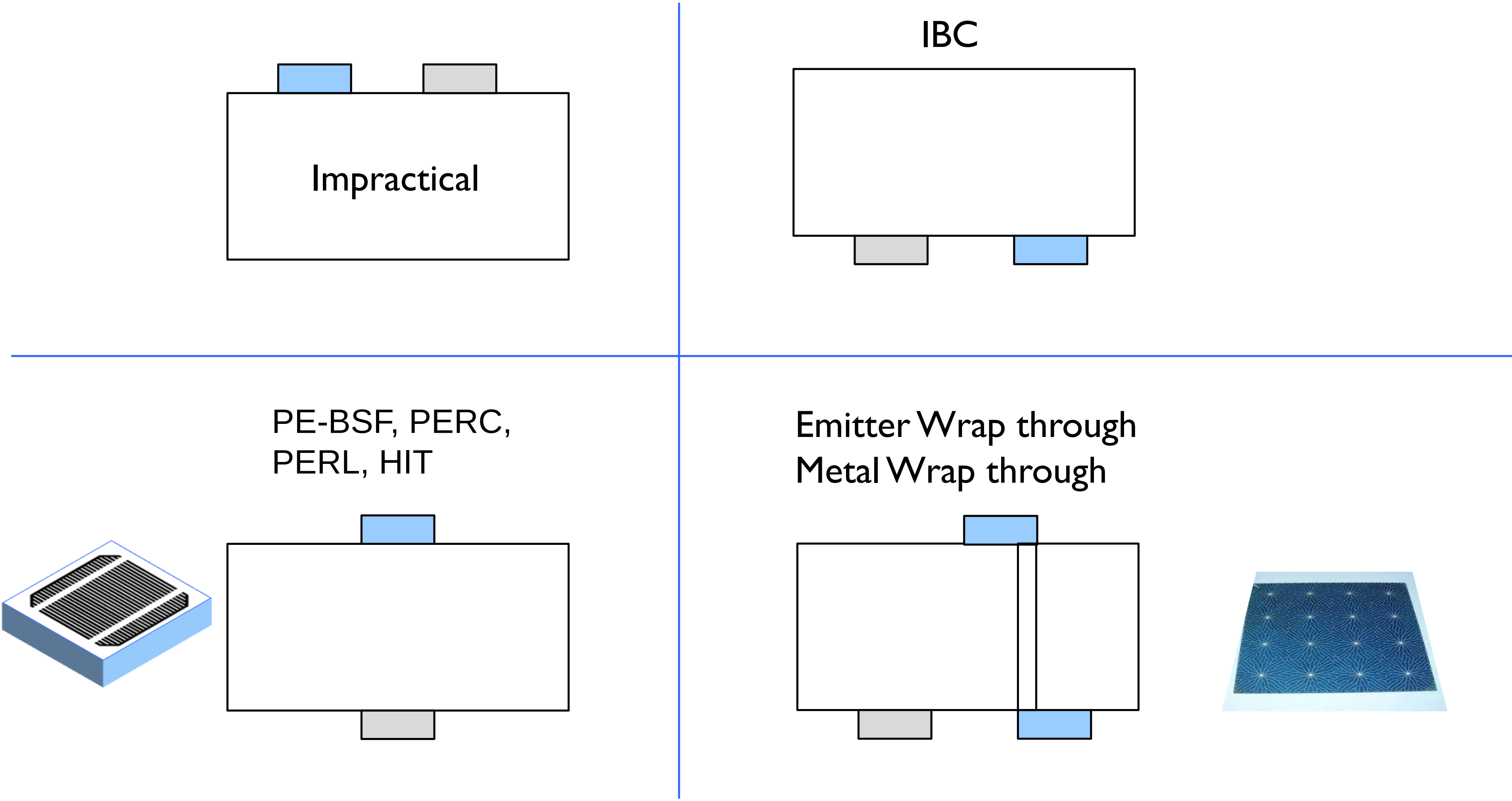
Optical design: Dead area loss



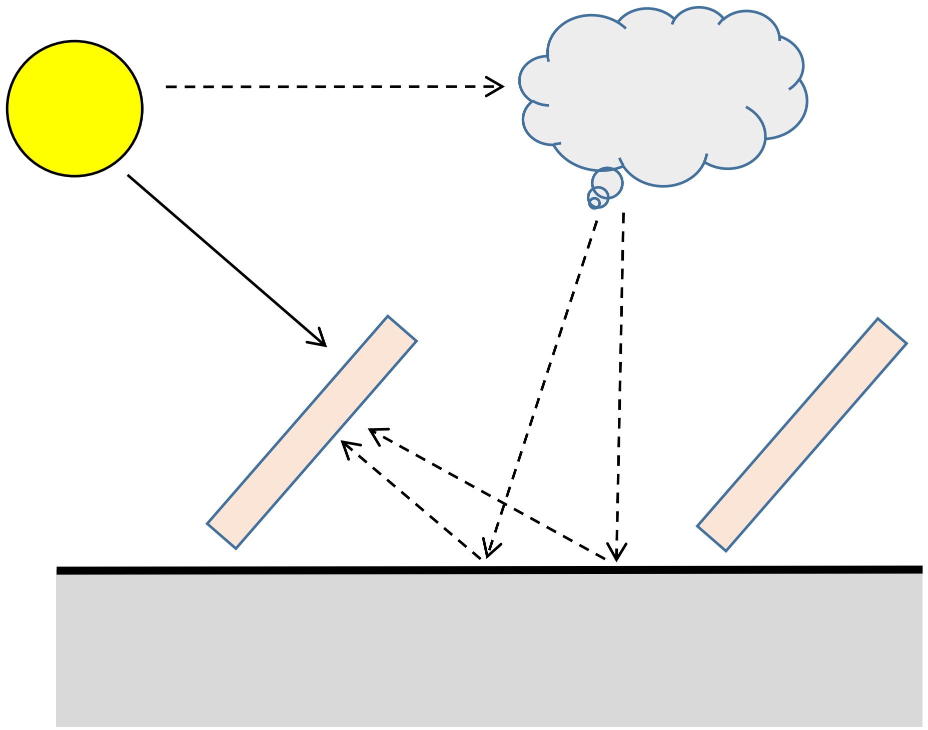
Outline

1) Three types of c-Si gridding
2) Physics of standard c-Si cell gridding
3) Physics of bifacial cell design
4) Normal grid vs. percolation grid
5) Conclusion

Grid arrangement of c-Si



Theory of bifacial grid



Recall: monofacial solar cells

$$P_j = P_o \times N = (J_0^2 \rho) \times \frac{(n+1)^3}{3(3n+1)} \times \left(\frac{A^3}{L^2}\right) \times N$$

$$= (J_0^2 \rho) \times \frac{(n+1)^3}{3(3n+1)} \times \left(\frac{A_T}{N}\right)^3 (N/L^2) = c_1/N^2$$

$$P_{scribe} = (N-1)\delta \times L P_{ideal}/A_T \sim C_2 N$$

$$P_{ideal} = \left(\frac{I}{N}\right) \times (V \times N) = C_0$$

Recall: Optimum number of monofacial cells

$$P_j = c_1/N^2 \qquad P_{ideal} = C_0 \qquad P_{scribe} \sim C_2 N$$

$$P_{out} = P_{ideal} - P_j - P_{scribe}$$

$$= C_0 - C_1/N^2 - c_2 N$$

$$N_{opt} = (2C_1/c_2)^{\frac{1}{3}}$$

Homework: Theory of bifacial grid

Joule Shadow

$$P_{out} = P_o(1+R) - P_{j,R} - P_{s,R} - P_{j,F} - P_{s,F}$$

$$= C_0 - C_{1,R}/N_R^2 - C_{2,R}N_R - C_{1,F}/N_F^2 - c_{2,F}N_F$$

$$C_{1,F} = (J_0^2\ \rho_F\ /3)\ (A_T^3/L^2)$$

$$C_{2,F} = P_0\delta$$

$$C_{1,R} = (J_0^2\ \rho_R\ /3)\ (A_T^3/L^2)$$

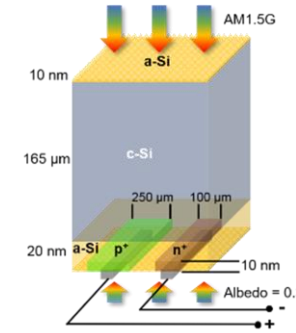
$$C_{2,R} = RP_0\delta$$

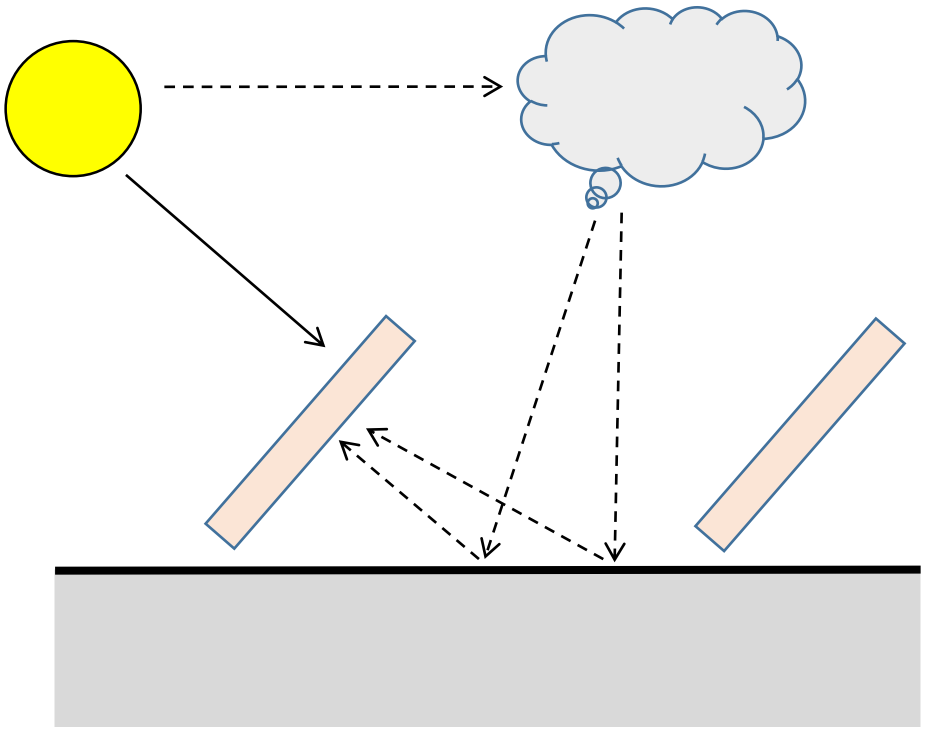
$$\frac{dP_{out}}{dN_F} = 0 \qquad N_F = \left(\frac{2C_{1,F}}{P_0}\right)^{\frac{1}{3}}$$

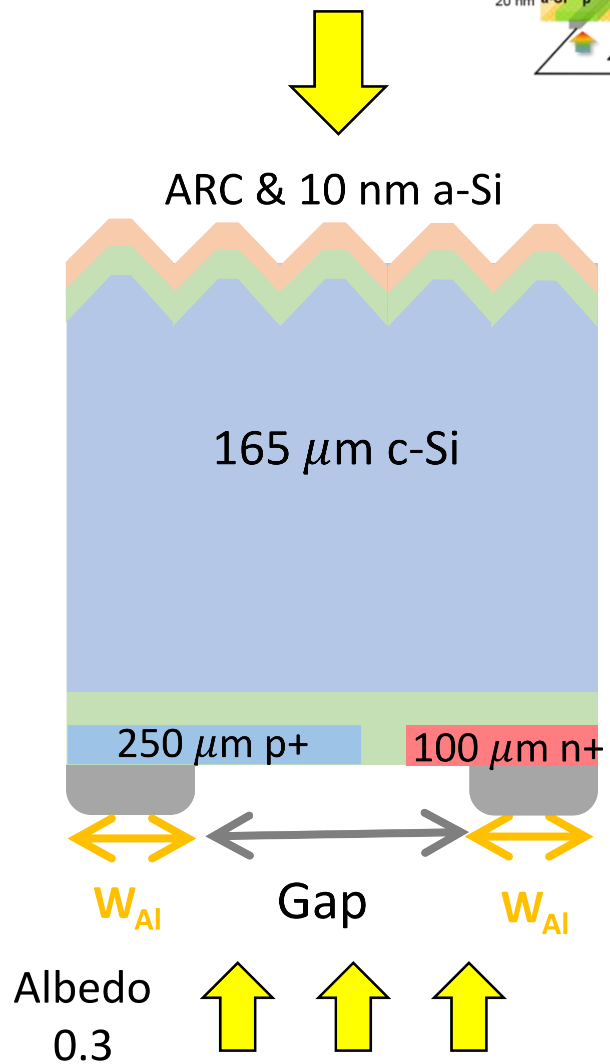
$$\frac{dP_{out}}{dN_B} = 0 \qquad N_R = \left(\frac{2C_{1,R}}{RP_0}\right)^{\frac{1}{3}}$$

$$\frac{N_F}{N_R} = \left(R\,\frac{\rho_T}{\rho_B}\right)^{\frac{1}{3}}$$

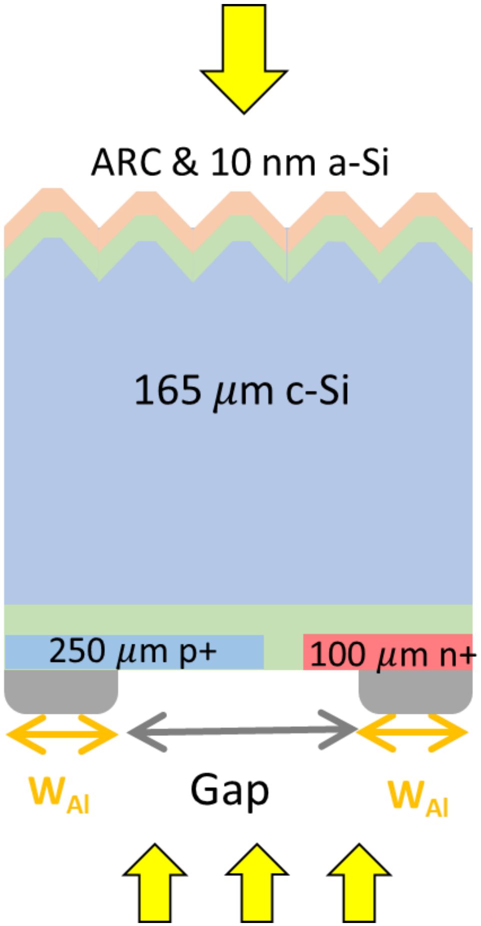
Theory of IBC bifacial grid







Shadow vs. resistance optimization



$$P_{out}(w,\alpha) = P_{ideal}(\alpha) - P_r(w,\alpha) - P_s(w,\alpha)$$

$$P_{ideal}(\alpha) = P_{ideal}(1+\alpha)$$

$$P_s(w,\alpha) = P_{ideal}\,(1-w)\alpha$$

$$P_r(w,\alpha) = kJ_0^2(1+\alpha w)^2\left(\frac{\rho}{(1-w)t_{Al}}\right)$$

$$w \equiv W_g/W_p$$

$$W_{Al} = W_p - W_g \equiv W_p(1-w)$$

Optimum gap and maximum power

$$P_{out}(w,\alpha) = P_{ideal}(\alpha) - P_r(w,\alpha) - P_s(w,\alpha)$$

$$dP_{out}/dw = 0$$

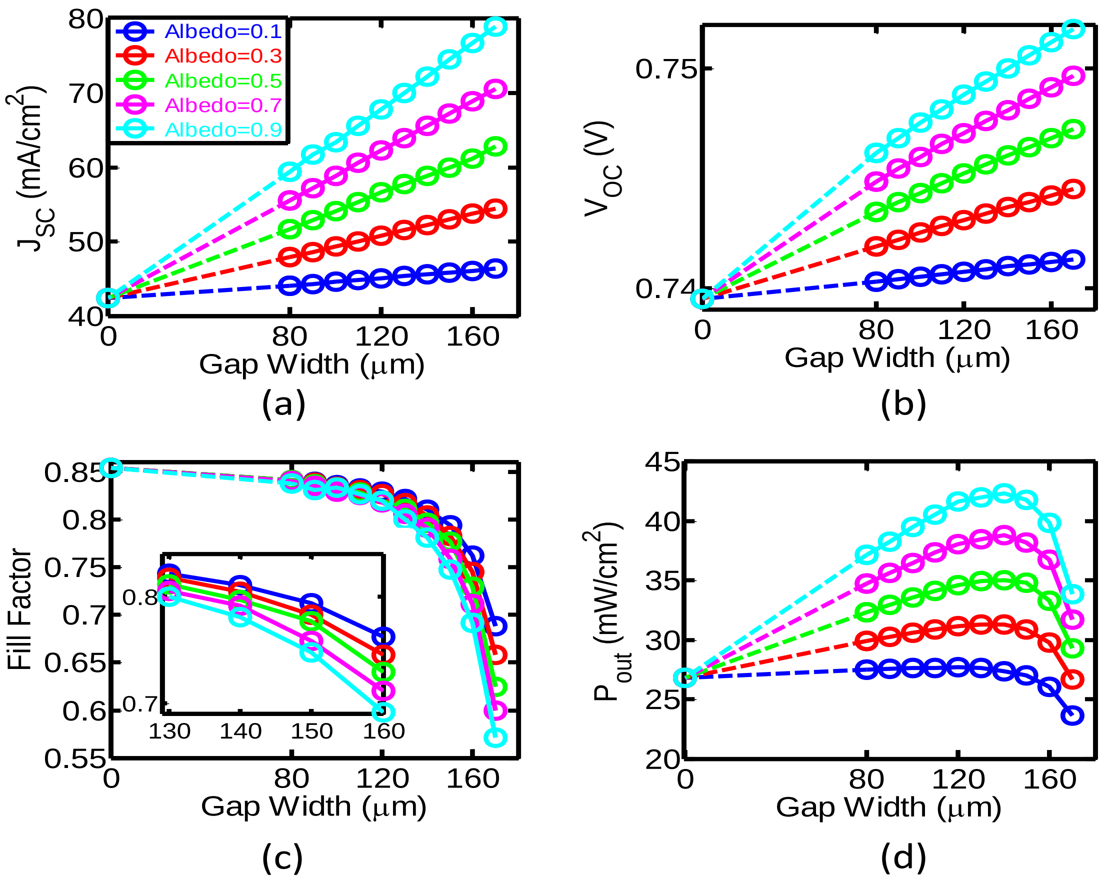
Optimum gap:

$$w_{opt} = 1 - \frac{1+\alpha}{\sqrt{\alpha\,(\alpha + c)}}$$

Maximum power:

$$P_{out} = (1+\alpha)\left(1 - 2\sqrt{\frac{\alpha}{c}}\right)$$

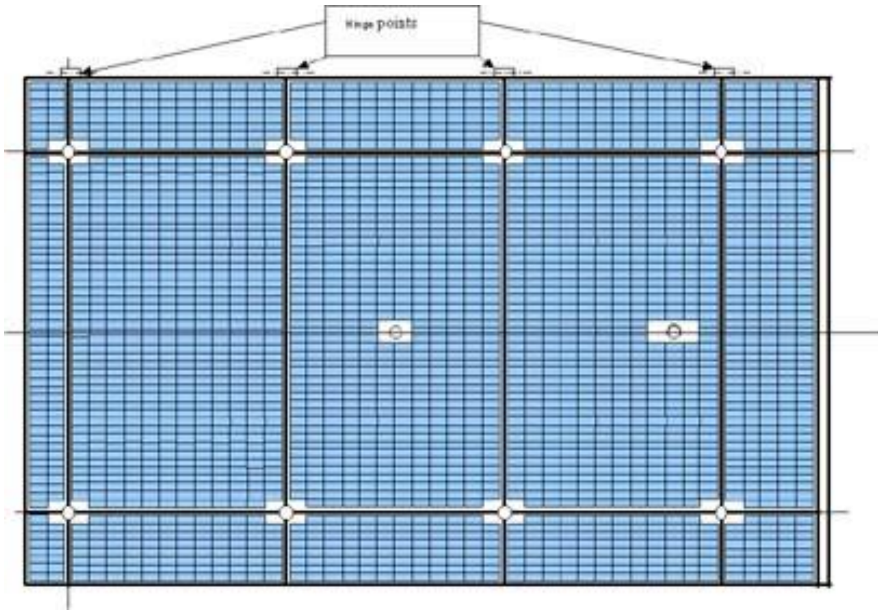
$$c^{-1} \equiv J_0^2\left(\frac{L_{Al}^2\rho}{2t_{Al}} + \rho_c\right)/P_0$$

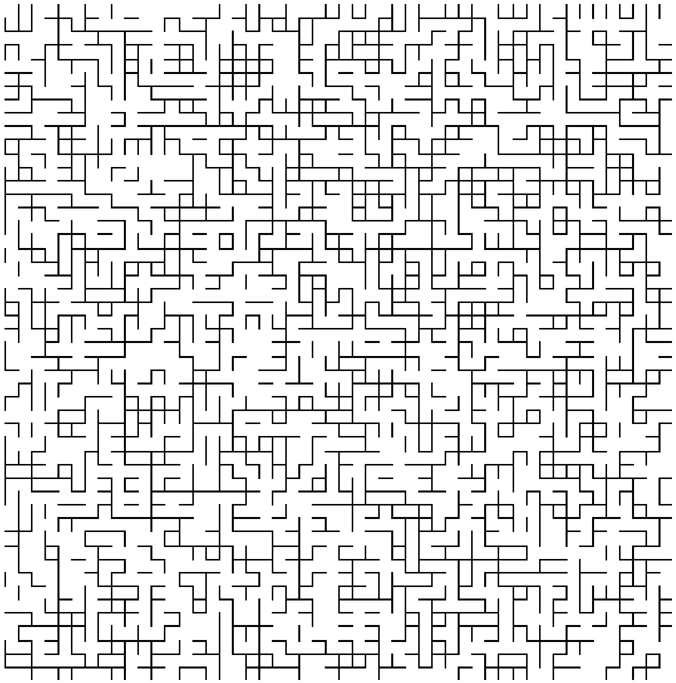


Outline

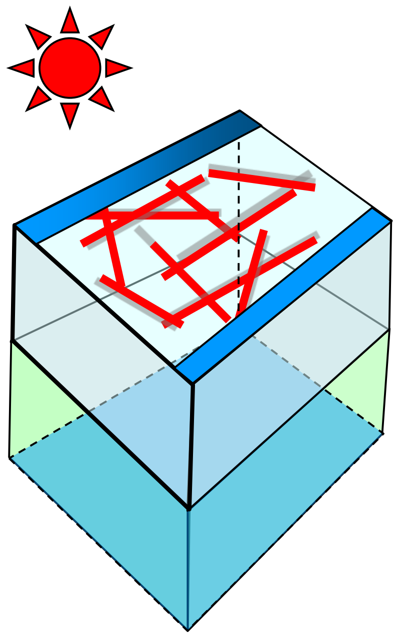
1) Three types of c-Si gridding
2) Physics of standard c-Si cell gridding
3) Physics of bifacial cell design
4) Normal grid vs. percolation grid
5) Conclusion

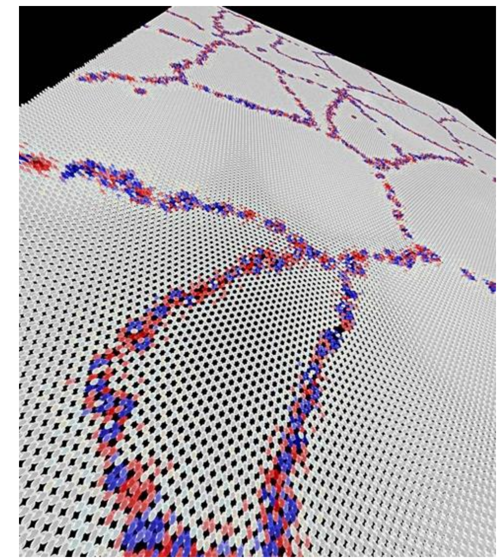
Ordered vs. Percolating systems Robustness against Cracks

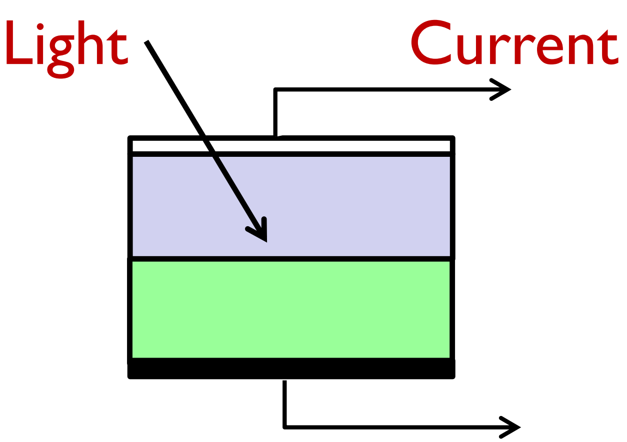


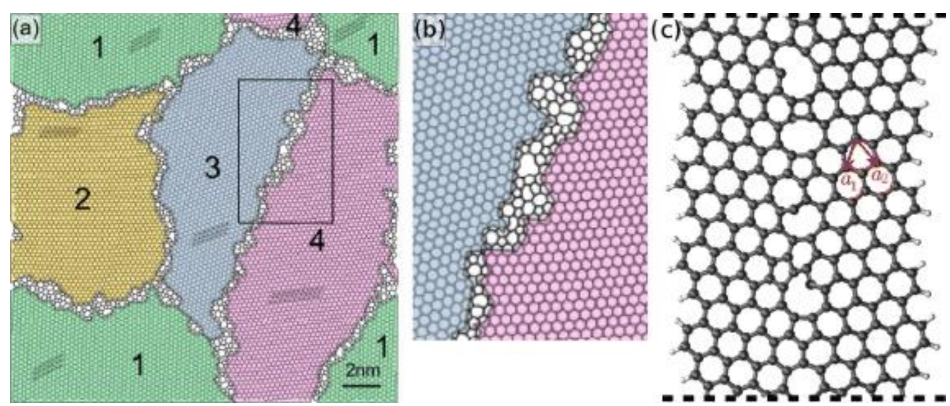


Conductivity vs. Transparency





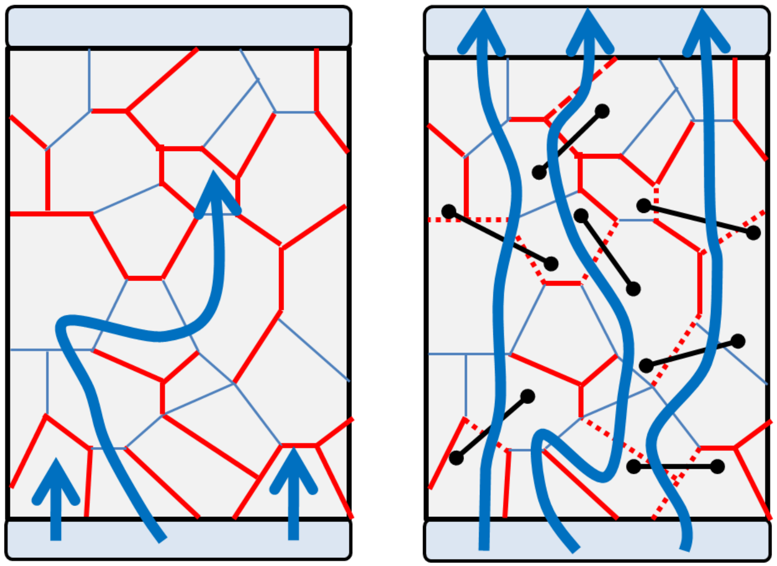


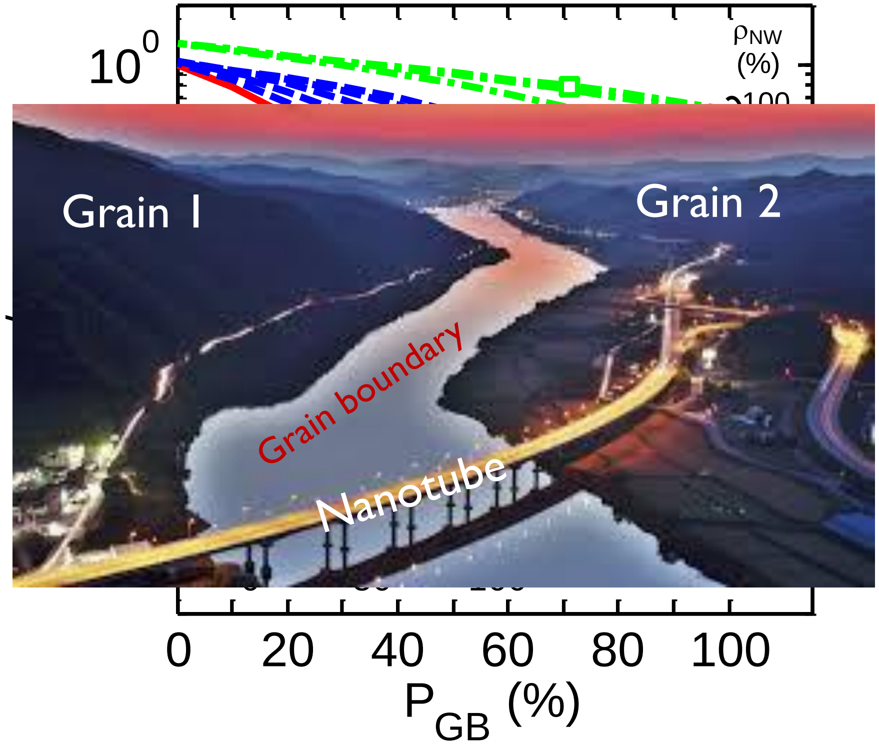


ITO costly, unstable, and prone to shunt formation

‘Positive’ Percolation Doping

C. Jeong Nano Letters, 2011.



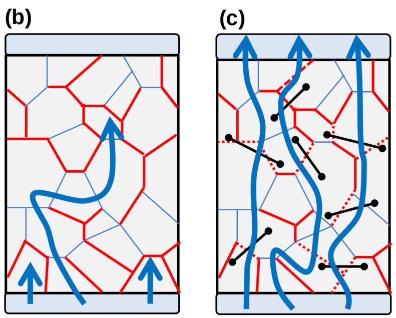


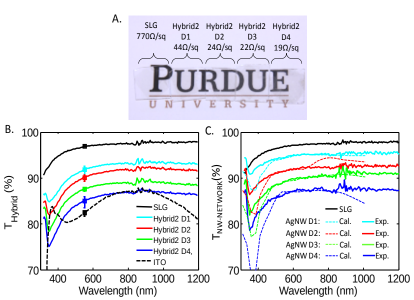
$$G = \frac{\sigma \times W}{L}$$

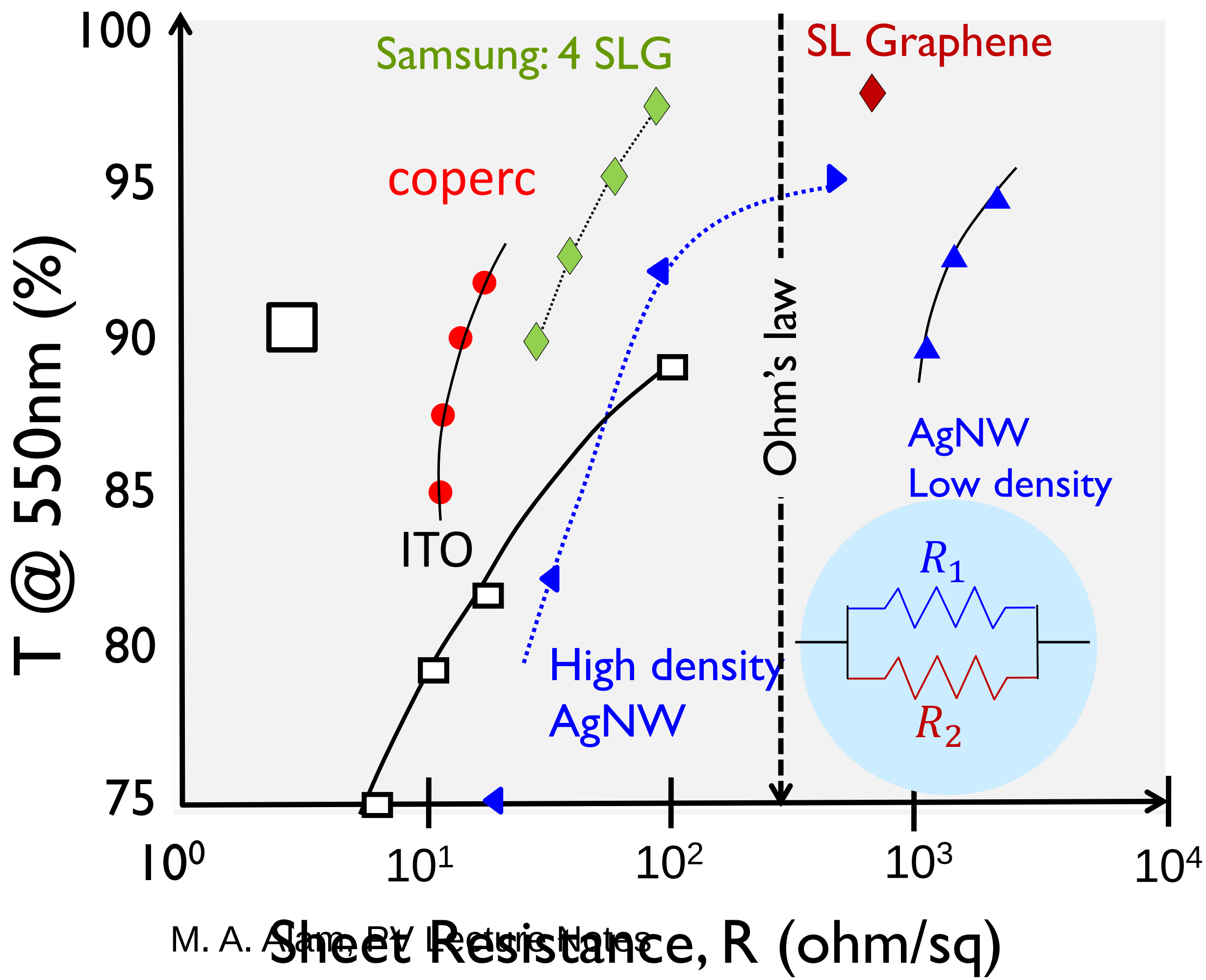
Percolating doping manipulates transport channels

World record performance!

~10 ohms/sq at 90% transmission







Conclusions

- Series resistance plays a deeply important role in the design of solar modules.
- c-Si PV has additional series resistance compared to thin-film solar cell. Hierarchical gridding keeps the "excess resistance" in c-Si cell to a minimum. Modern simulation tools are helpful.
- . C-Si industry is adopting half-cell approach to mimic thin-film PV.
- Bifacial technologies require special grid design.

Self-assessment

1. How does half-cell reduce series resistance loss. How does the strategy compare to that of thin-film solar cells.

2. For the same series resistance, c-Si solar cells will always have higher series resistance loss compared to thin-film solar cells. Explain.

3. What is the essential difference between nutrient flow in a leaf and that of current collection in a solar cell?

4. Mention a few key characteristics of the bifacial solar grids.

5. Emitter-wrap through, metal-wrap-through, smart-grid, and IBC cells all reduce the following loss mechanism of a crystalline solar cell.

References

Back-surface field: https://www.youtube.com/watch?v=i4jqmTR-rv4

HIT cells: https://www.youtube.com/watch?v=FfU9jxGnYzs
https://www.youtube.com/watch?v=HaCAwTIc9QM
https://www.youtube.com/watch?v=SLvMjSHoVfk

PERC (PERL, HIT; PERT, PERF) Emitter-Wrap through
https://www.youtube.com/watch?v=fVhjVWwvOCI

Optimal tilt (very shallow tilt)
https://www.youtube.com/watch?v=mb0l17XxQBY

Tilt calculator https://www.youtube.com/watch?v=MNSu9Rnlm9c