

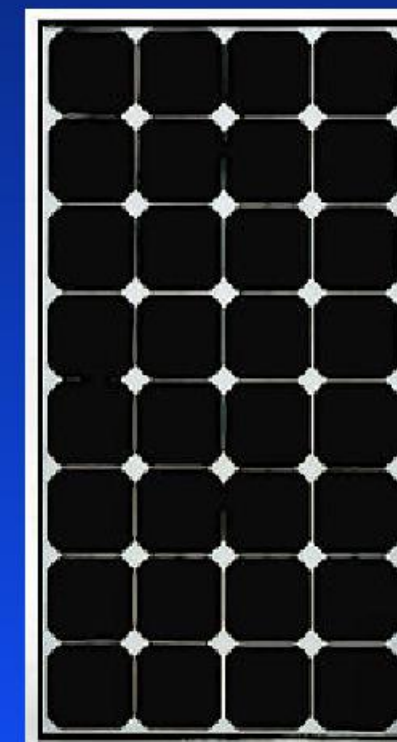


Australian Centre for Advanced Photovoltaics

“Evolution of High Efficiency Silicon Solar Cell Design”

Martin A. Green

University of New South Wales





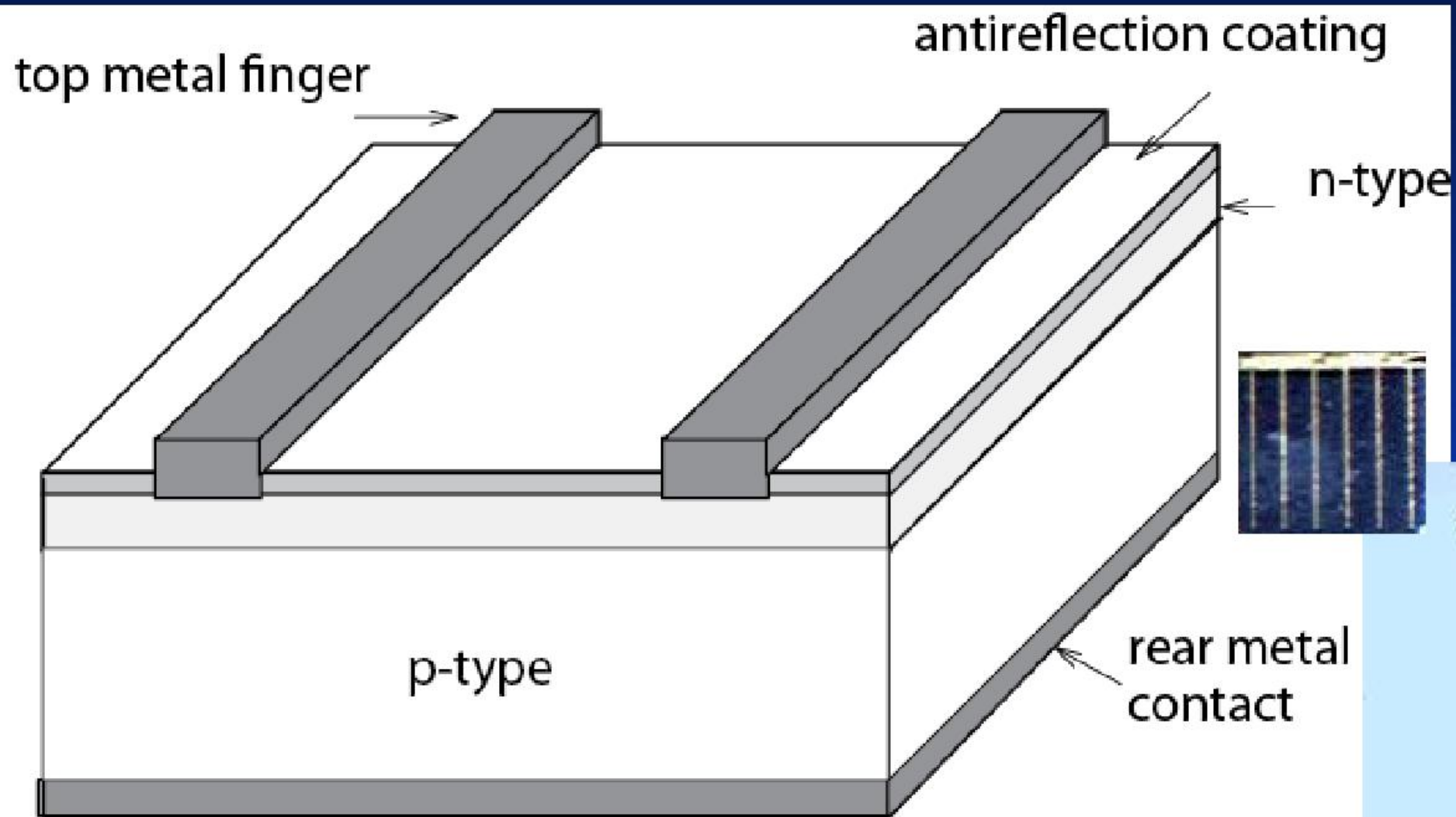
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- Questions-



ACAP

Conventional space cell

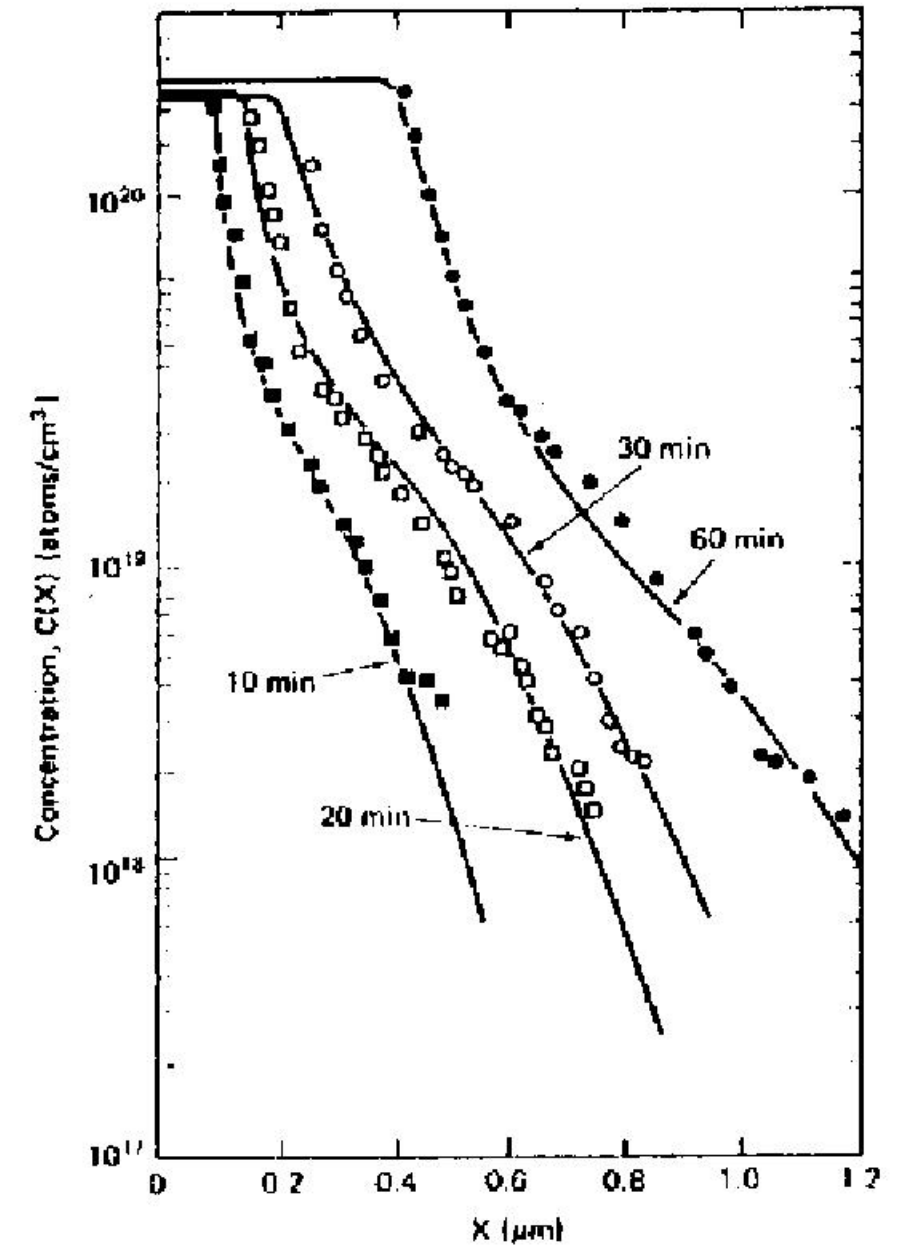
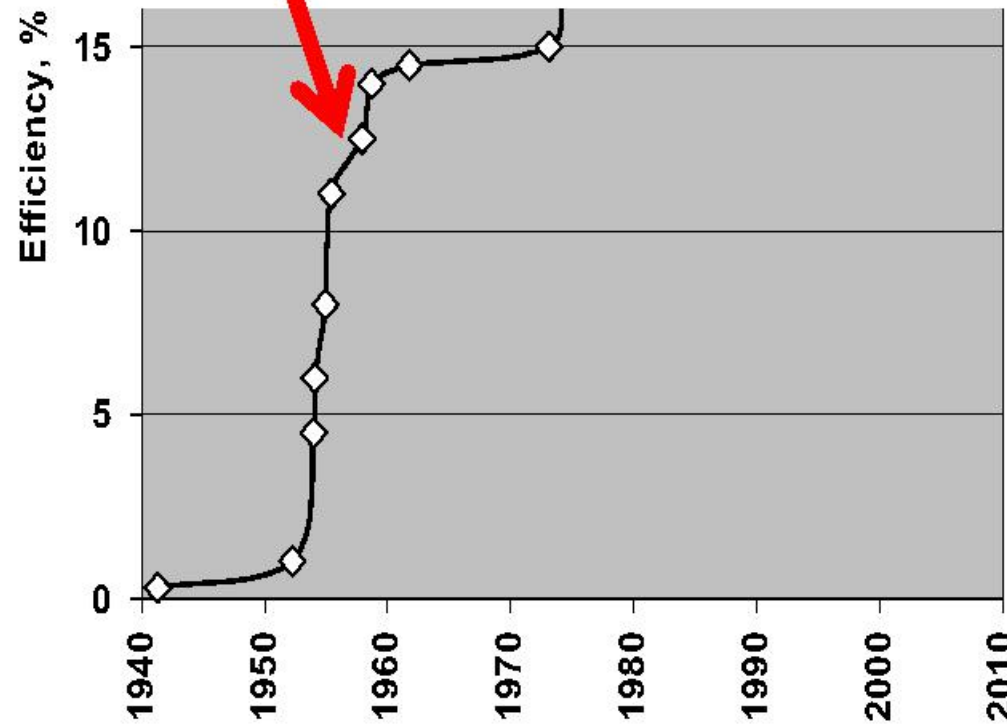
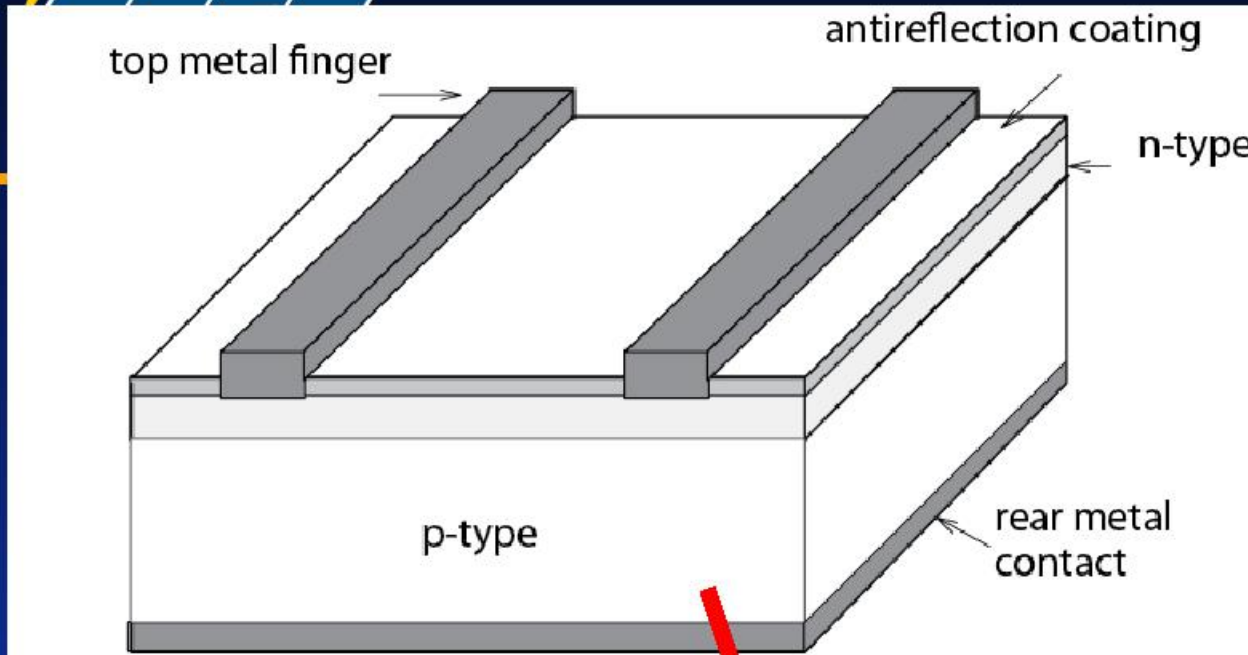


Vanguard I (1958)



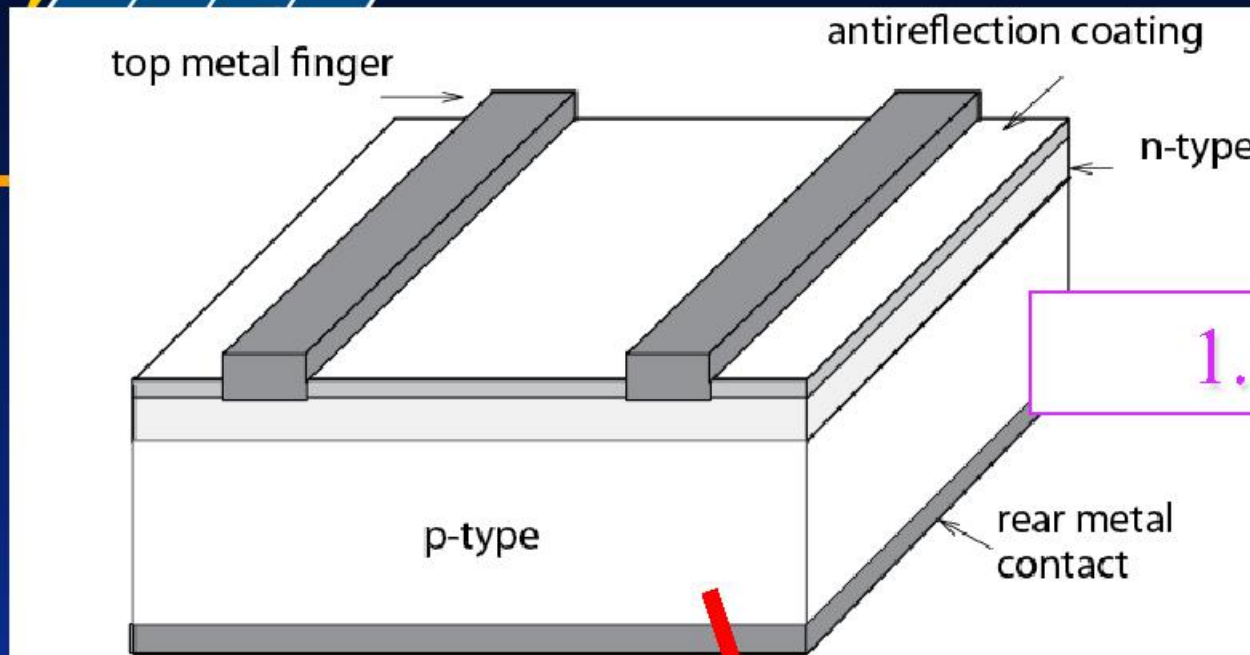


Conventional space cell

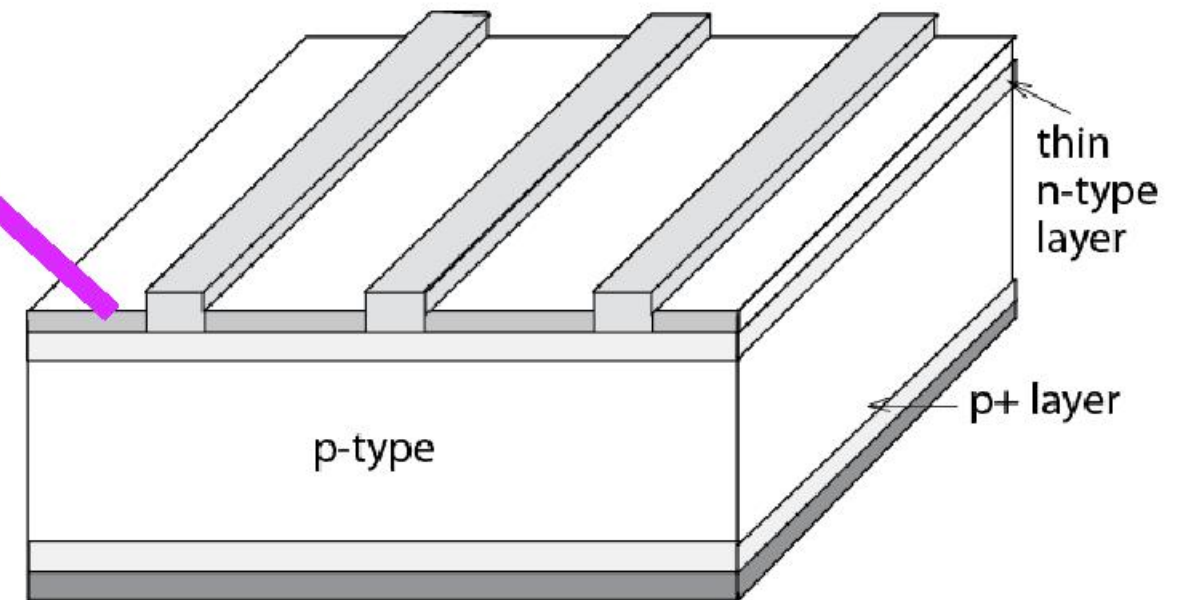
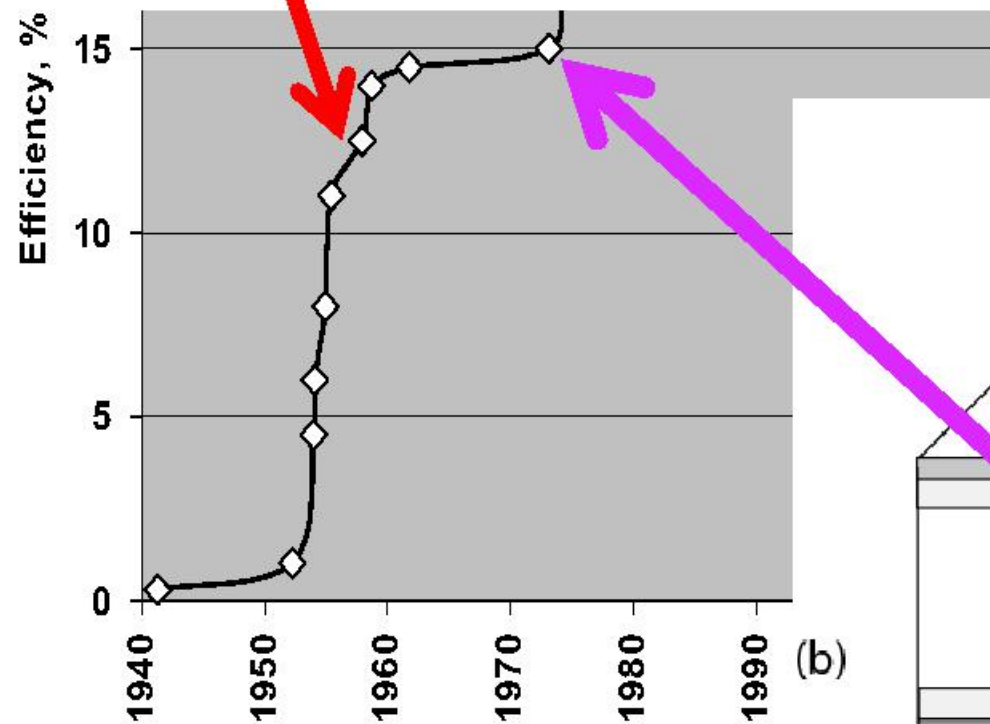




“Violet” cell (1972)

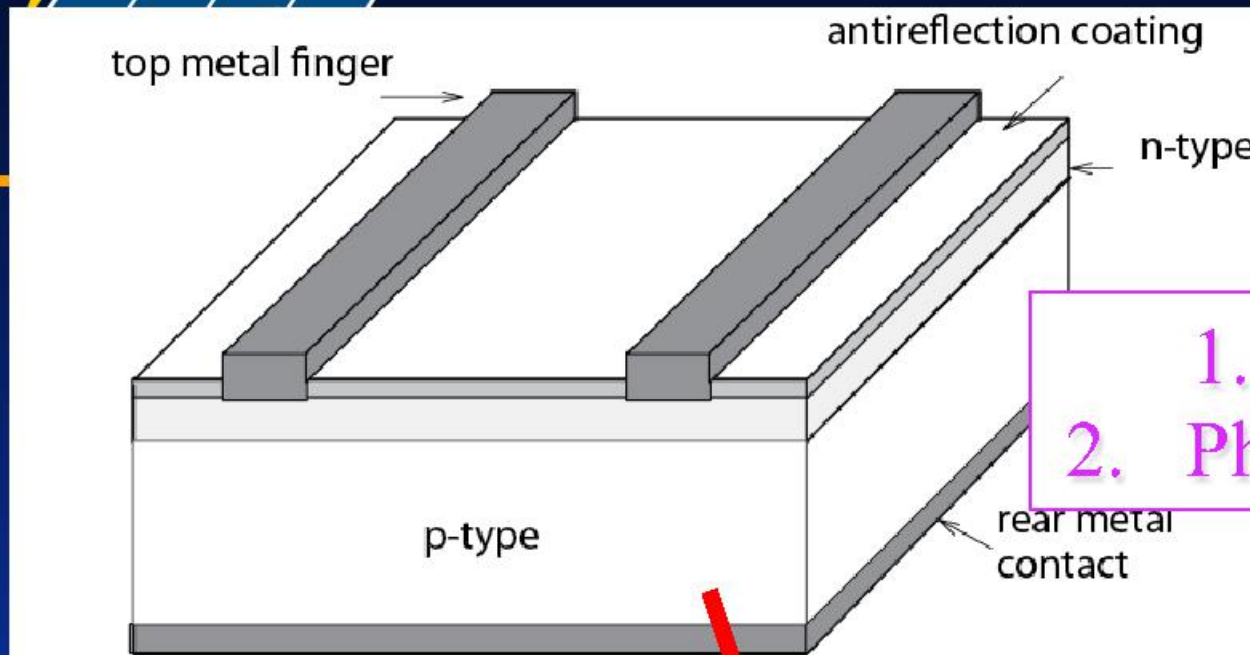


1. Light top diffusion (no dead layer)

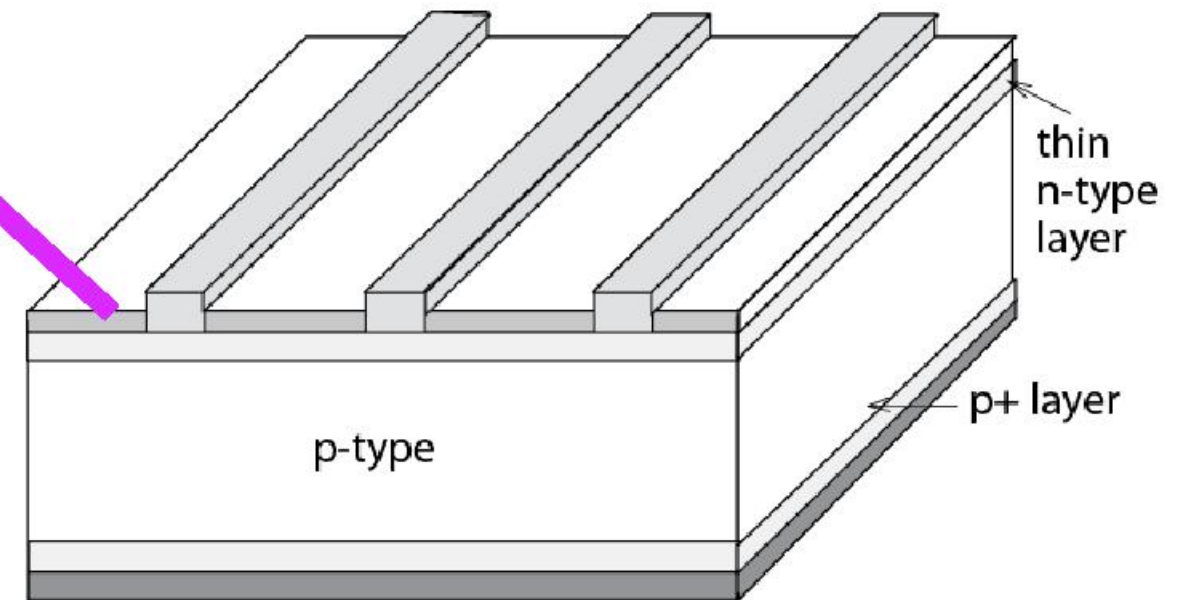
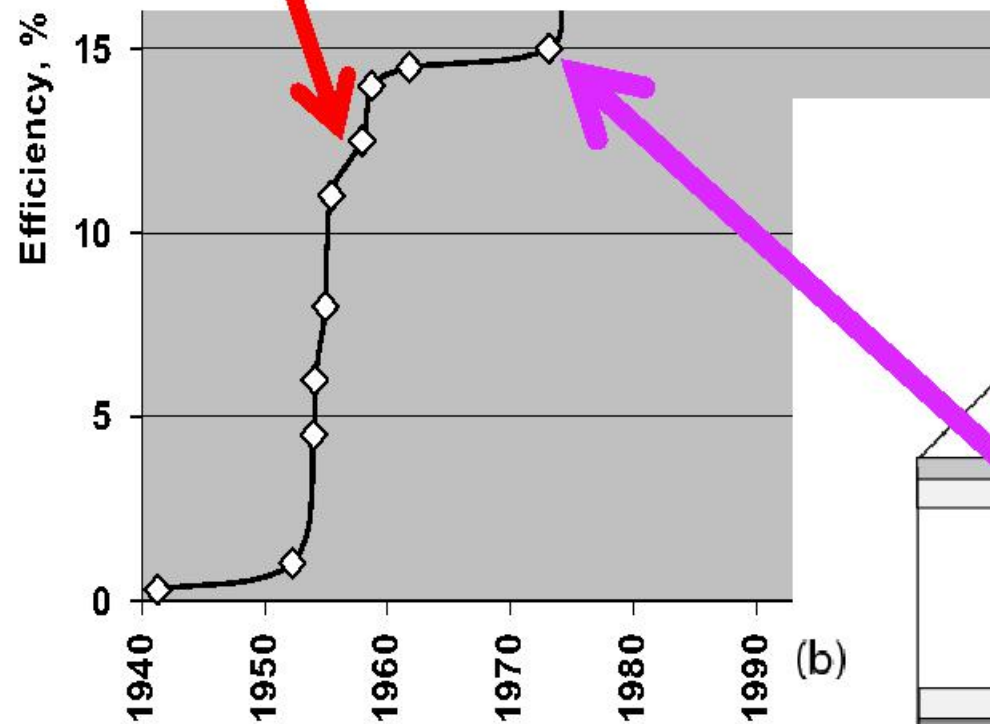




“Violet” cell (1972)

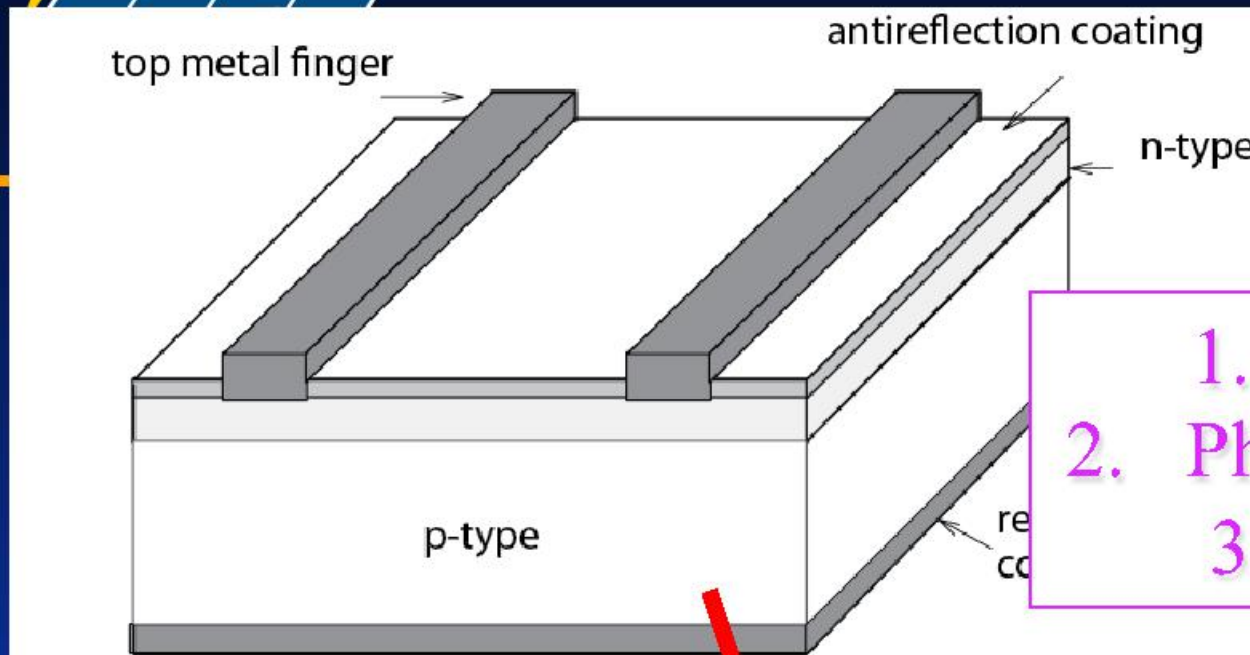


1. Light top diffusion (no dead layer)
2. Photolithographically defined top contacts

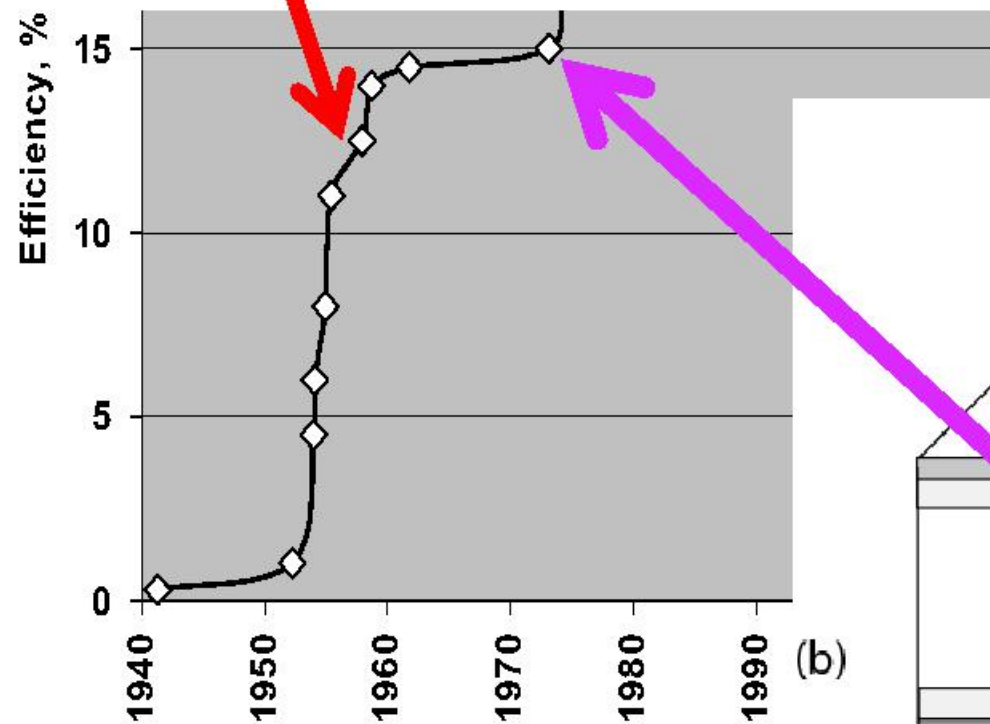




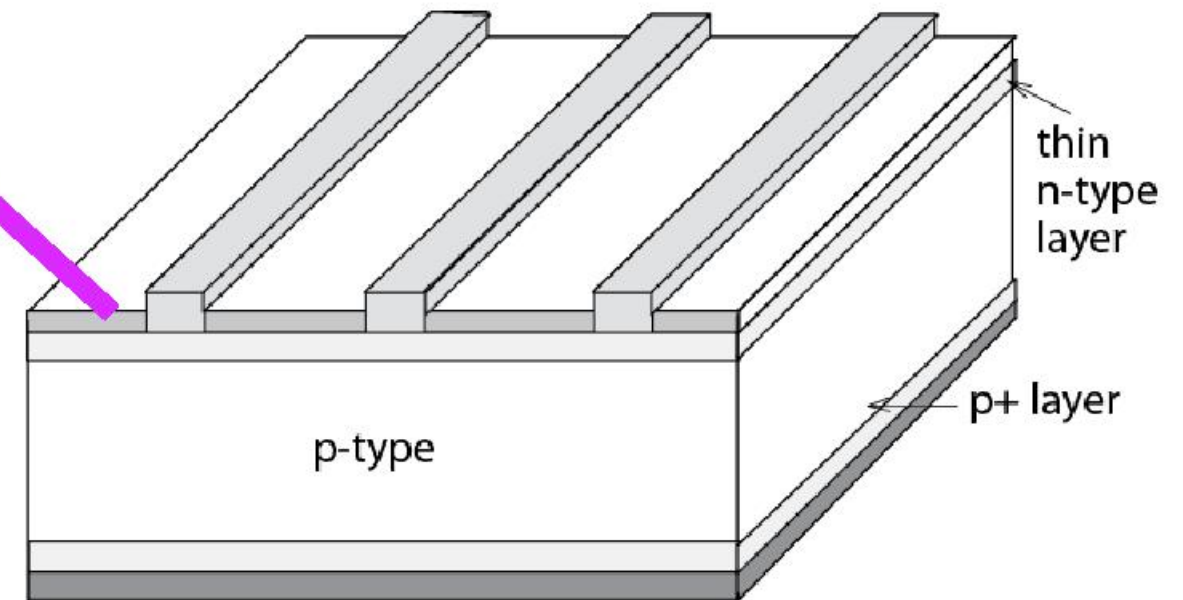
“Violet” cell (1972)



1. Light top diffusion (no dead layer)
2. Photolithographically defined top contacts
3. Rear Al BSF (back surface field)

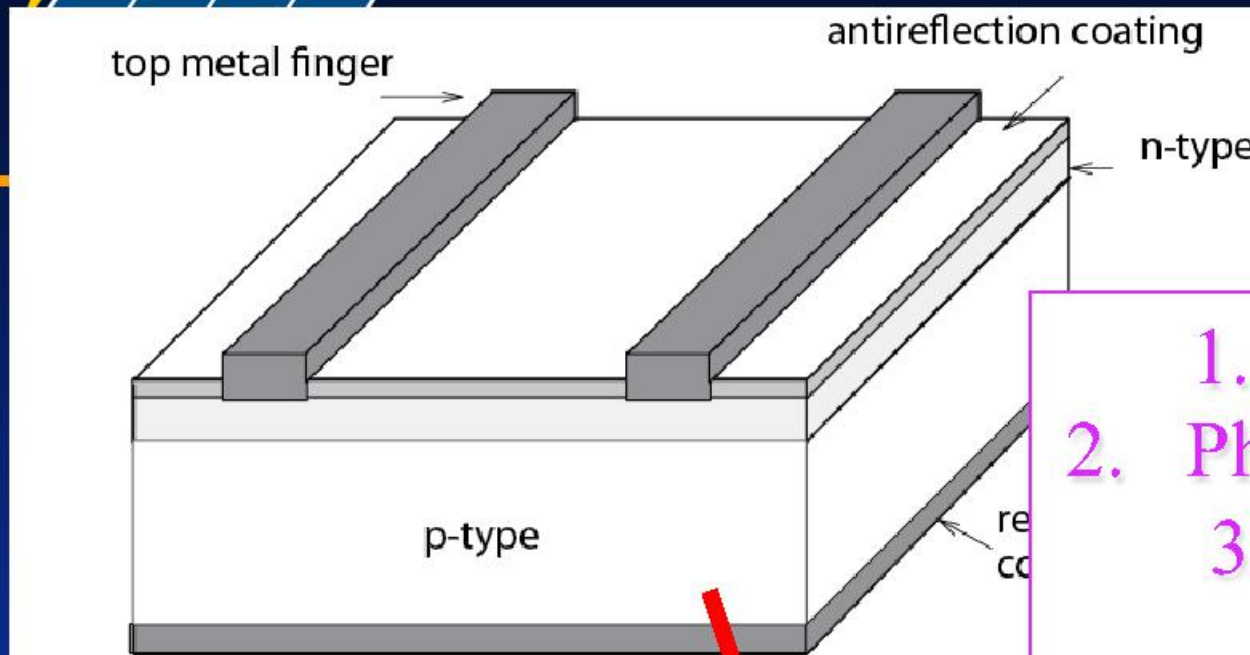


(b)

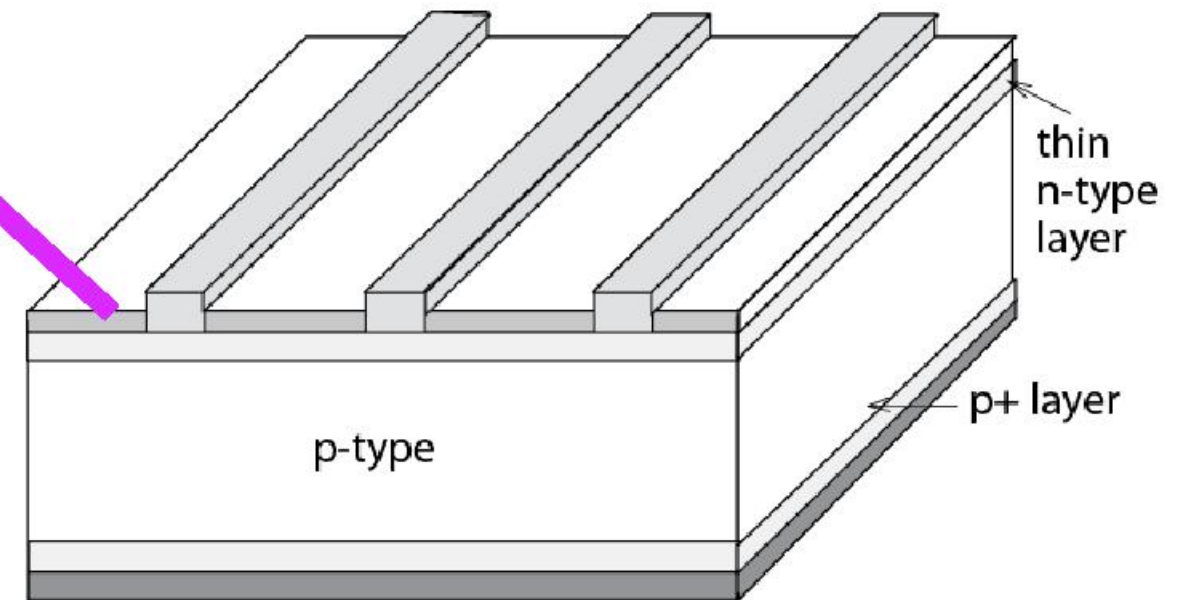
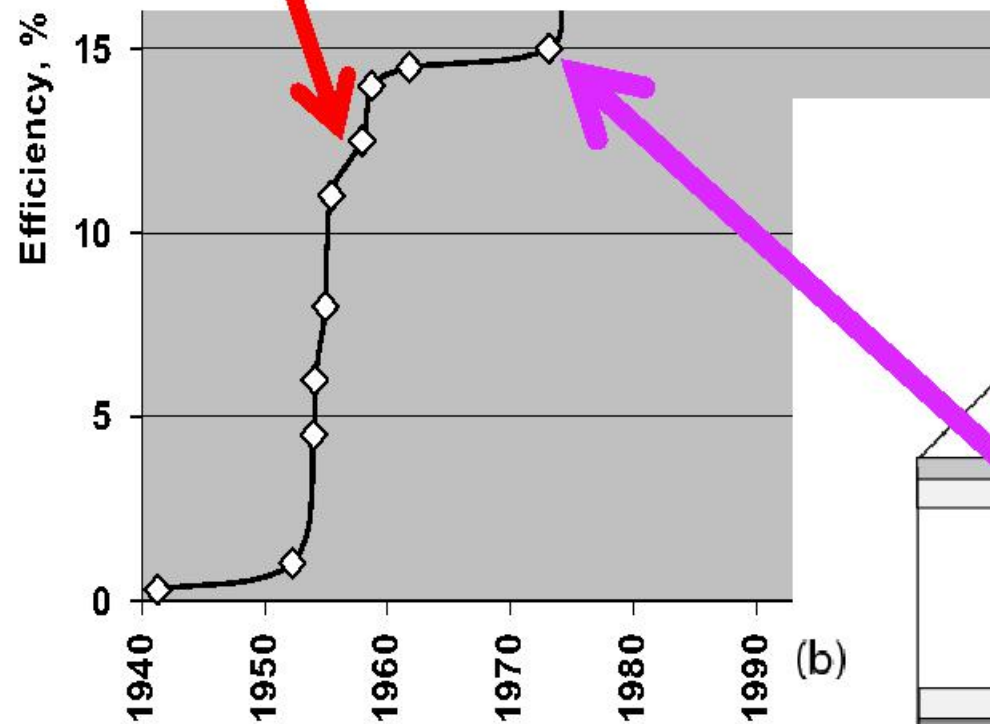




“Violet” cell (1972)

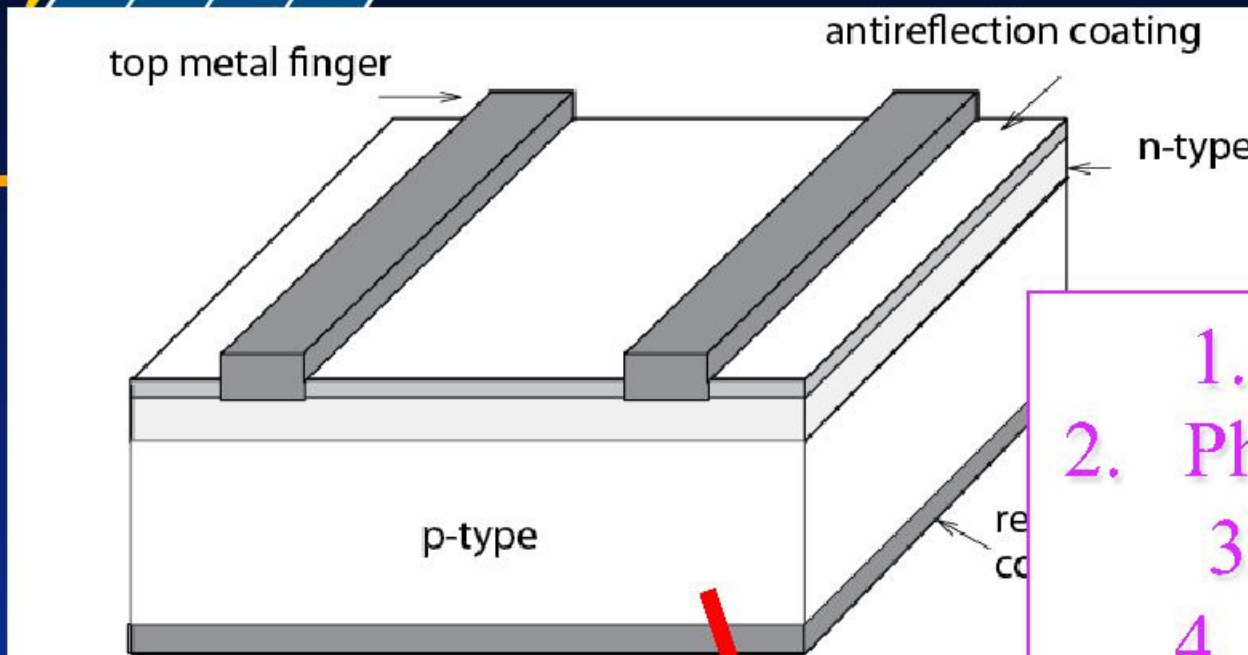


1. Light top diffusion (no dead layer)
2. Photolithographically defined top contacts
3. Rear Al BSF (back surface field)
4. Higher index AR coating

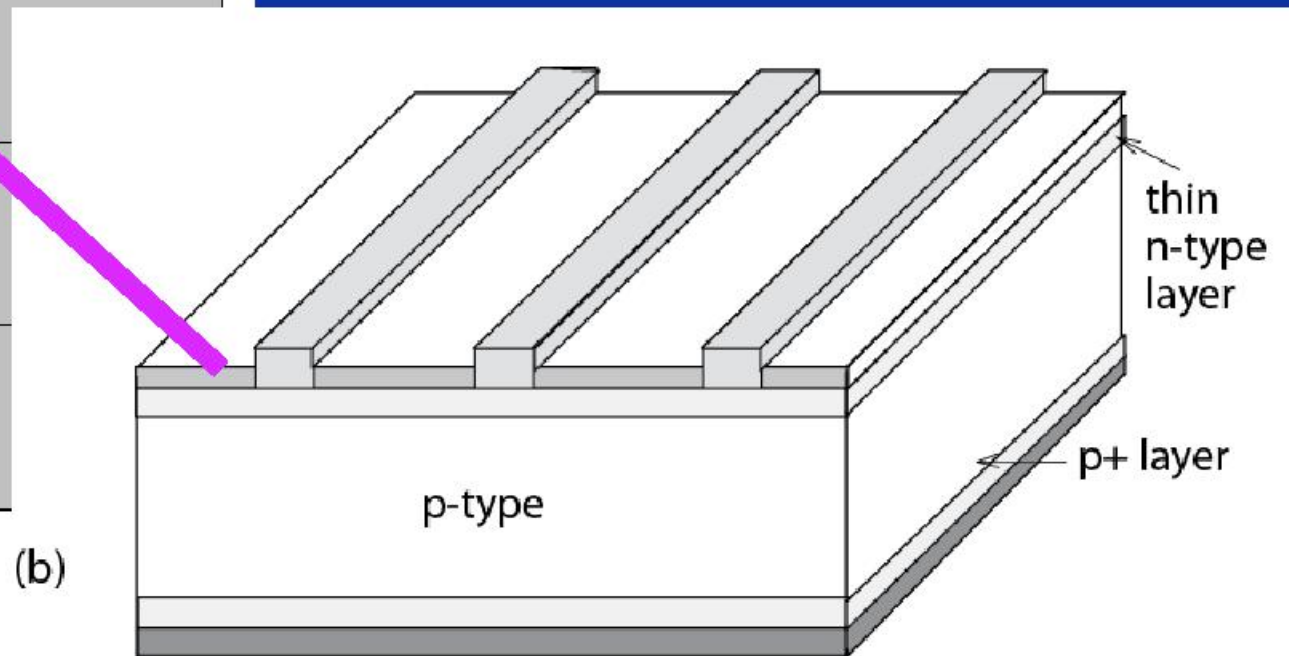
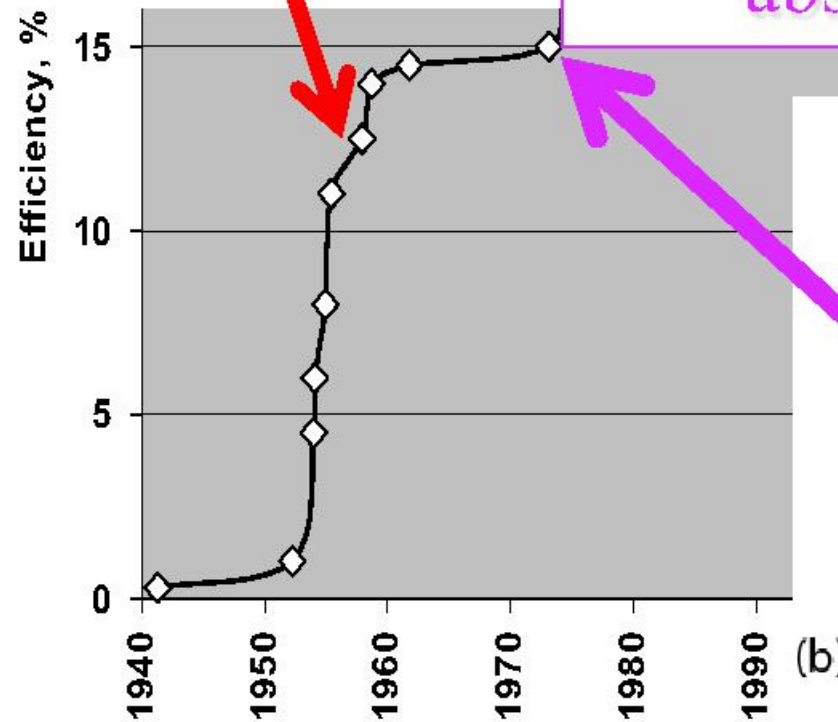




“Violet” cell (1972)

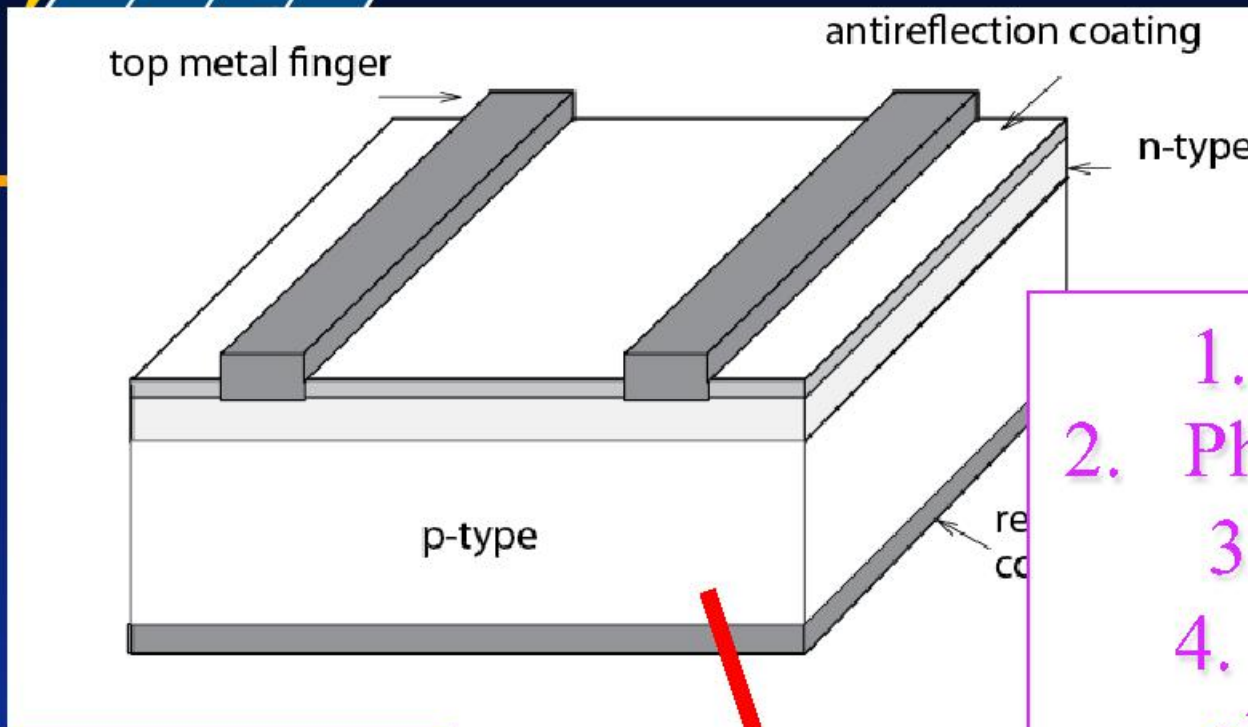


1. Light top diffusion (no dead layer)
2. Photolithographically defined top contacts
3. Rear Al BSF (back surface field)
4. Higher index AR coating (also less absorbing, thinner giving “violet” colour)

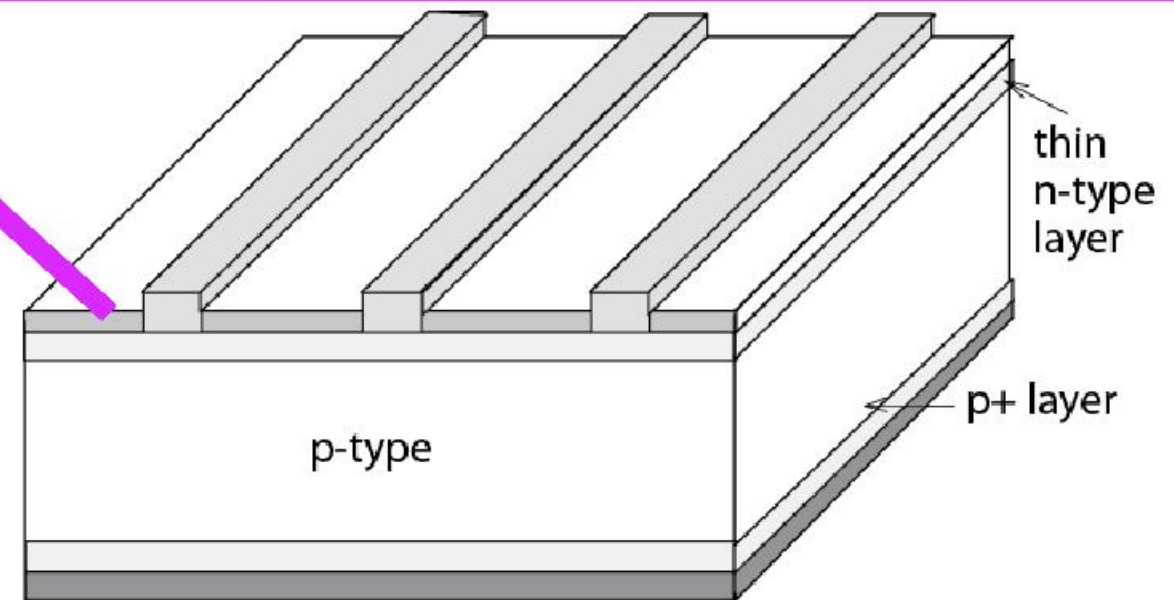
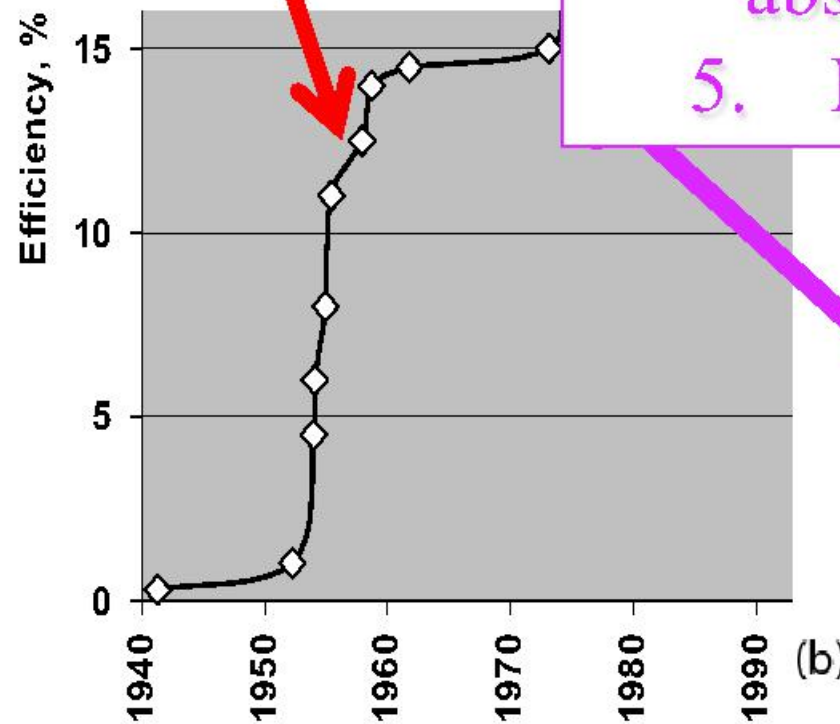




“Violet” cell (1972)

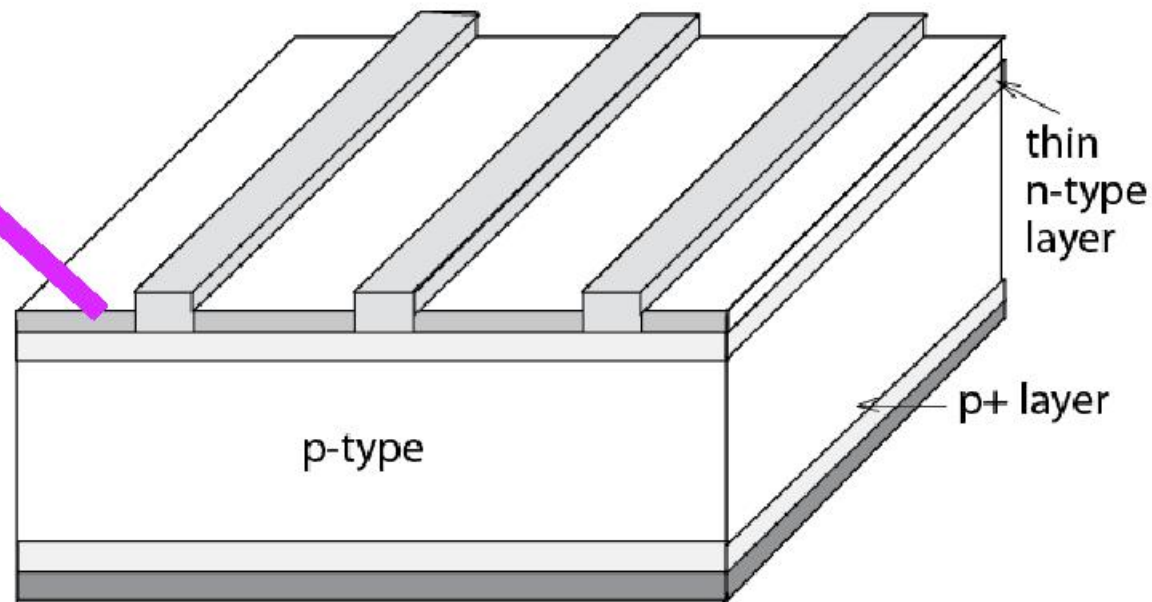
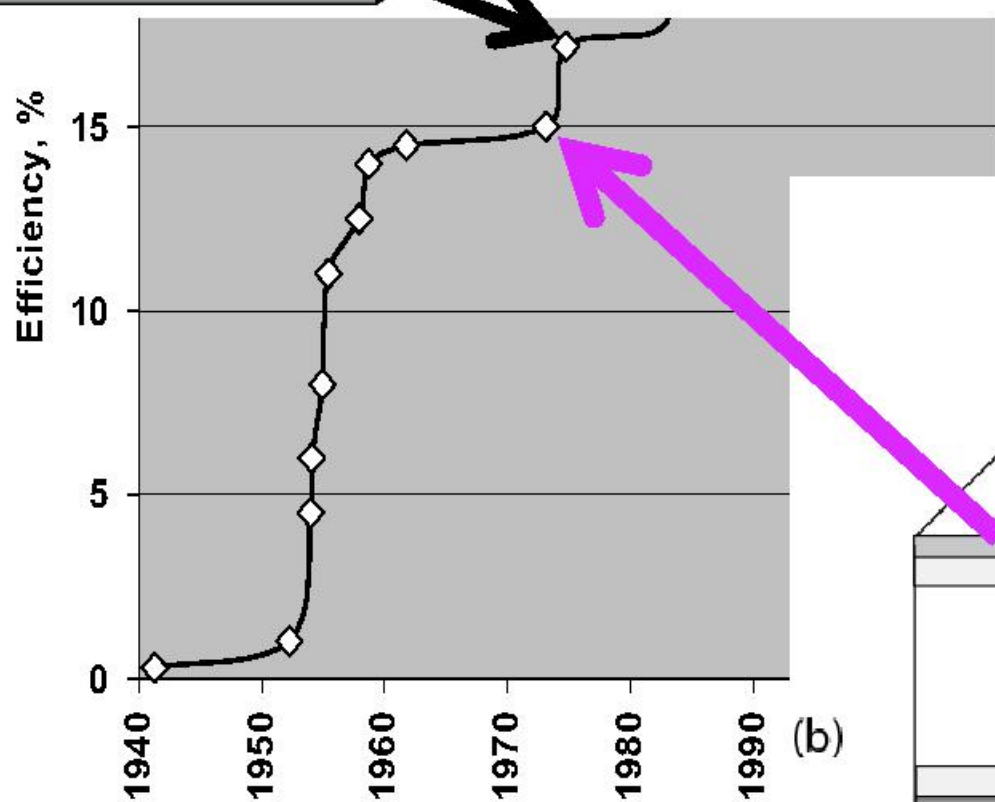
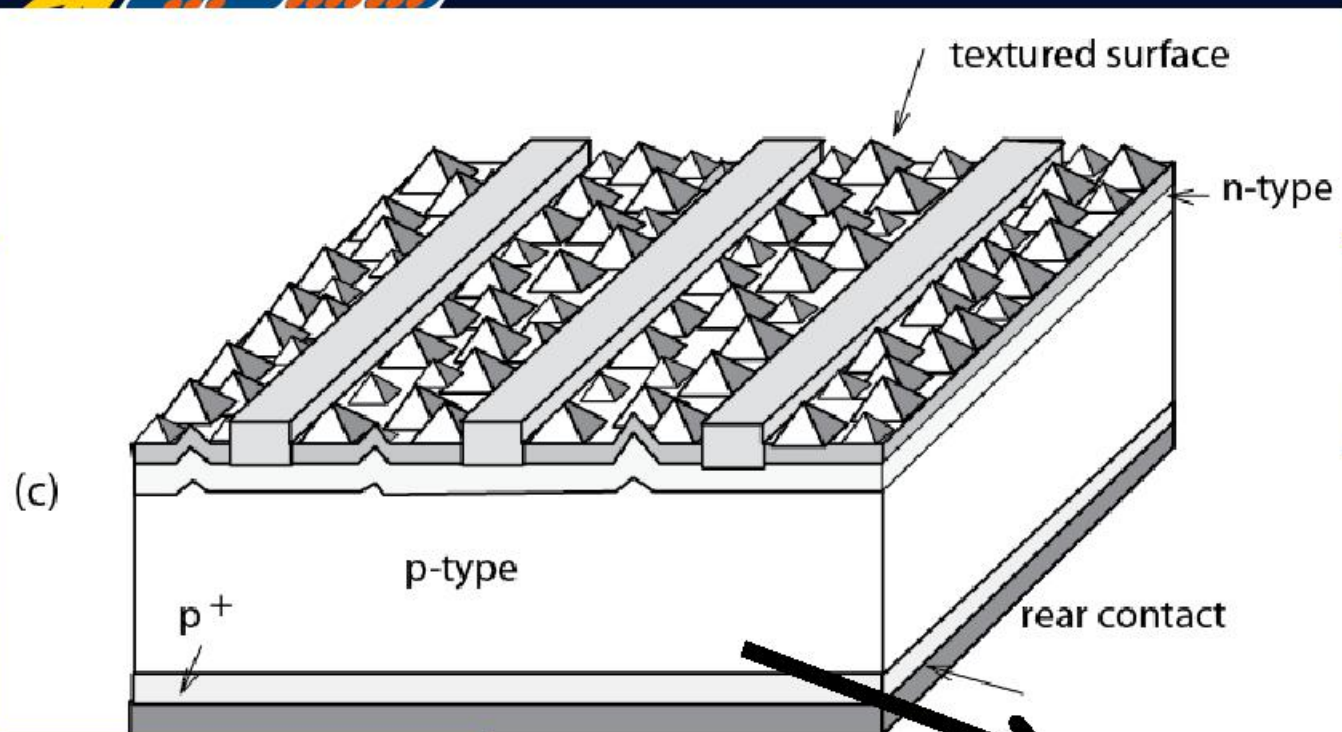


1. Light top diffusion (no dead layer)
2. Photolithographically defined top contacts
3. Rear Al BSF (back surface field)
4. Higher index AR coating (also less absorbing, thinner giving “violet” colour)
5. Higher doped substrate (2 ohm_{cm})



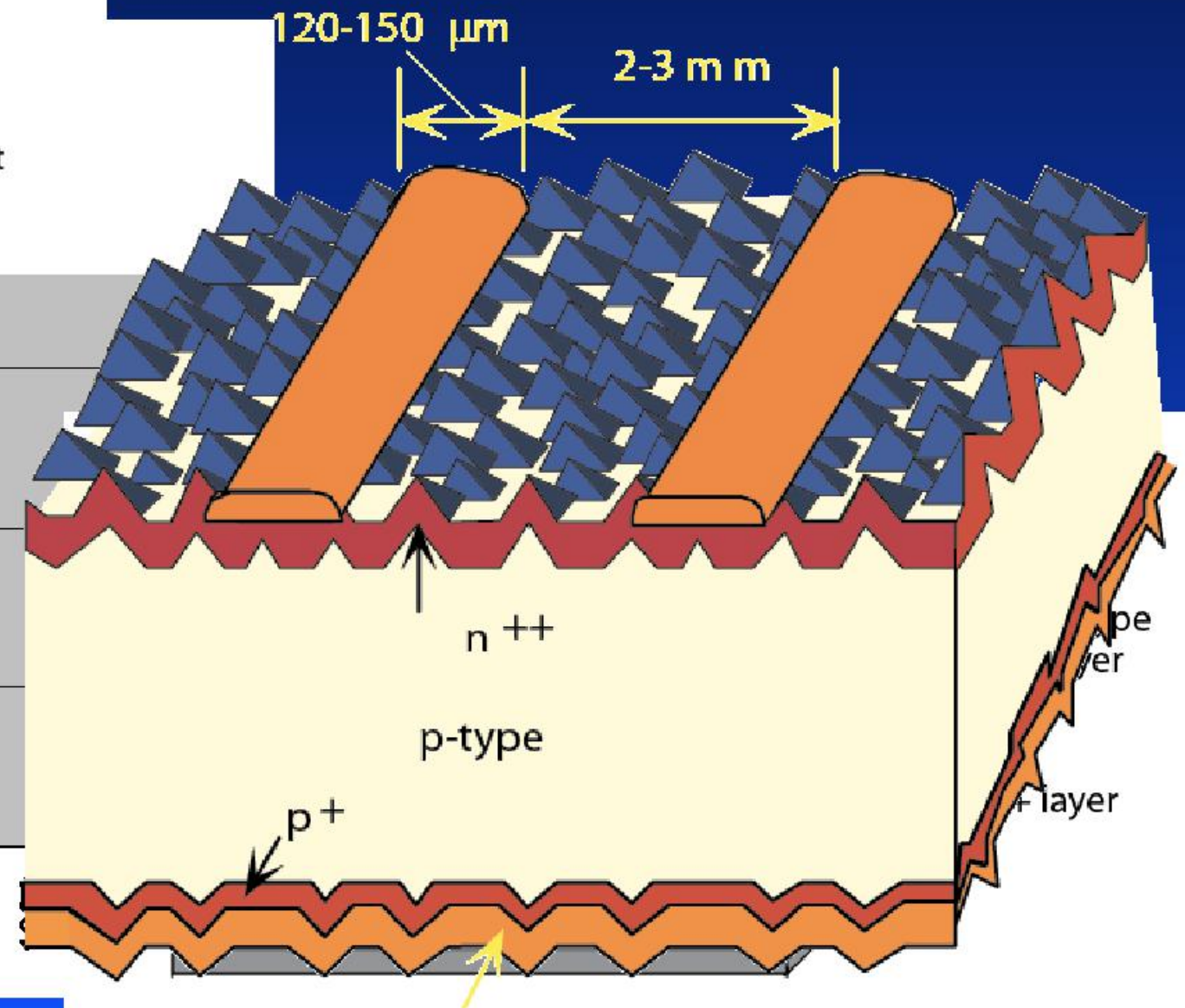
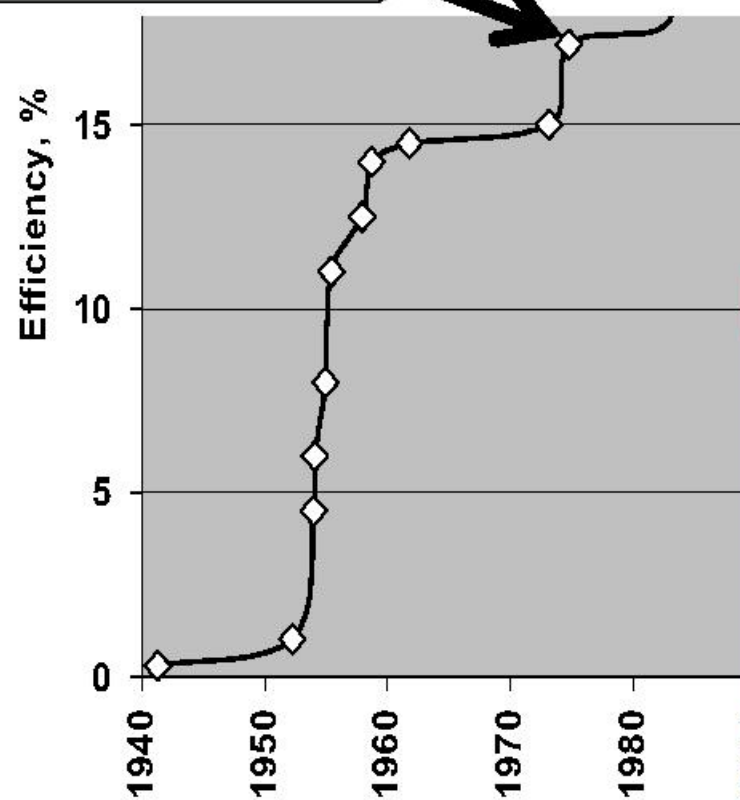
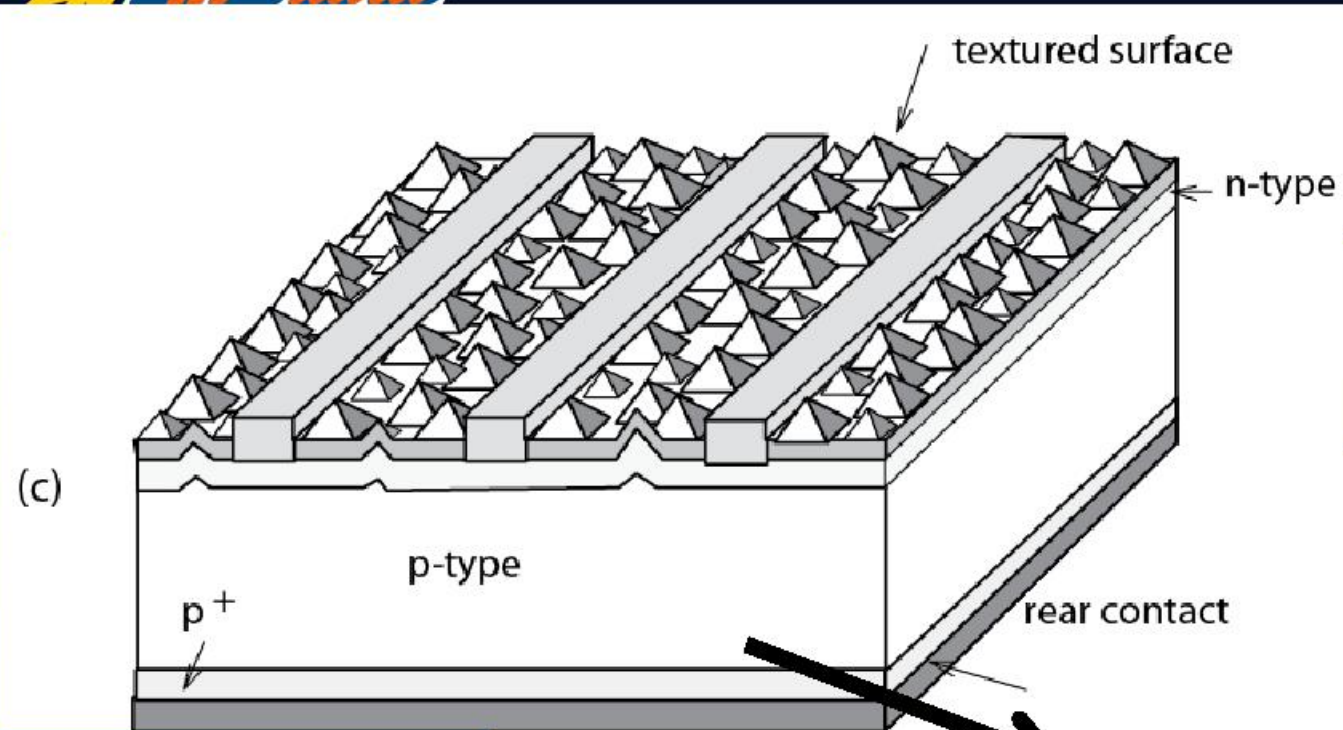


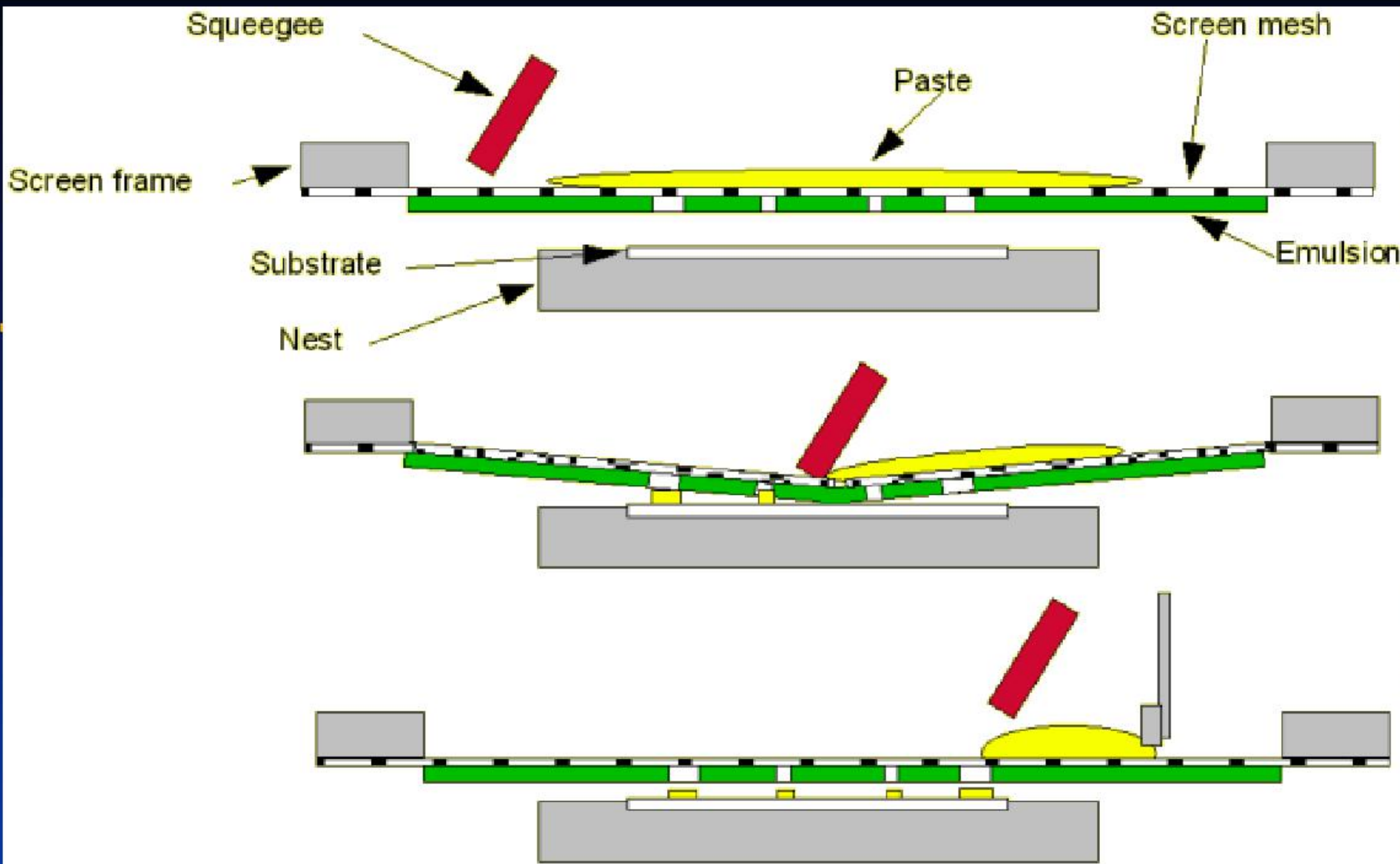
"Black" cell (1974)



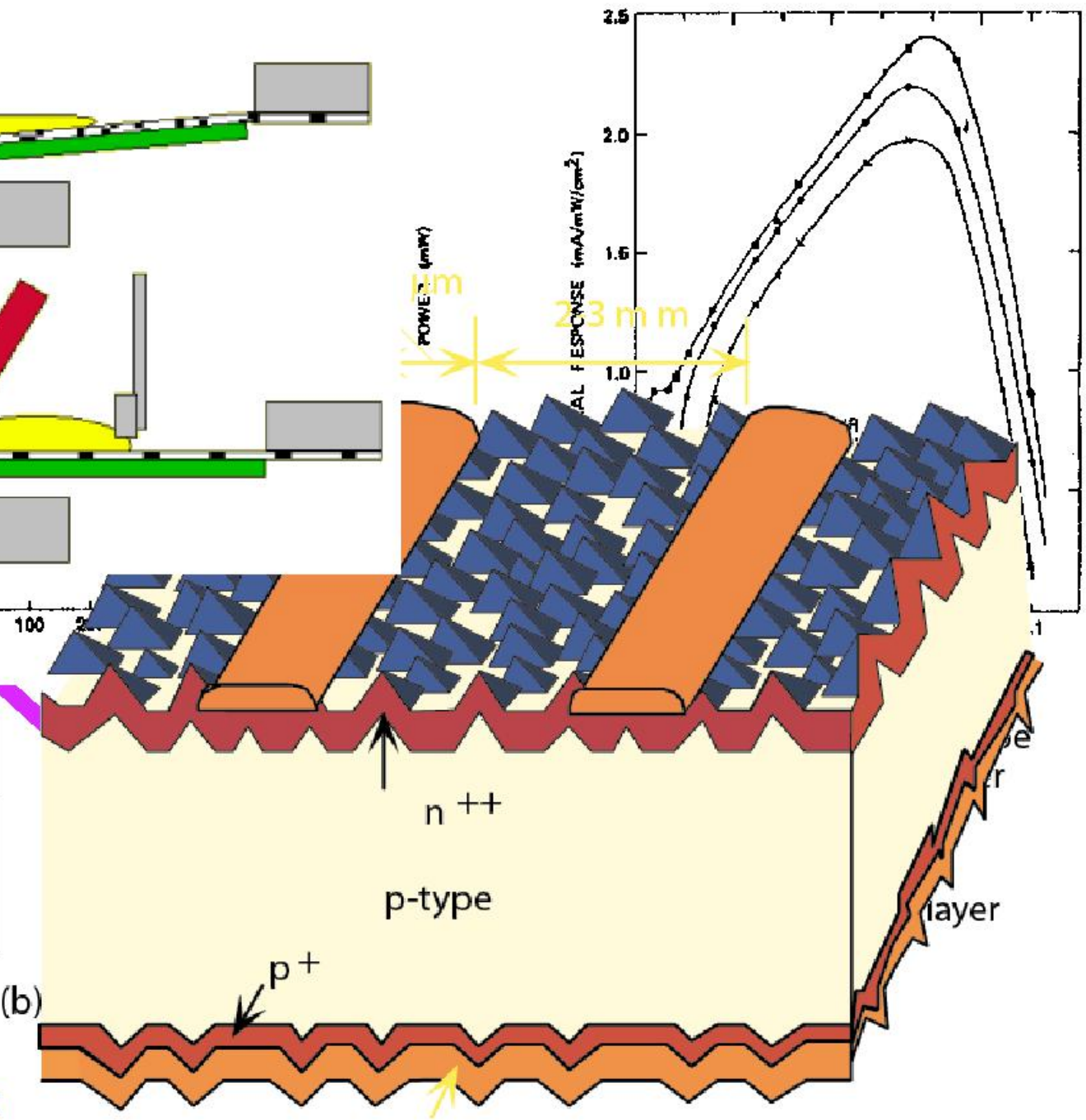
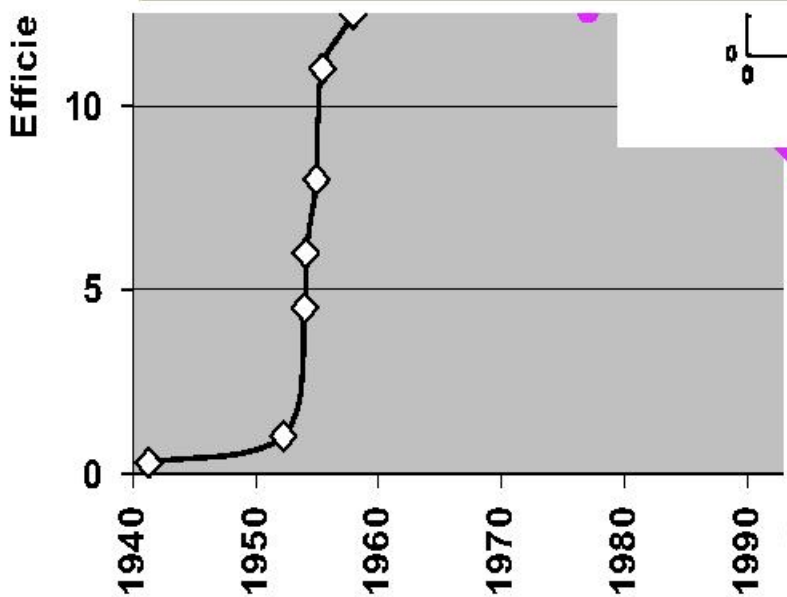


"Black" cell (1974)





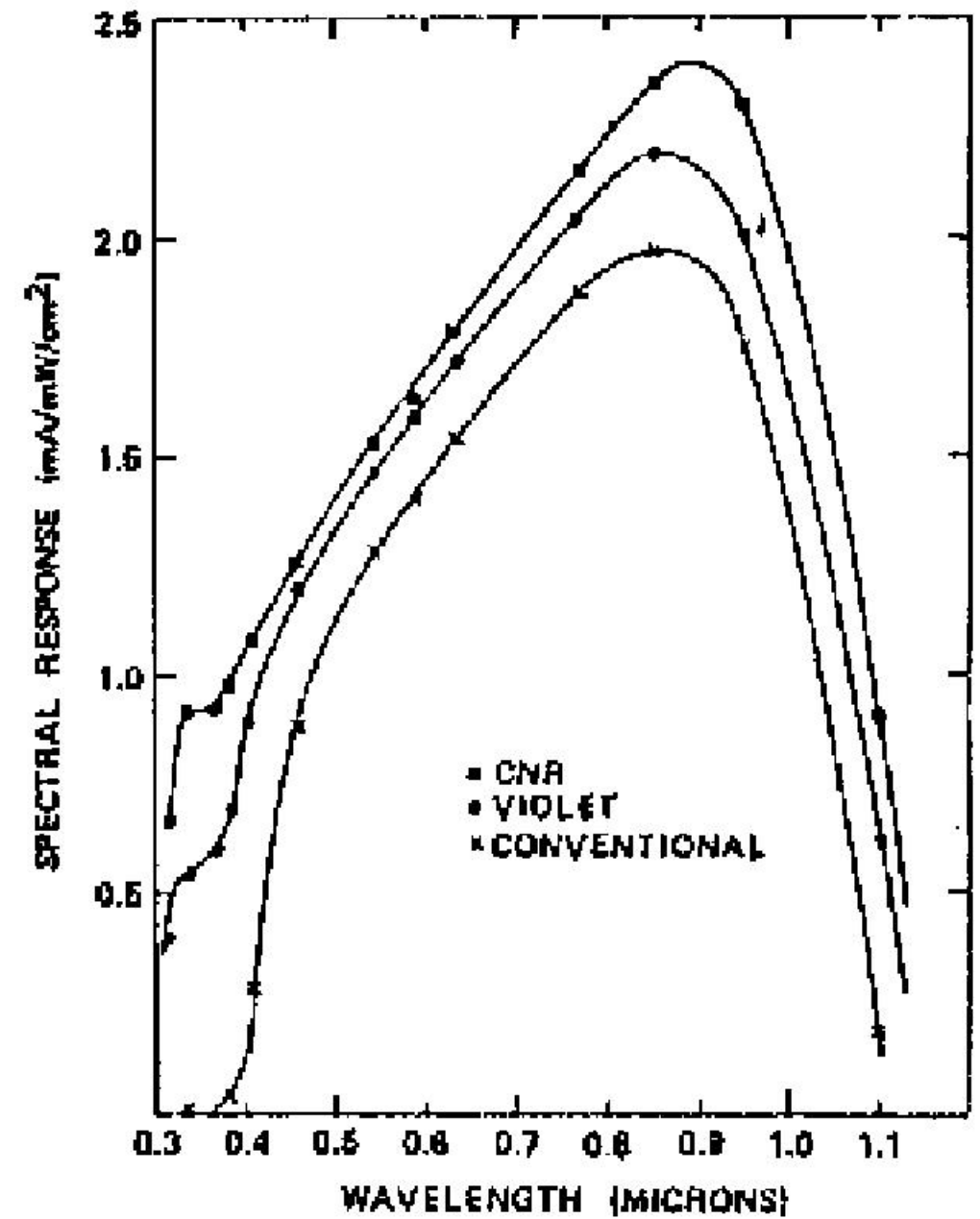
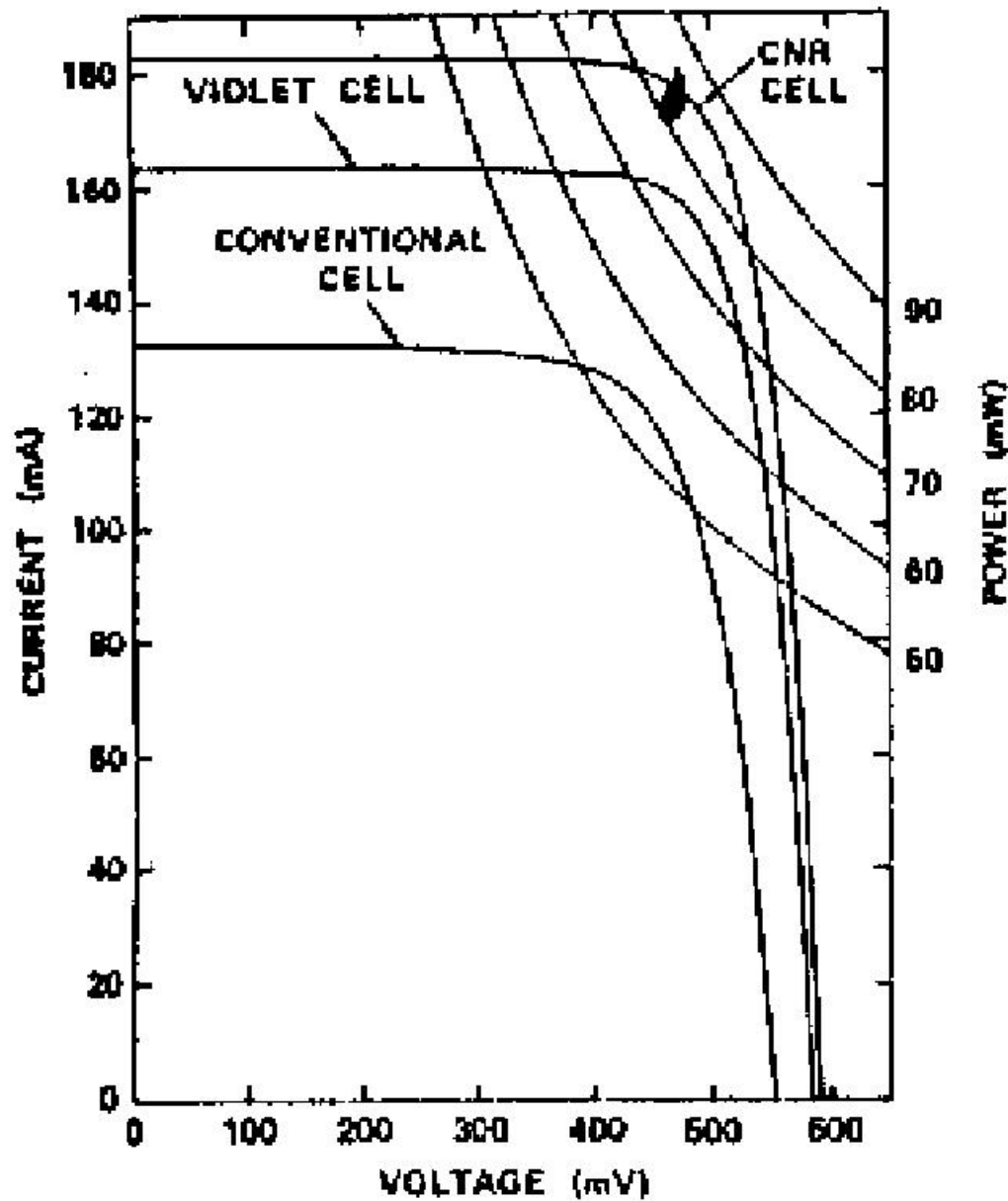
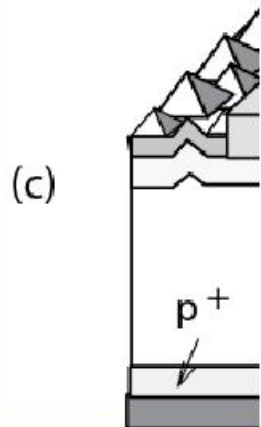
"Black" cell (1974)



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"Black" cell (1974)



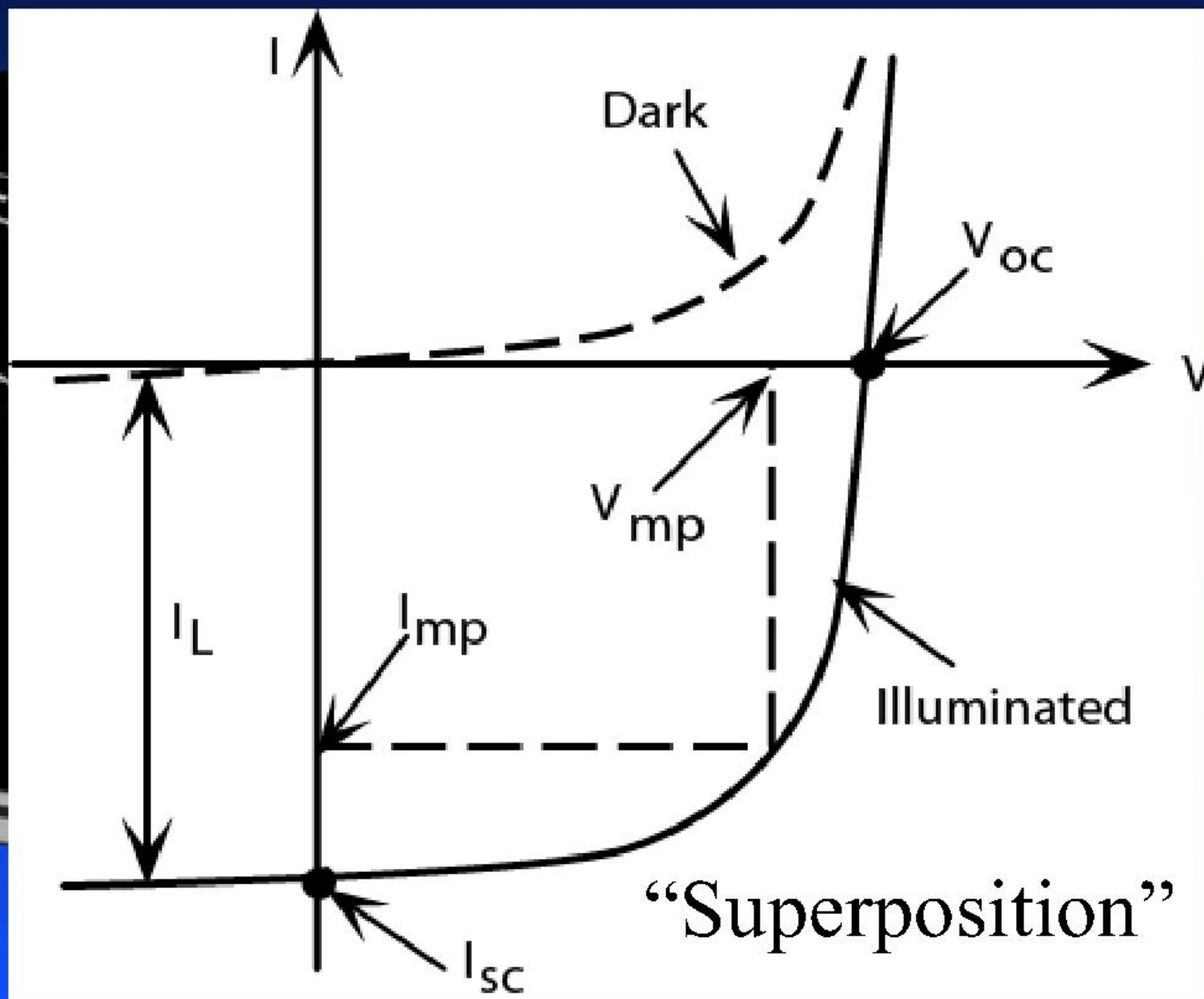
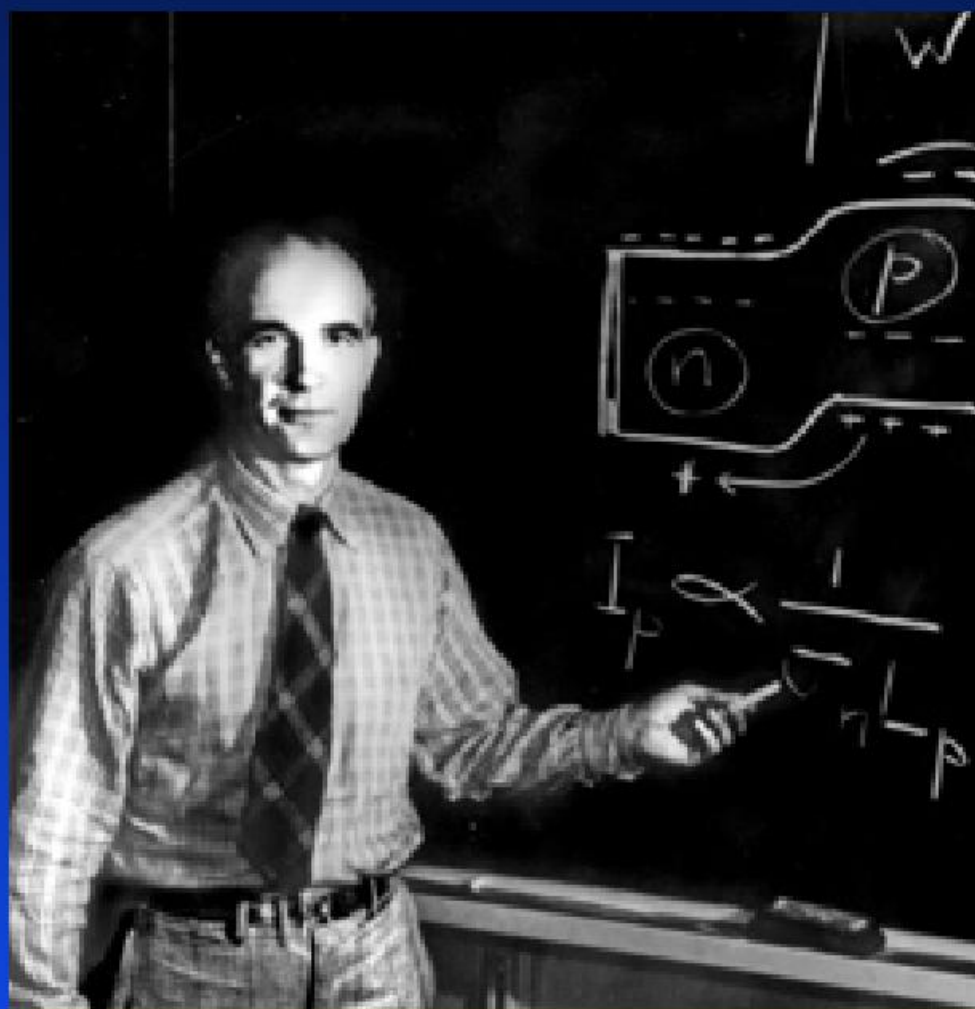


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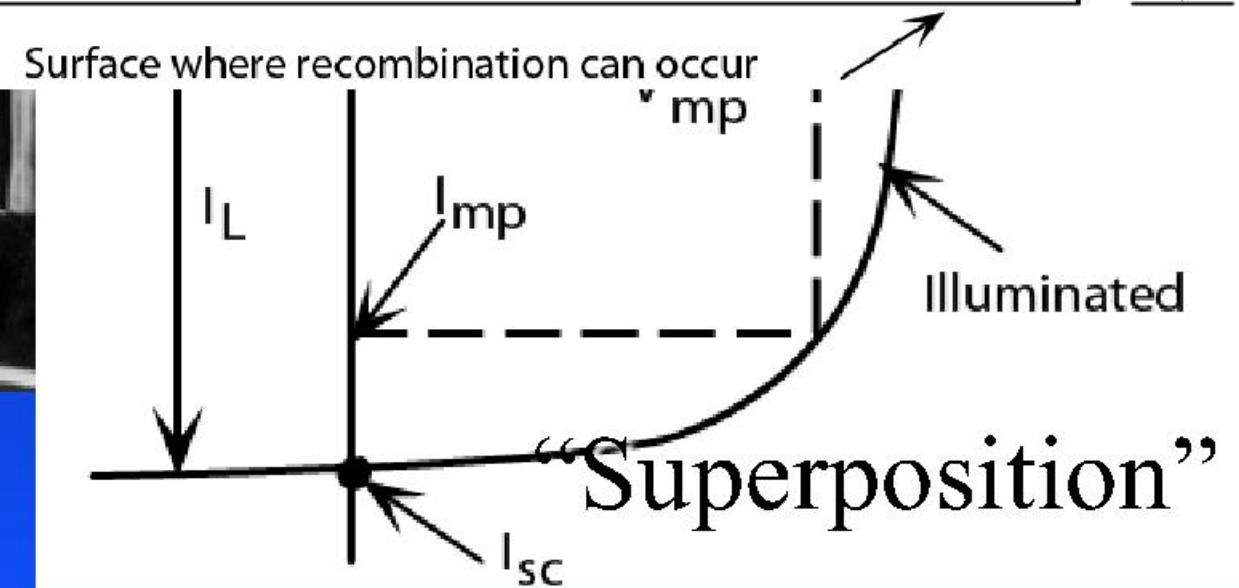
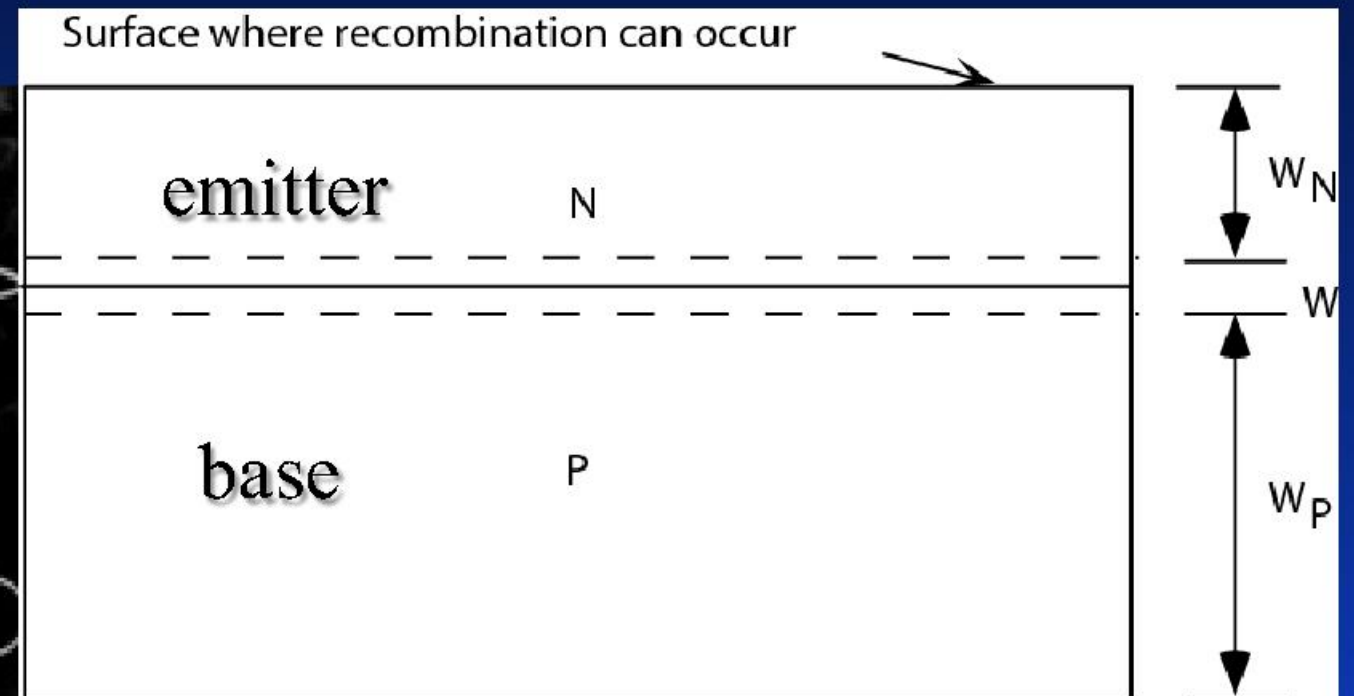
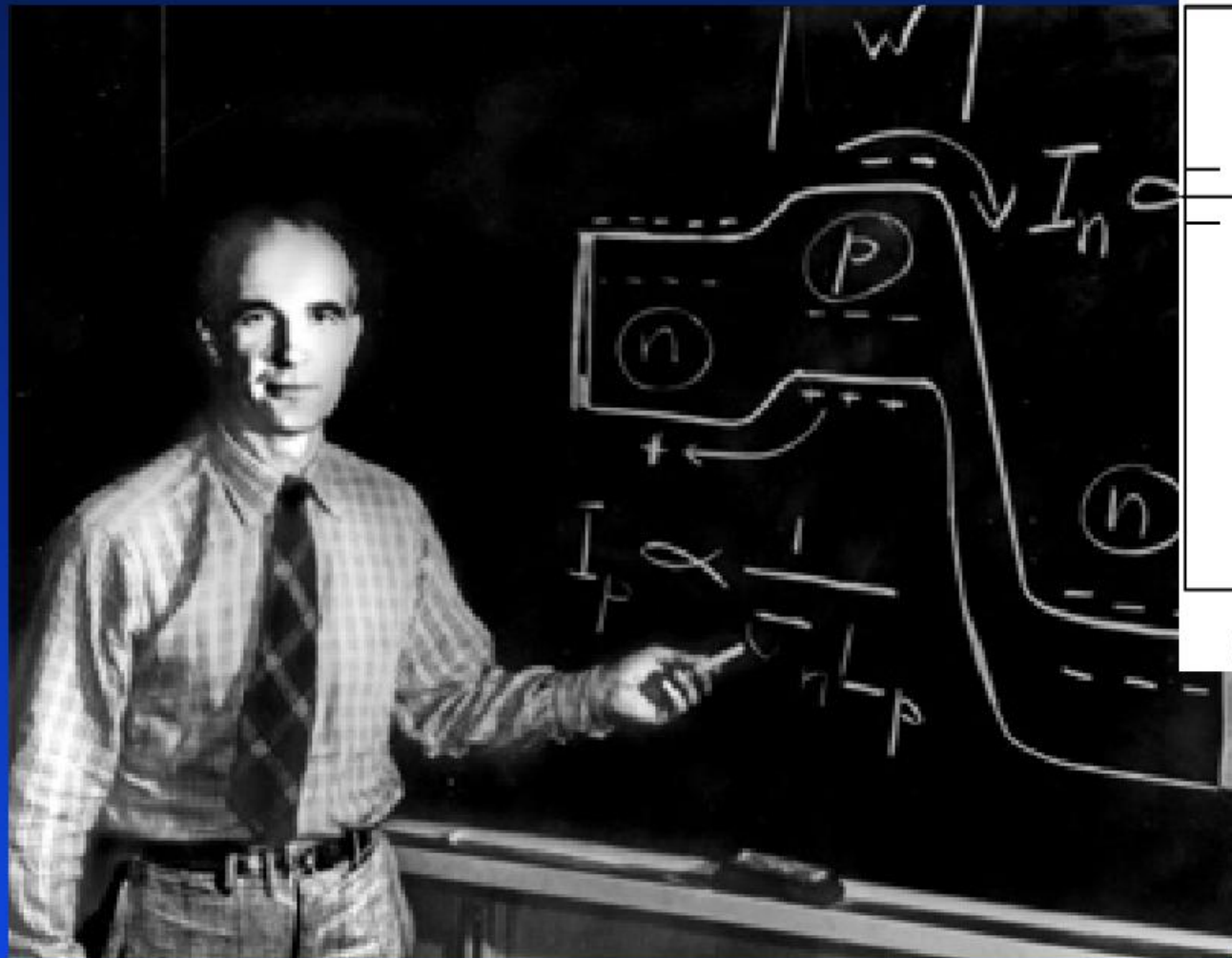


Can treat light & dark separately!



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Can treat light & dark separately!



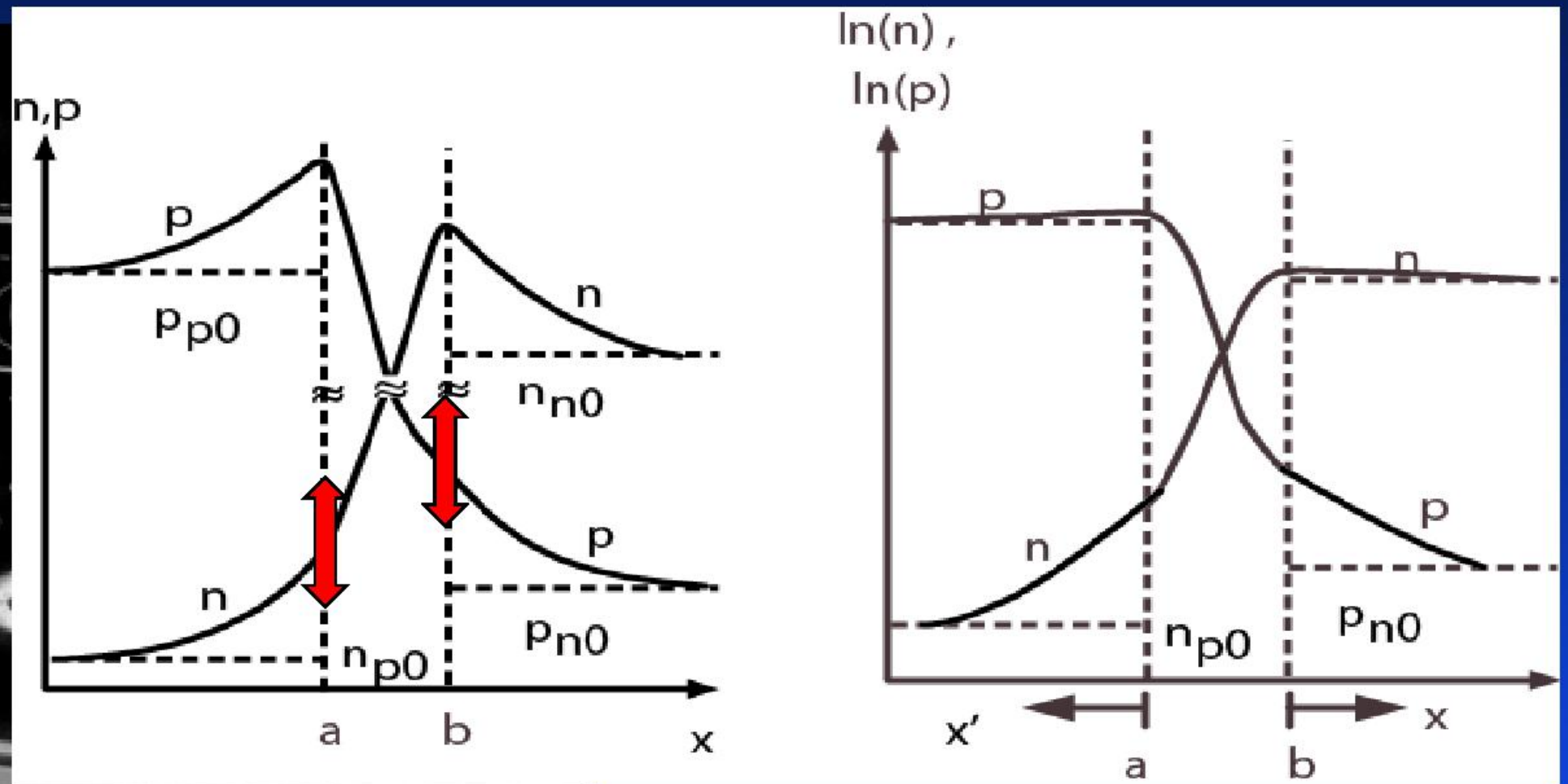
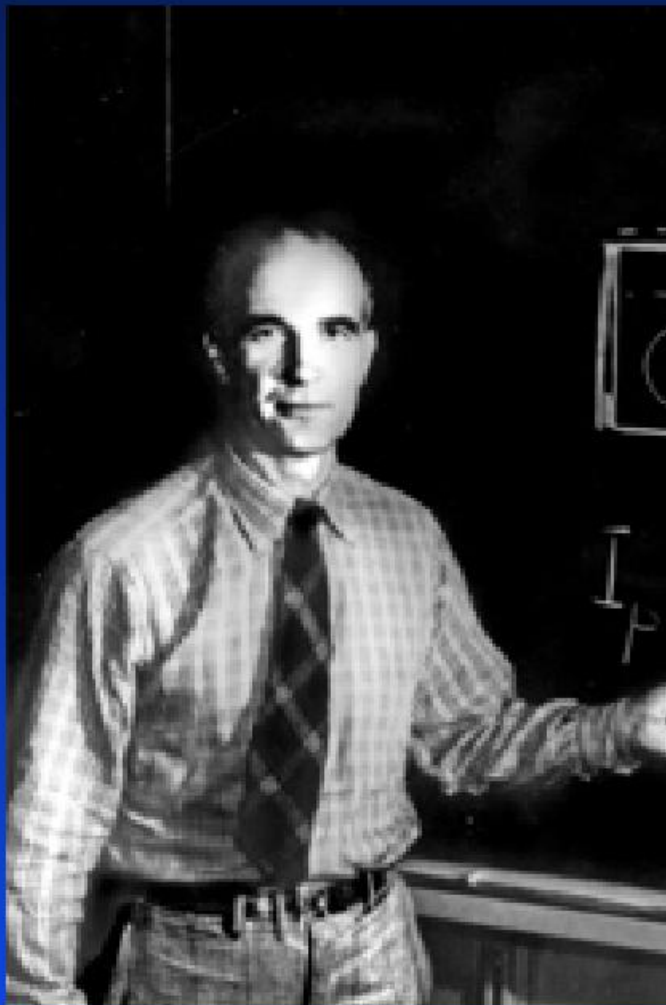


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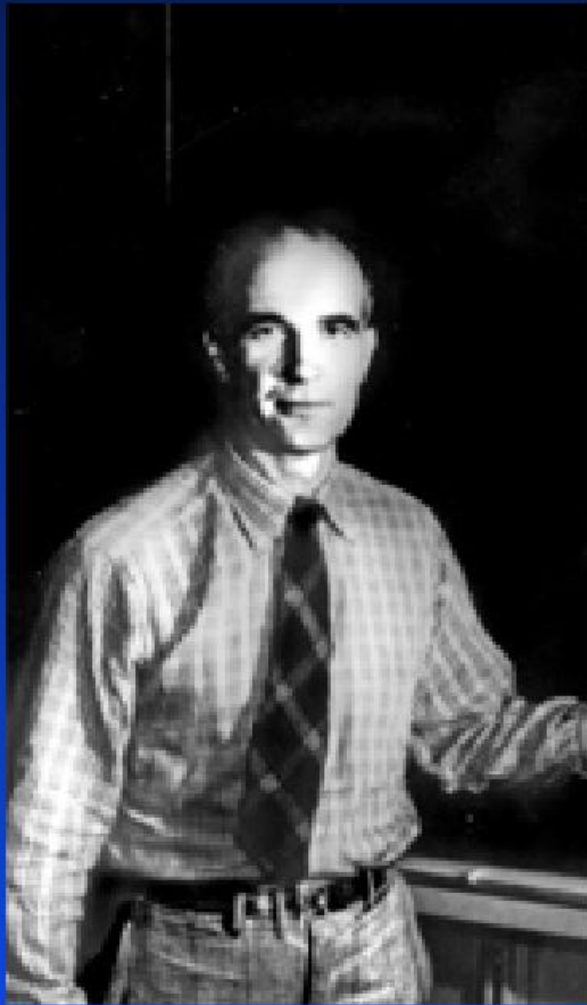
-Questions-

Re-cap: pn junction theory

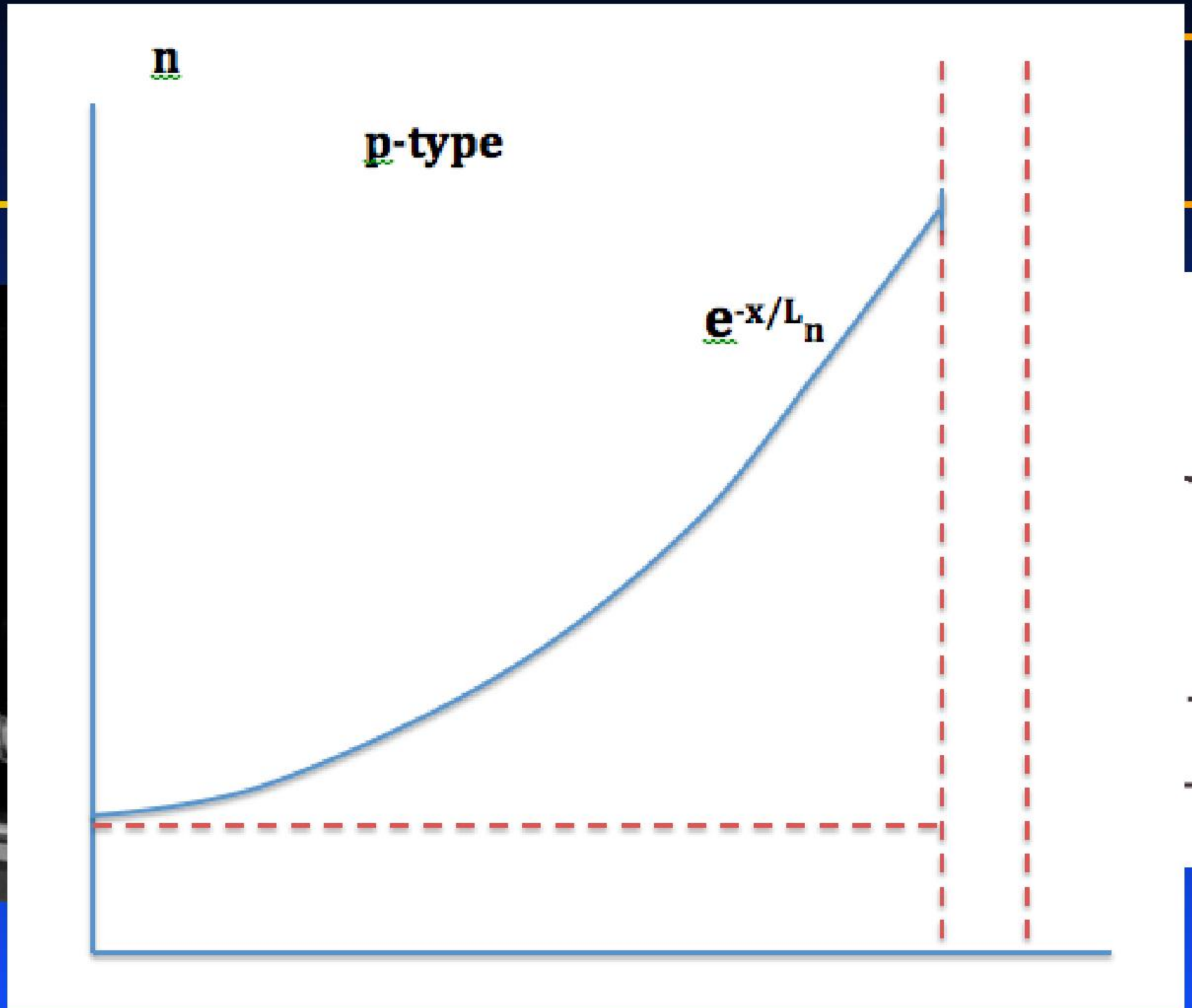




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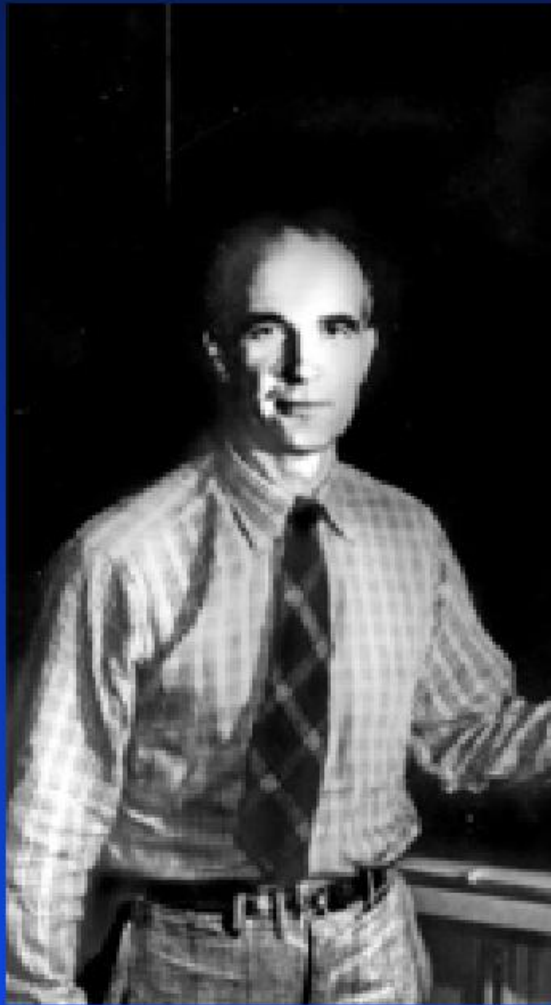


UNSW

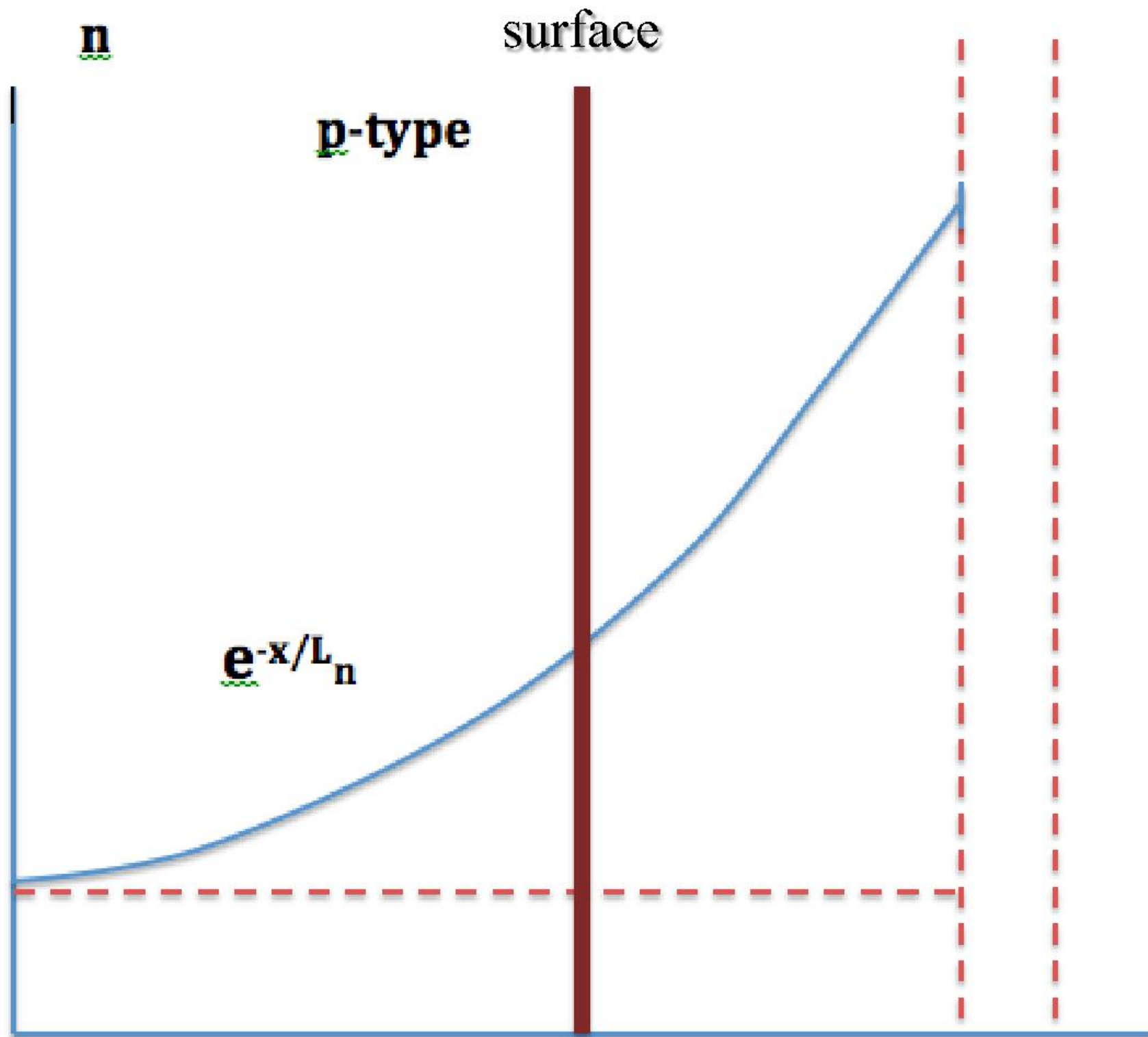




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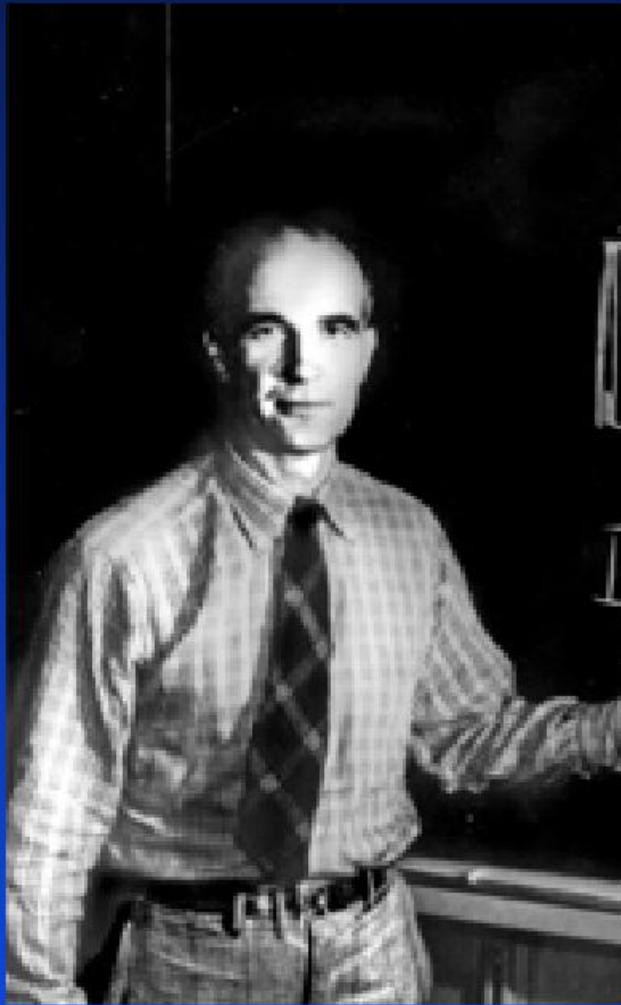


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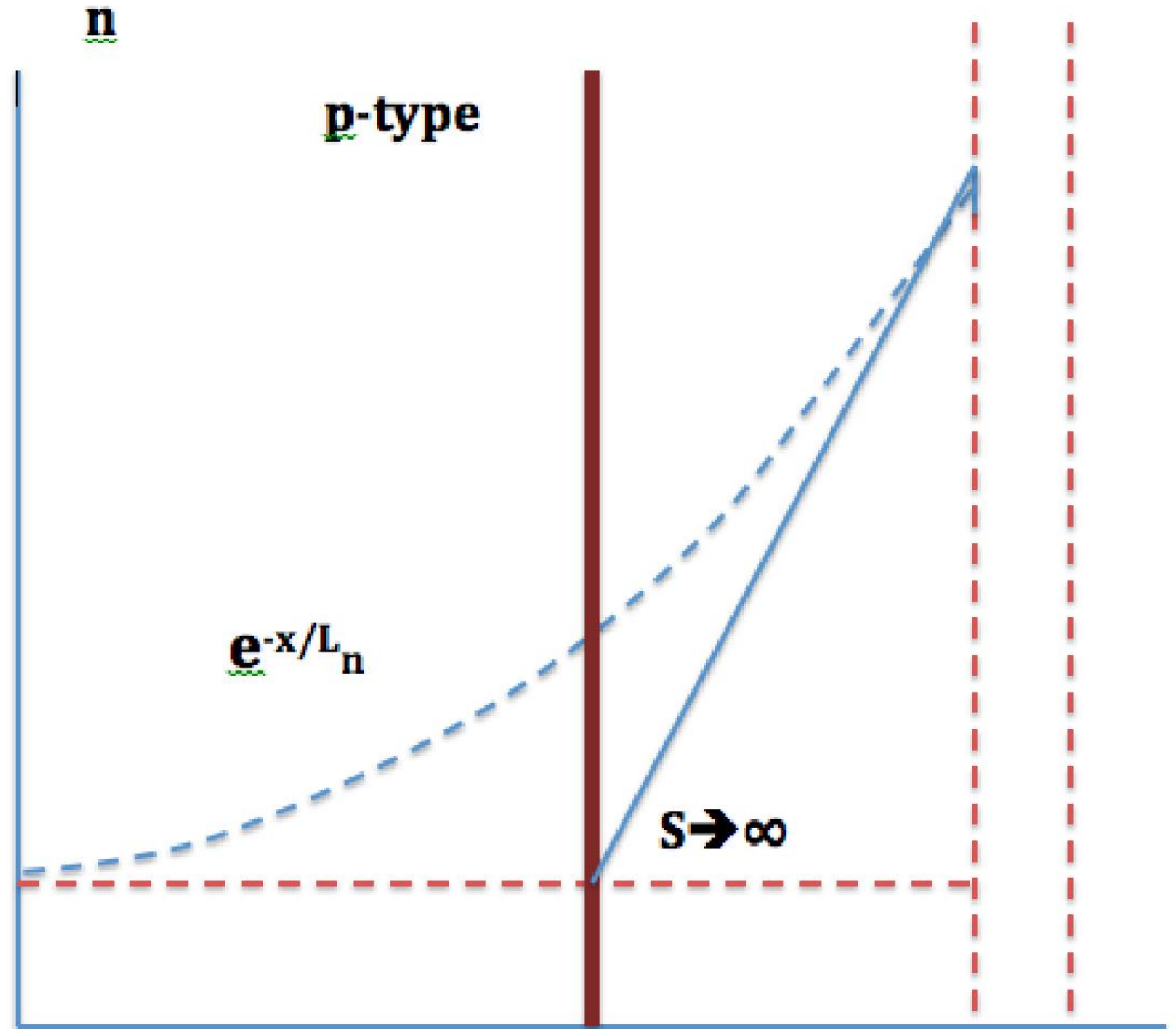




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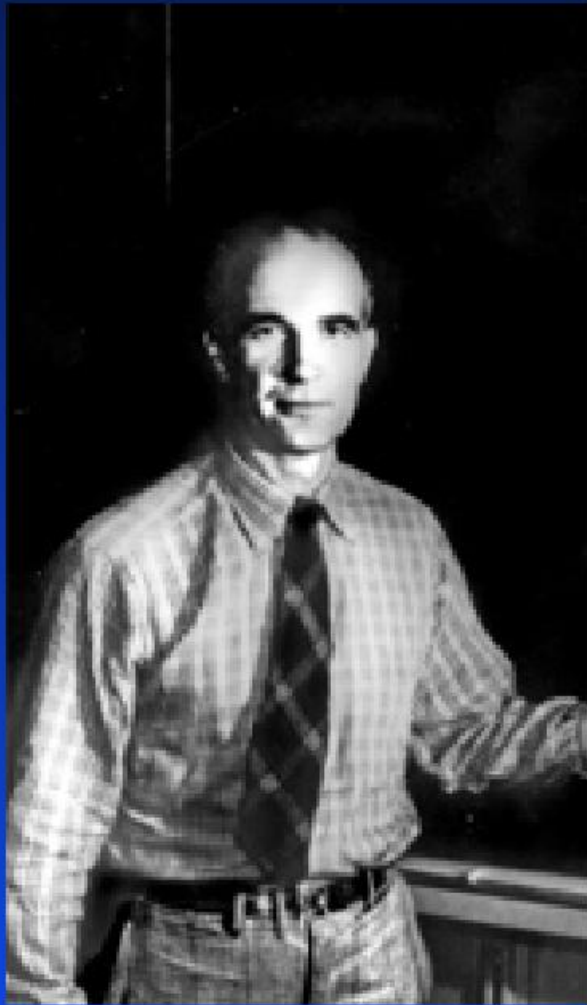


UNSW

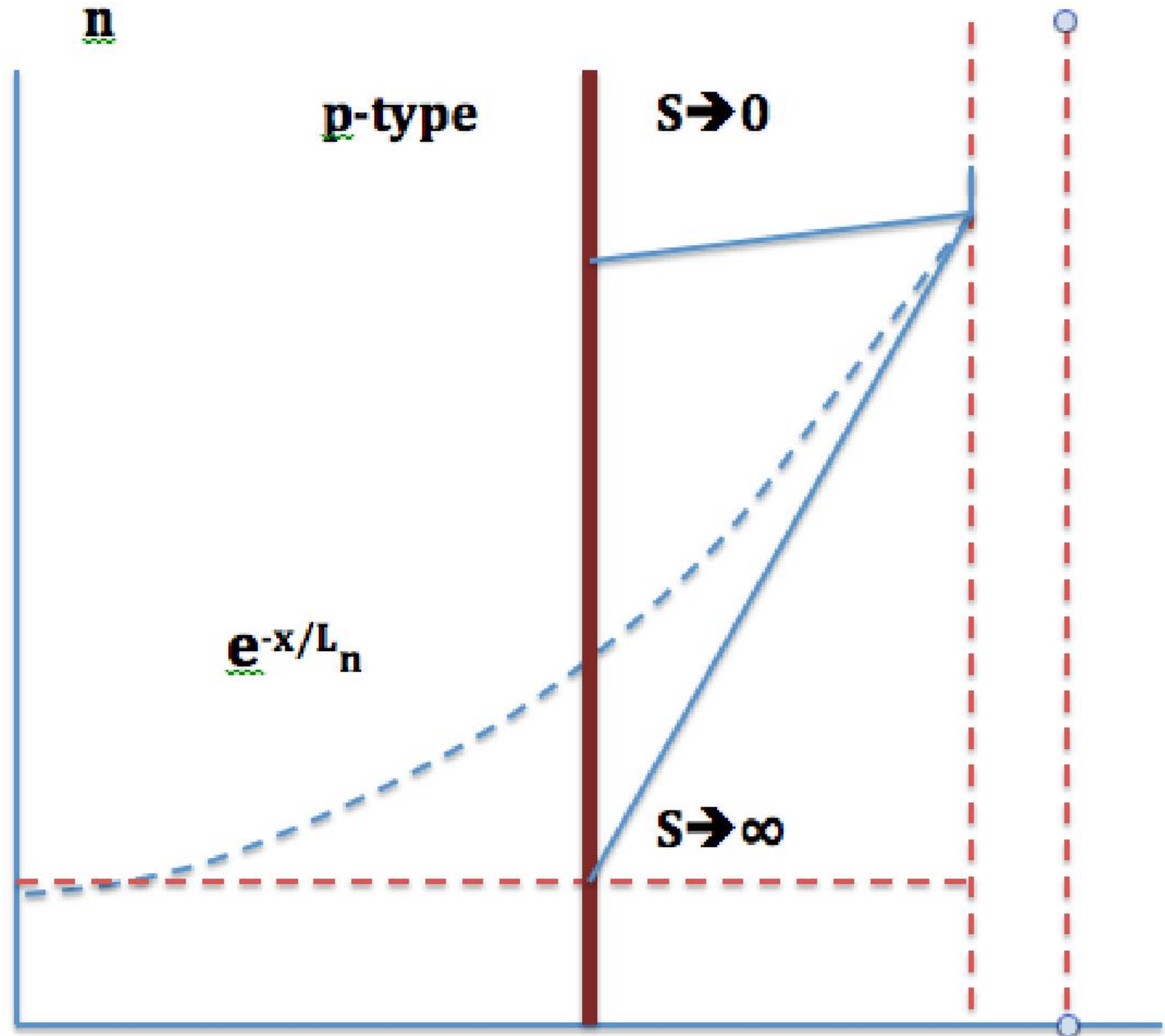




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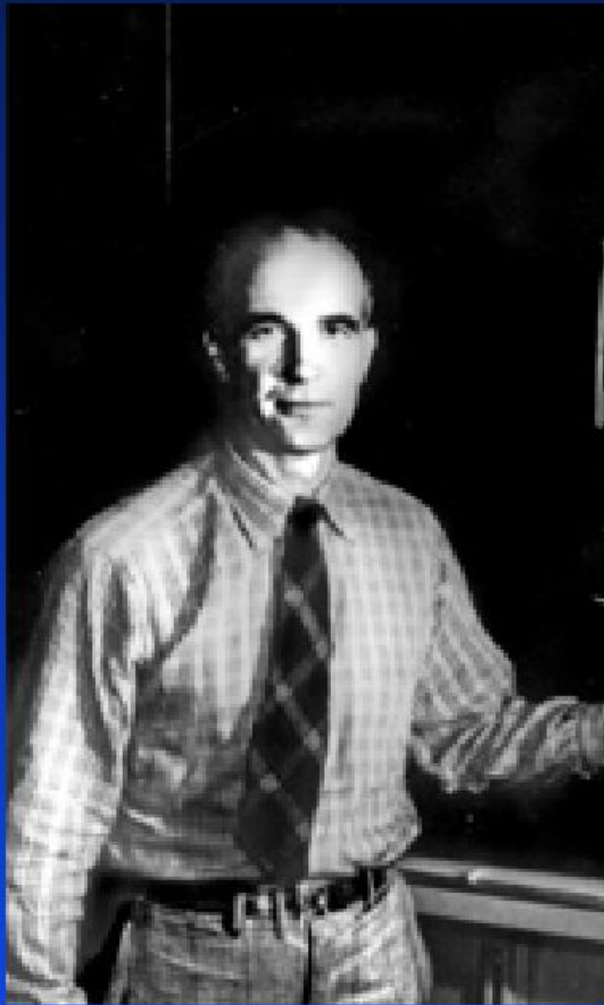


UNSW

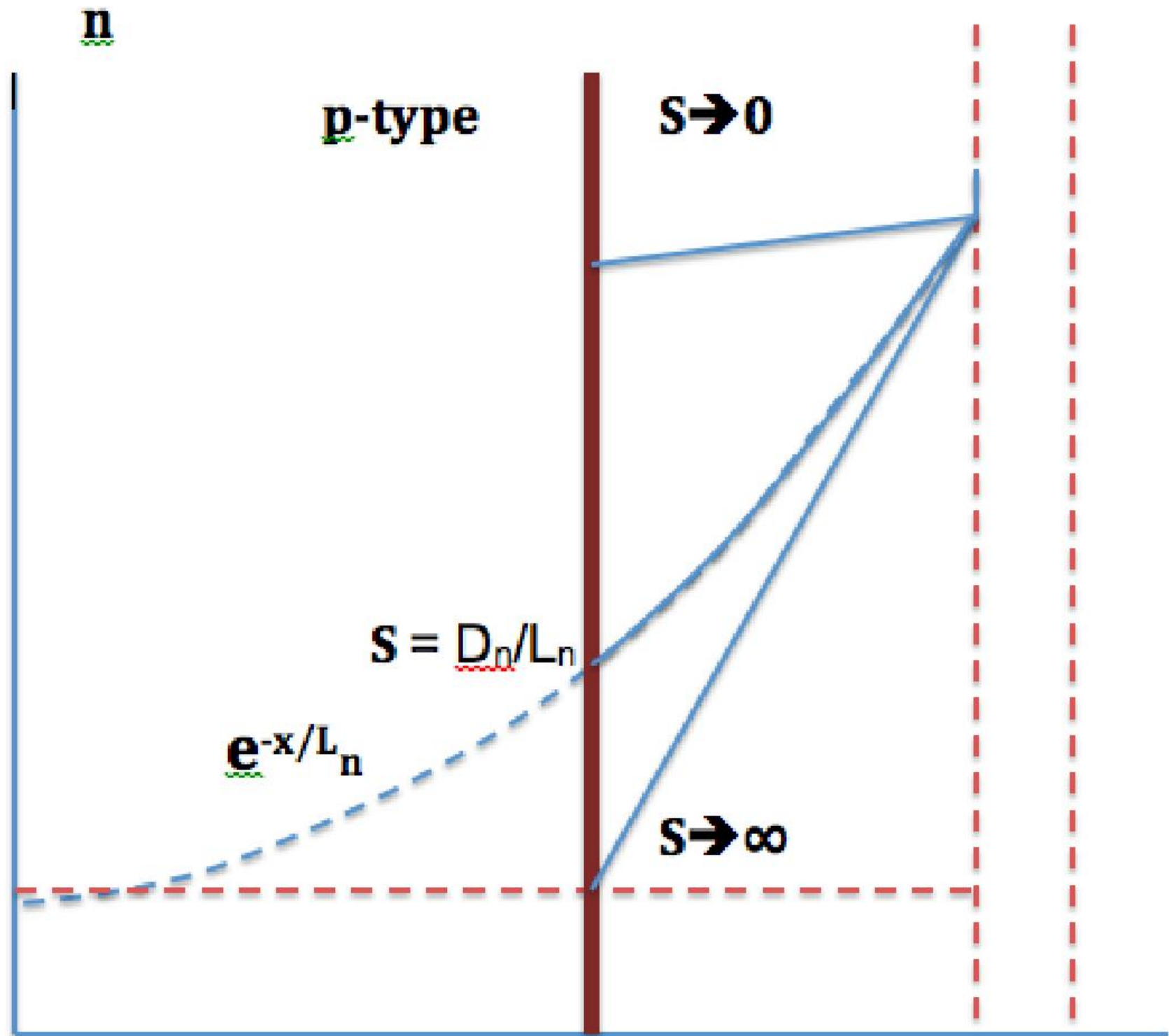




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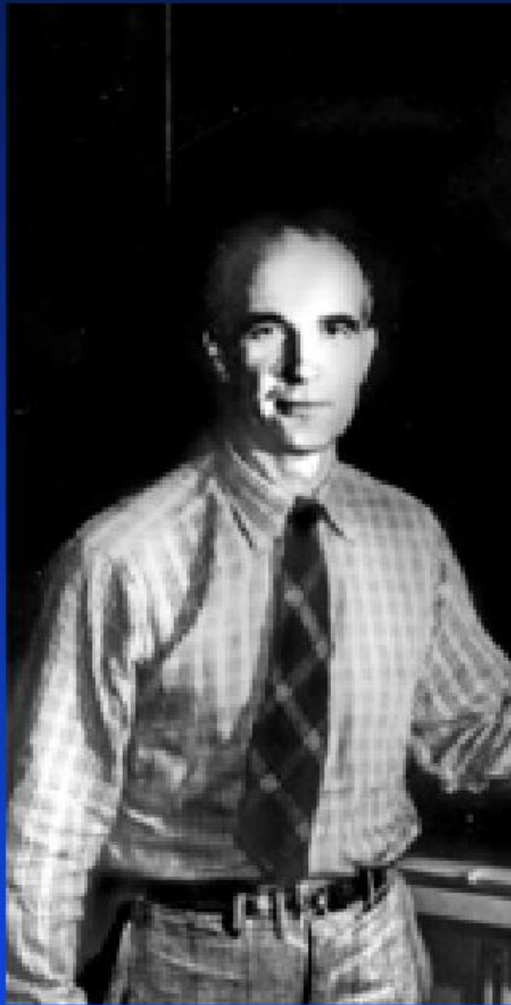


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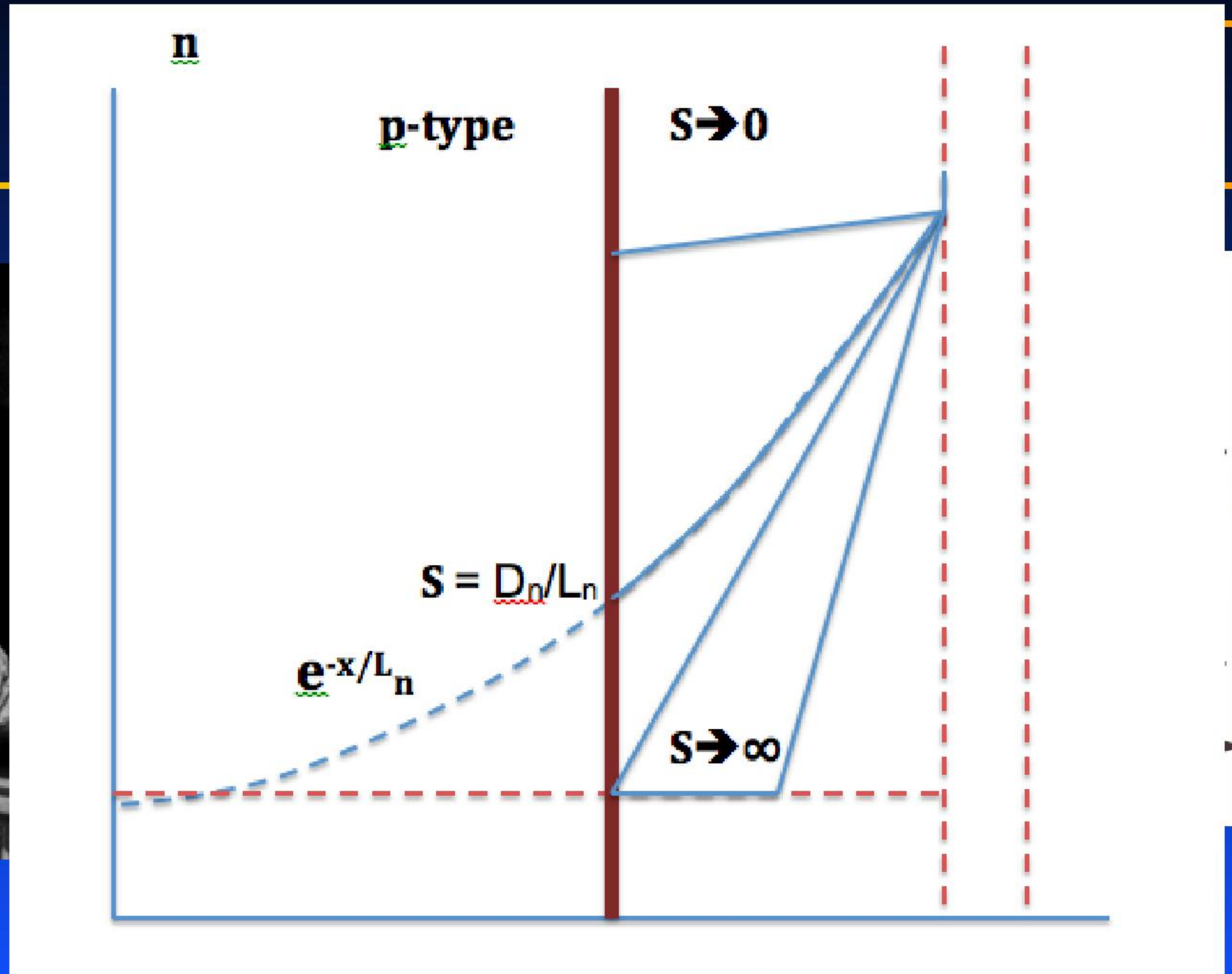




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“Dark/Light” Reciprocity

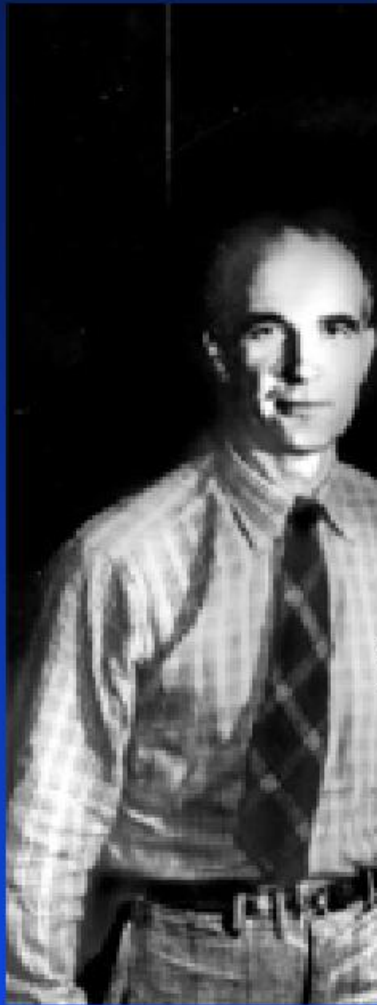
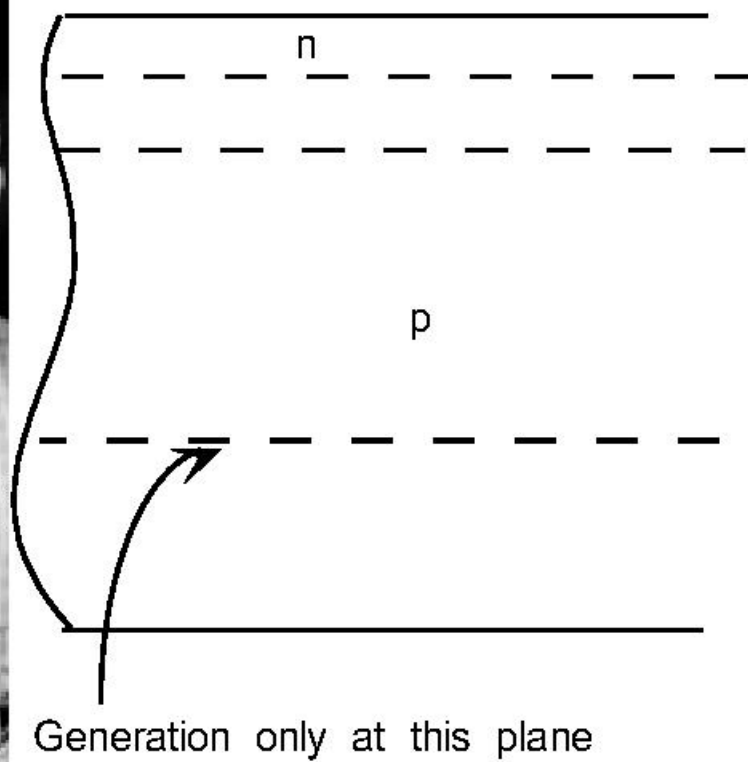
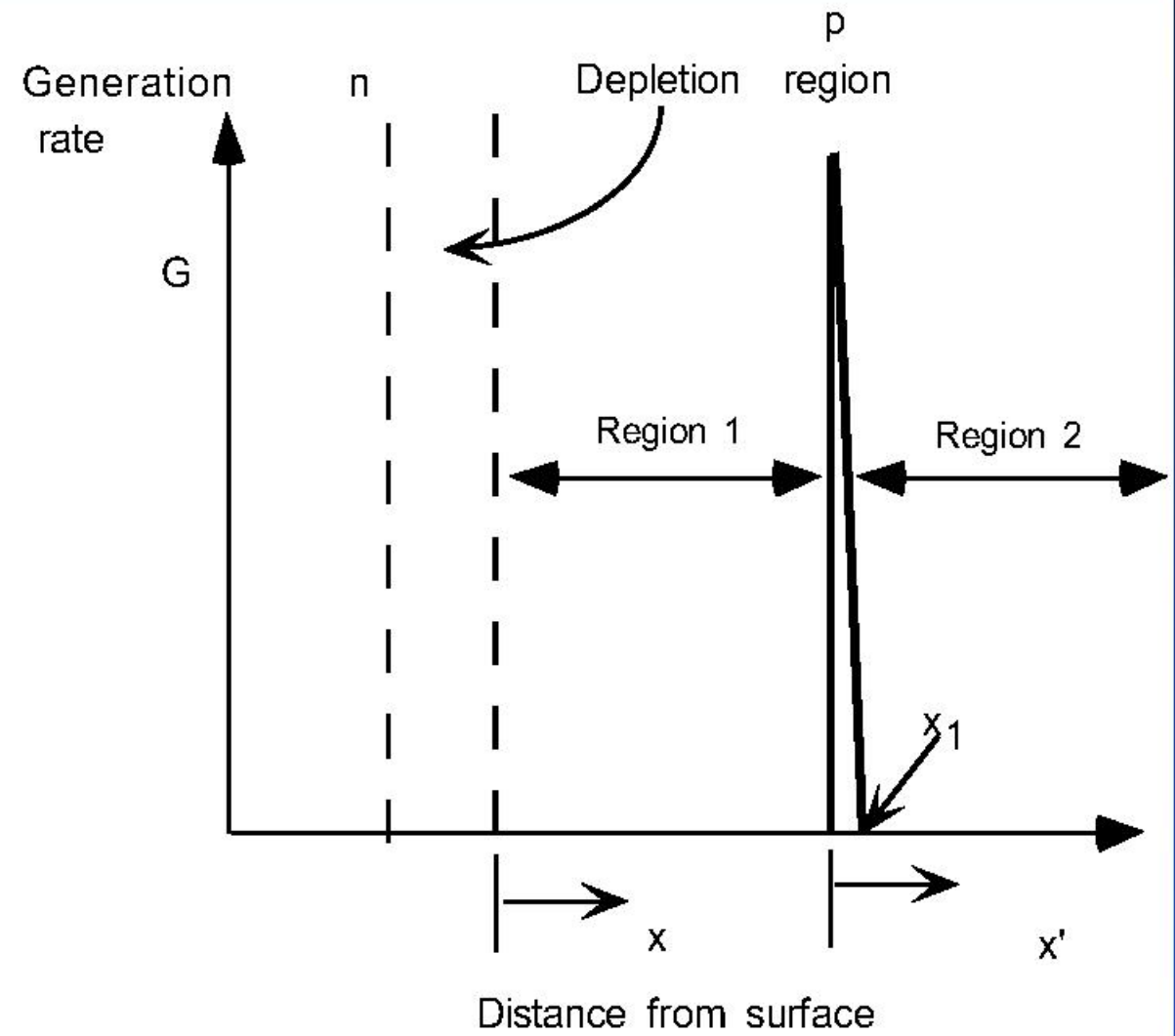


Fig. 8.1 “Red book”



(a)



(b)



“Dark/Light” Reciprocity

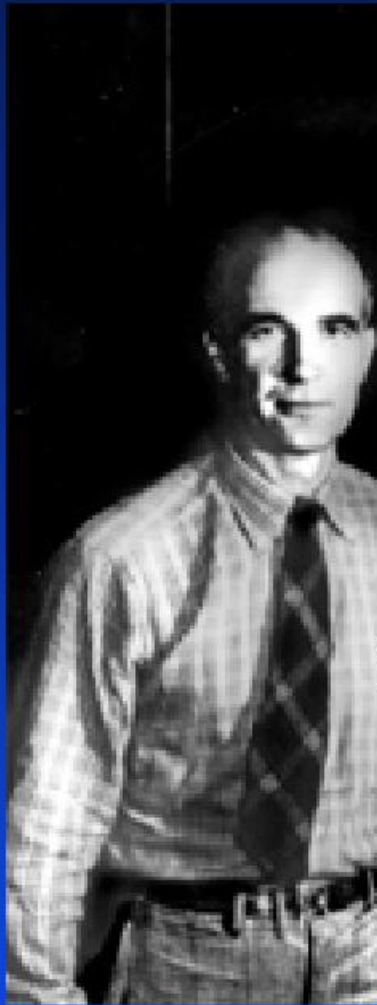
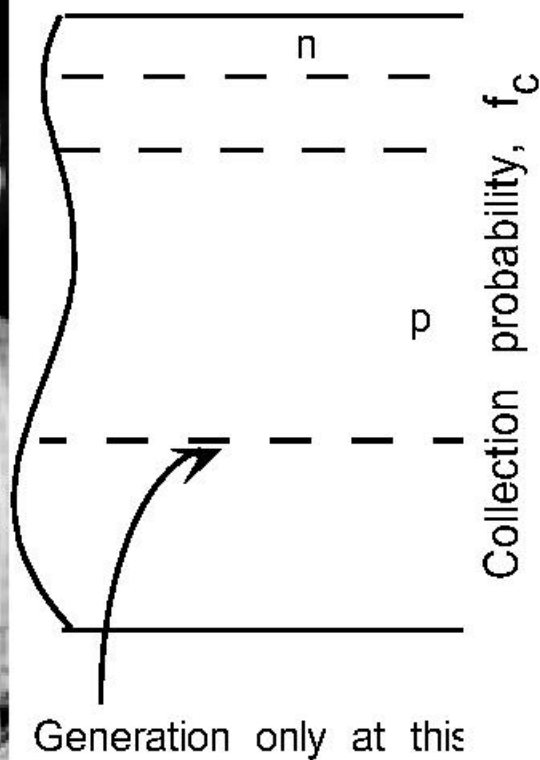
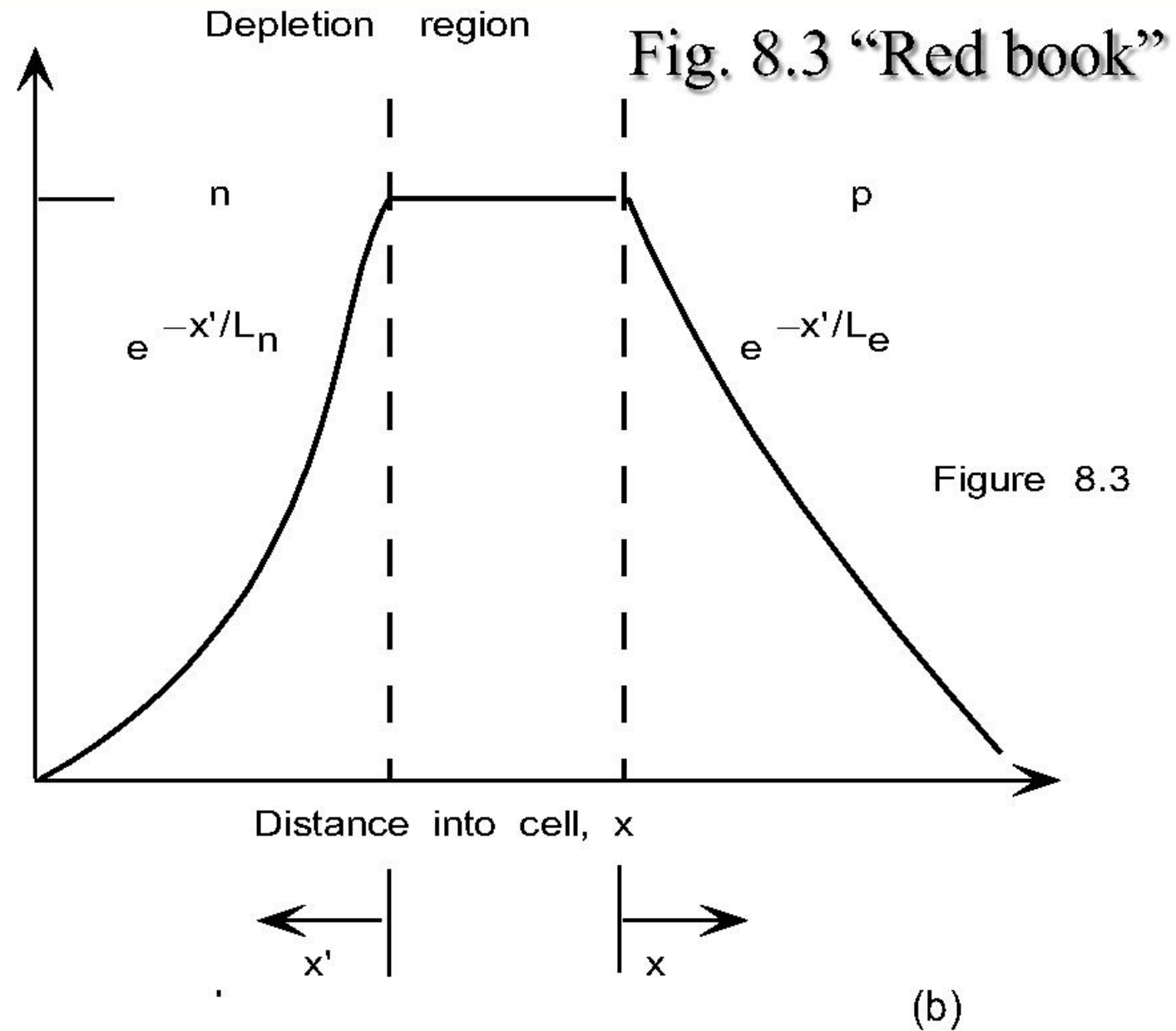


Fig. 8.1 “R



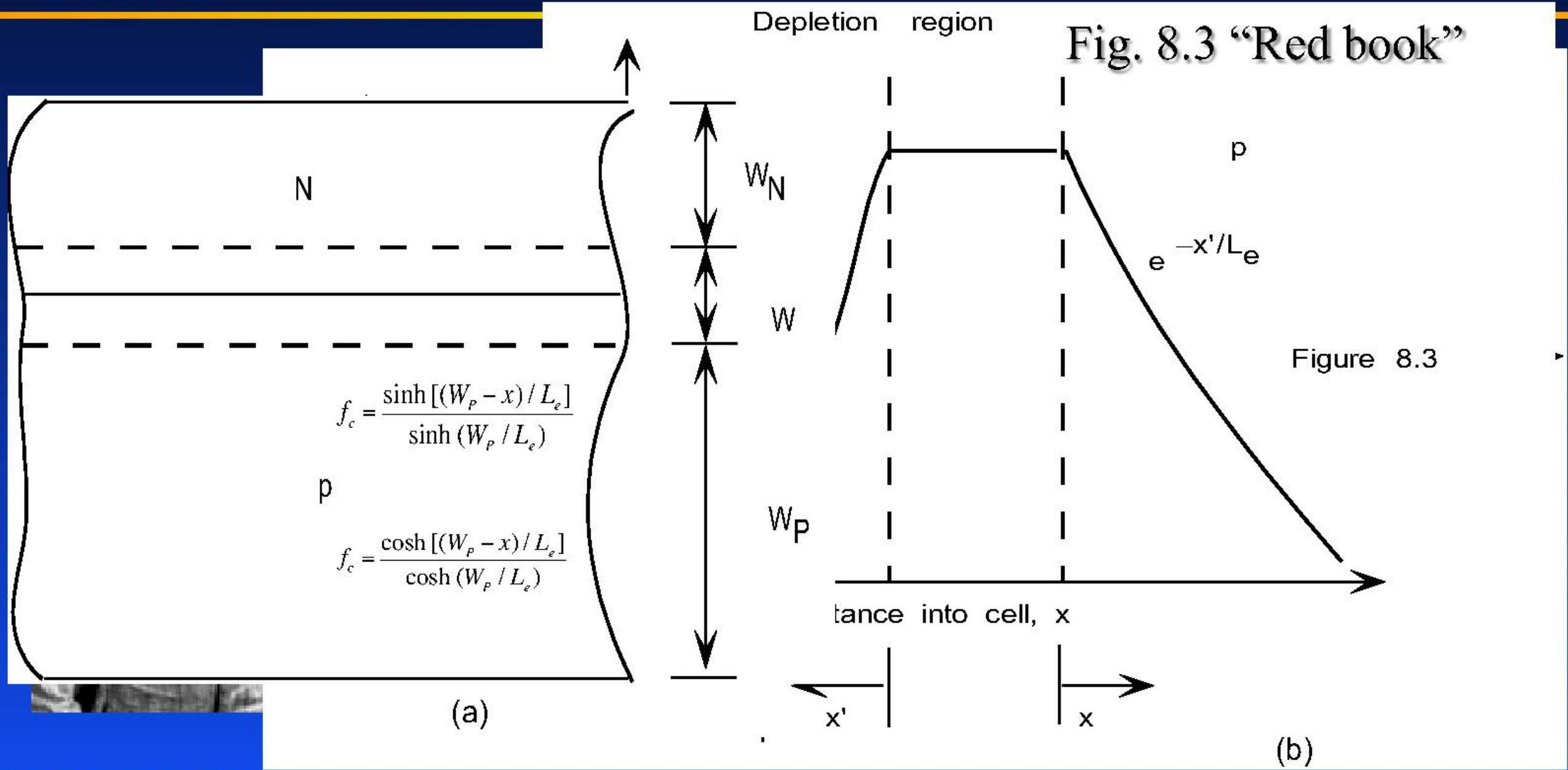
(a)



(b)

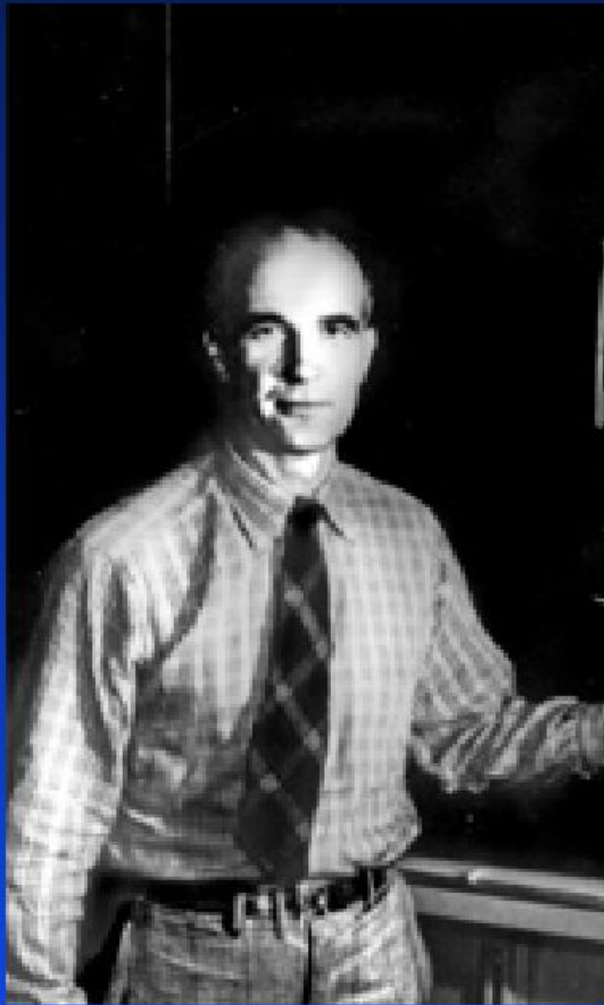


“Dark/Light” Reciprocity





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n

p-type

$S \rightarrow 0$

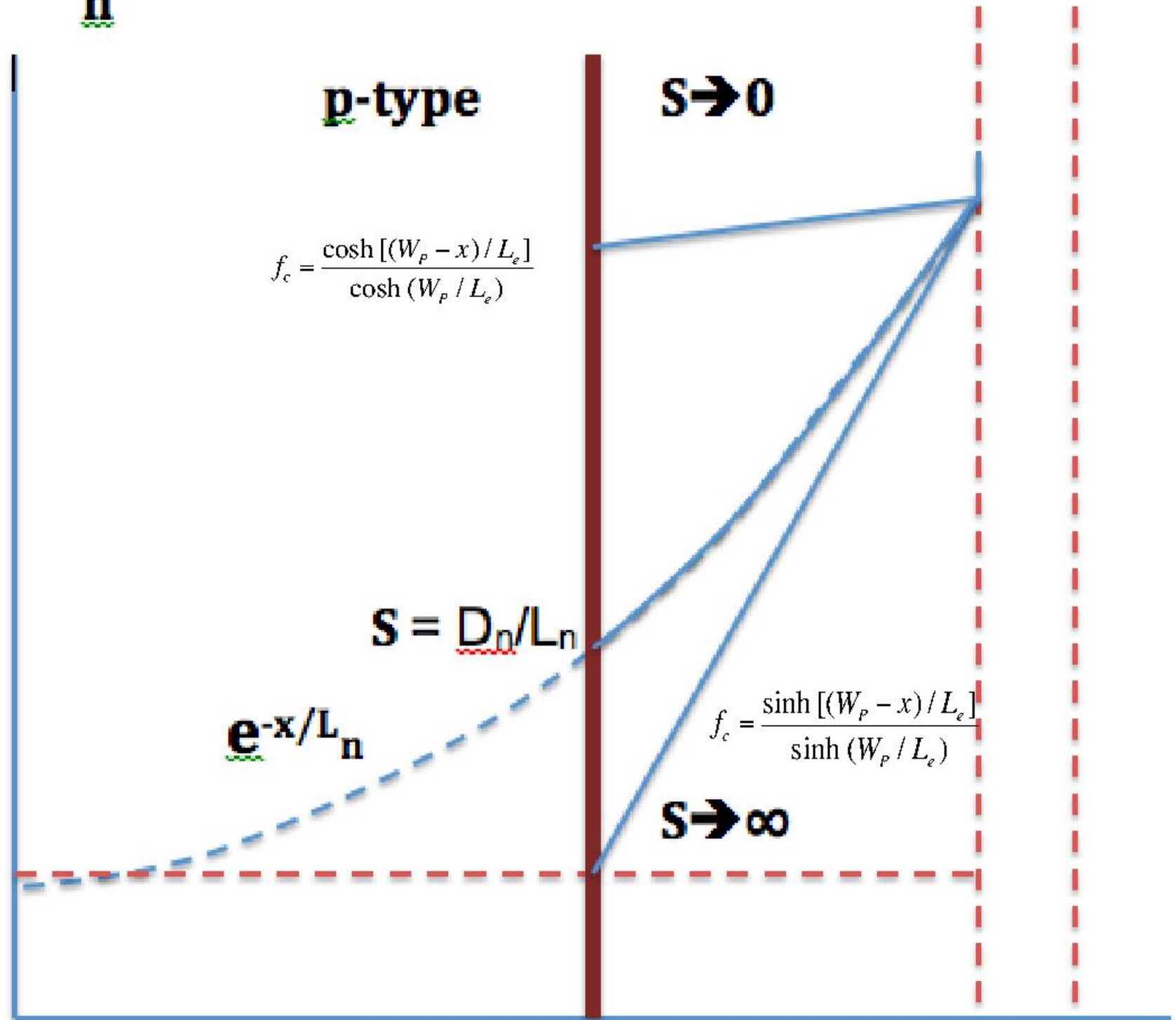
$$f_c = \frac{\cosh [(W_p - x) / L_e]}{\cosh (W_p / L_e)}$$

$S = D_n / L_n$

e^{-x / L_n}

$$f_c = \frac{\sinh [(W_p - x) / L_e]}{\sinh (W_p / L_e)}$$

$S \rightarrow \infty$





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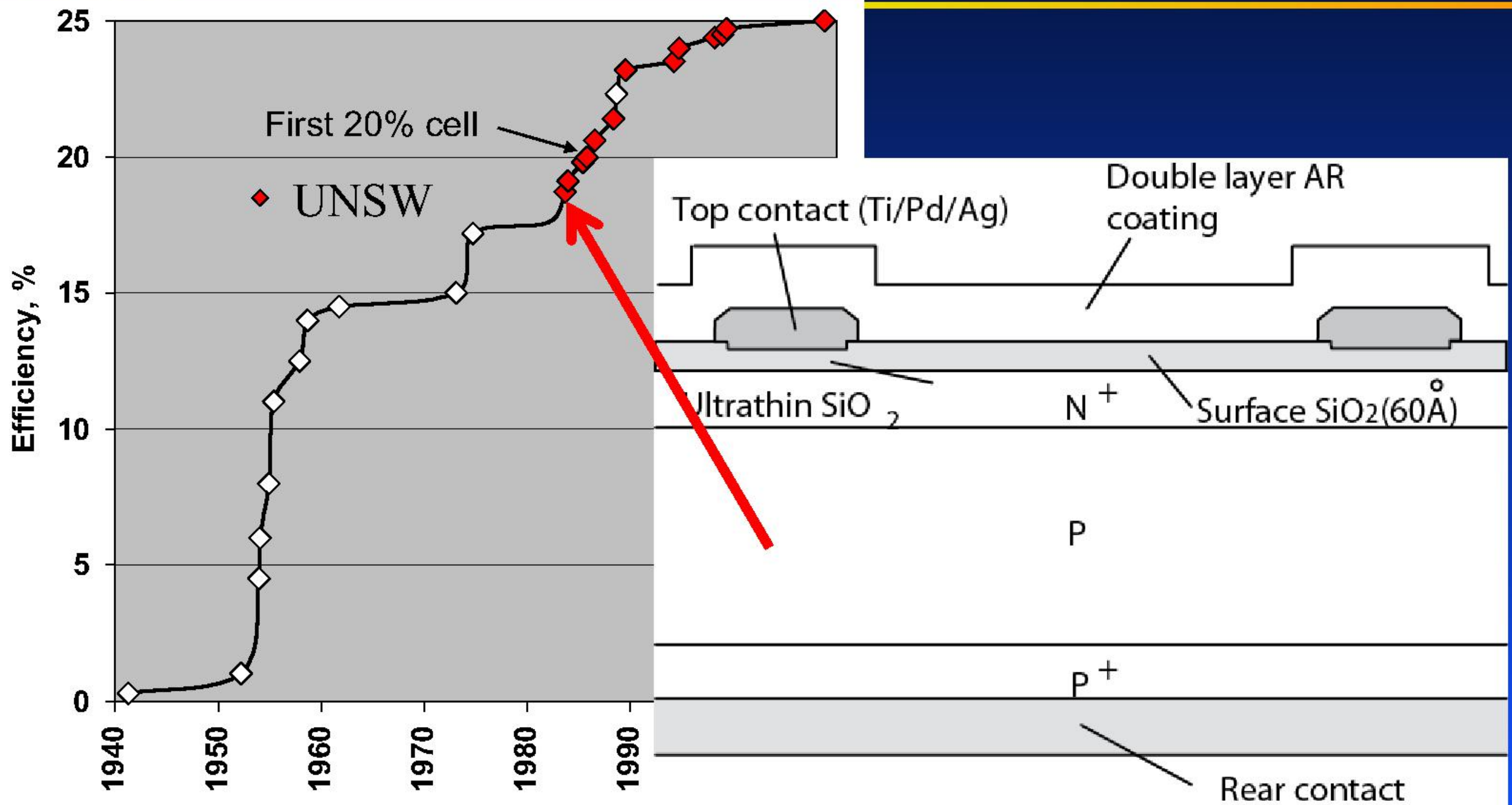
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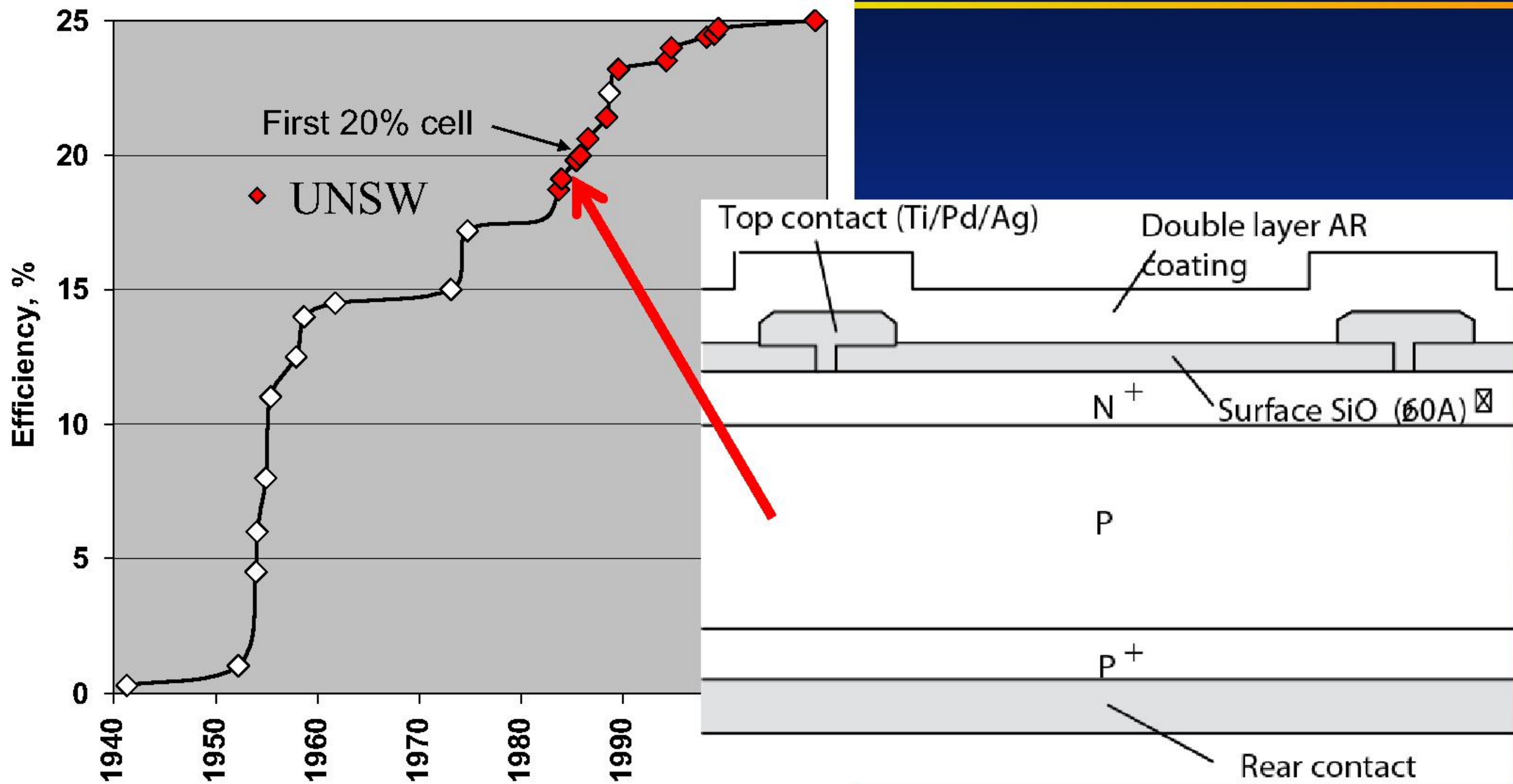
MINP cell (1983)





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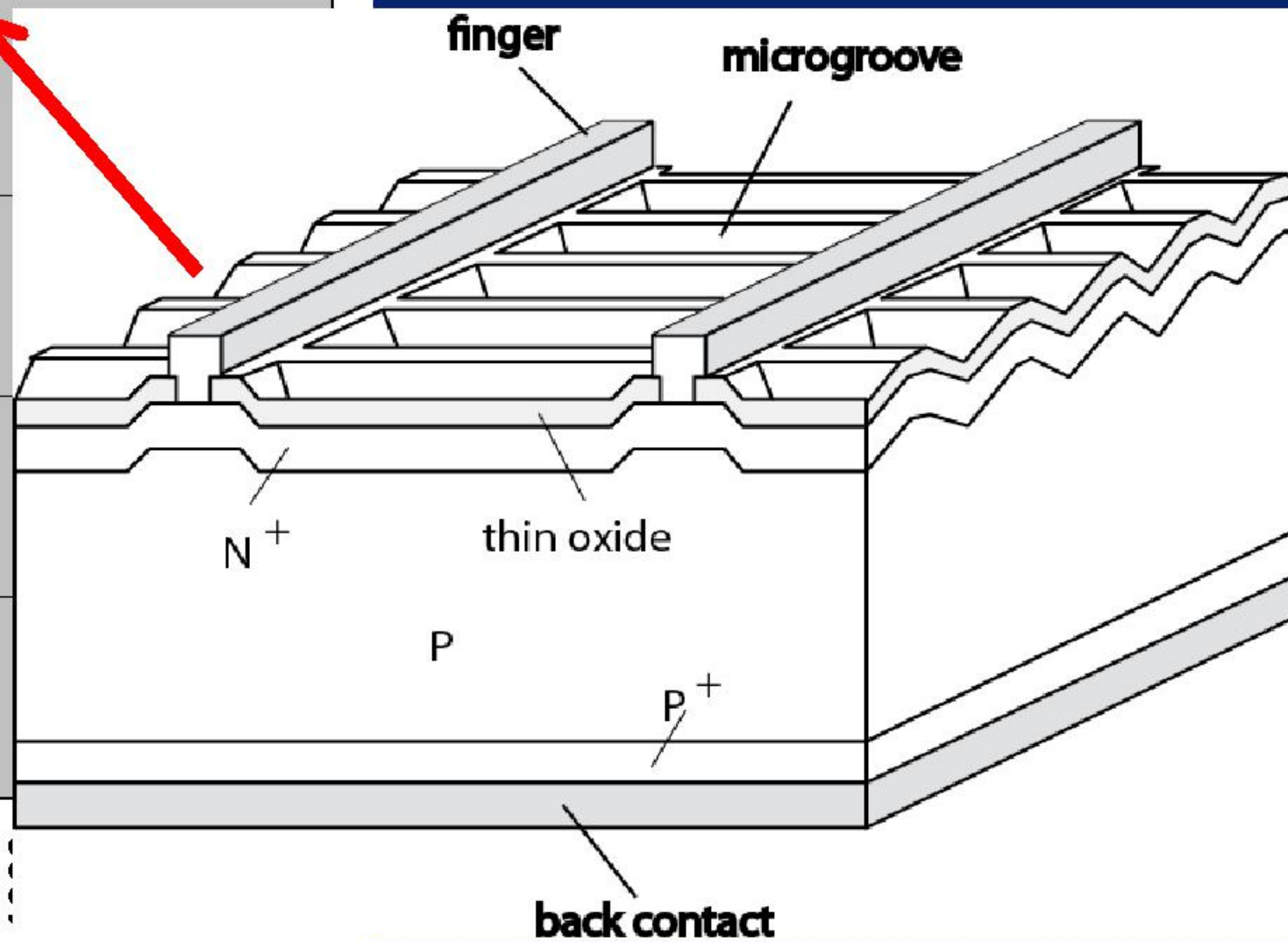
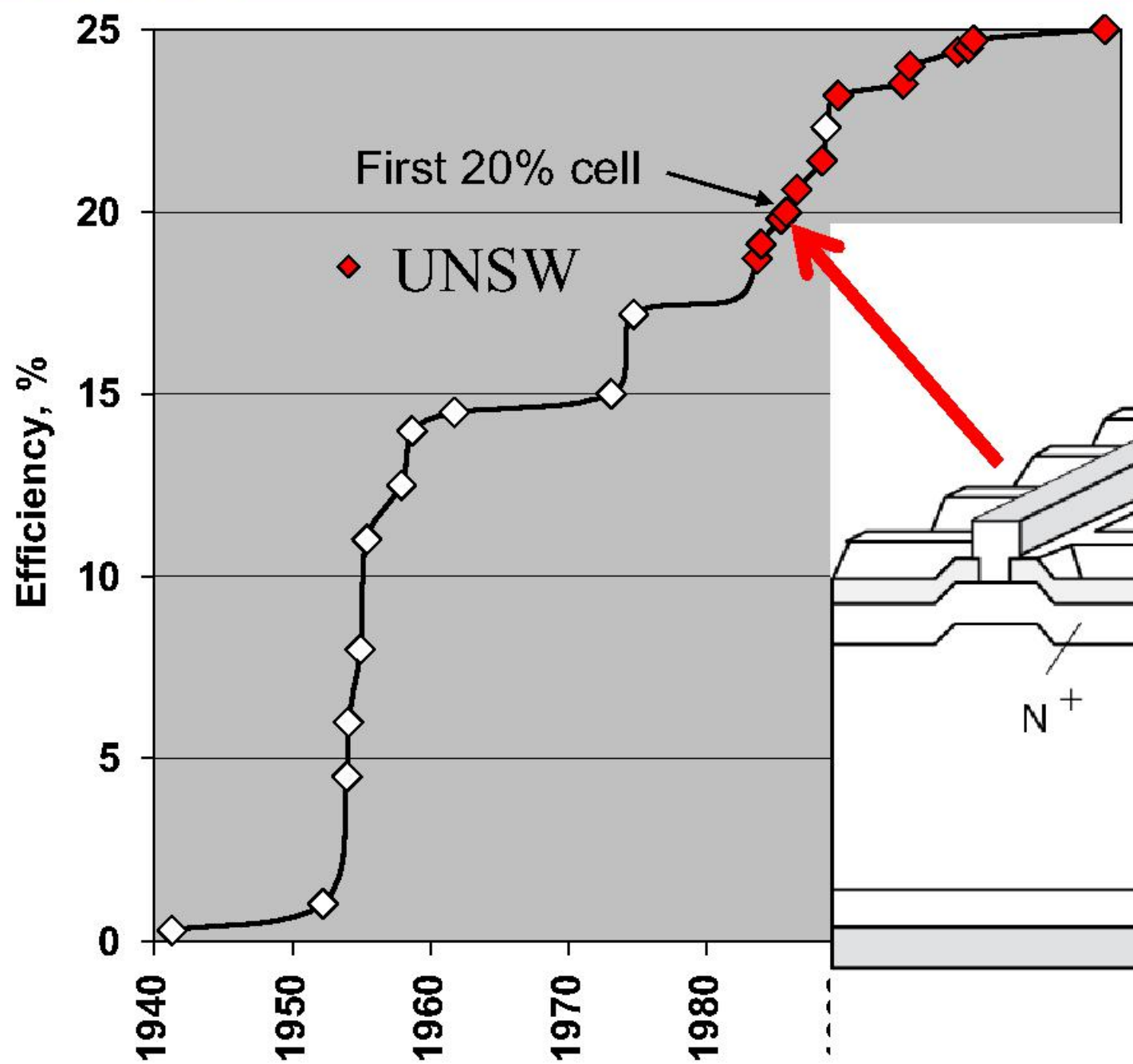
PESEC cell (1984)





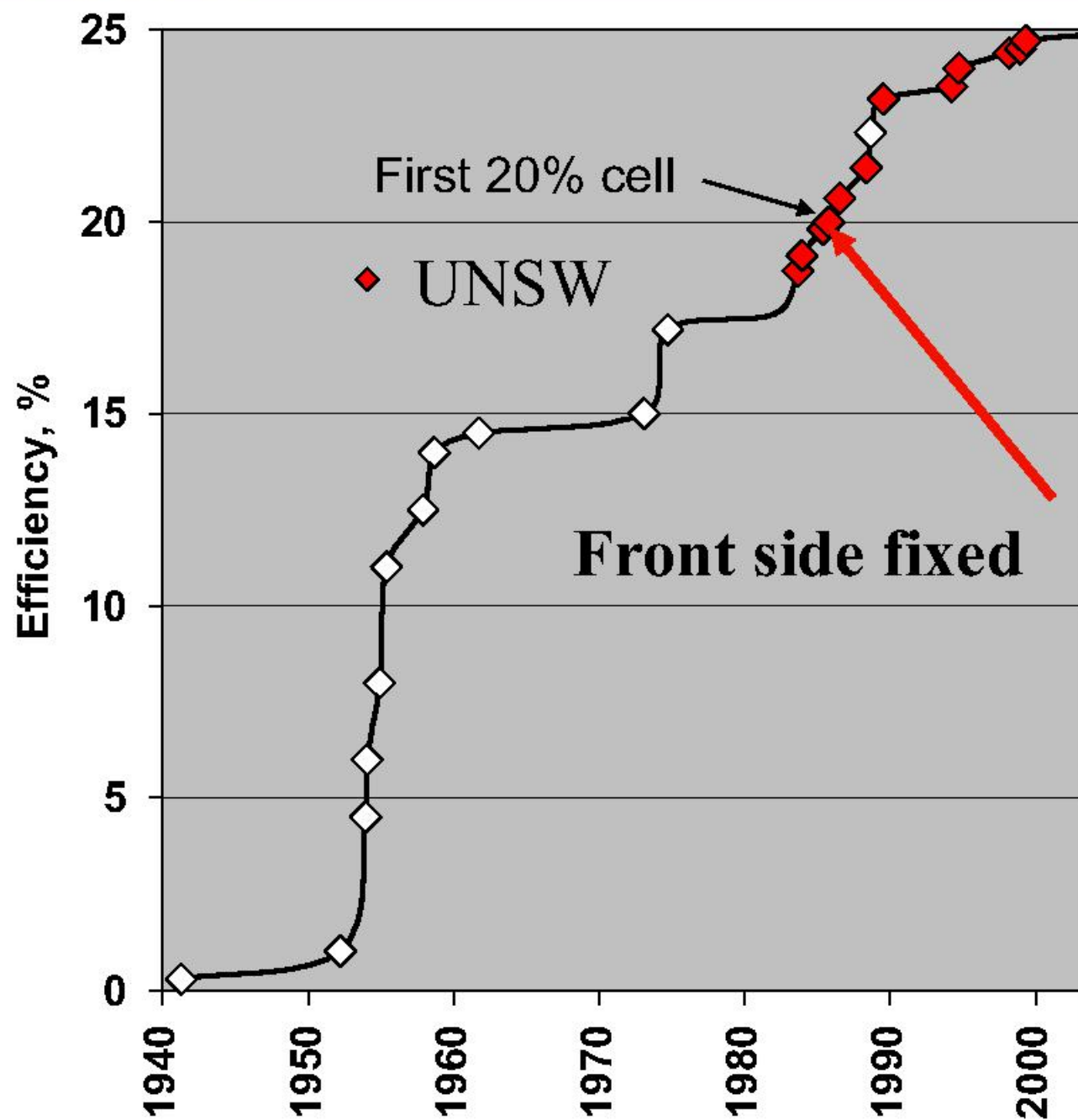
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μg -PESC cell (1985)



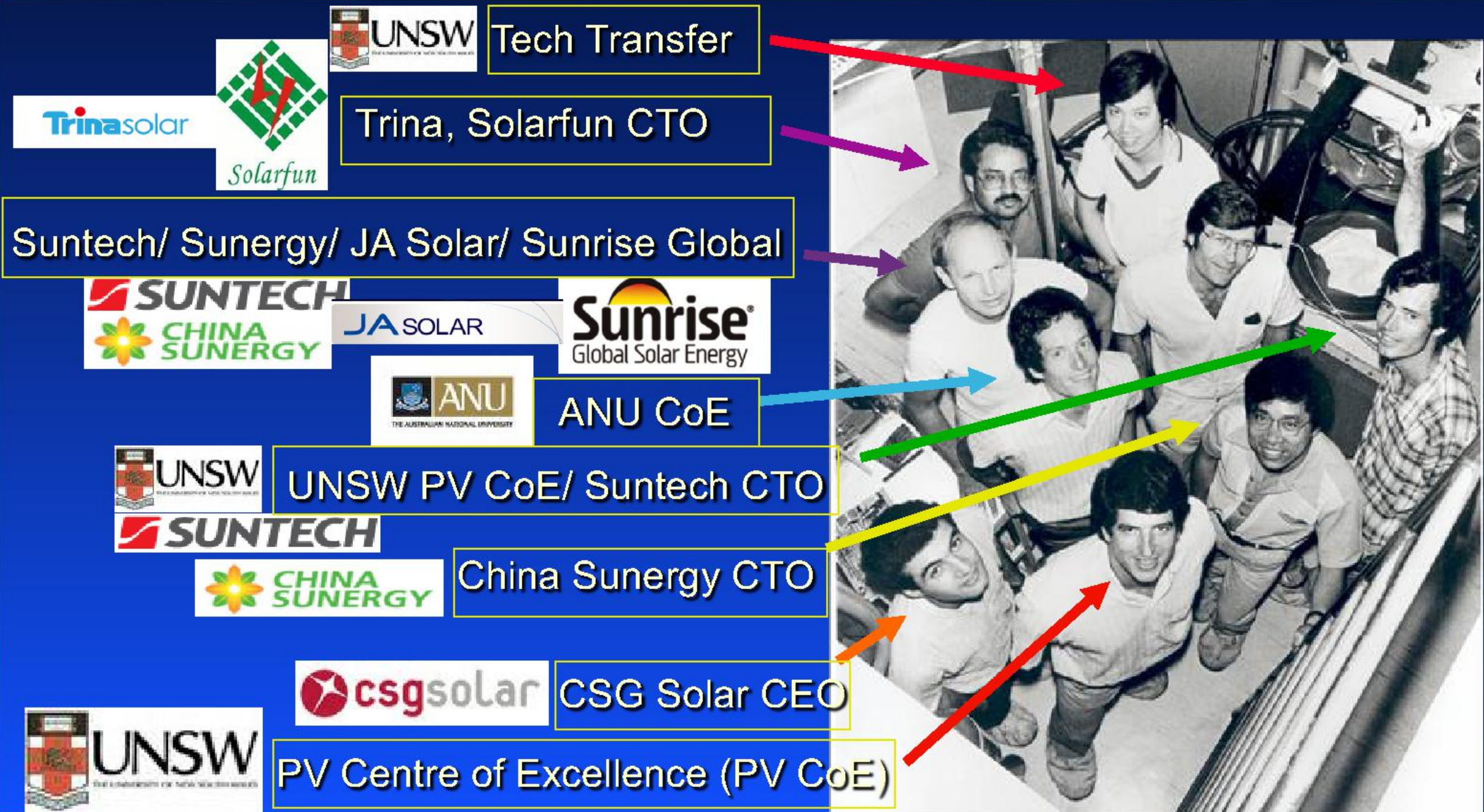


Improved efficiency: 20% and beyond





Improved efficiency: 20% and beyond





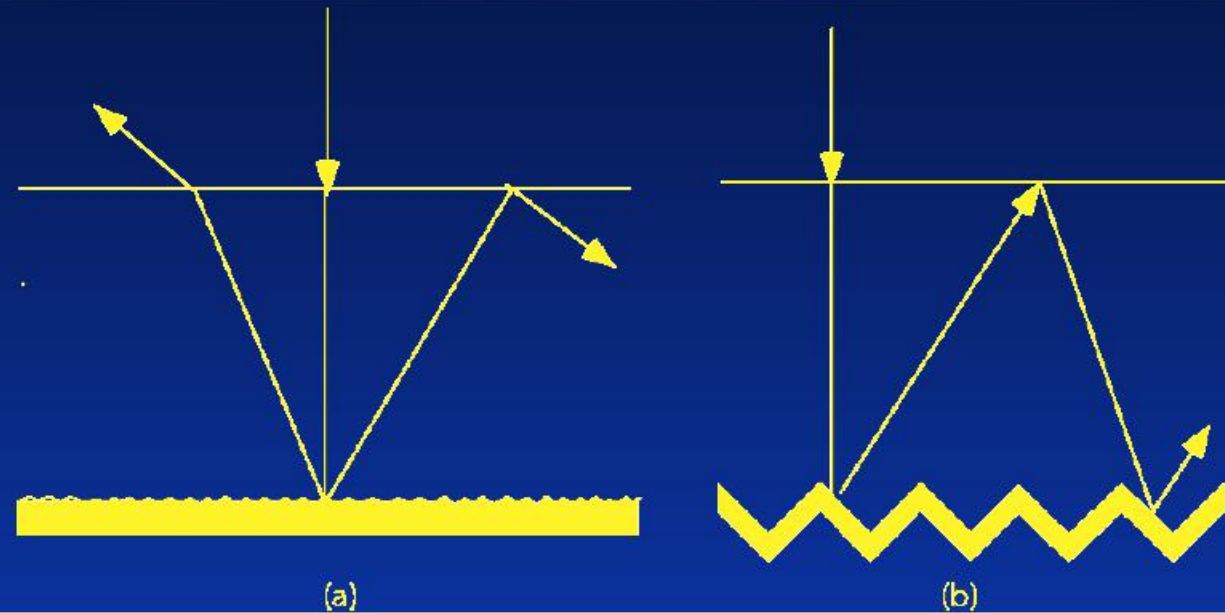
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Light trapping



$$\begin{aligned} PL &= 4n^2W \text{ [Goetzberger (1981); Yablonoitch (1982)]} \\ &= 4n^2W/\sin^2\theta \text{ [Campbell \& Green (1986)]} \end{aligned}$$



Ping Sheng (1983): "choosing the grating parameters so the gap in $\rho(\omega)$ falls below absorption edge ... rob photon states ... $\rho(\omega)$ exceeds n^2 limit"



Outline –Lecture 2

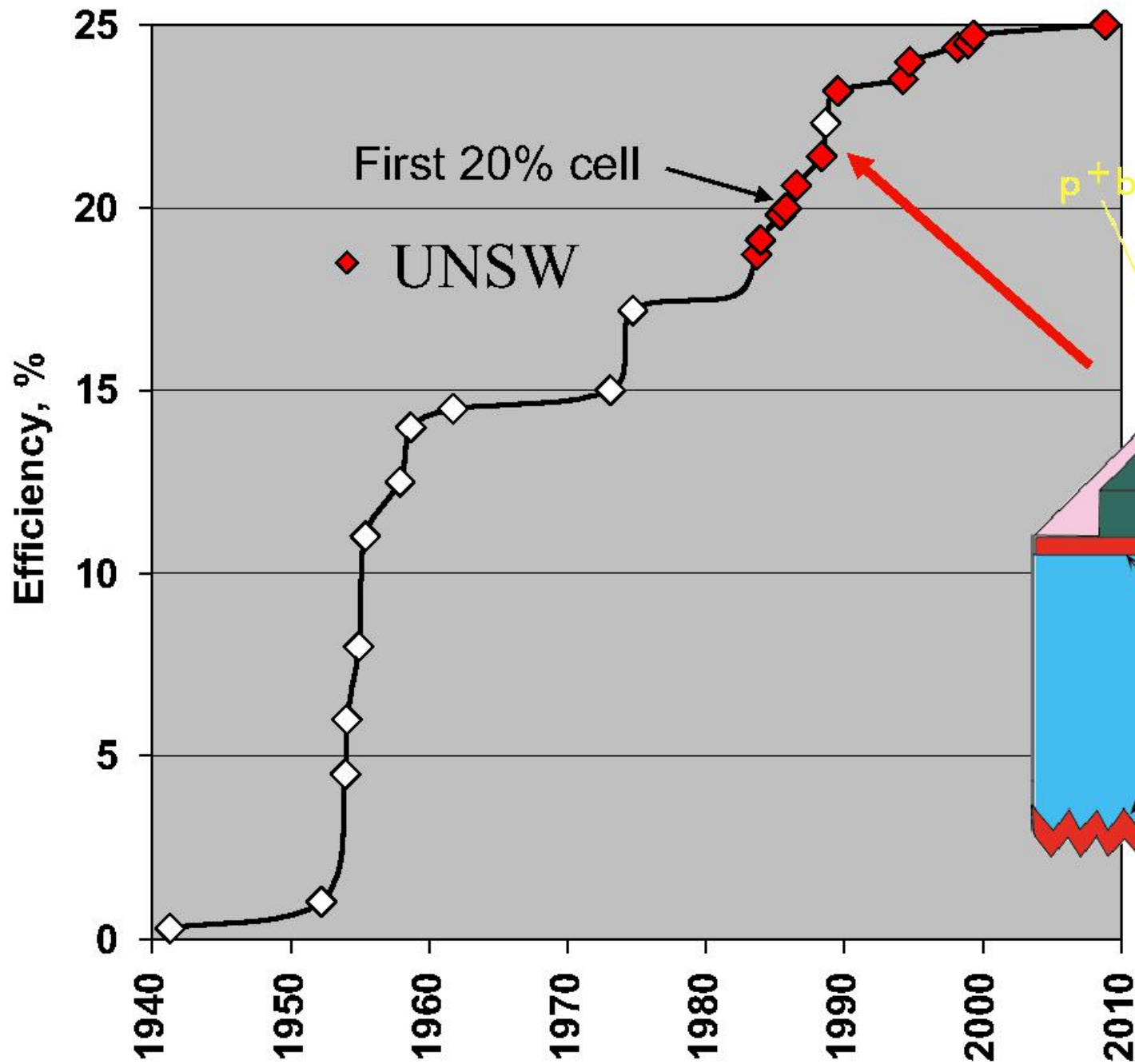
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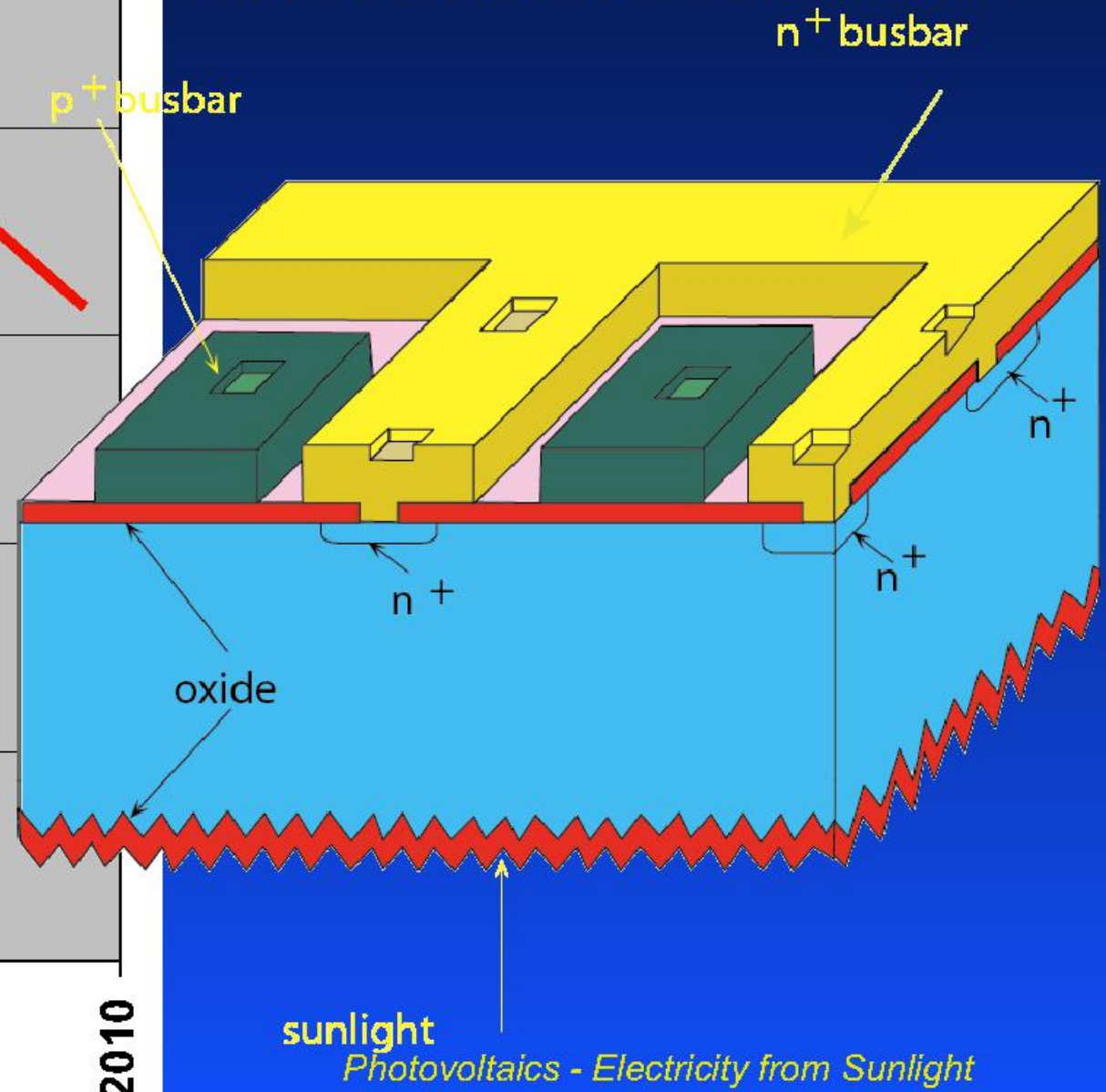


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Improved efficiency: 22% cells



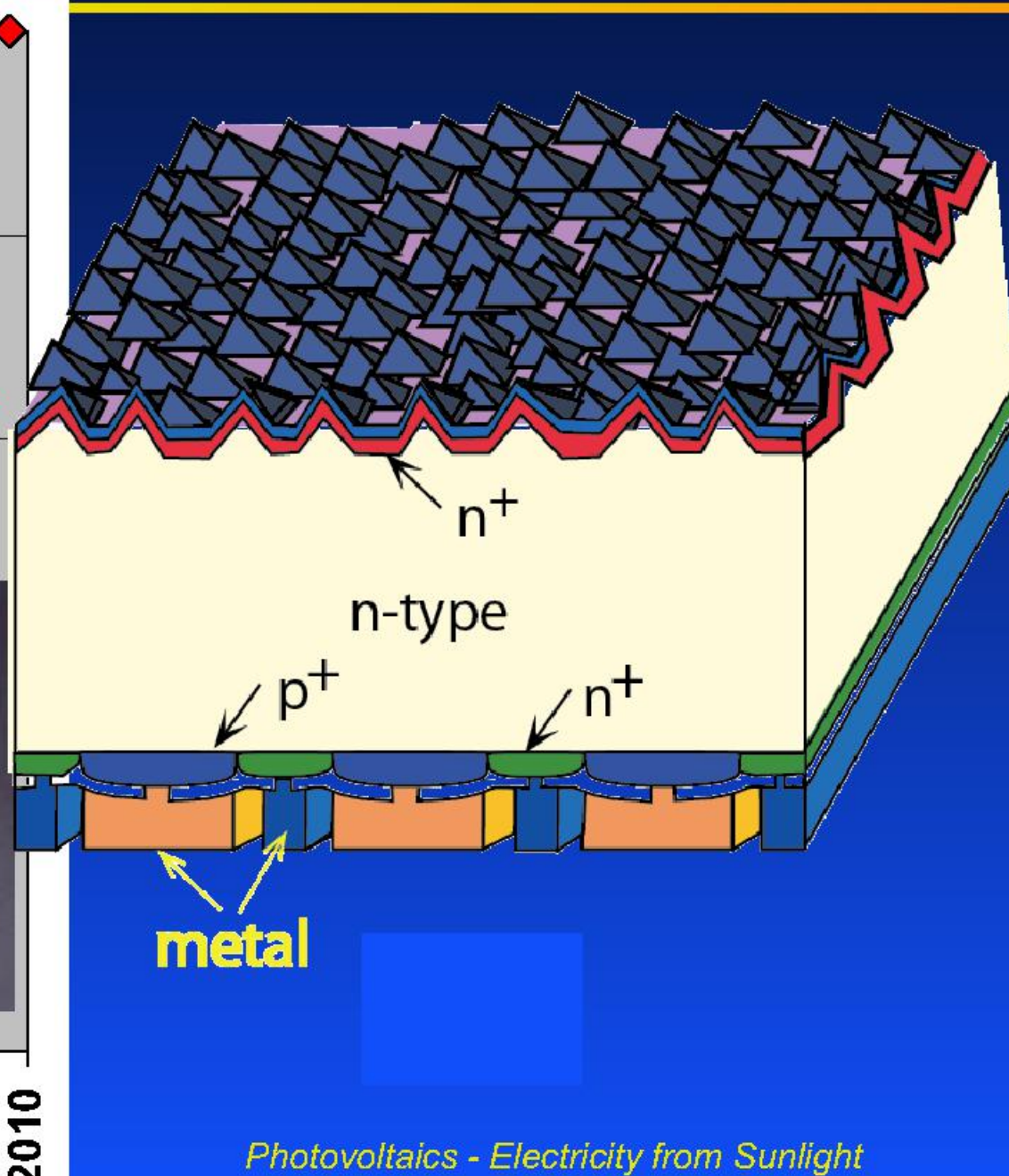
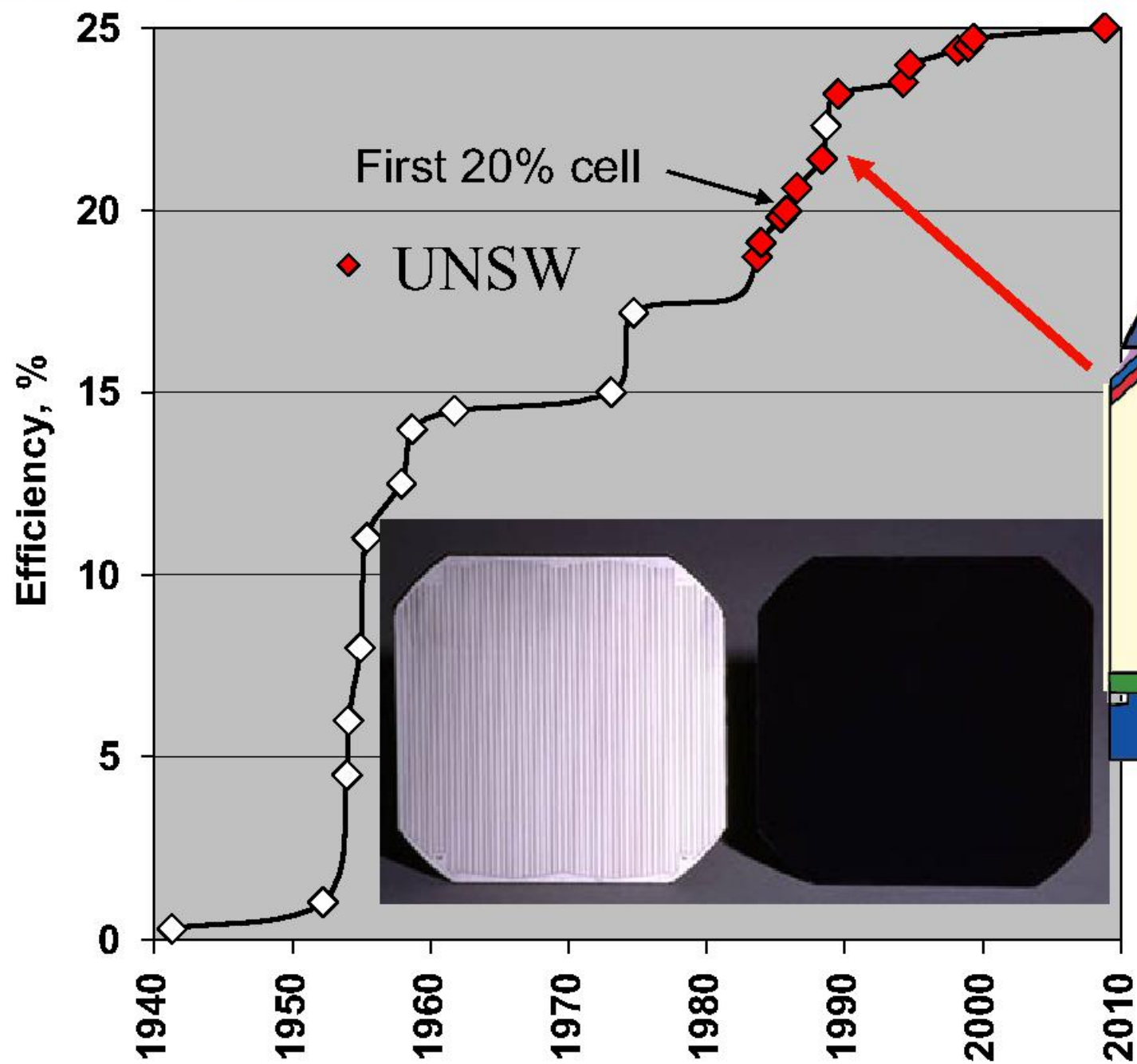
Stanford Uni Rear Junction Cell





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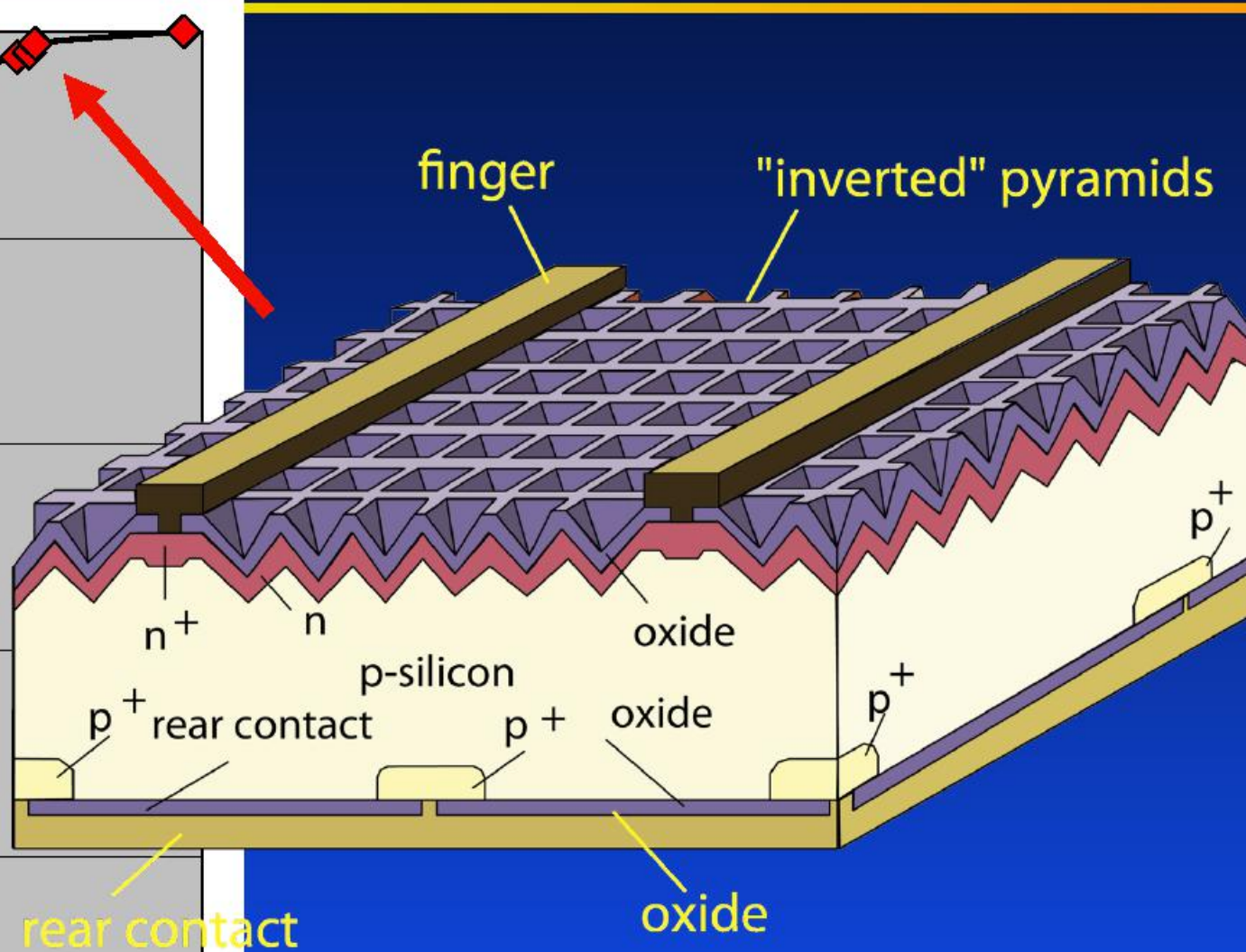
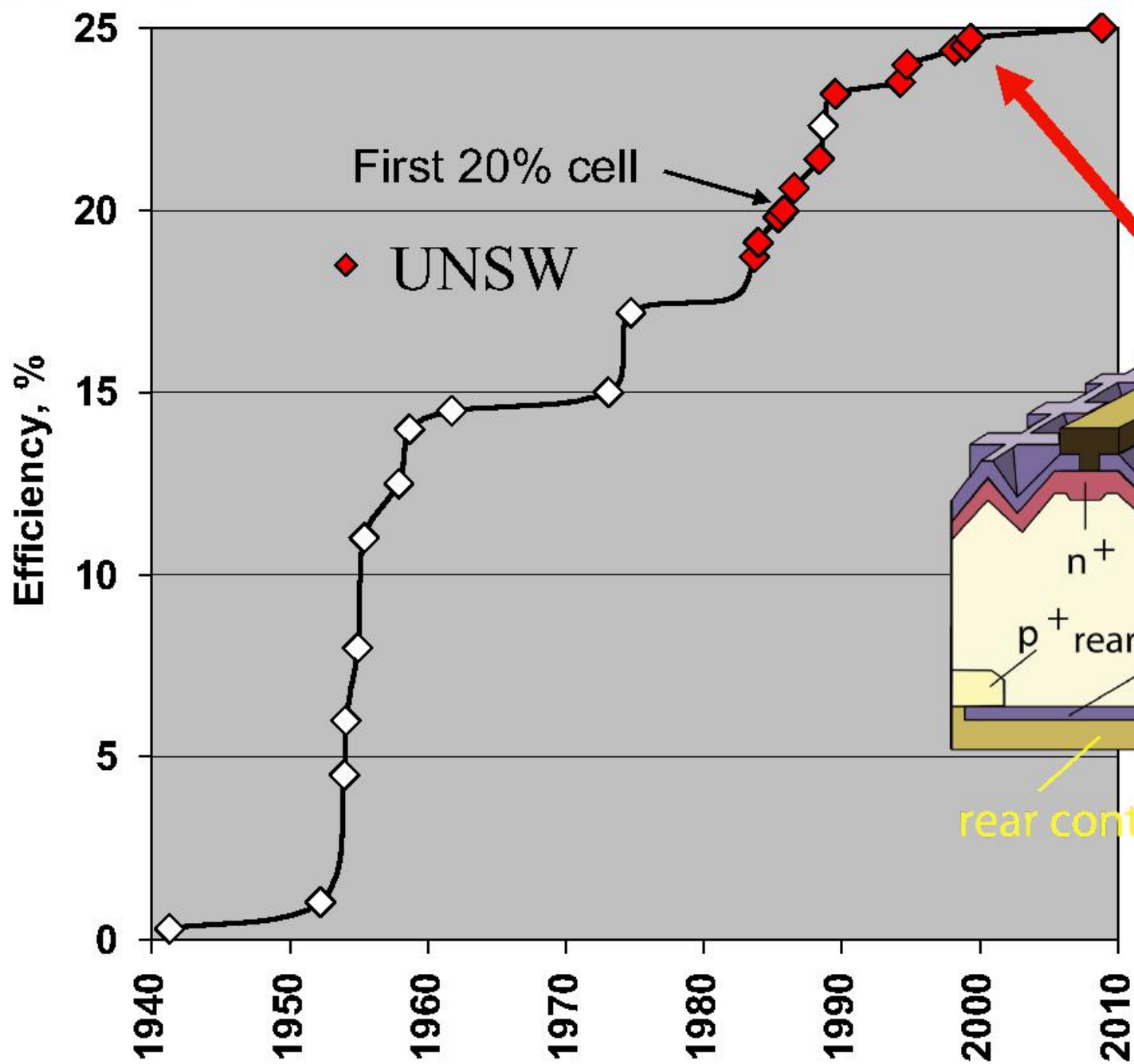
Improved efficiency: 22% cells



Photovoltaics - Electricity from Sunlight



Improved efficiency: 25% PERL cells



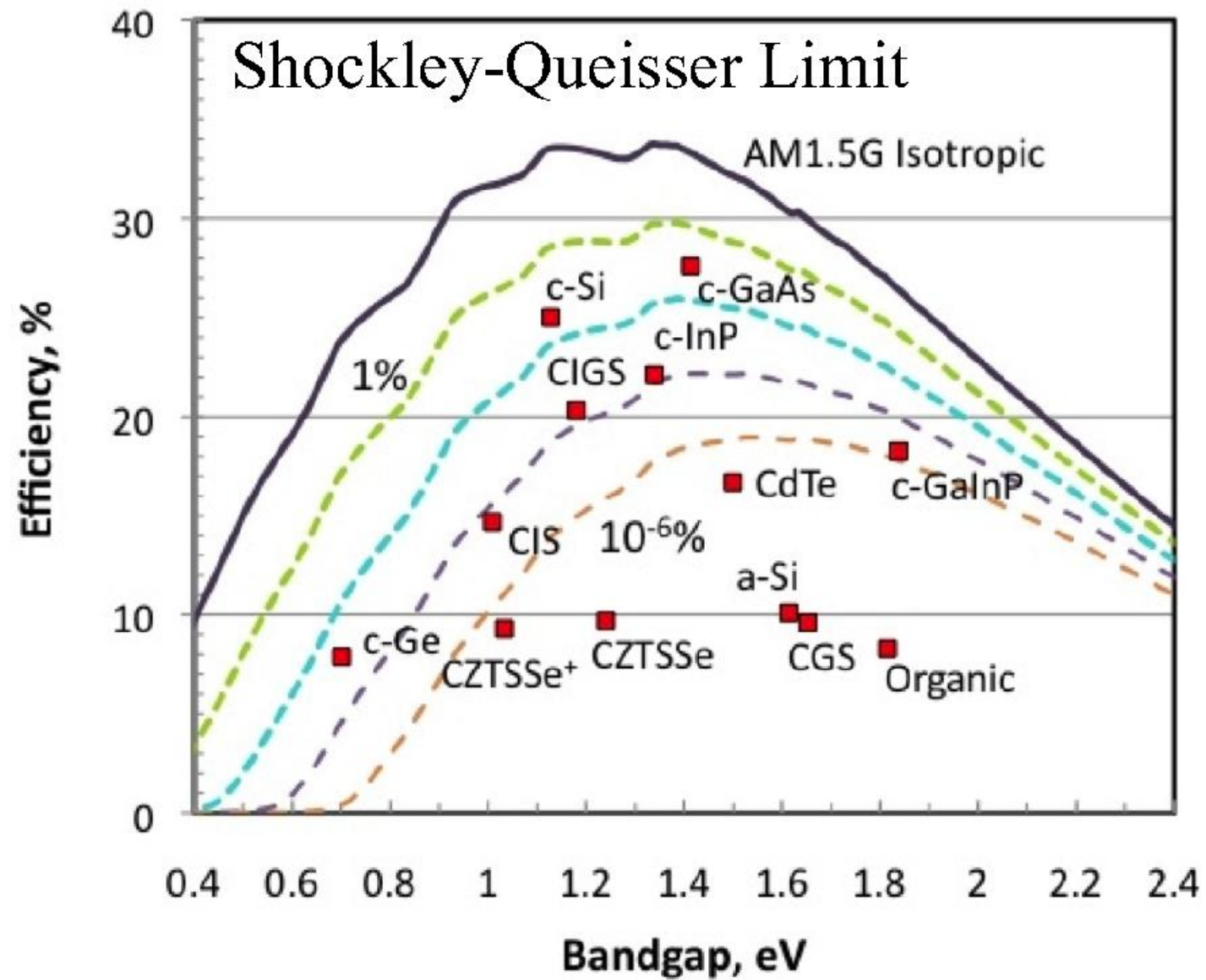


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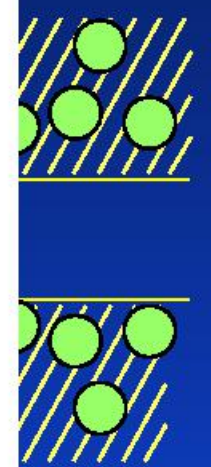
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 7. Evolution of Si cell design II
 8. Principle III – “PV/LED” Reciprocity
 9. The future
- Questions-



ACAP



(direct)



$$P = qV \int_{E_G}^{\infty} \int_{\Omega} \{N_{BB}(6000K) - \exp(qV/kT) N_{BB}(300K)\} dE d\Omega$$

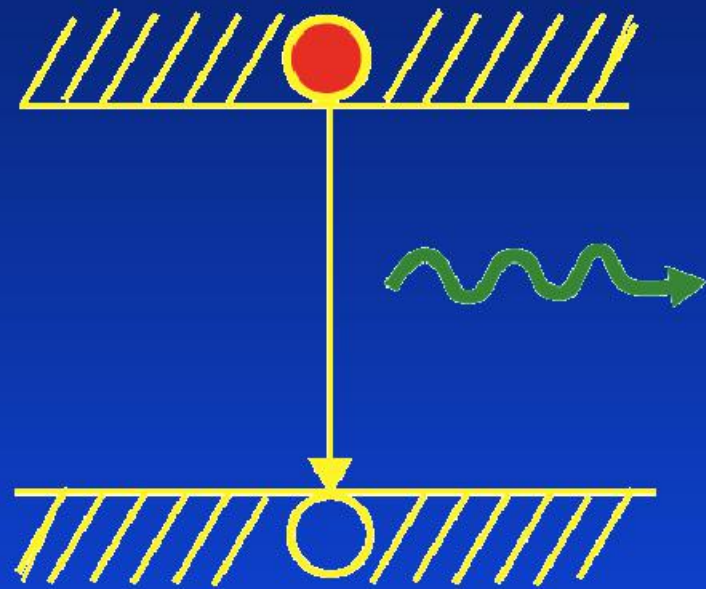
UNSW

Photovoltaics - Electricity from Sunlight

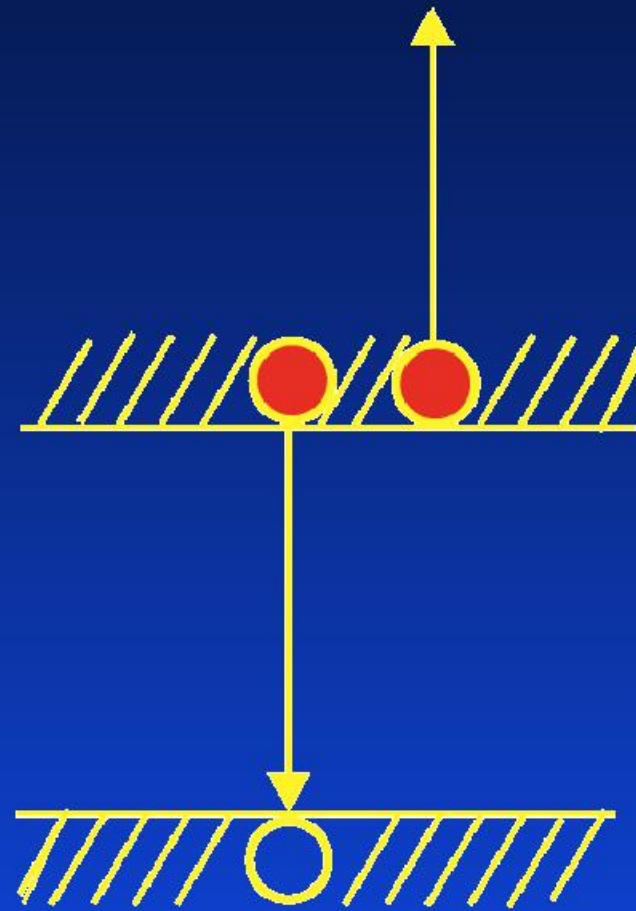


ACAP

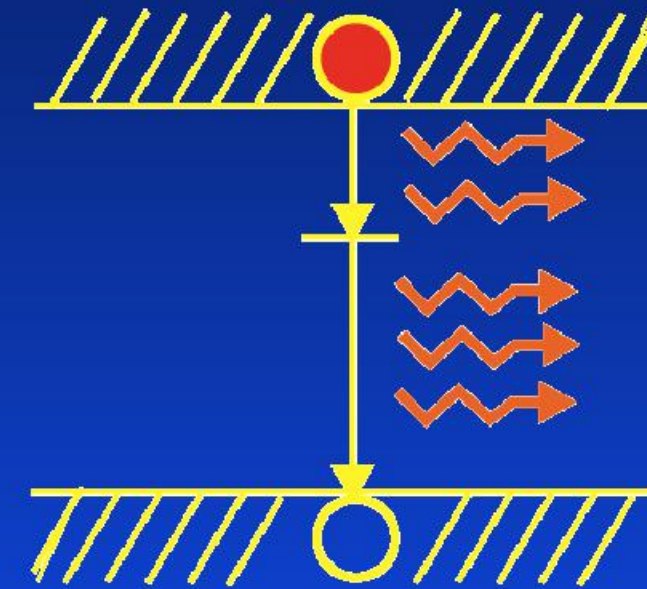
Other recombination paths



radiative



Auger

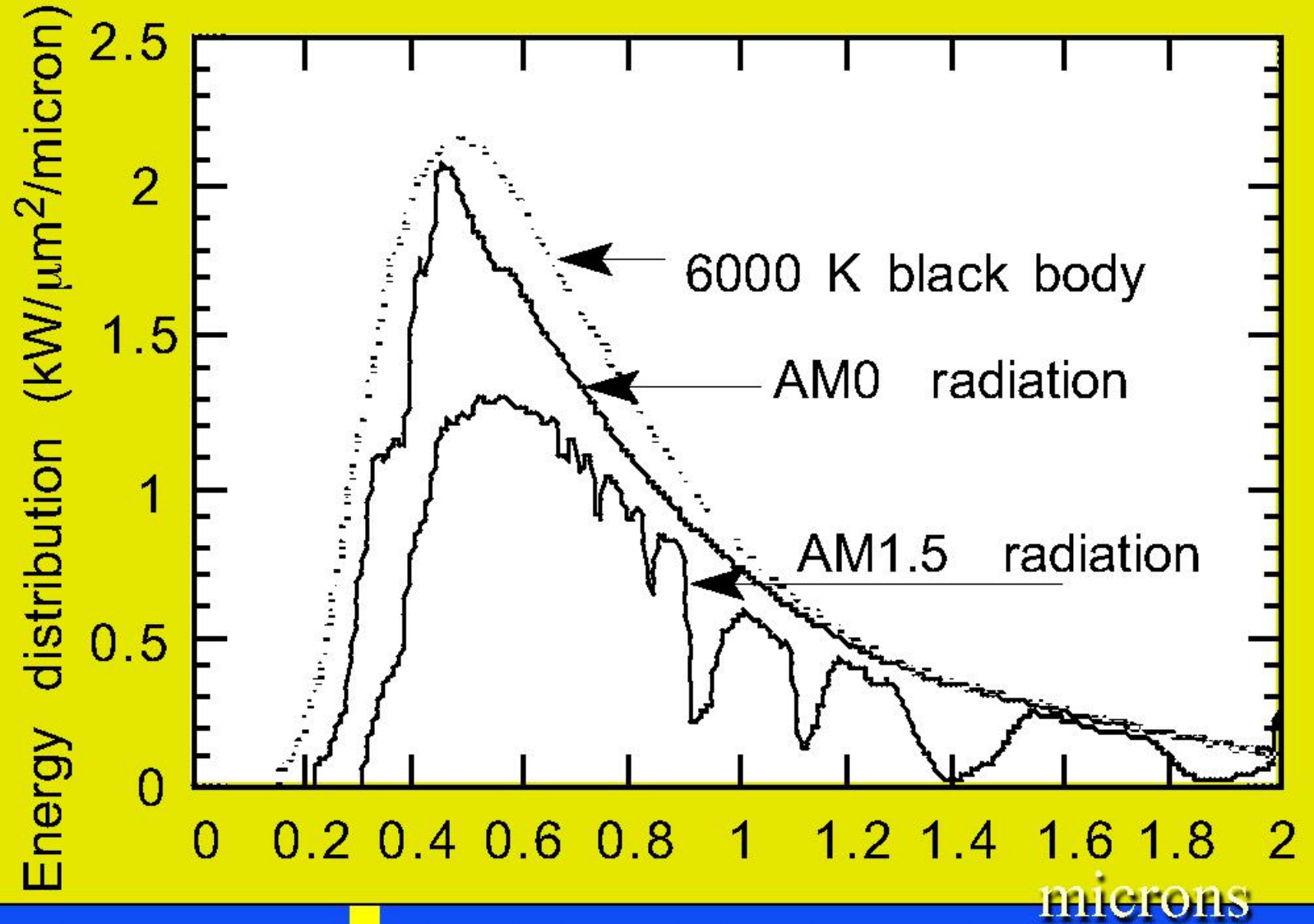


defect



ACAP

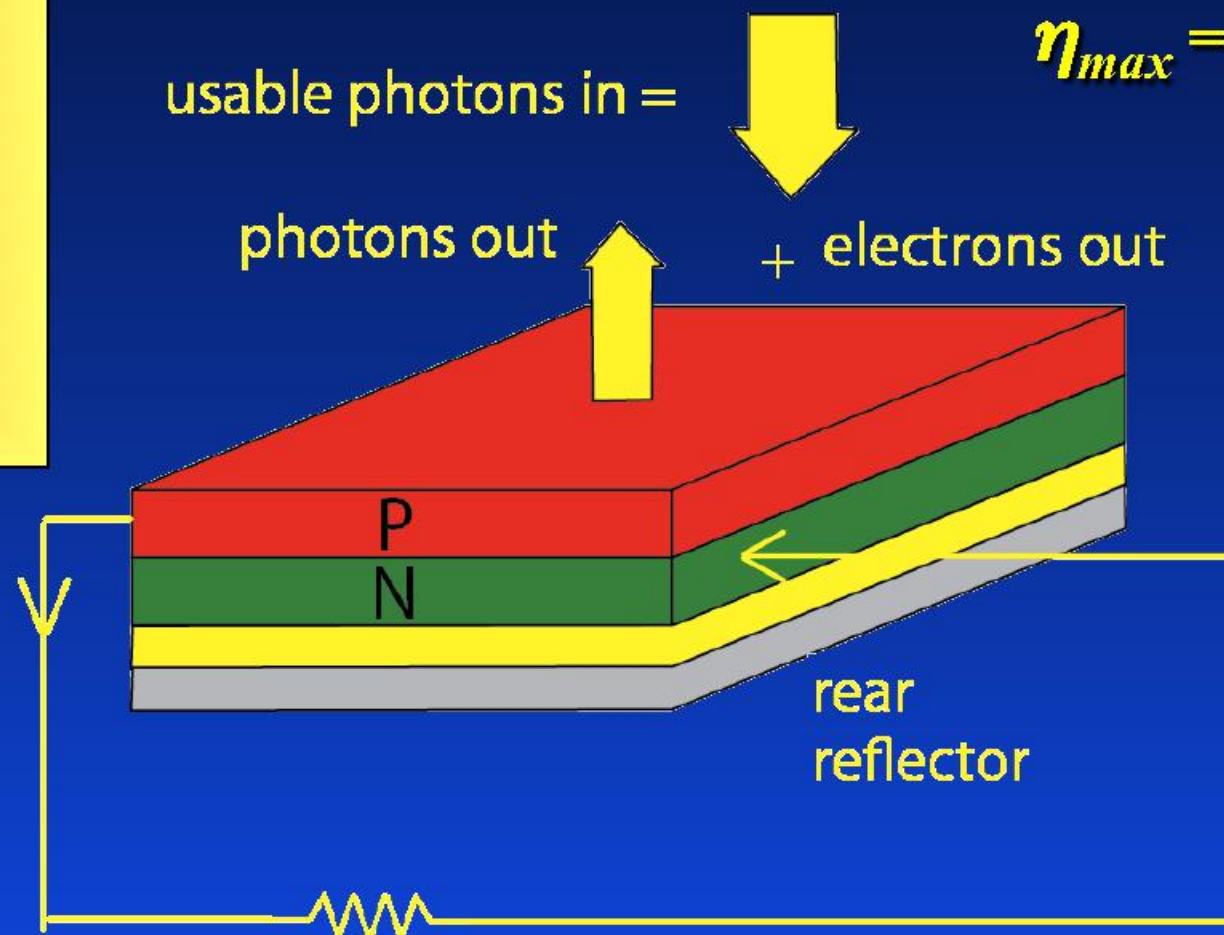
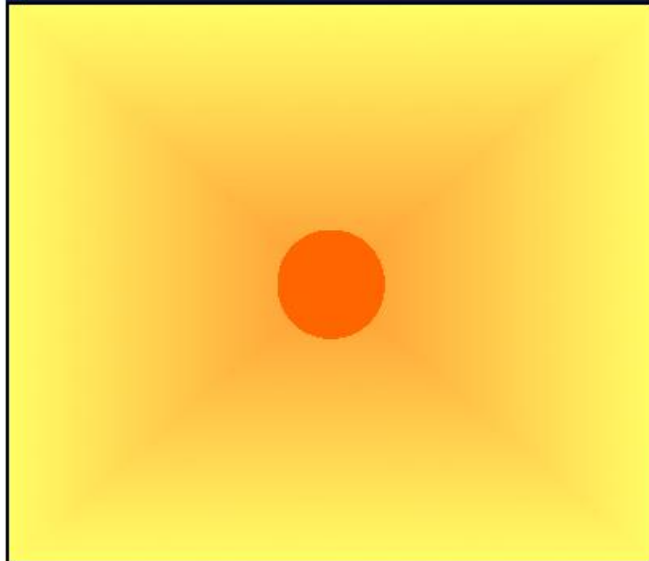
Black bodies (Planck)



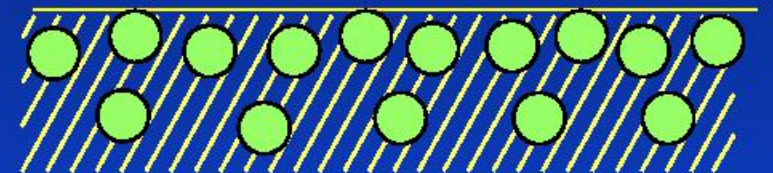
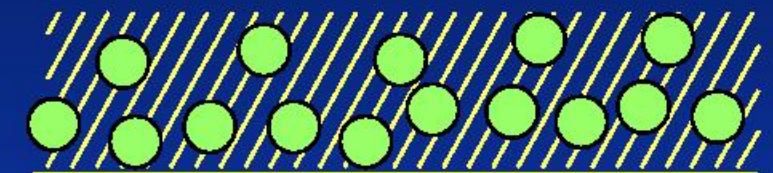


ACAP

Shockley-Queisser



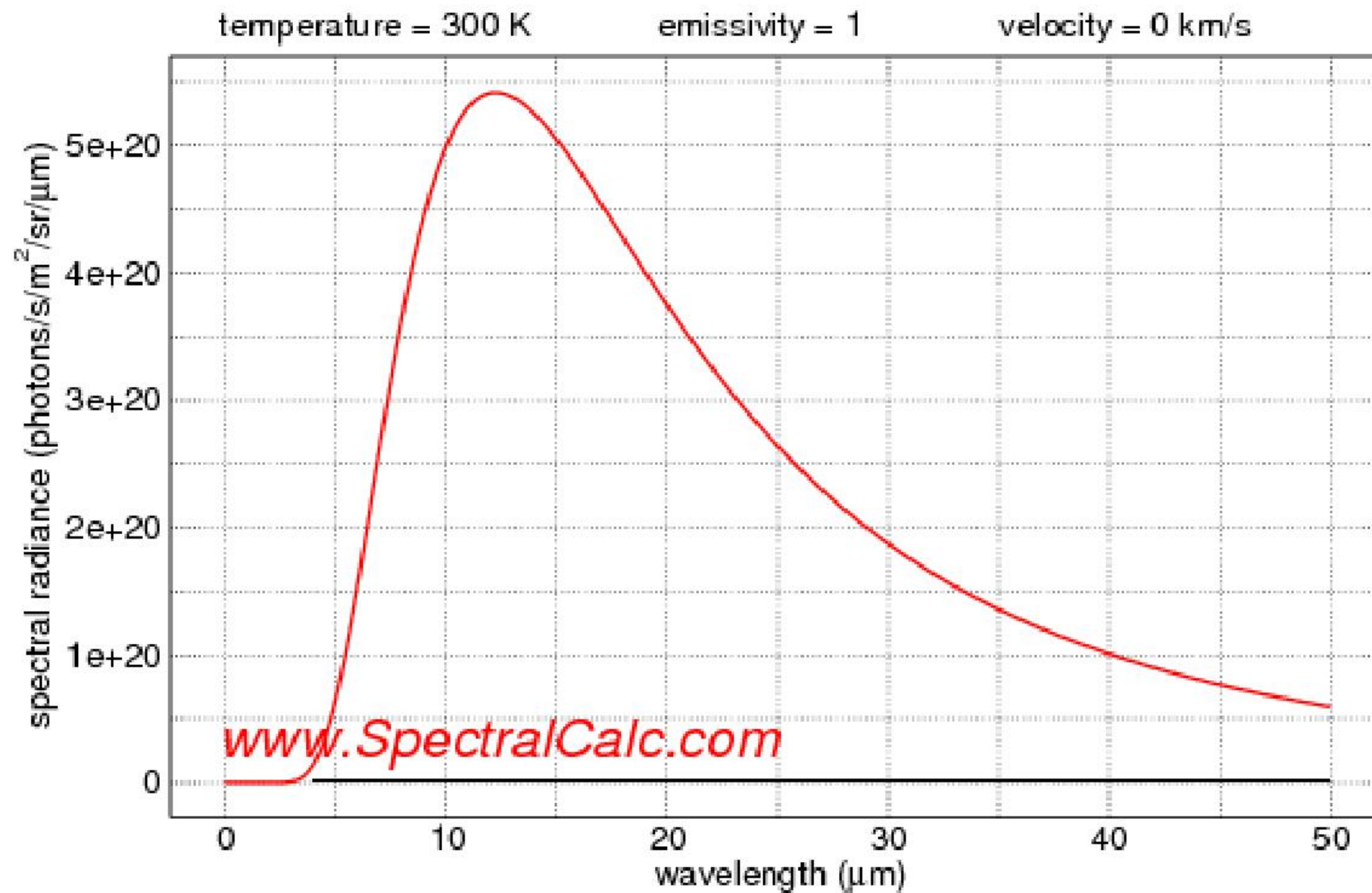
$$\eta_{max} = 31\% \text{ (global)} = 41\% \text{ (direct)}$$



$$P = qV \int_{E_G}^{\infty} \int_{\Omega} \{N_{BB}(6000K) - \exp(qV/kT) N_{BB}(300K)\} dE d\Omega$$



Blackbody 300K

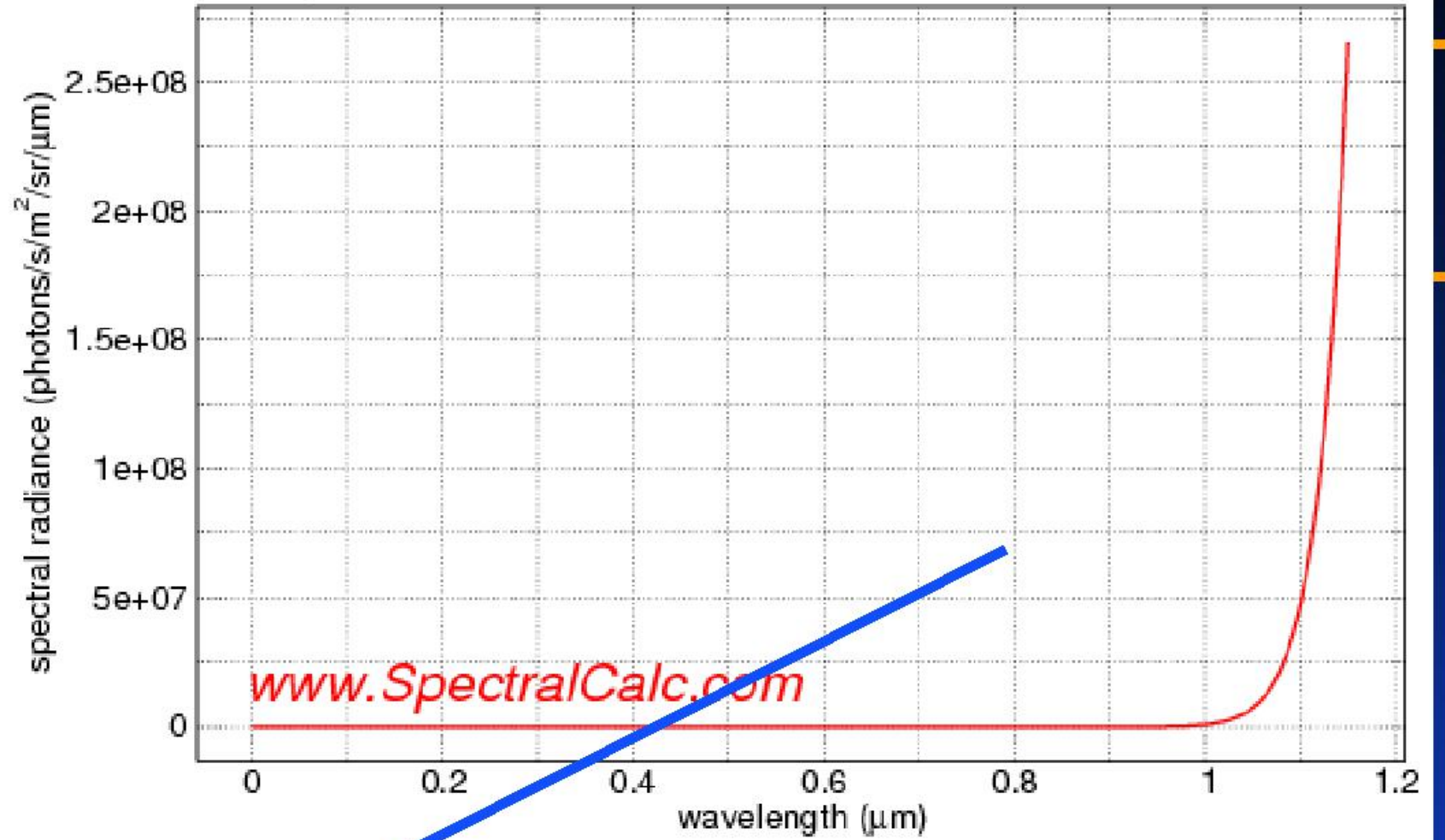




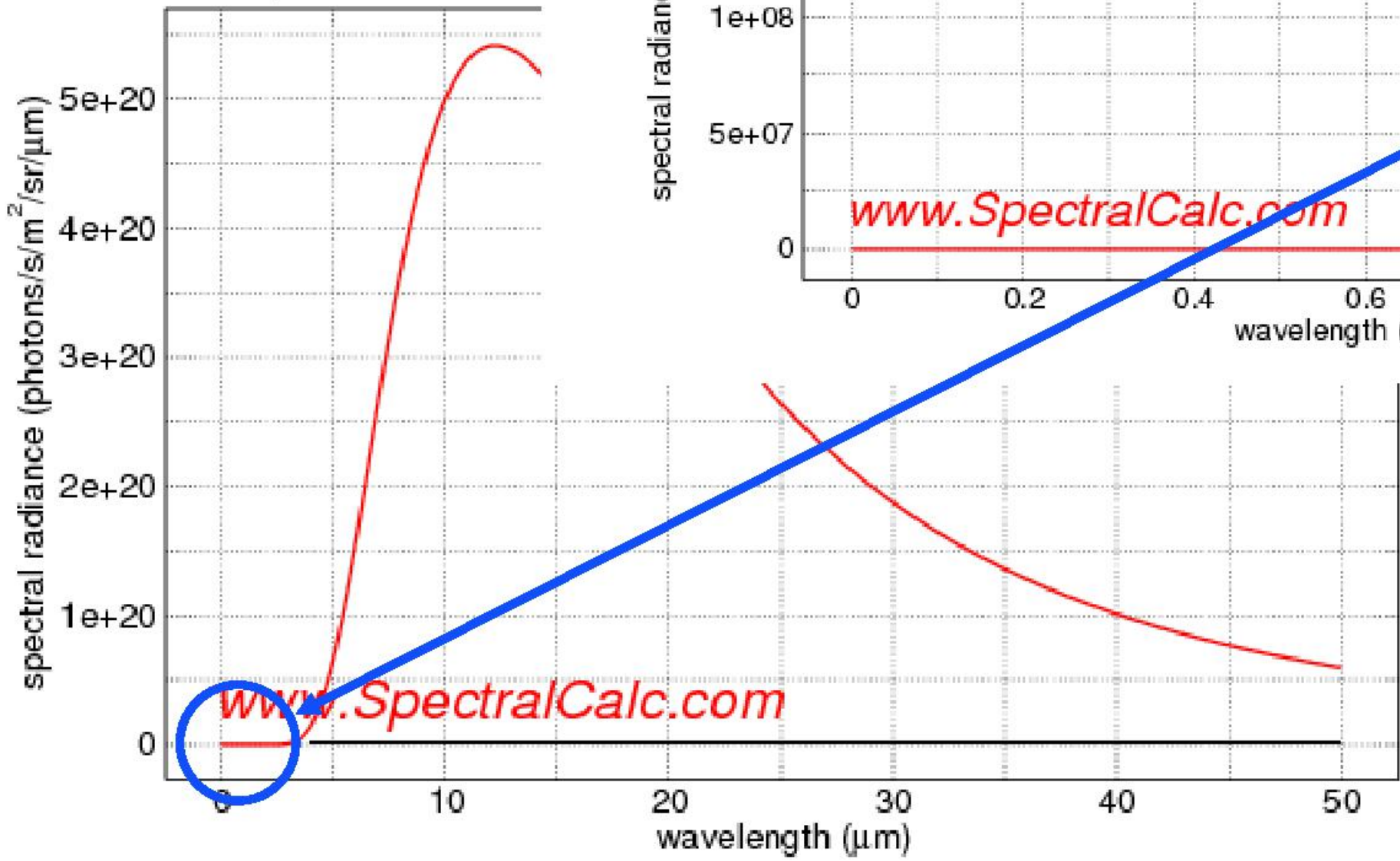
temperature = 300 K

emissivity = 1

velocity = 0 km/s



temperature = 300 K



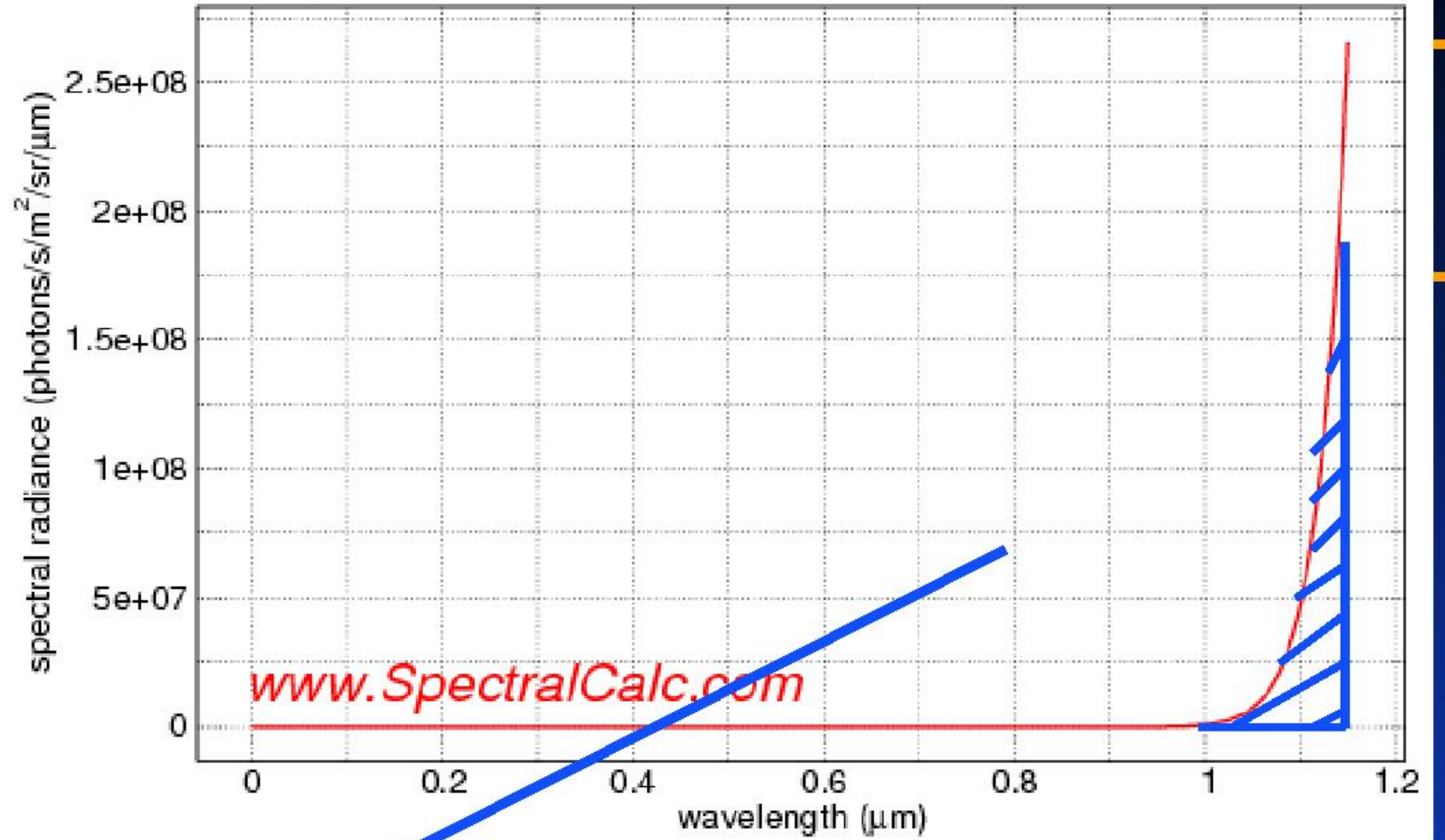
Electricity from Sunlight



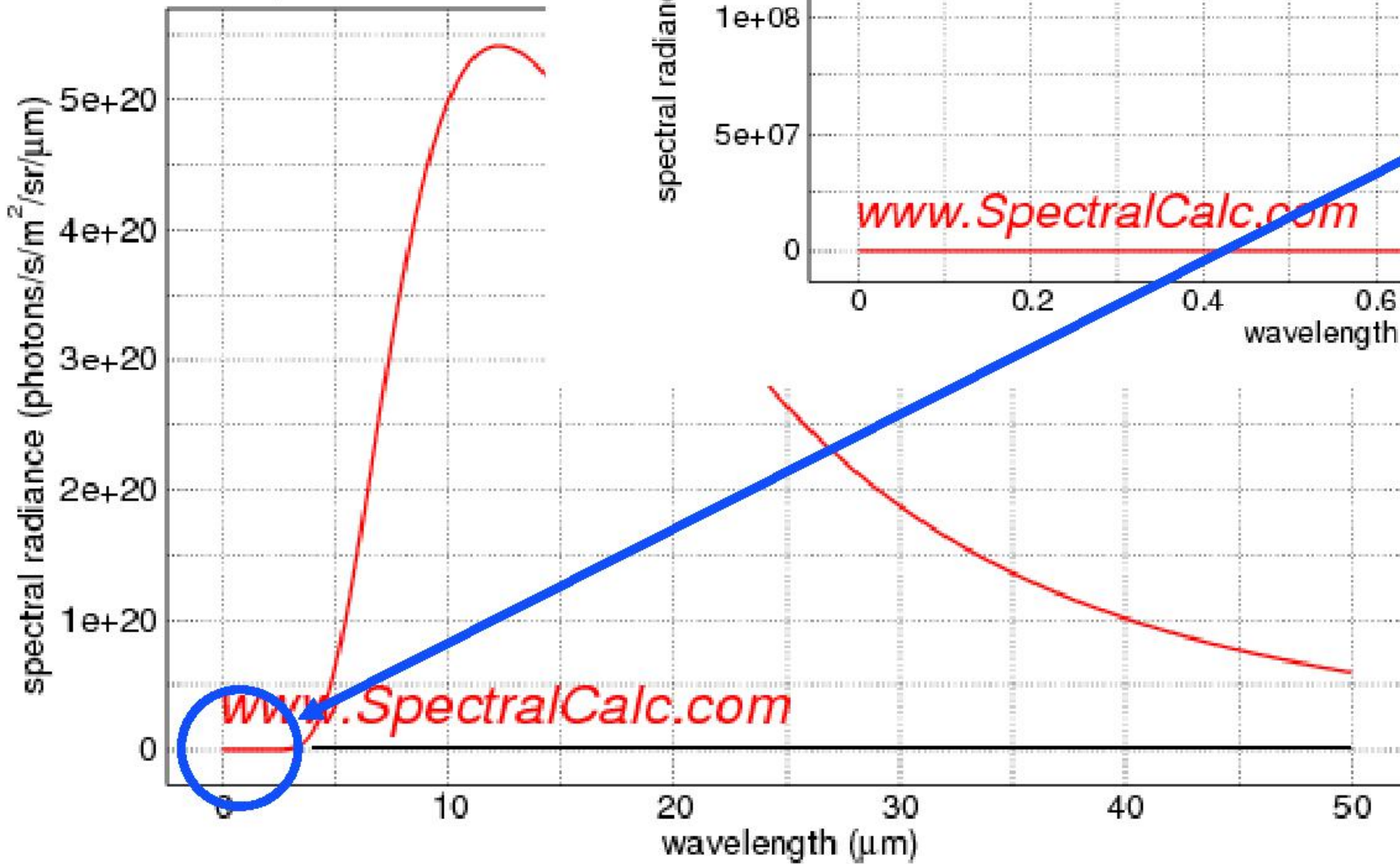
temperature = 300 K

emissivity = 1

velocity = 0 km/s



temperature = 300 K



Electricity from Sunlight



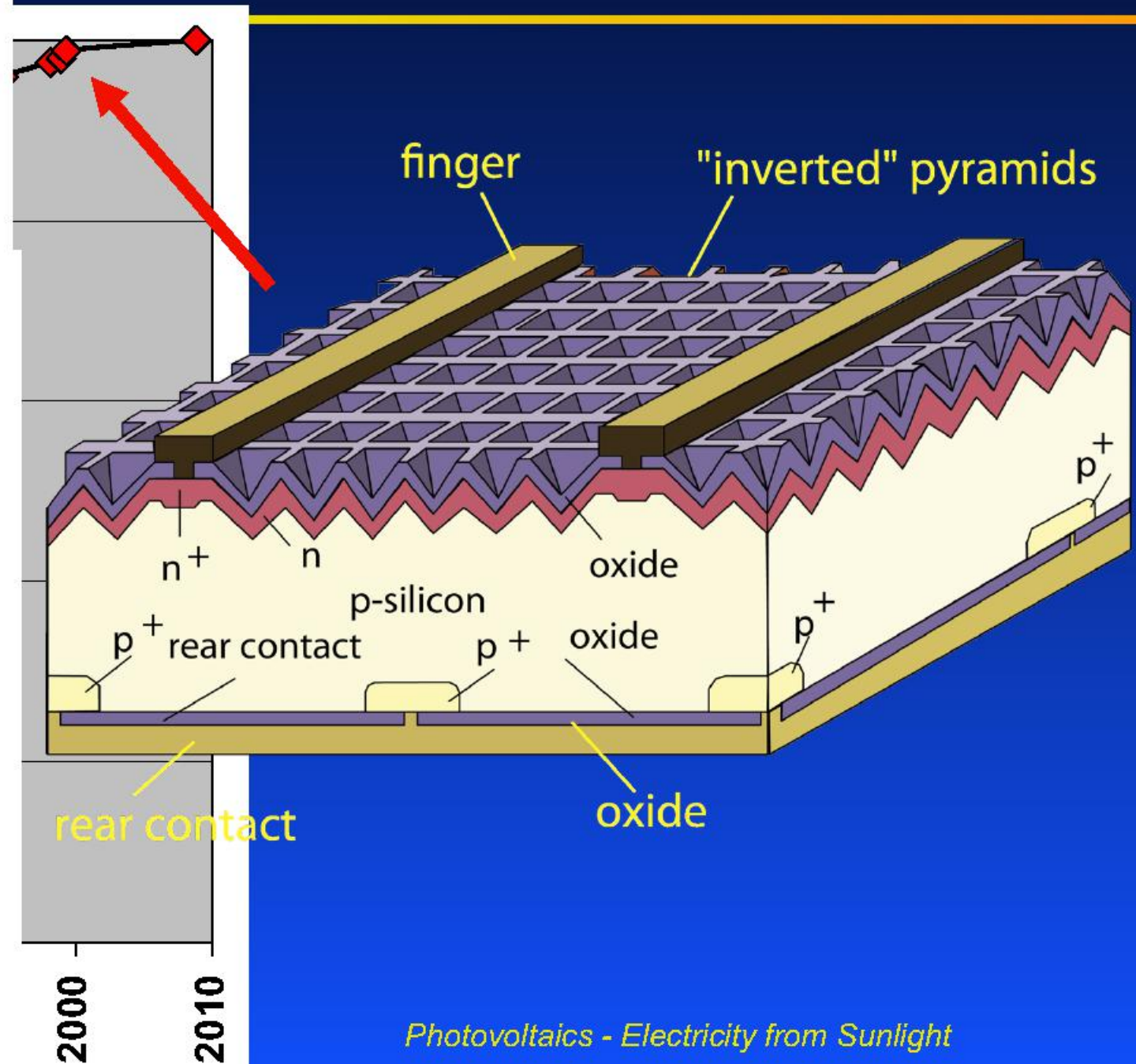
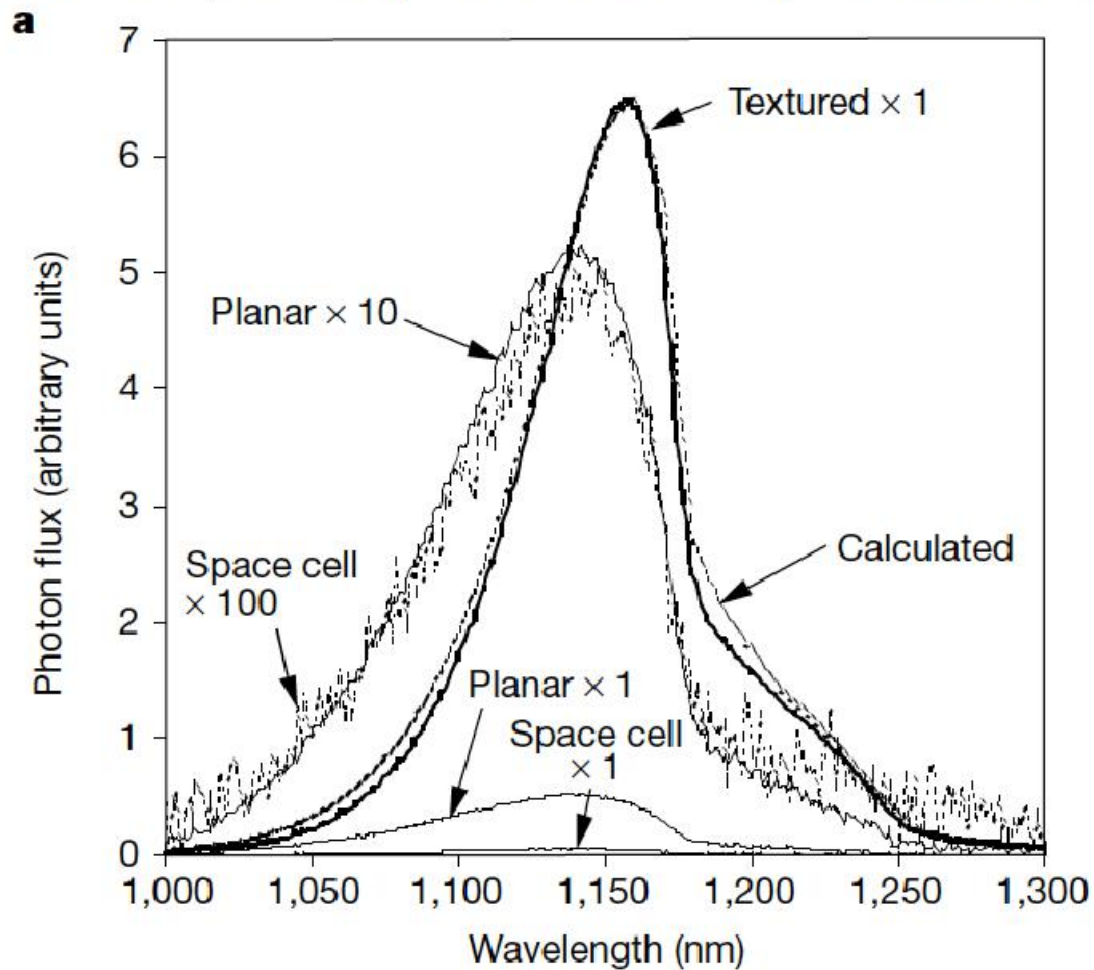
Actual efficiency: Si cells

Efficient silicon light-emitting diodes

Martin A. Green*, Jianhua Zhao†, Aihua Wang†, Peter J. Reece‡ & Michael Gal‡

* Centre for Third Generation Photovoltaics; † Photovoltaics Special Research Centre; and ‡ School of Physics, University of New South Wales, Sydney, New South Wales 2052, Australia

NATURE | VOL 412 | 23 AUGUST 2001 | www.nature.com



Photovoltaics - Electricity from Sunlight

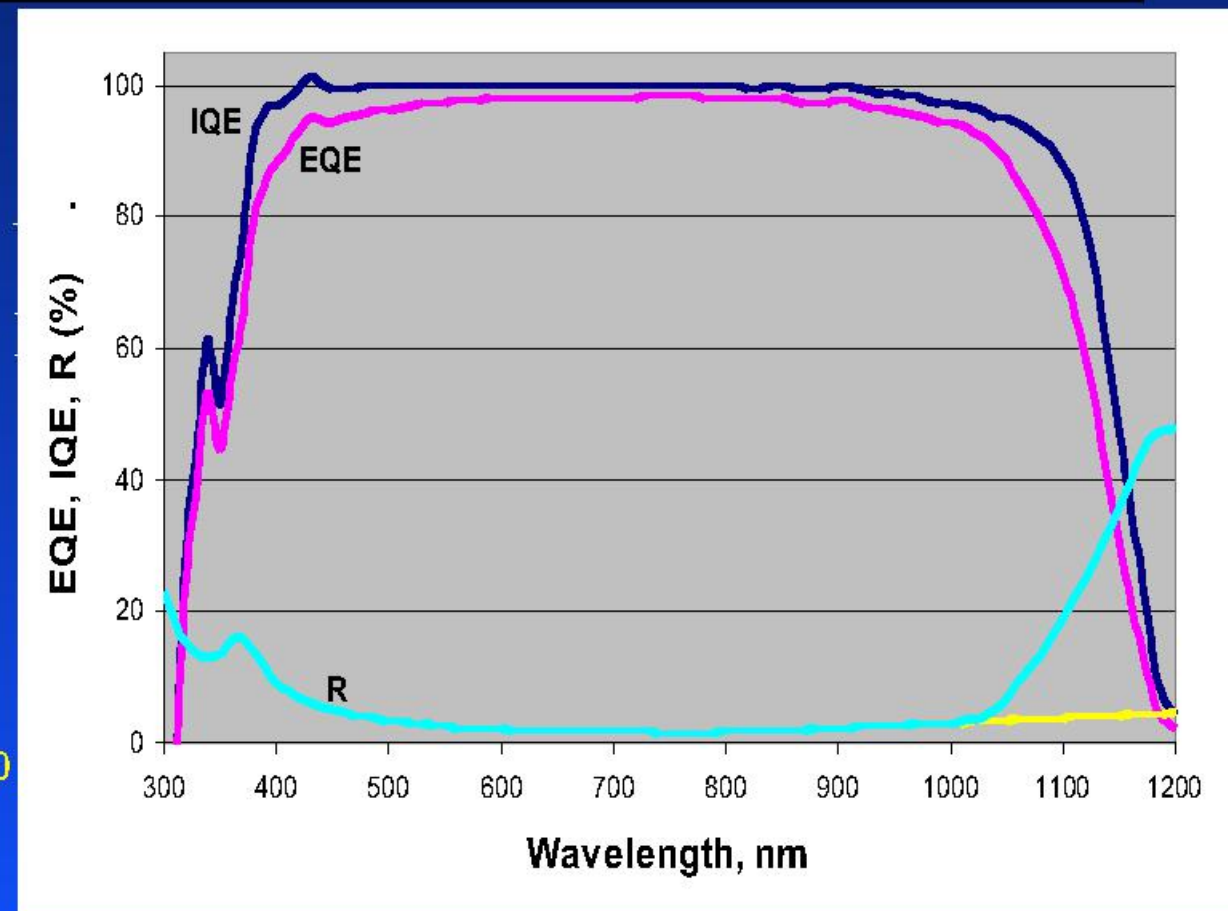
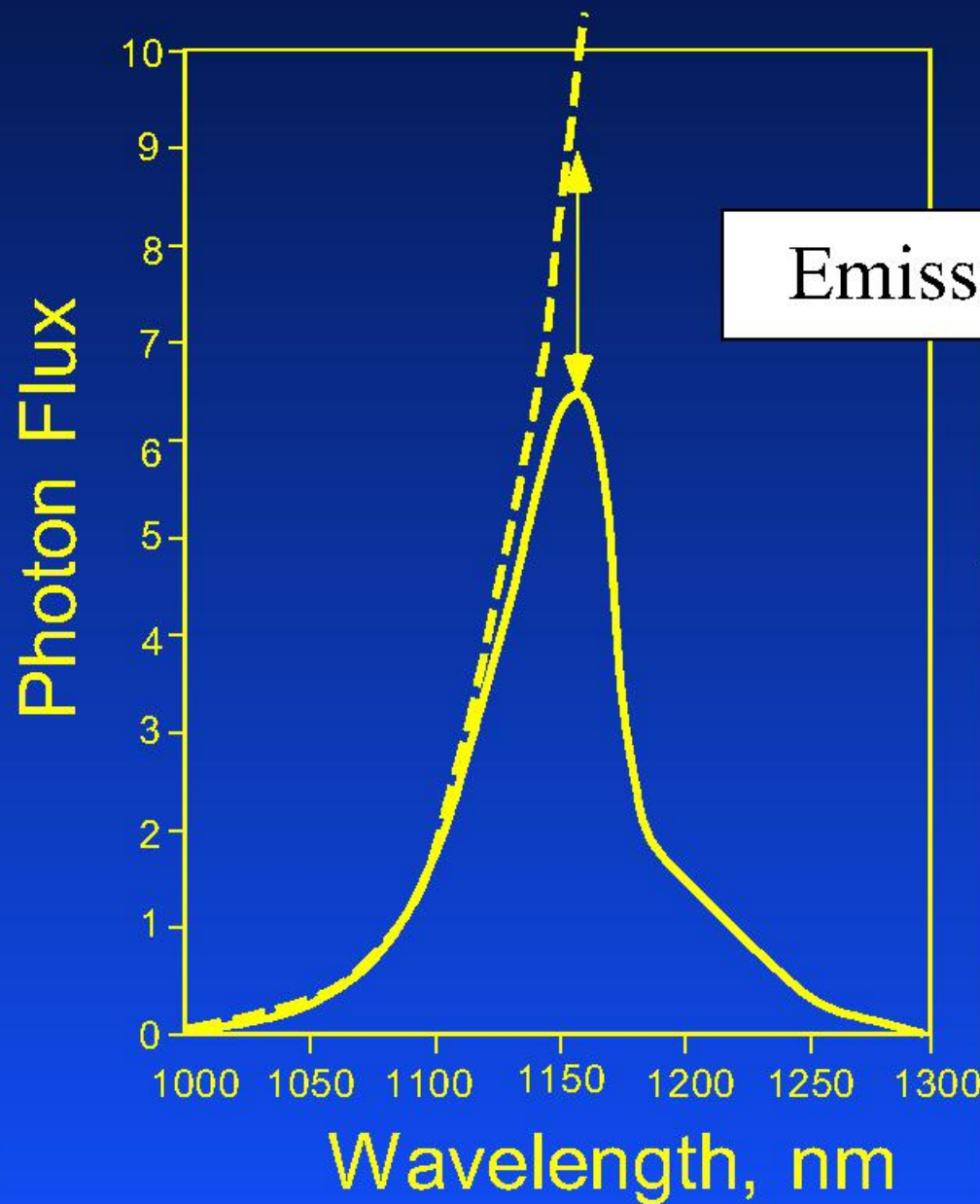


Blackbody LED

Uwe Rau

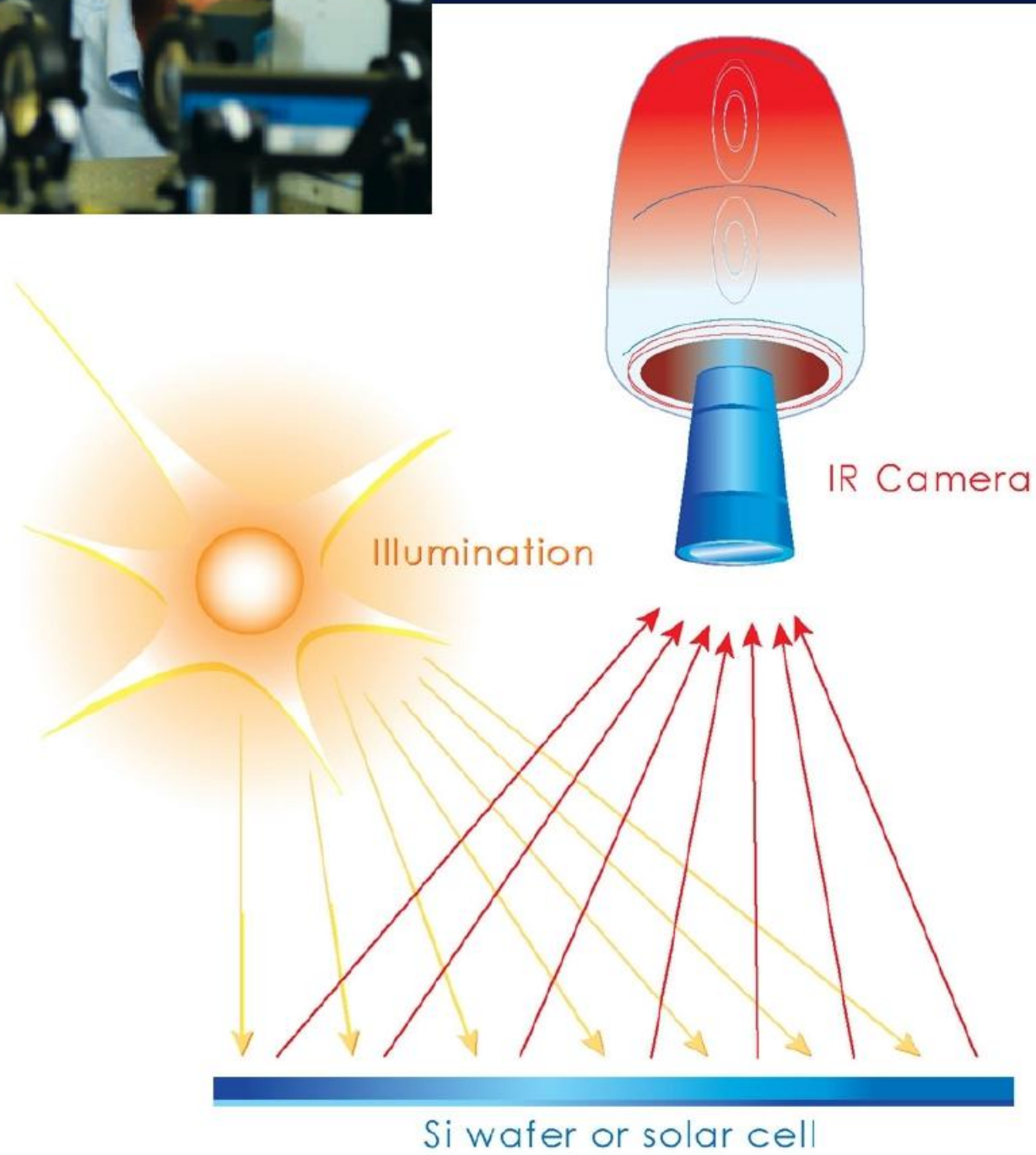
Physical Review B 76, 085303, 2007

$$\text{Emission} = \text{EQE(PV)} * \text{BB} * \exp(qV/kT)$$

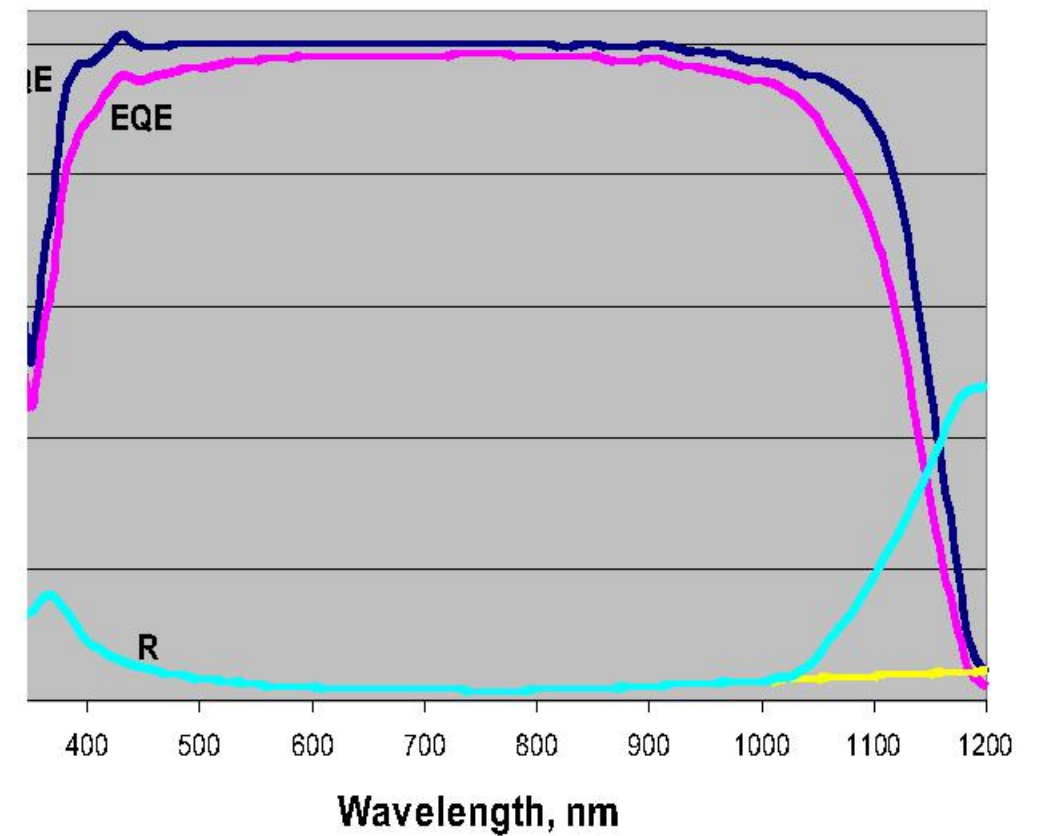


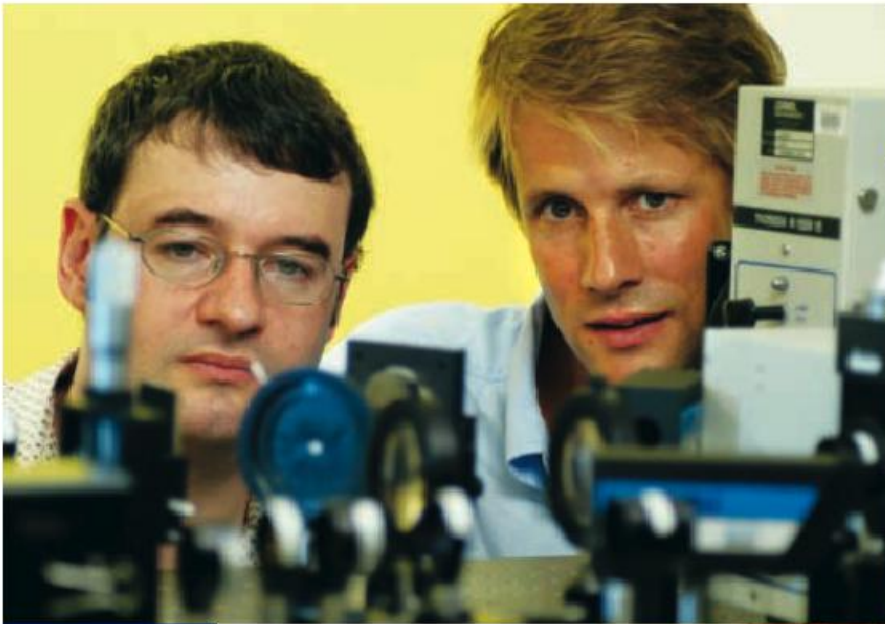


Blackbody LED



$$EQE(PV) * BB * \exp(qV/kT)$$





bt imaging
INNOVATE. CONTROL. YIELD.

LED



T



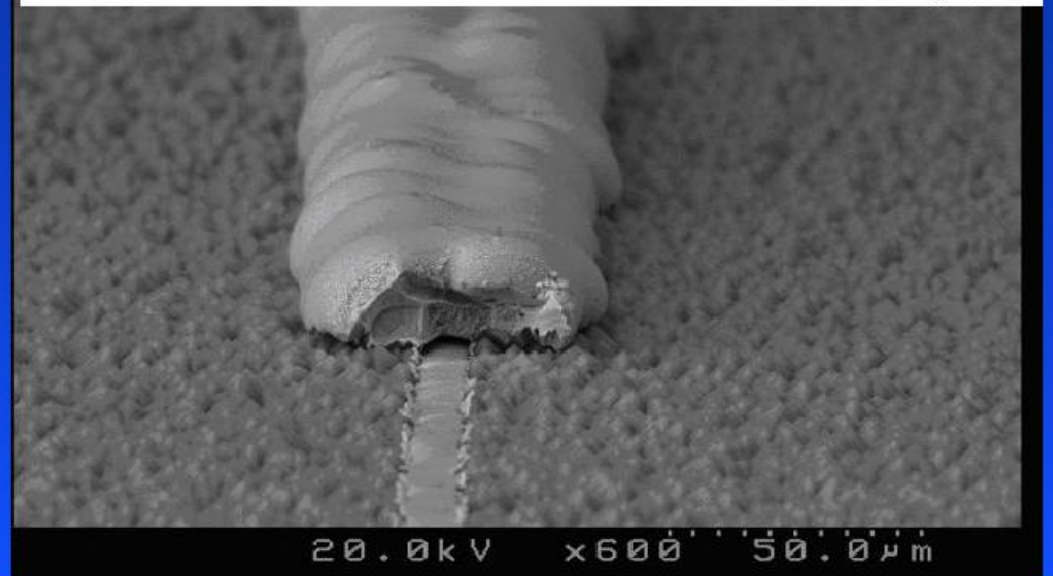
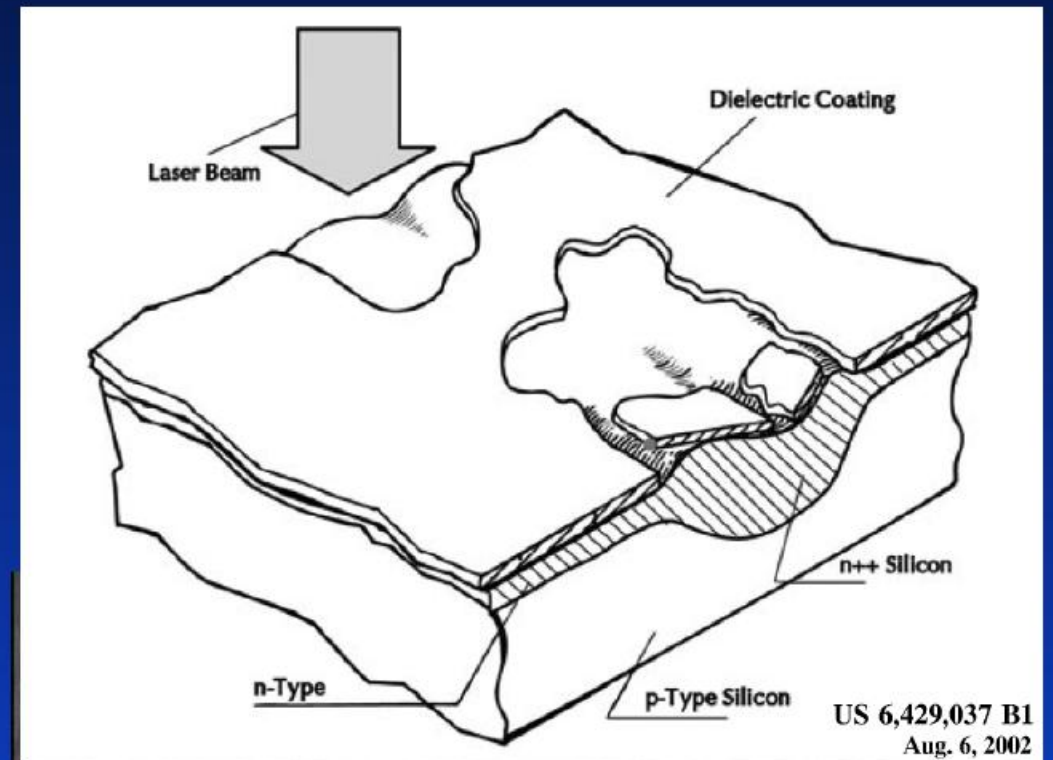
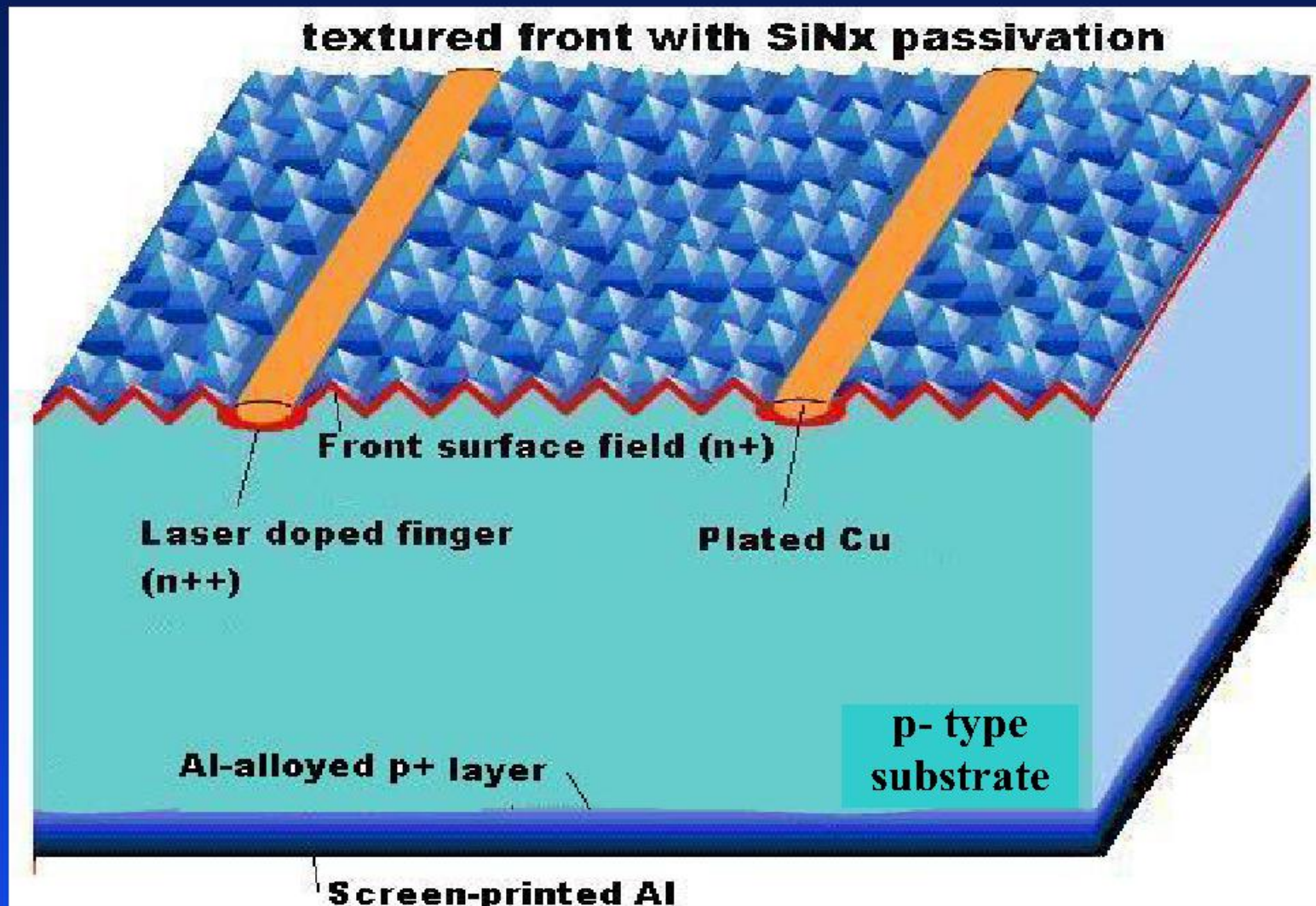


Outline –Lecture 2

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2. Principle I – “Dark/Light Superposition”
3. Improving “emitters”
4. Principle II – “Dark/Light” Reciprocity
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9. The (near)future

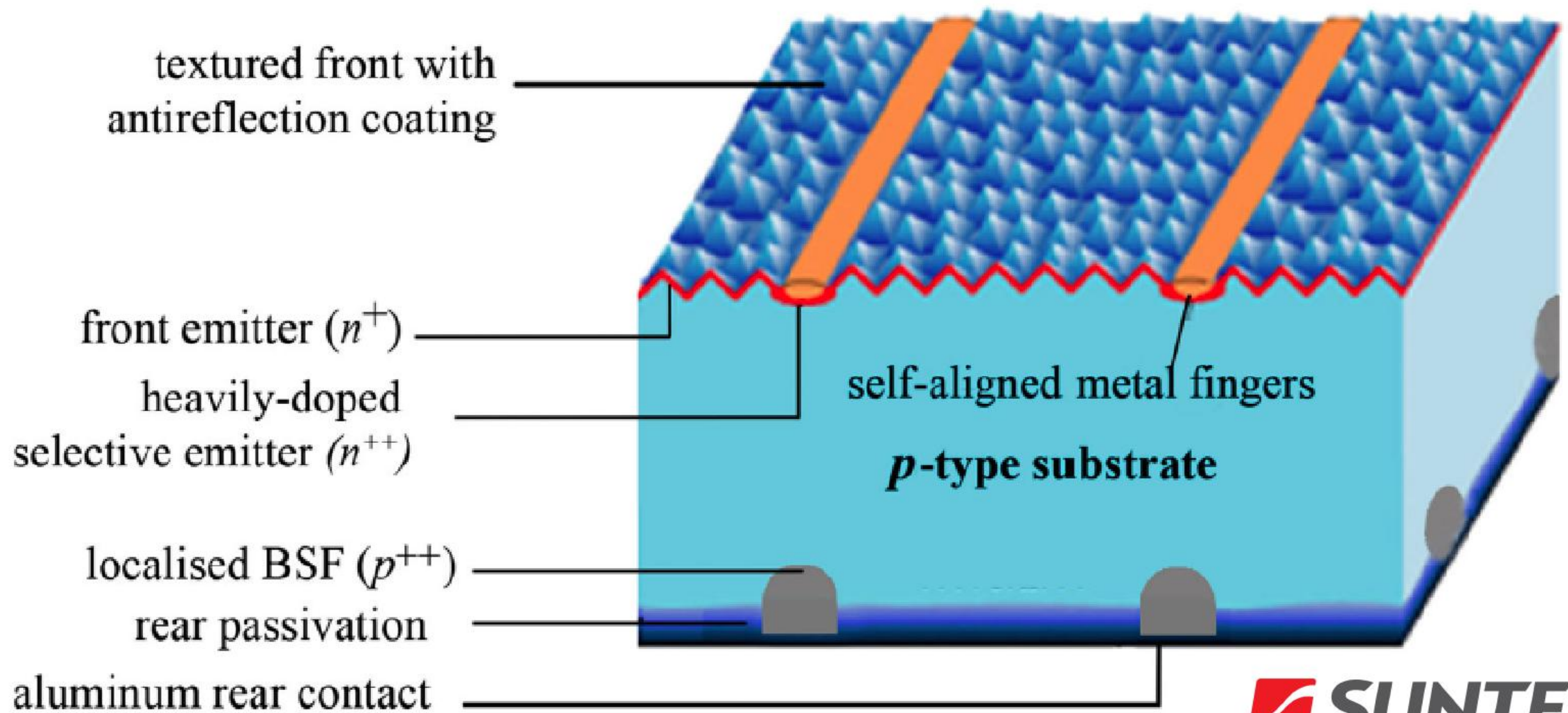


Improved efficiency: LDSE



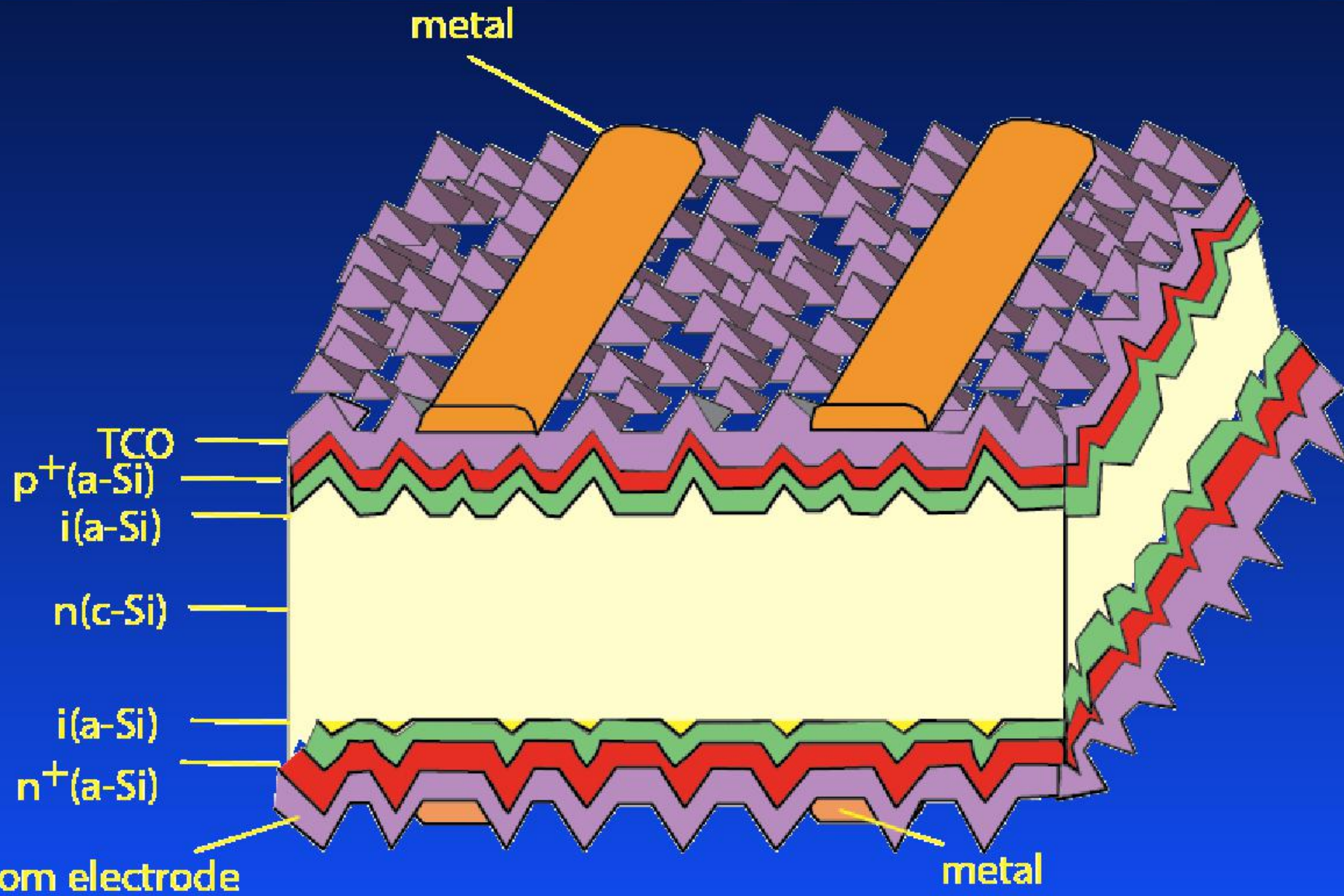


Improved efficiency: 20.3% Pluto cell



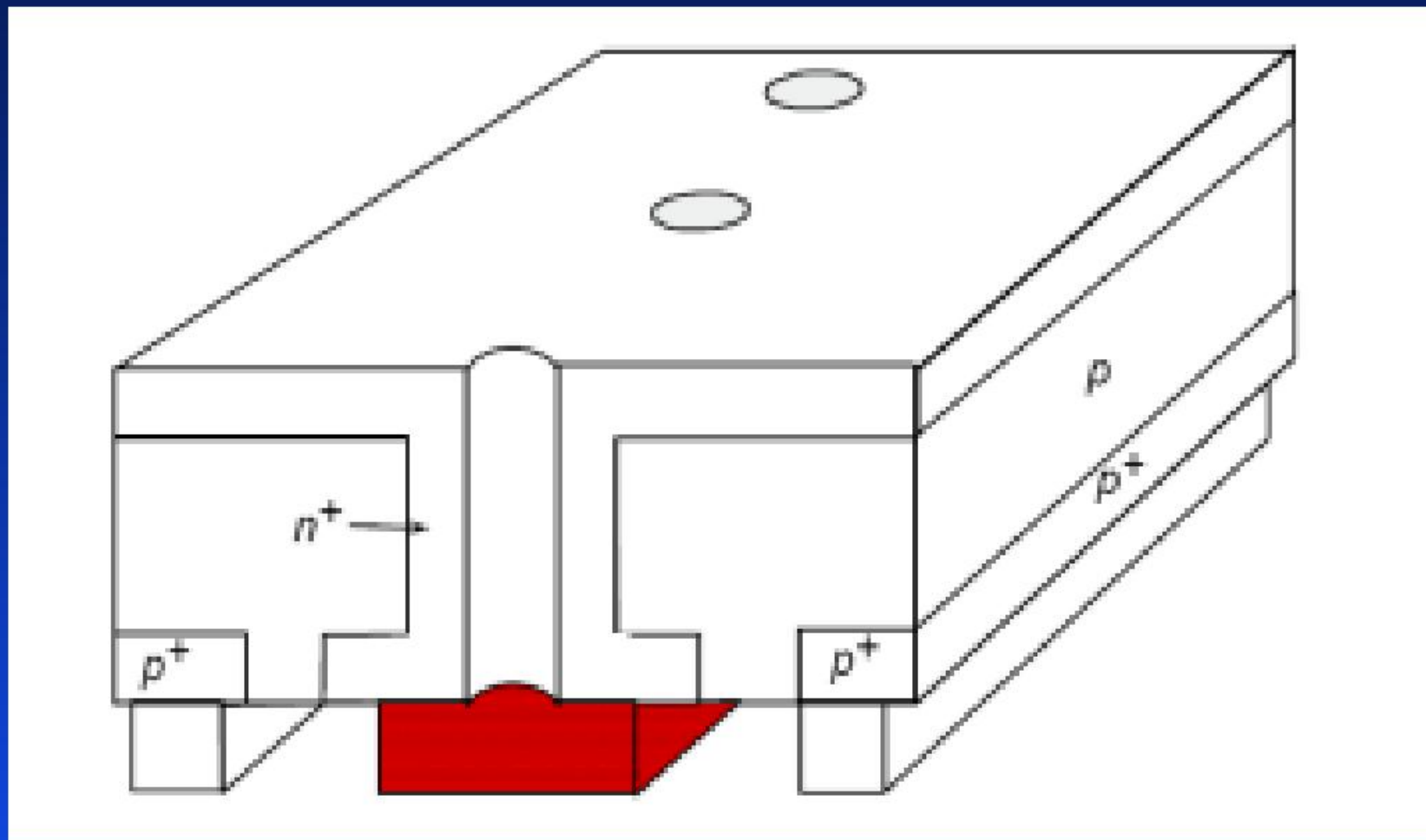


Other approaches: HIT cell



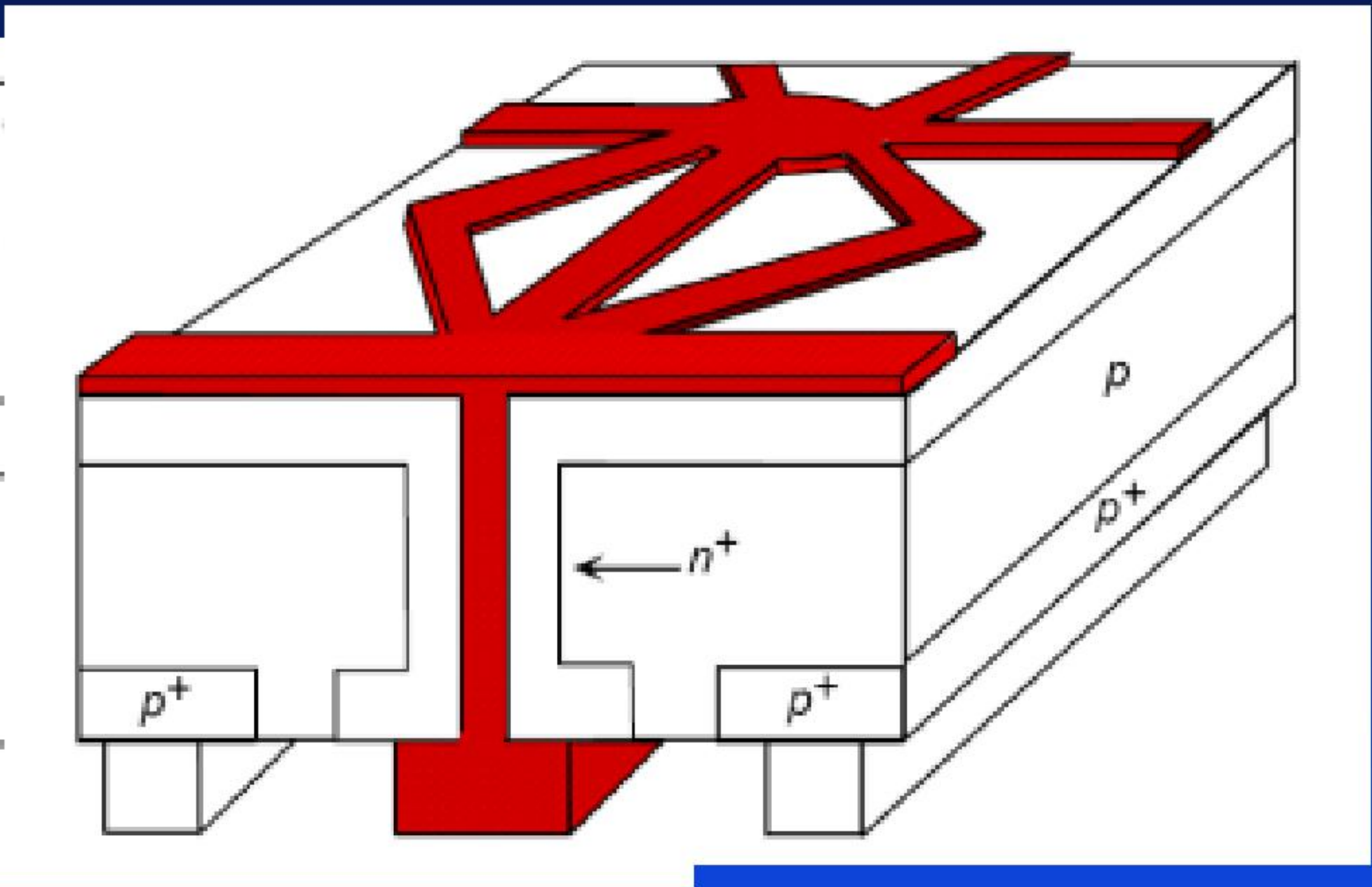
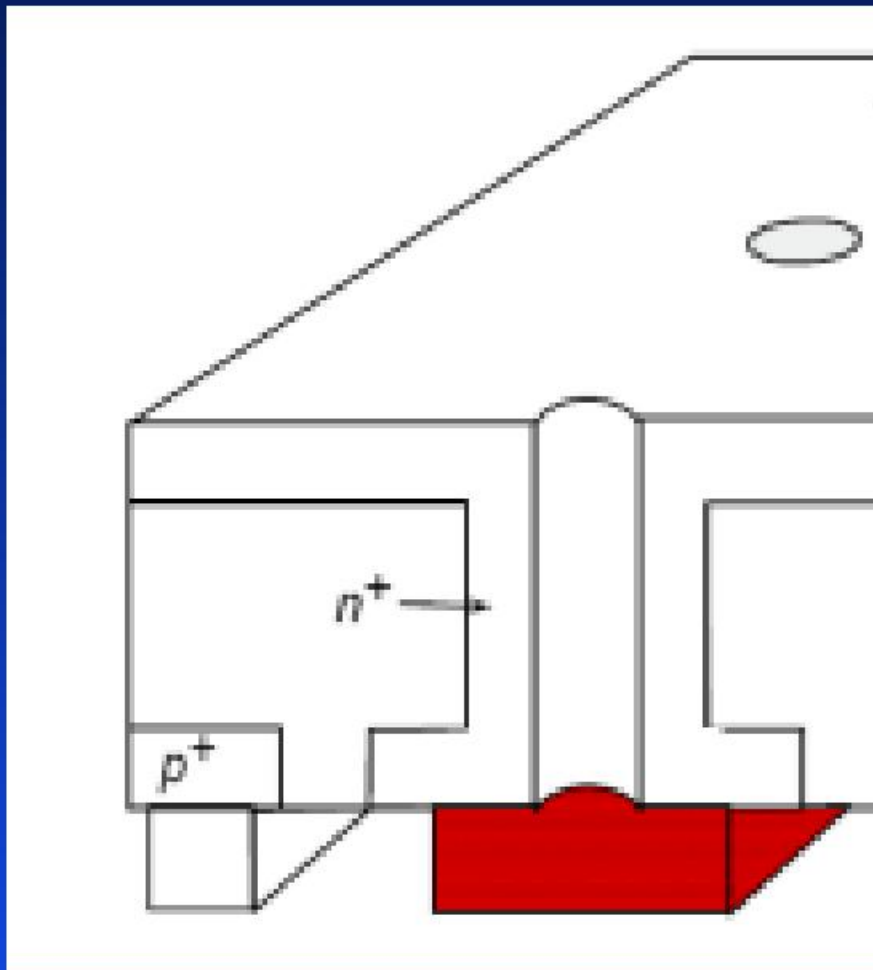


Other approaches: *EWT* cell





Other approaches: MWT cell



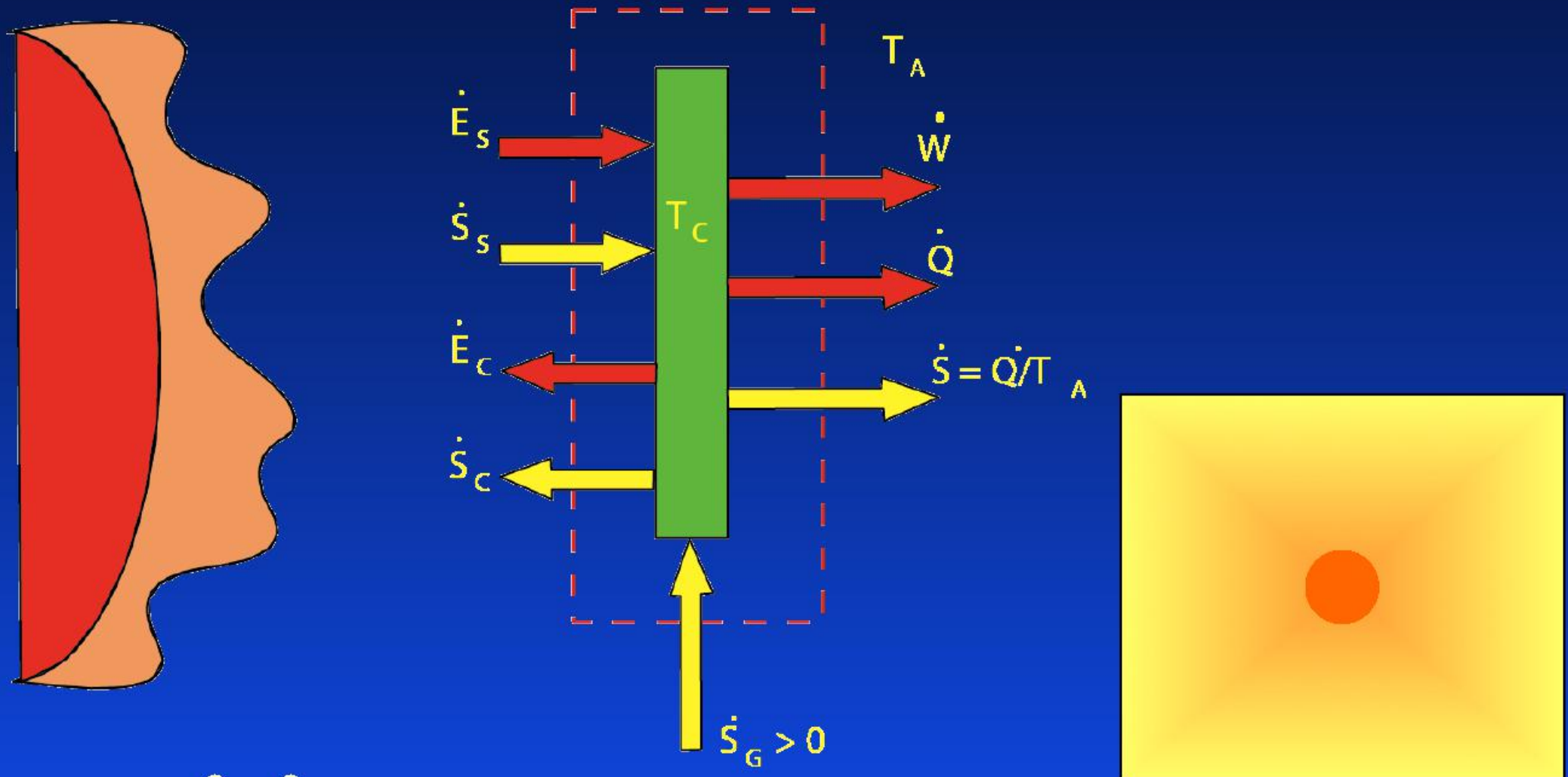


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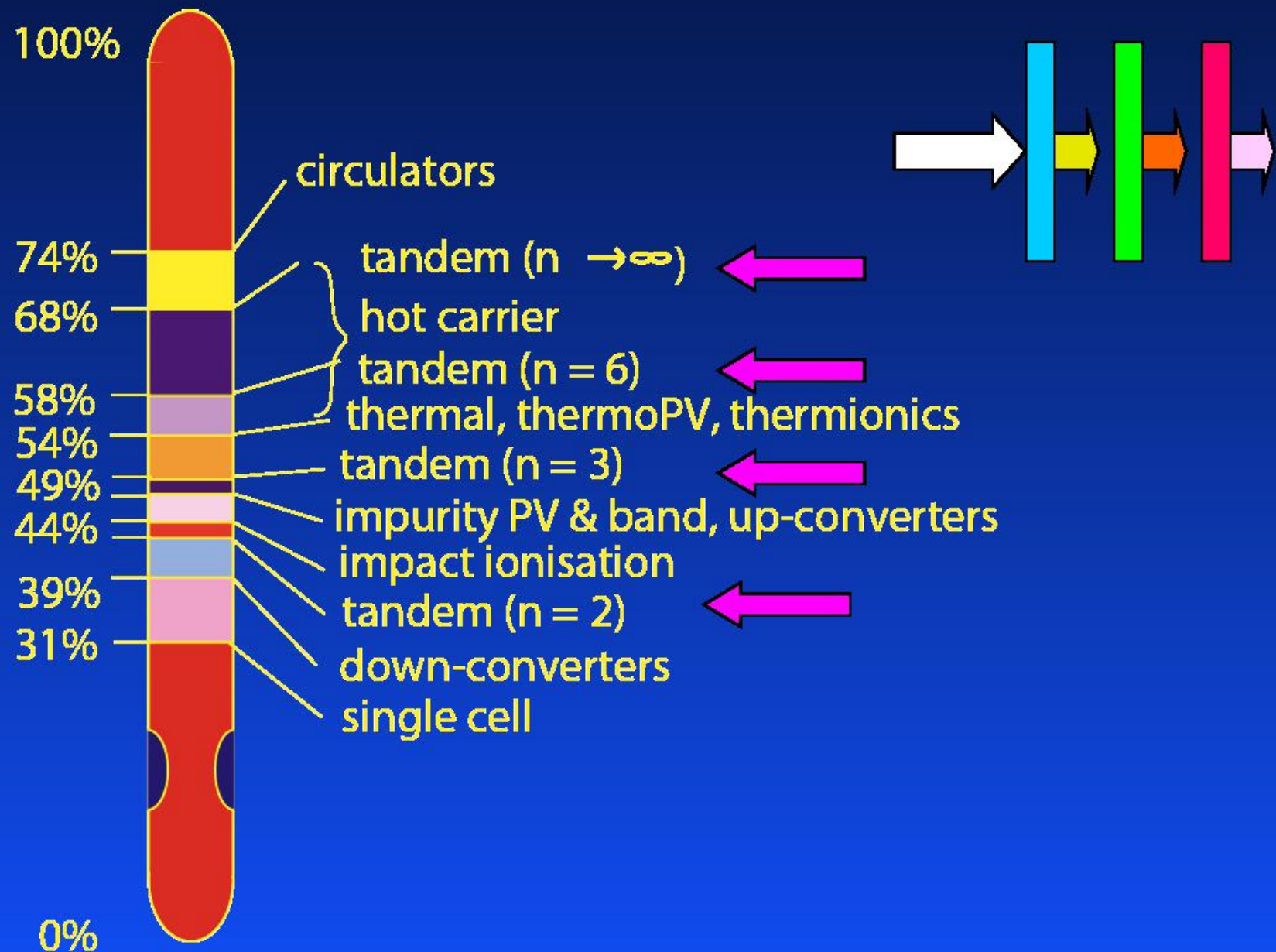
Thermodynamic efficiency limits



$$\eta \leq (1 - T_A \dot{S}_s / \dot{E}_s) = 93.3\% \text{ (direct)} = 73.7\% \text{ (global)}$$



Third generation options

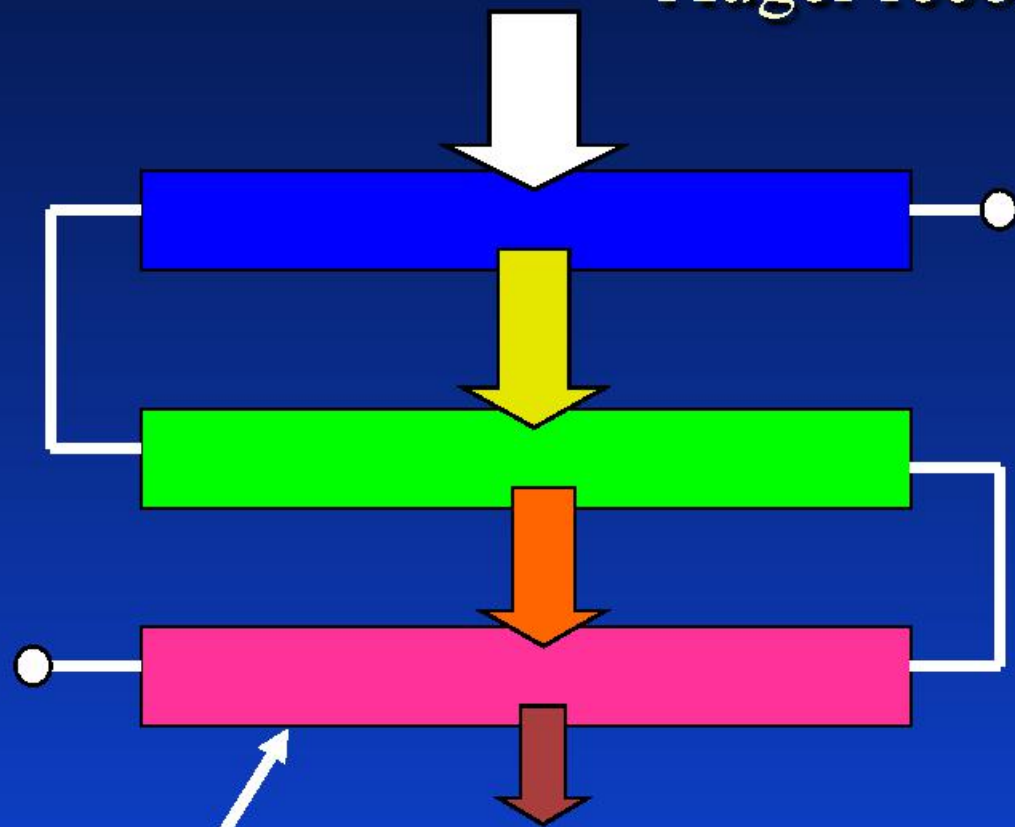




ACAP

c-Si tandem

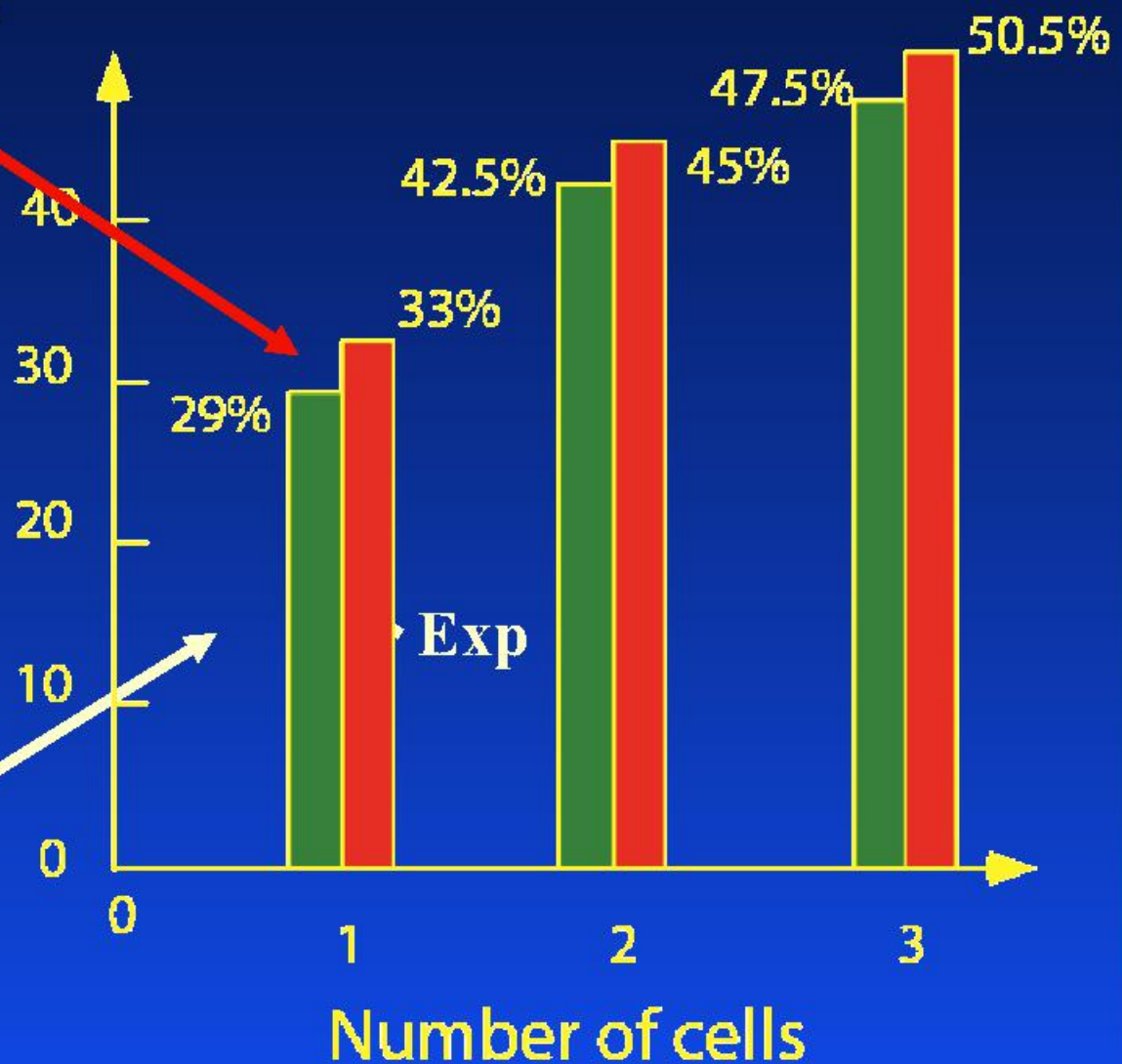
Auger recombination



Free choice or Si

- Free choice
- Si bottom cell

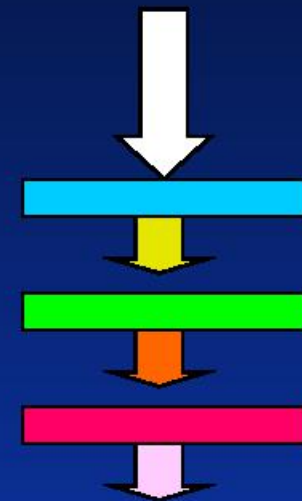
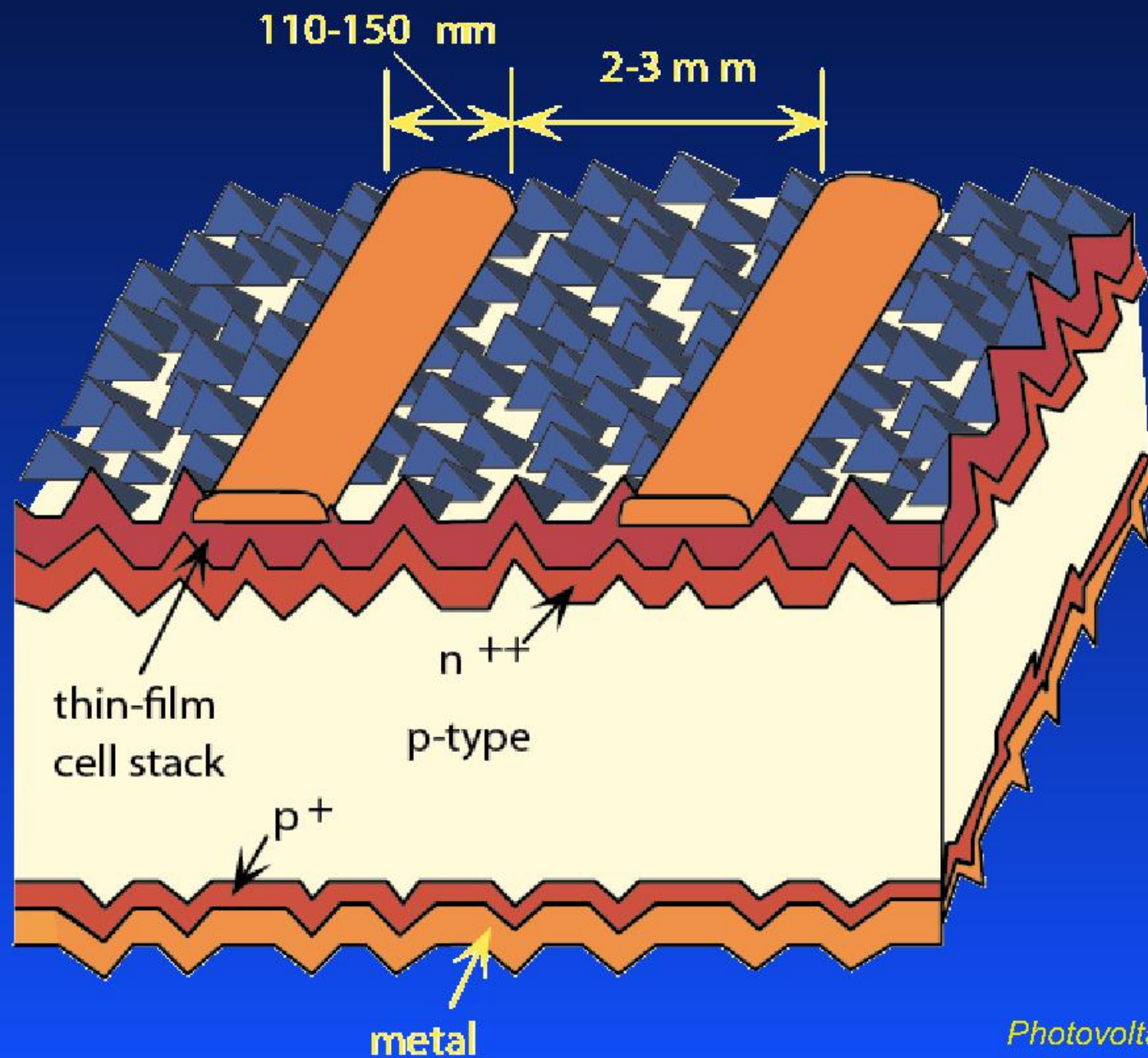
AM1.5G Efficiency



UNSW



Si wafer-based tandem stack





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