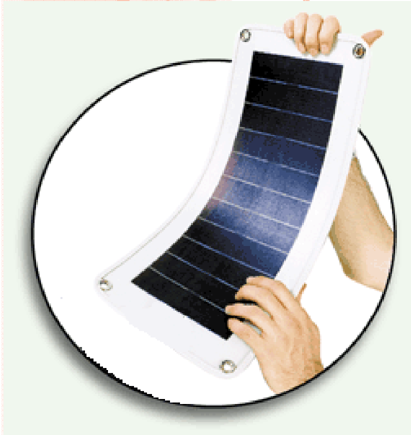

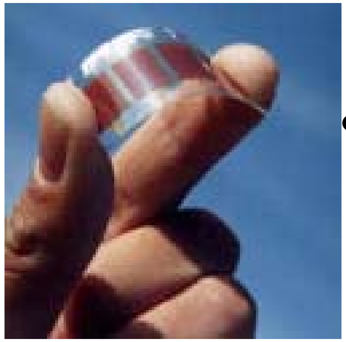

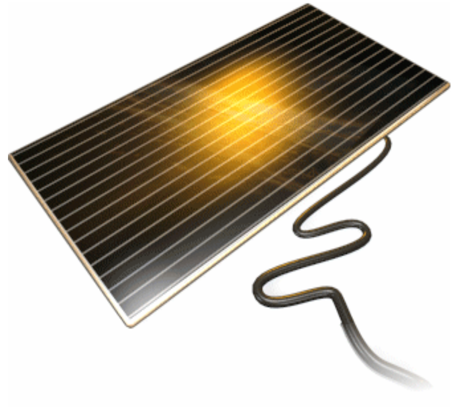

MAXIMISING INCIDENT POWER ABSORPTION IN MULTIJUNCTION SOLAR CELLS

Piyush Keshri

4th year, B.Tech (EE)

IIT Kanpur

Mentor: Prof. S.S.K. Iyer,IIT Kanpur

1st Indo US Research Academy, 7-11th Oct'08, Pune

ACKNOWLEDGEMENT

I *specially,* "Thank"

'Prof. Gautam Biswas'

and all the

Organizers

involved in

"1st Indo US Research Academy 7-11th Oct'08"

who have made it possible.

My *Sincere Gratitude*

goes towards all the

Professors, Students & Staff

who have whole heartedly devoted their precious time towards the success of this academy and have shown their dedication & commitment towards the research.

OUTLINE

- Motivation
  - Overview of various Solar cell efficiencies.
- Background
  - Solar Spectrum.
  - Efficiency of Solar cells and the parameters involved.
  - Multi junction Solar Cells.
  - Energy Losses and Useful Energy Harvested.
- Simulation/ Experimental Plan
  - Step Absorption Spectrum
    - Single junction Cells.
    - 2 & 3 junctions Cells.
    - Mismatch Losses.
  - Box Type Absorption Spectrum
    - Single junction Cells.
    - 2 junctions Cells.
  - Summary of Results
- Summary
- Future Outlook

OUTLINE

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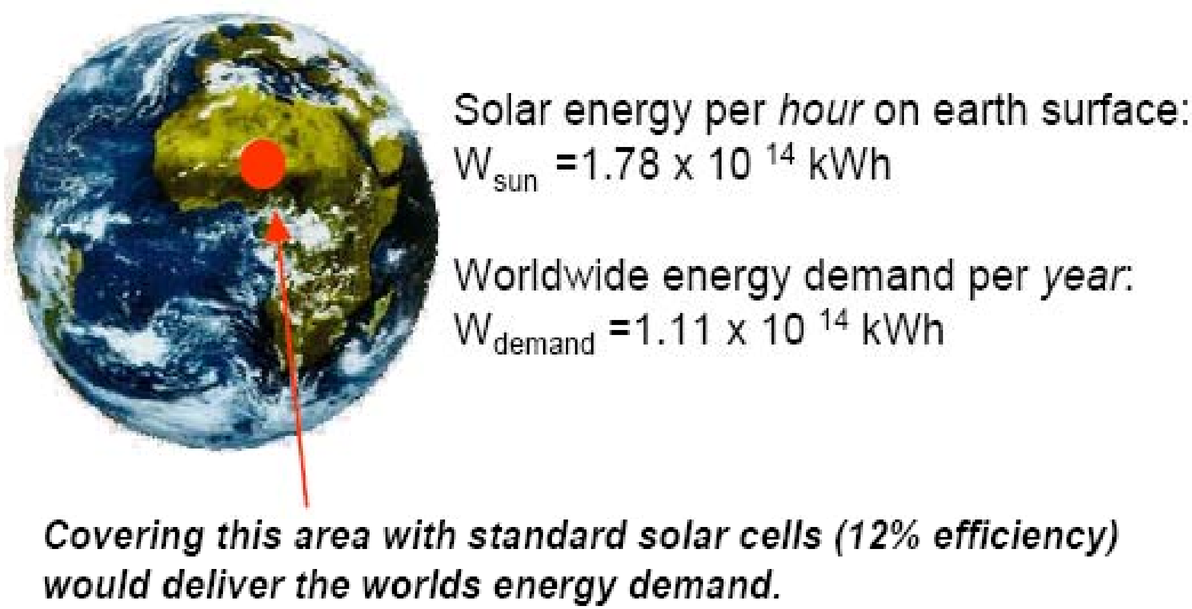
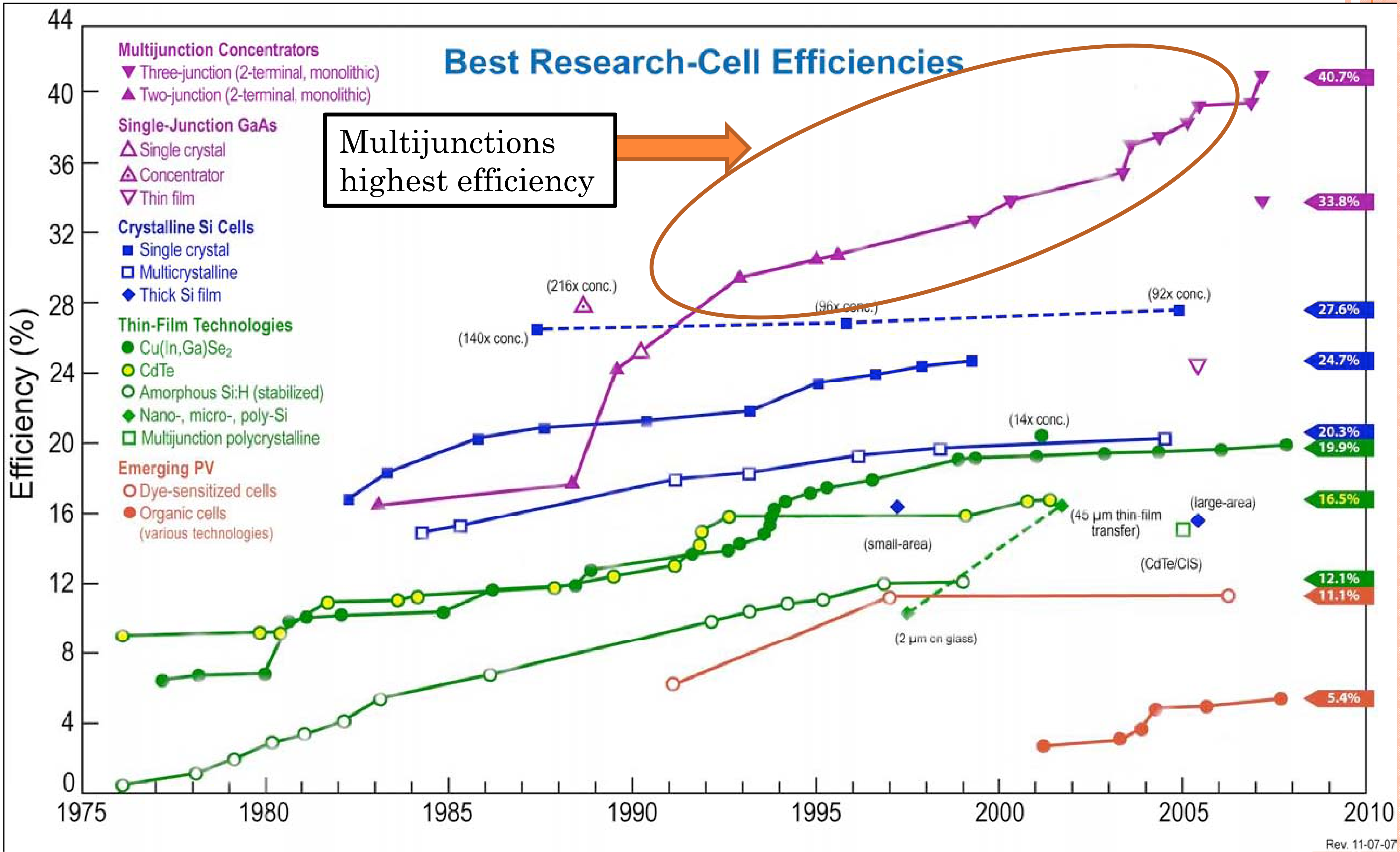
MOTIVATION

- Energy crisis
- Renewable source of Energy
- Green Energy – Non-polluting & Environment friendly
- Useful in remote areas
- Quiet
- Reliable



Source: *Institute of Materials Research & Engineering*

OVERVIEW OF VARIOUS SOLAR CELLS



__Source:__ National Renewable Energy Laboratory

OUTLINE

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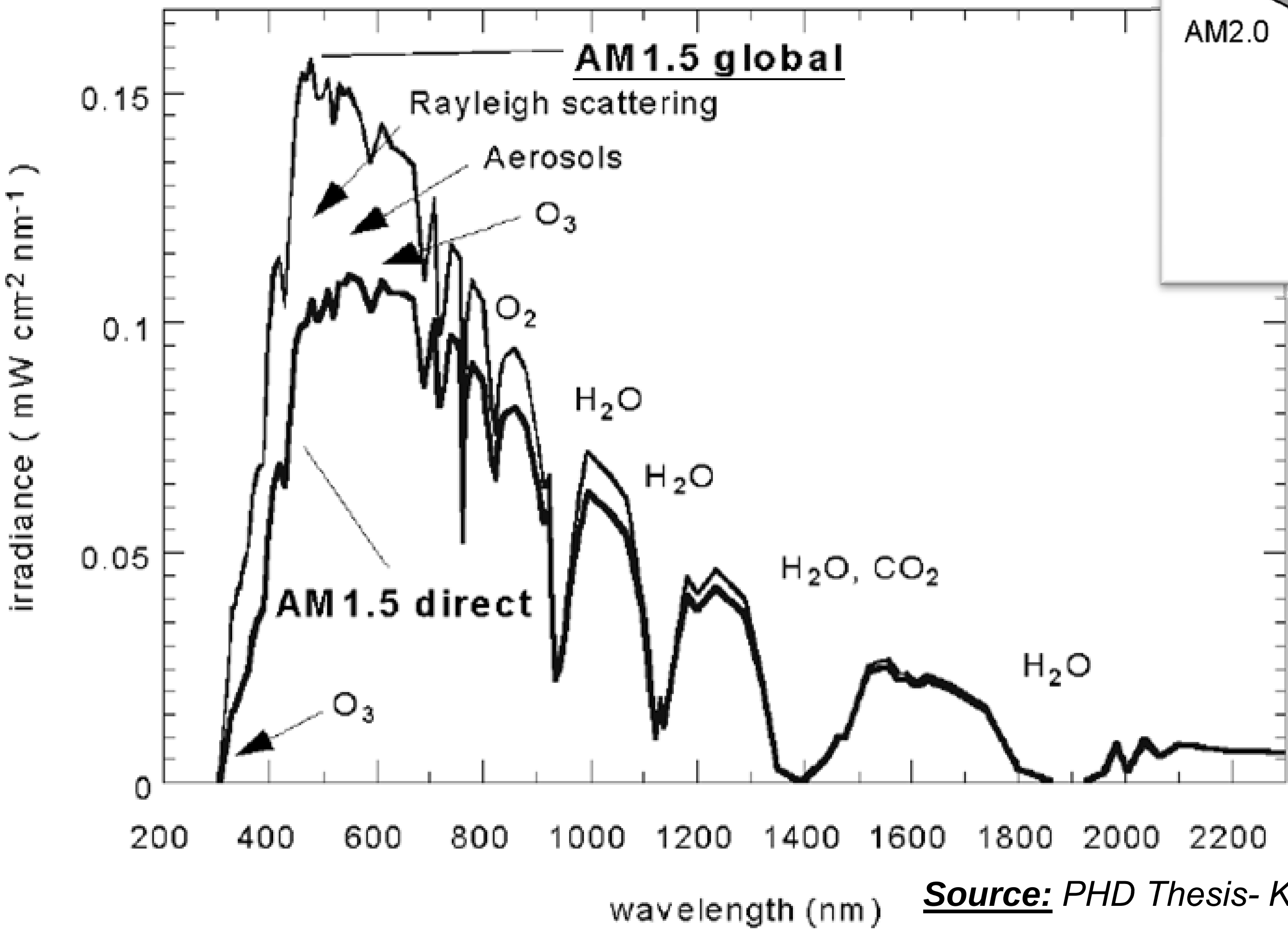
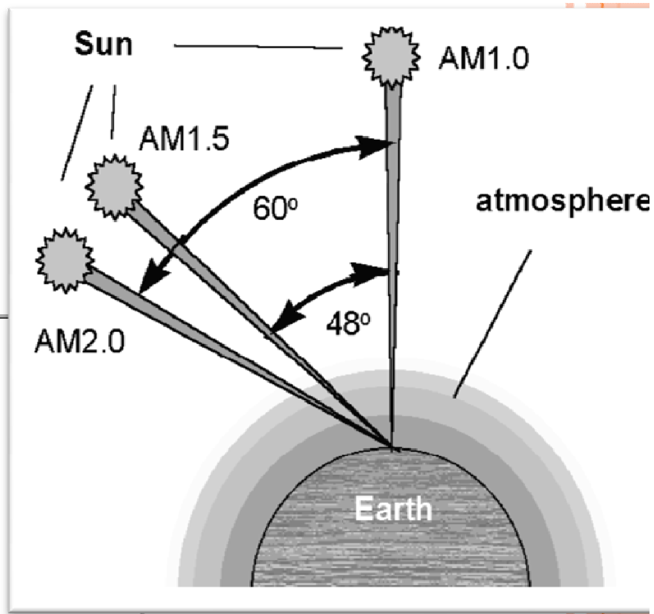
SOLAR SPECTRUM





Source: *PHD Thesis- K. Petritsch,July'00.*

***AM1.5G** spectrum is standard spectrum for solar cell measurements.*

EFFICIENCY OF SOLAR CELLS

- The photocurrent of a solar cell depends on:

No. of created charges collected at the electrodes i.e.

- Fraction of photons absorbed (η_{abs}).
- Fraction of electron-hole pairs dissociated(η_{diss}).
- Fraction of (separated) charges reaching the electrodes (η_{out}).

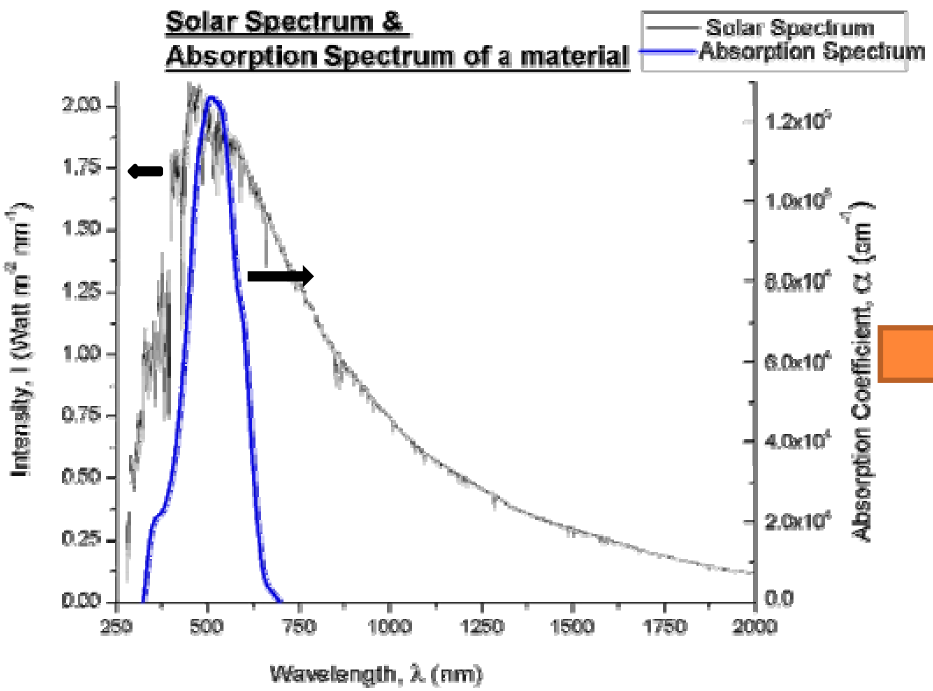
The overall photocurrent efficiency(η_j)

$$\eta_j = \eta_{abs} * \eta_{diss} * \eta_{out}$$

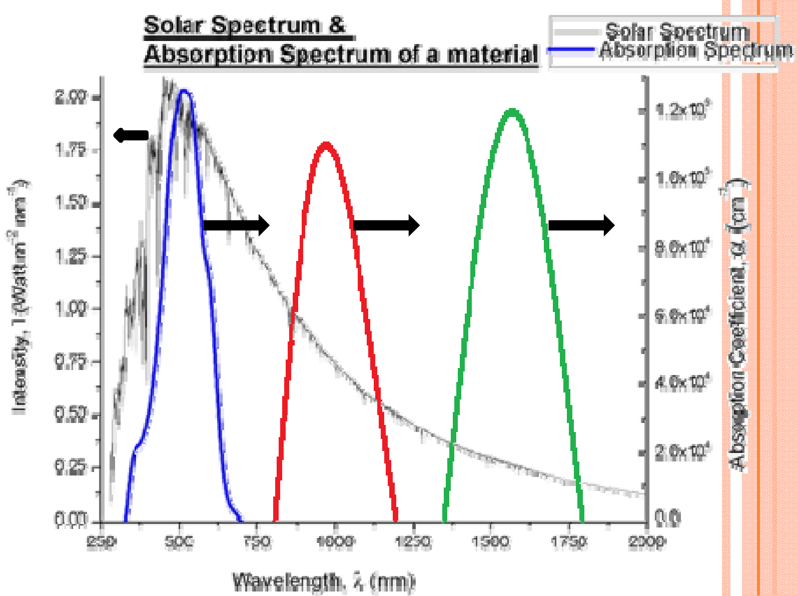
We are focused on the absorption efficiency

Photon absorption Efficiency (η_{abs})

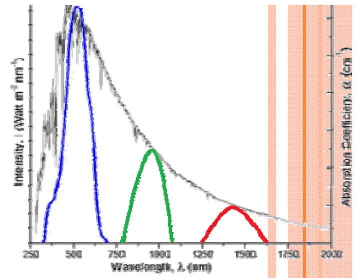
- **Photon Absorption Efficiency (η_{abs}) of a matl. depends upon:**
  - Material Absorption Spectrum- Absorption coefficient of the material (α).
  - Width of the material layer (d).
  - Intensity observed at depth d of material, $I=I_o e^{-\alpha d}$.



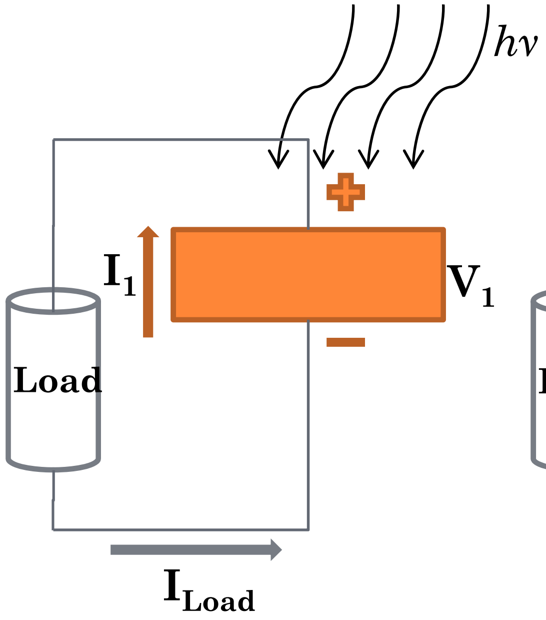
To increase $\boldsymbol{\eta_{abs}}$ use Multi junction Cells

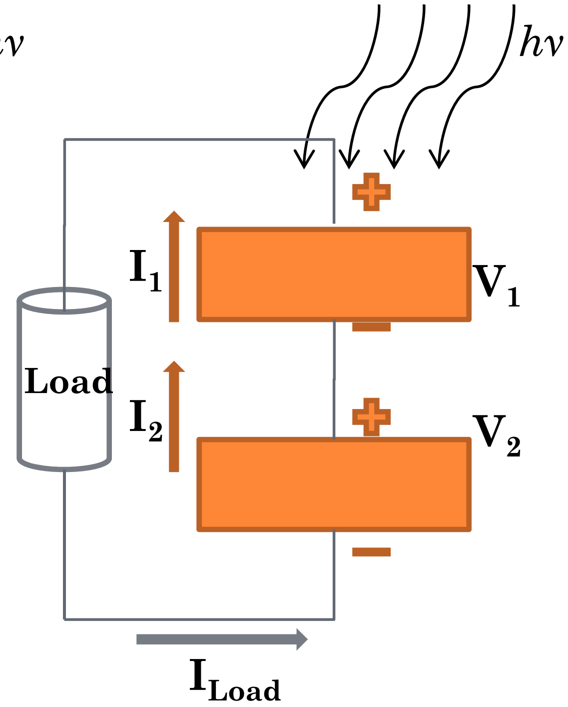


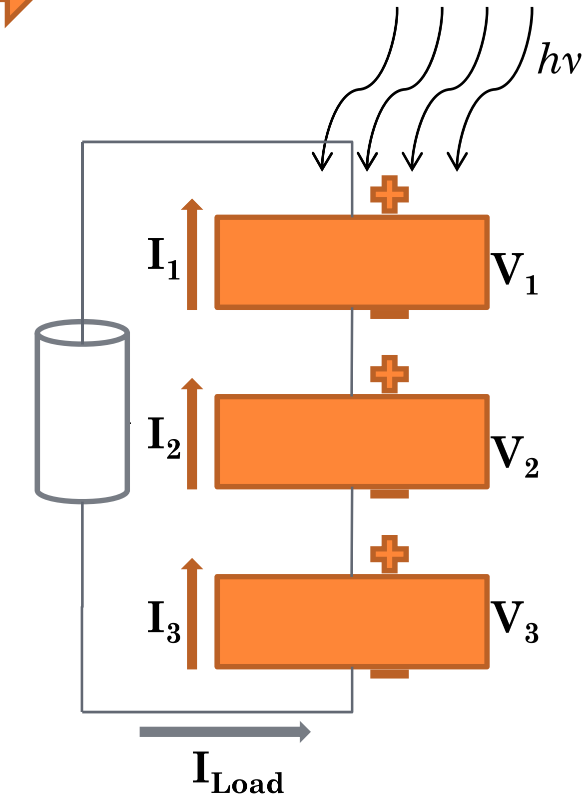
MULTI JUNCTION SOLAR CELLS



Single Junction | Two Junction | Three Junction







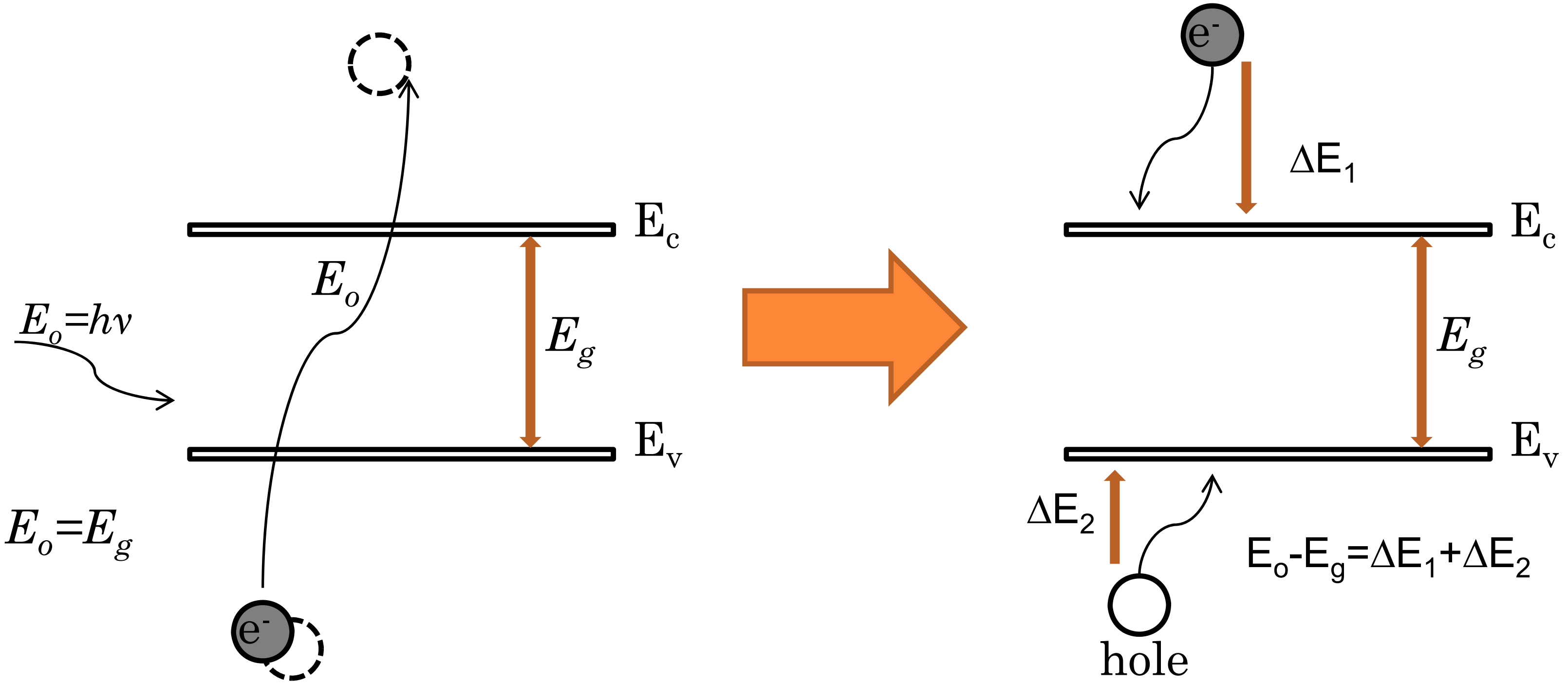
$V_{Load} = V_1$
$I_{Load} = I_1$
Efficiency $= E_{eff1}$

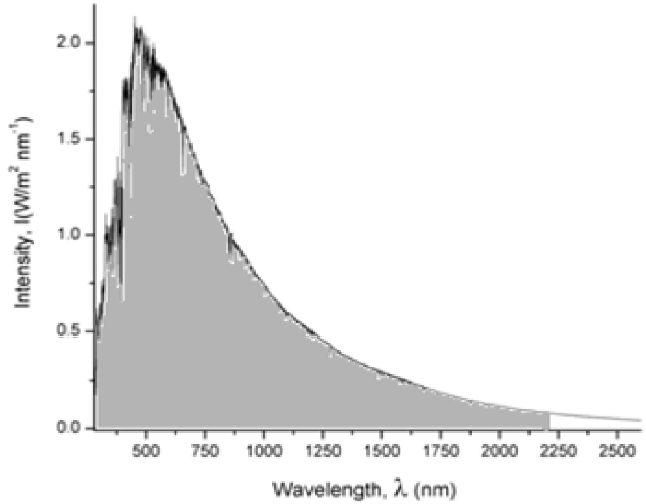
$V_{Load} = V_1 + V_2$
$I_{Load} \approx \min\{I_1, I_2\}$
E_{eff2}

$V_{Load} = V_1 + V_2 + V_3$
$I_{Load} \approx \min\{I_1, I_2, I_3\}$
E_{eff3}

$E_{eff1} \ll E_{eff2} \ll E_{eff3}$

PHOTONS ABSORBED & ENERGY LOSSES





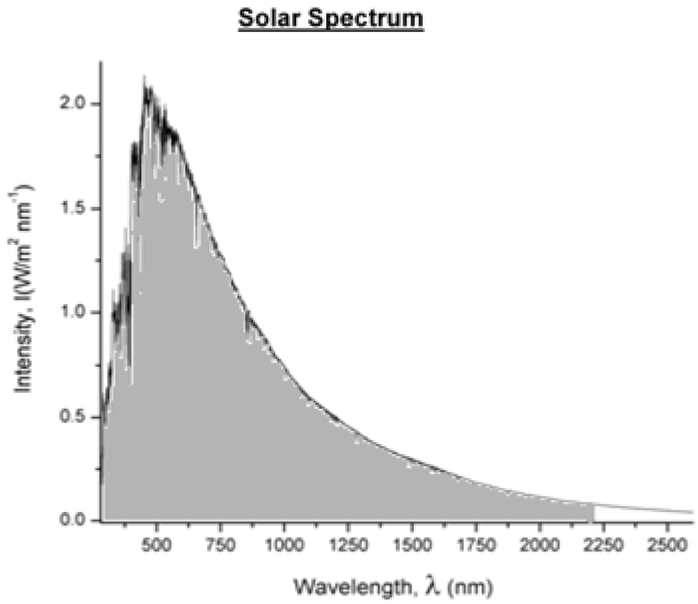
- Optical Loss = E_0, if $E_o < E_g$
- Thermal Loss = $E_o - E_g$, if $E_o \geq E_g$

Useful energy harvested from solar spectrum

- Fraction of Harvested Energy(η_{HE}) from Solar spectrum depends upon:
  - Fraction of photons absorbed (η_{ph})
    - η_{ph} α Photon Absorption Efficiency (η_{abs})
  - Fraction of useful energy obtained from absorbed photons (η_{ue})

$$\eta_{ue} = \frac{\text{Useful energy available after photo absorption}}{\text{Total energy absorbed from photons absorption}} \Rightarrow \eta_{ue} = \frac{E_o - E_g}{E_o}$$

$$\boxed{\eta_{HE} = \eta_{ph} * \eta_{ue}}$$



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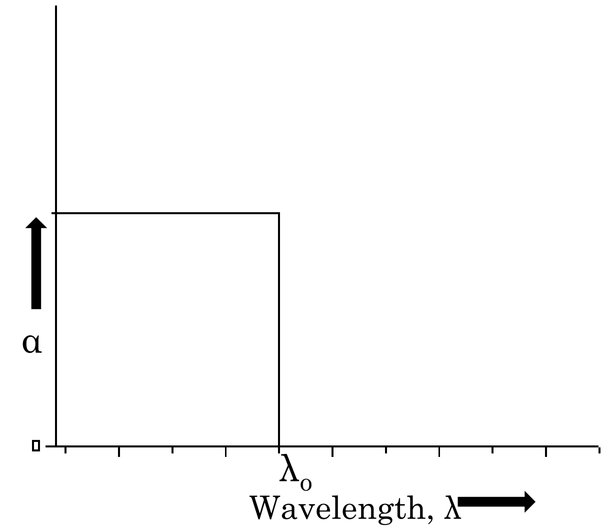
SIMULATION/EXPERIMENTAL PLAN

Step Absorption Spectrum

e.g. Inorganic Semiconductors

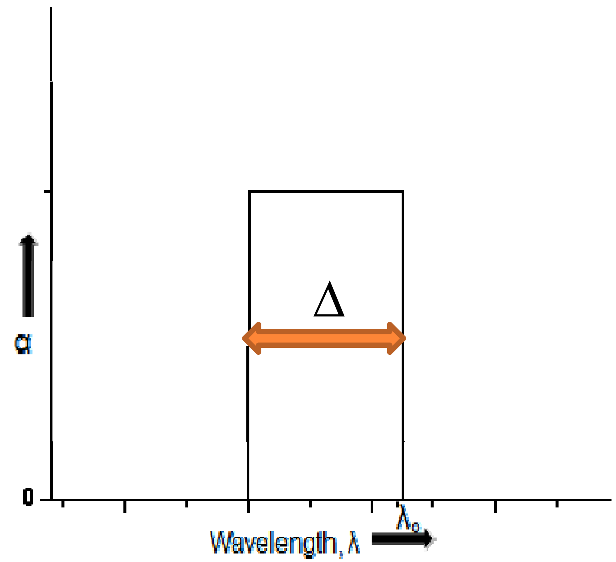
- Single Junction Cells
- 2 junction cells
- 3 junction cells



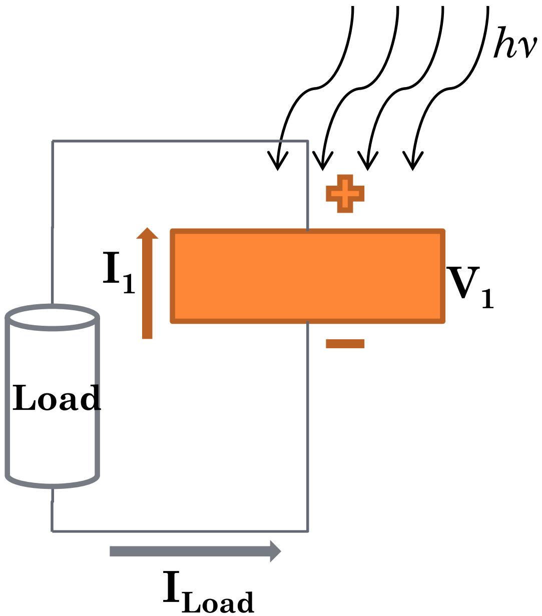
Box Type Absorption Spectrum

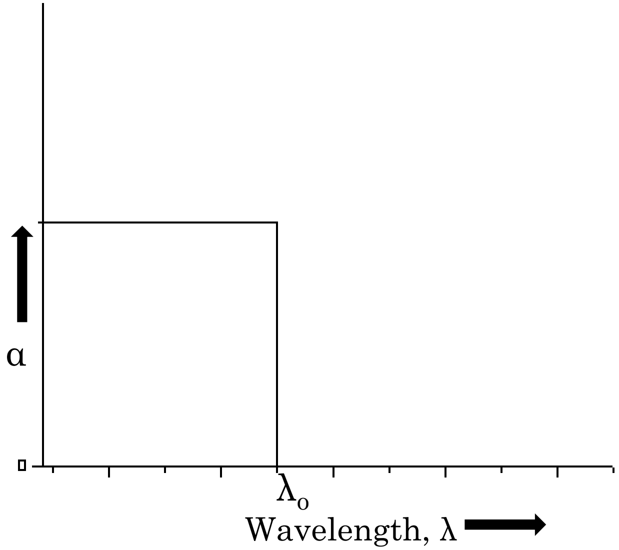
e.g. Organic Solar cells

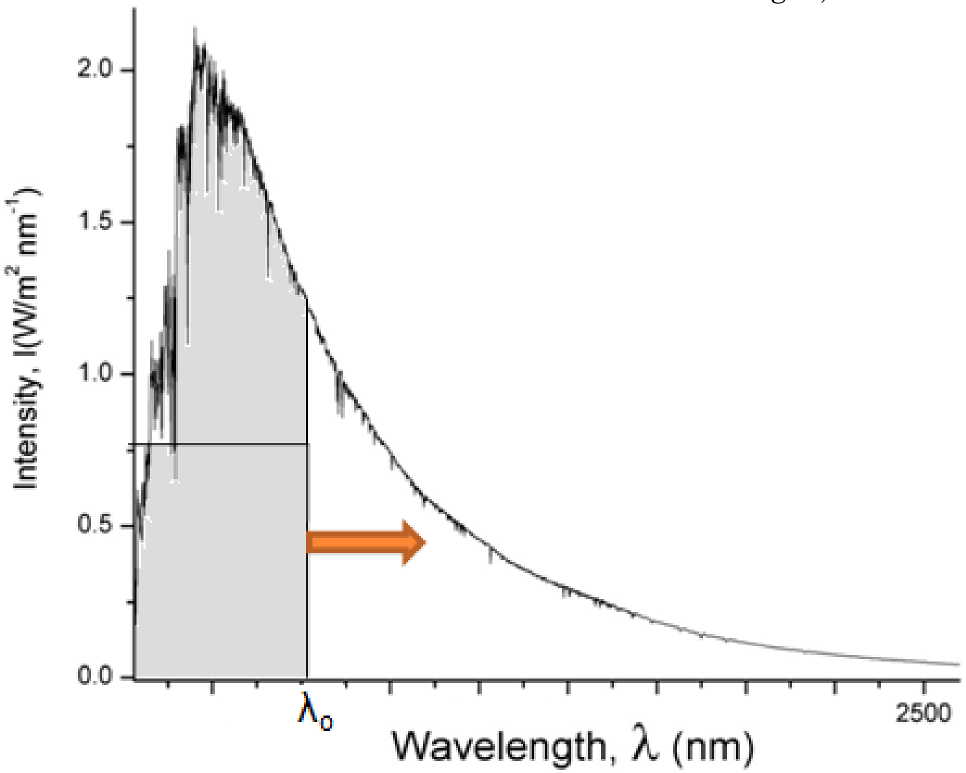
- Single Junction Box Type
- 2 junction Box type



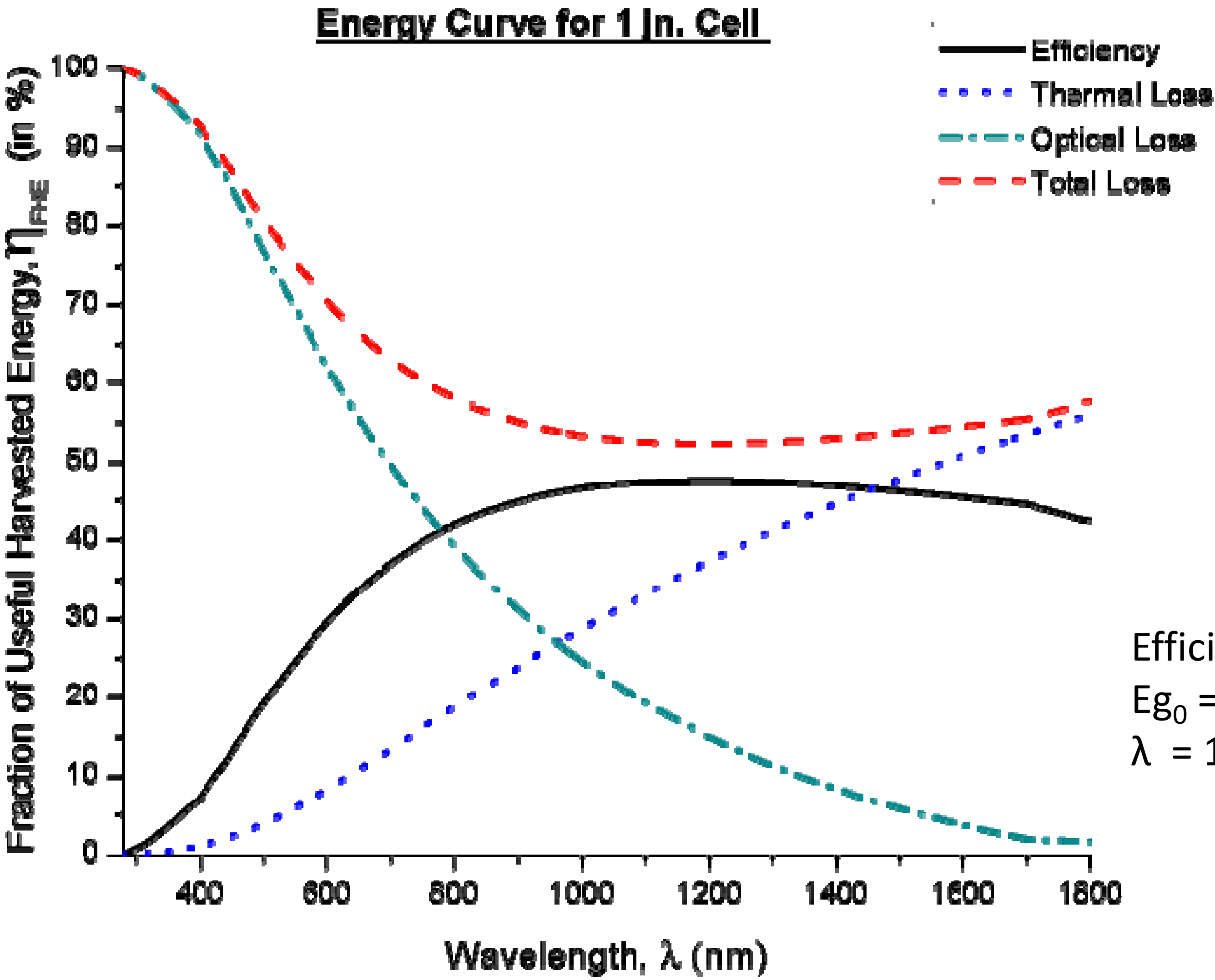
Single Junction Cells

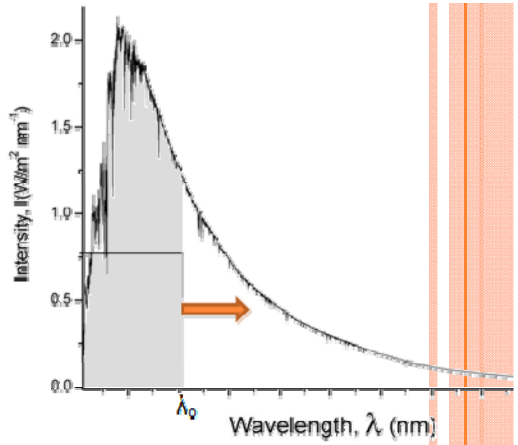






Single Junction Solar Cells



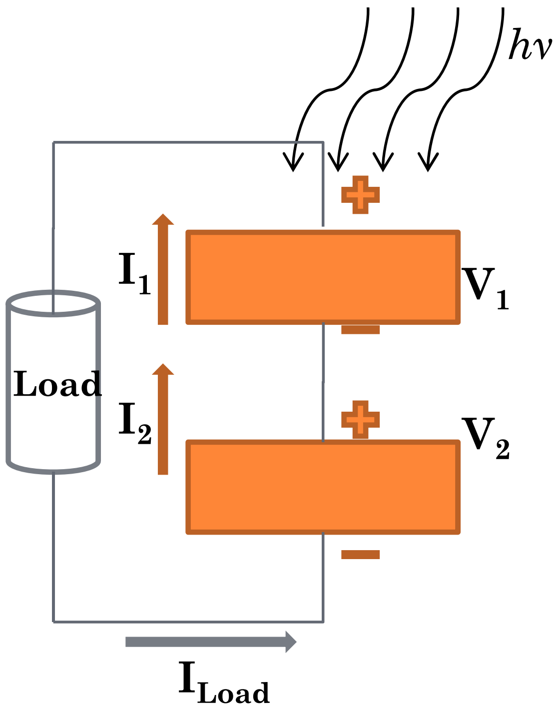


Efficiency,η = 47.63%

Eg_0 = 1.0423 eV

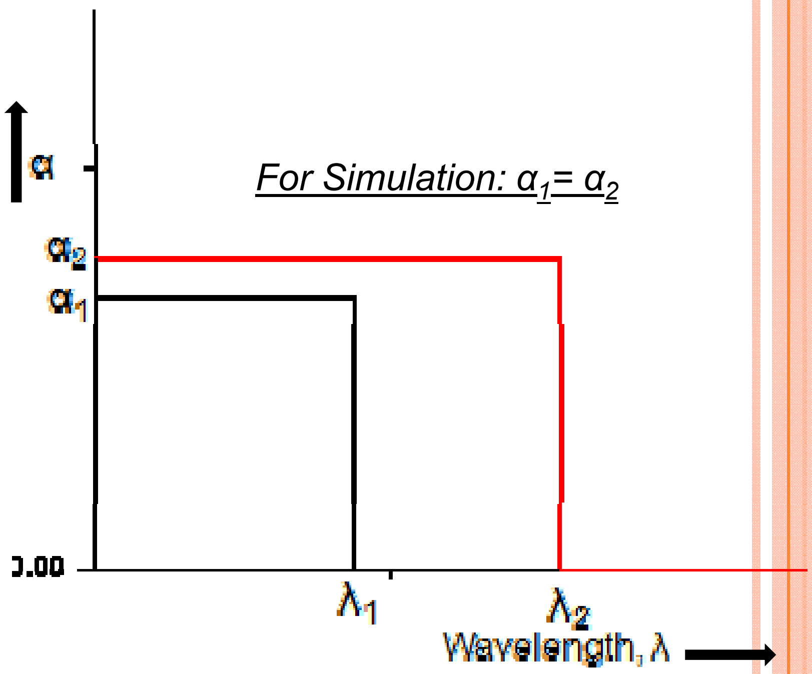
λ = 1197nm

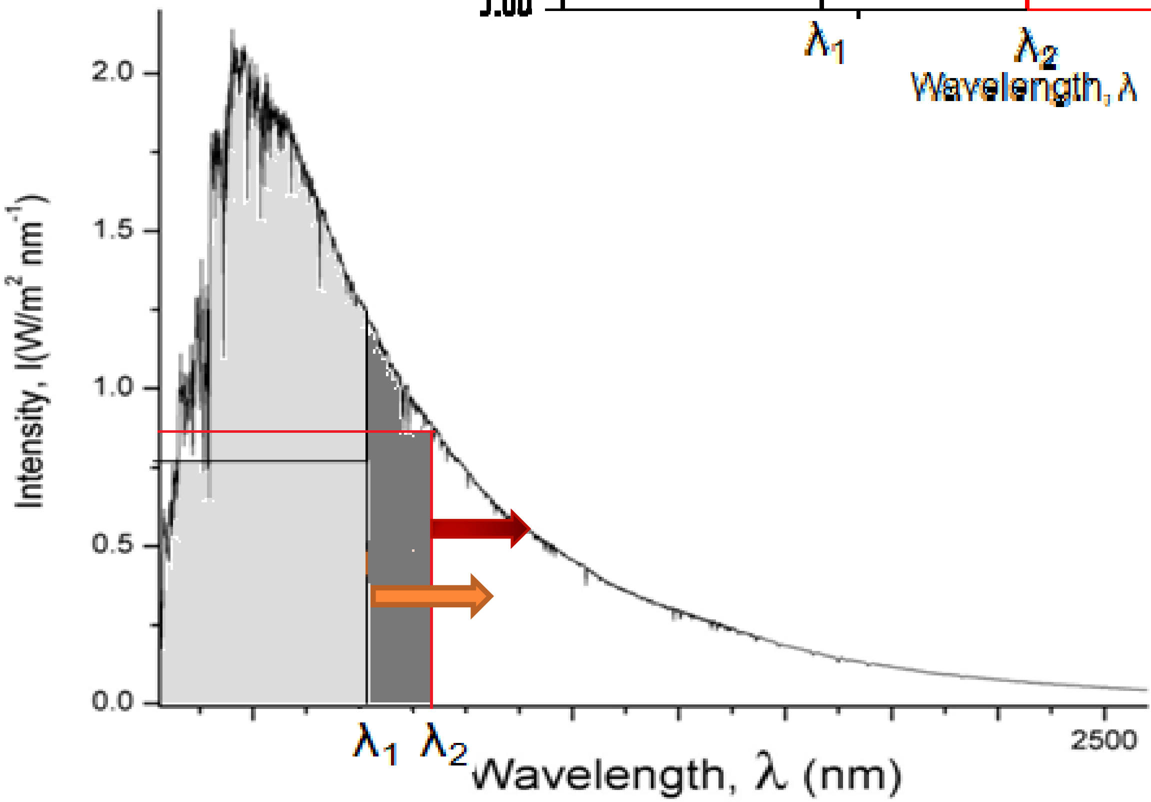
Double Junction Cells



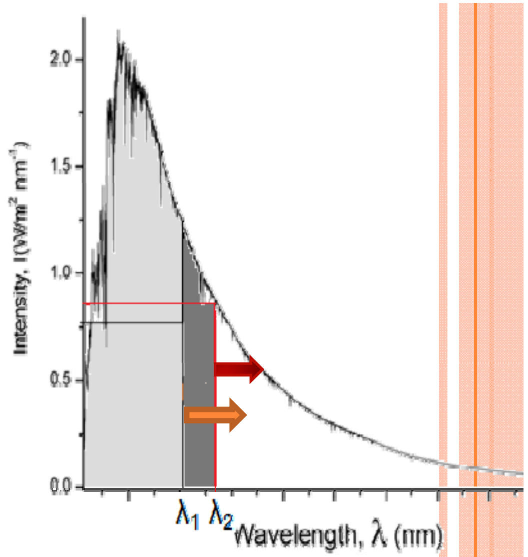
$V_{Load} = V_1 + V_2$

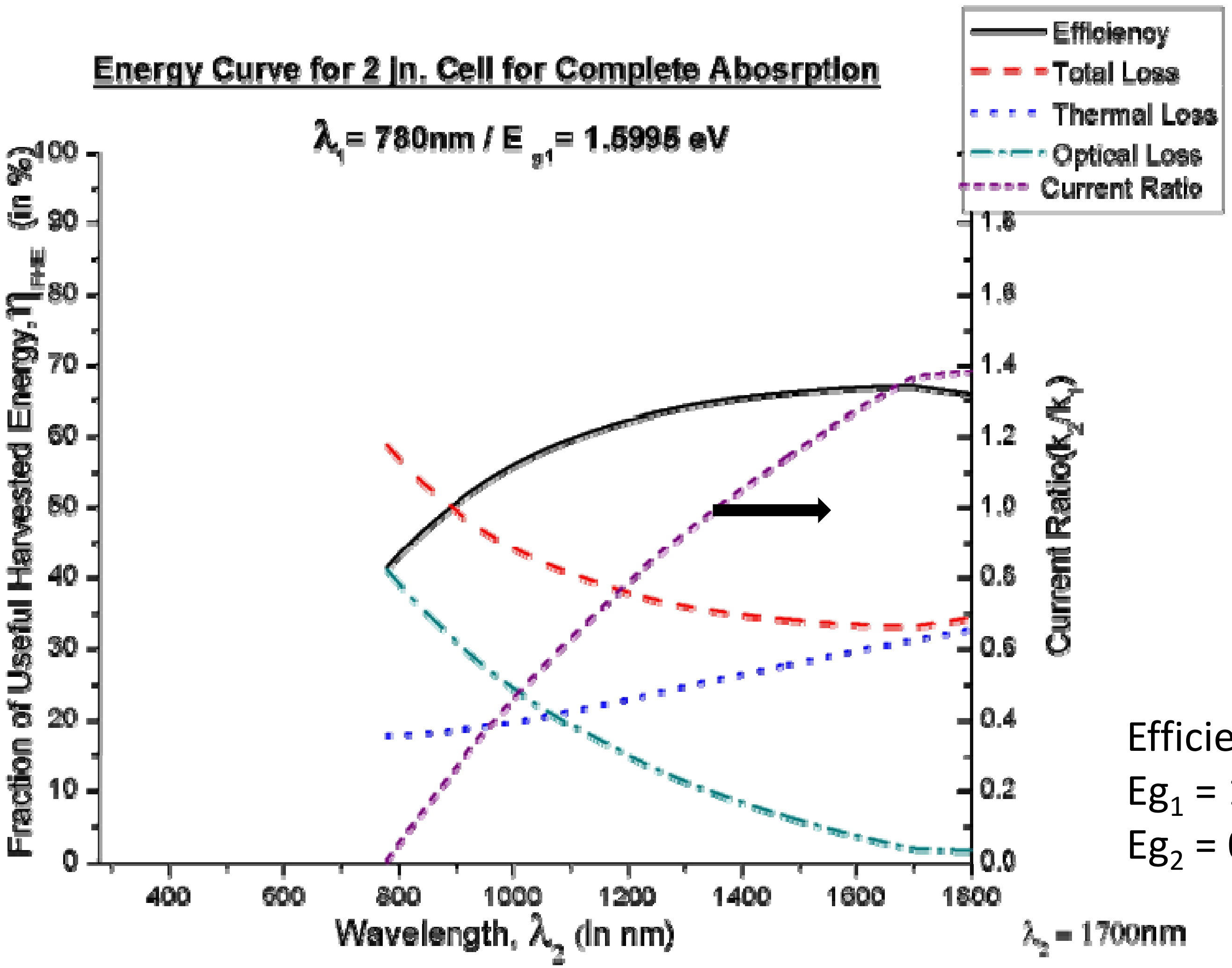
E_{eff2}





ENERGY FOR 2 JN. SOLAR CELLS



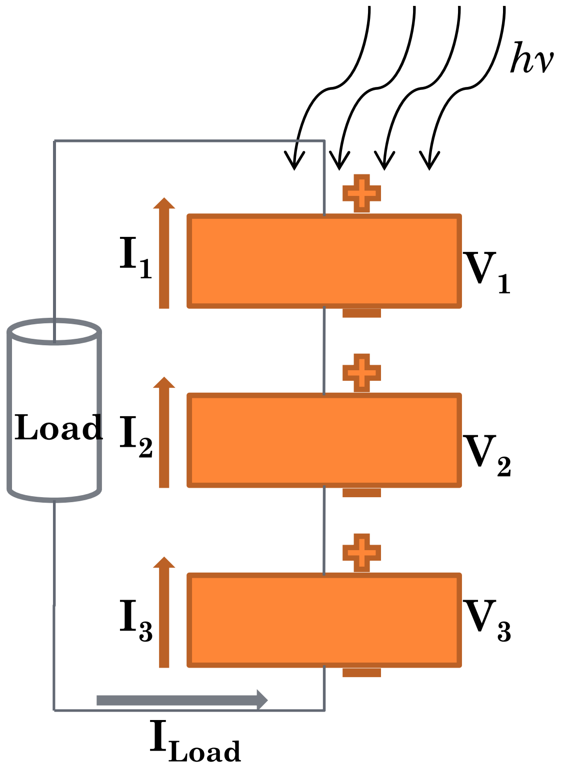


Efficiency,η = 66.85%

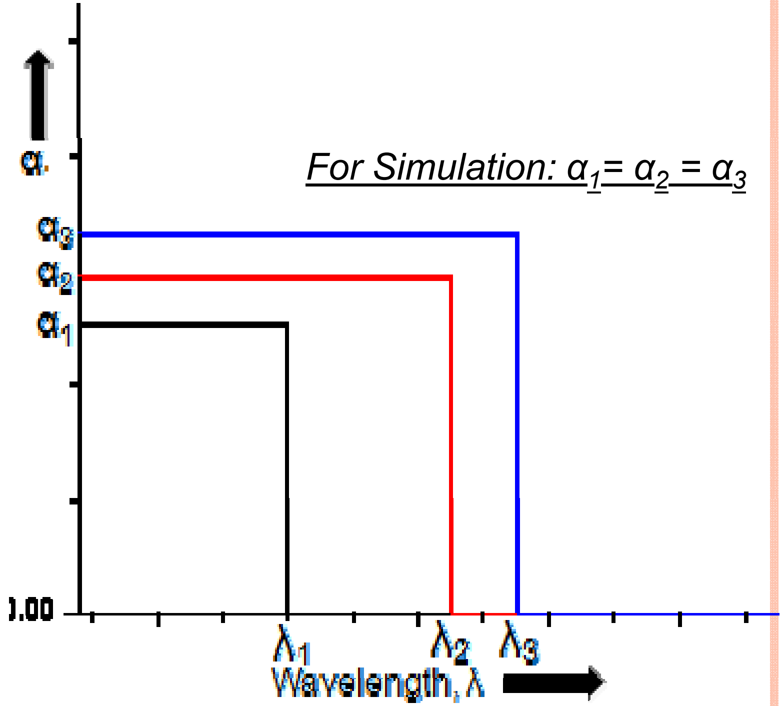
Eg_1 = 1.5995 eV/780nm

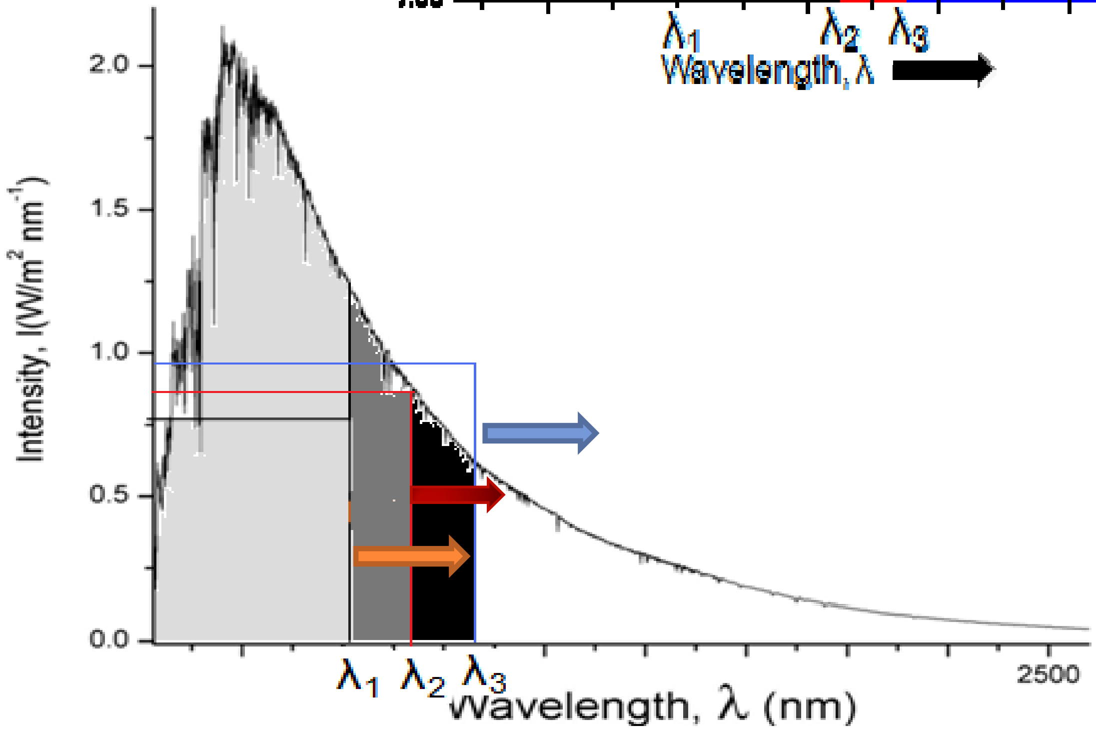
Eg_2 = 0.7339 eV/1700nm

TRIPLE JUNCTION CELLS



$V_{Load} = V_1 + V_2$
$I_{Load} \approx \min\{I_1, I_2\}$
E_{eff2}

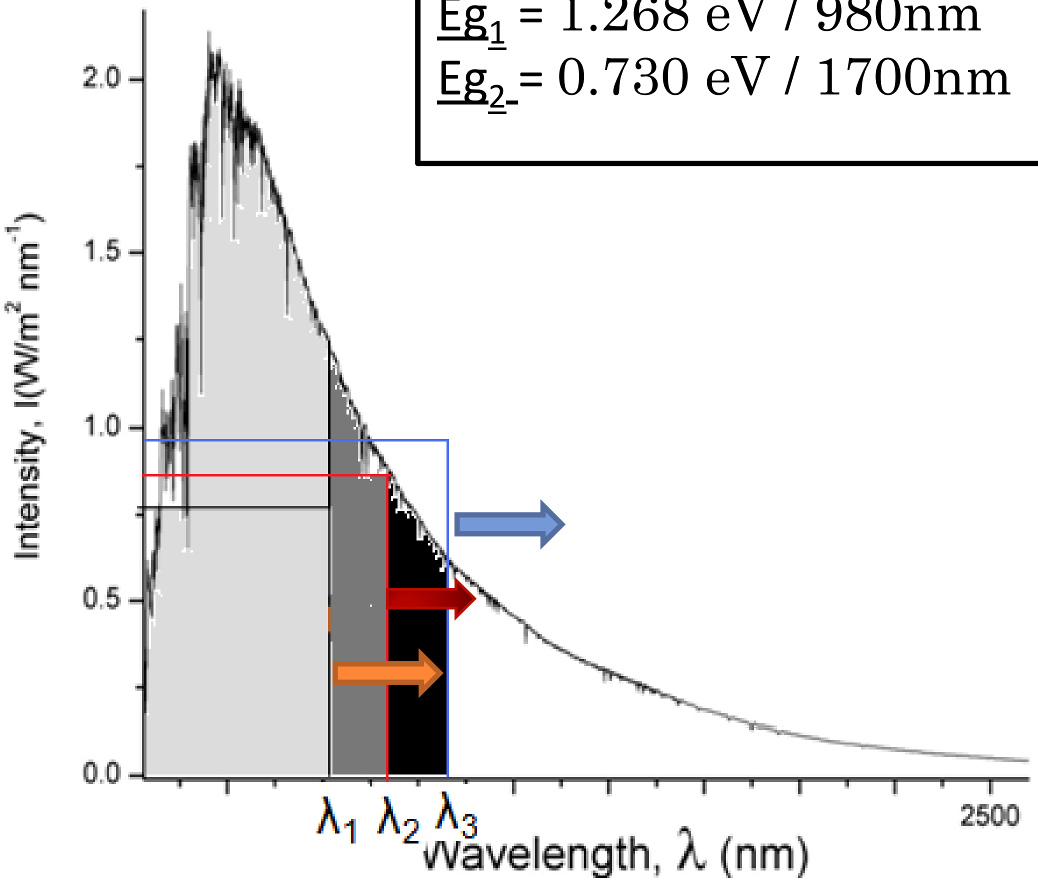


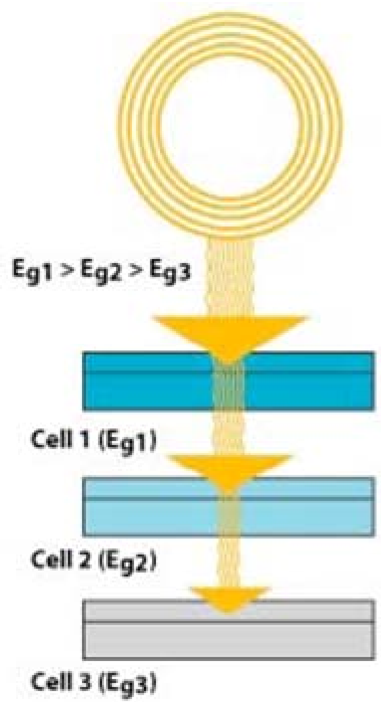


Triple Junction Solar Cells

- Maximized Efficiency of 3 junction cell corresponds to:

Efficiency,η = **75.79%**
Eg_0 = 1.830 eV / 680nm
Eg_1 = 1.268 eV / 980nm
Eg_2 = 0.730 eV / 1700nm

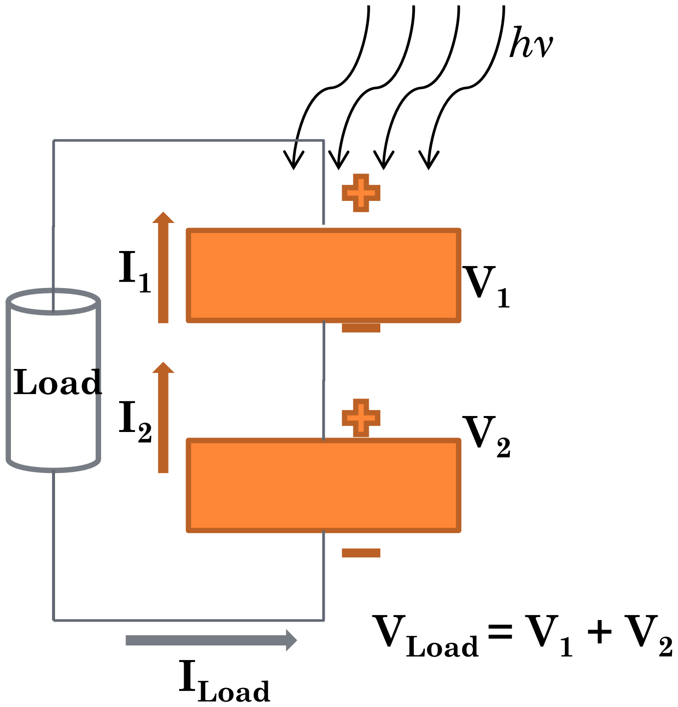


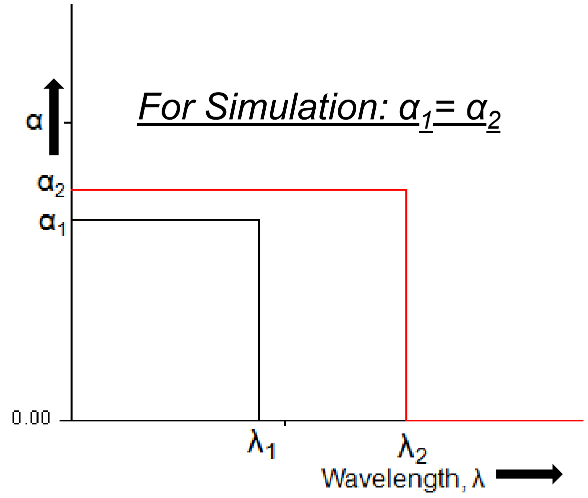


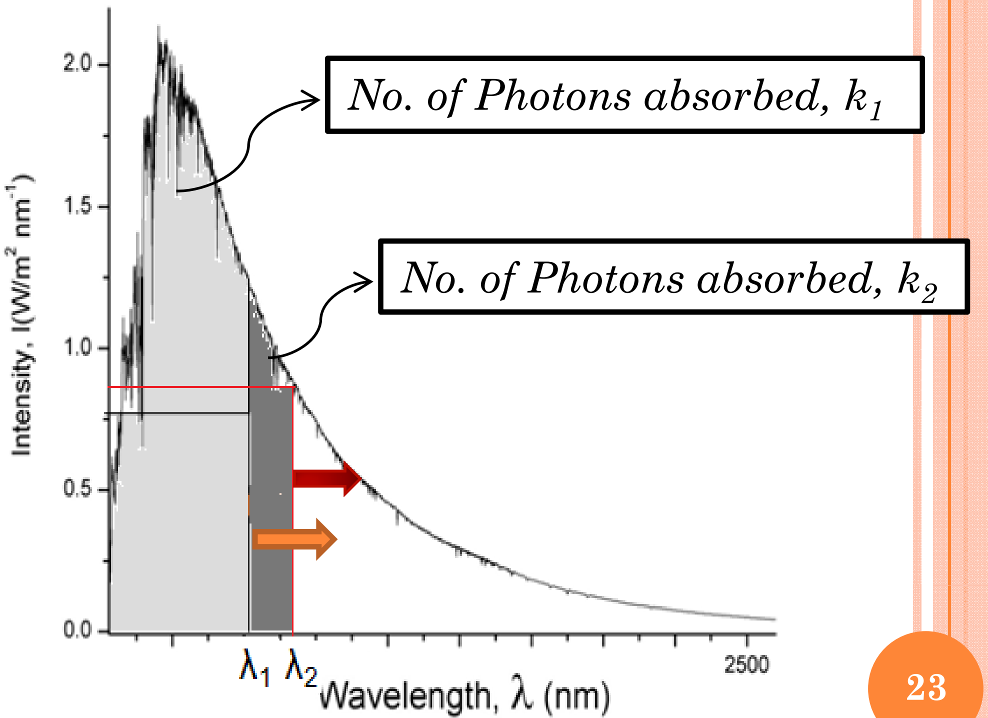
SUMMARY
(MAXIMIZED EFFICIENCIES OF VARIOUS MULTIJUNCTION CELLS)

Parameters	Single junction Solar Cells	2 junction Solar Cells	3 junction Solar Cells
Efficiency (in %)	47.63%	66.85%	75.79%
Eg_1 / λ_1	1.0423 eV/ 1197nm	1.5995 eV/ 780nm	1.830 eV / 680nm
Eg_2 / λ_2		0.7339 eV/ 1700nm	1.268 eV / 980nm
Eg_3 / λ_3			0.730 eV / 1700nm

Mismatch Losses





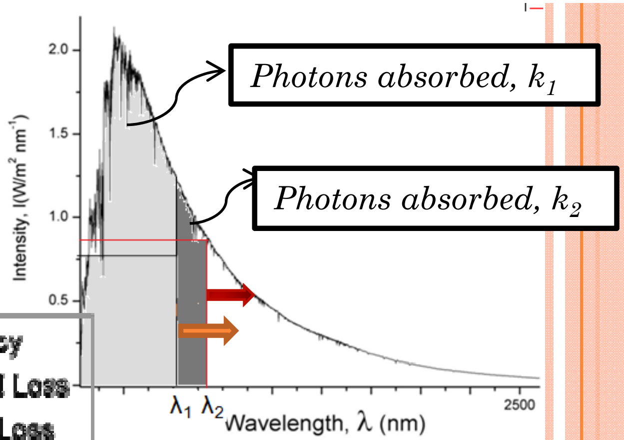


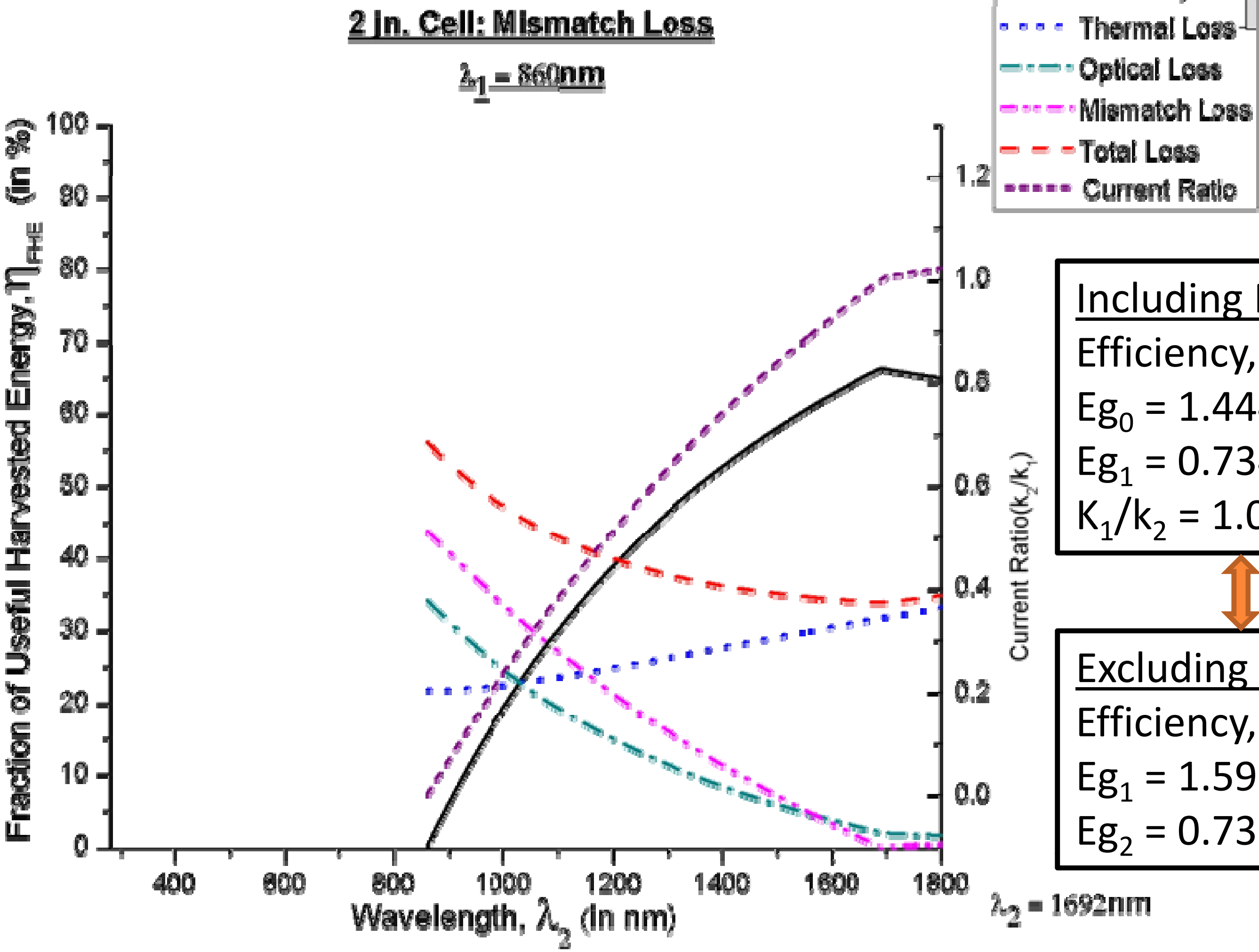
<u>Considering Mismatch Losses ($k_1 \neq k_2$)</u>

- Leads to the Mismatch Loss in the Material.
- $I_{Load} \approx \min\{I_1, I_2\}$

Mismatch Loss= (| k_1-k_2 |) * $E_{g\,(1/2)}$

Energy for 2 Jn. Solar Cells





Including MISMATCH Losses

Efficiency, η = 66.20%

Eg_0 = 1.444 eV/860nm

Eg_1 = 0.734 eV/1692nm

K_1/k_2 = 1.0003

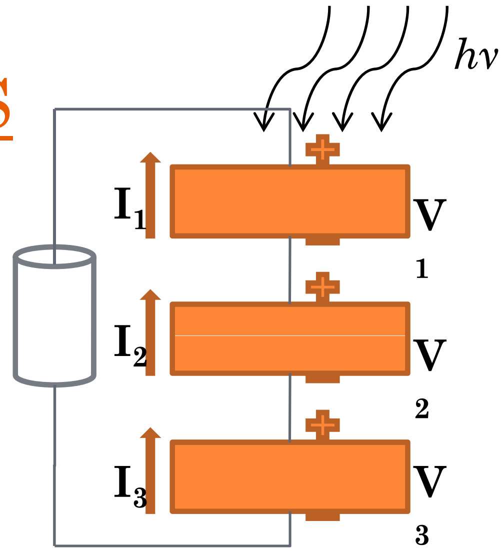
Excluding MISMATCH Losses

Efficiency, η = 66.85%

Eg_1 = 1.5995 eV/780nm

Eg_2 = 0.7339 eV/1700nm

ENERGY FOR 3 JN. SOLAR CELLS



Including MISMATCH Losses

Efficiency,η = 73.58%

Eg_1 = 1.830 eV/680nm

Eg_2 = 1.205 eV/1031nm

Eg_3 = 0.761 eV/1632nm

K_1/k_2= 1.0099

K_2/K_3= 0.9521

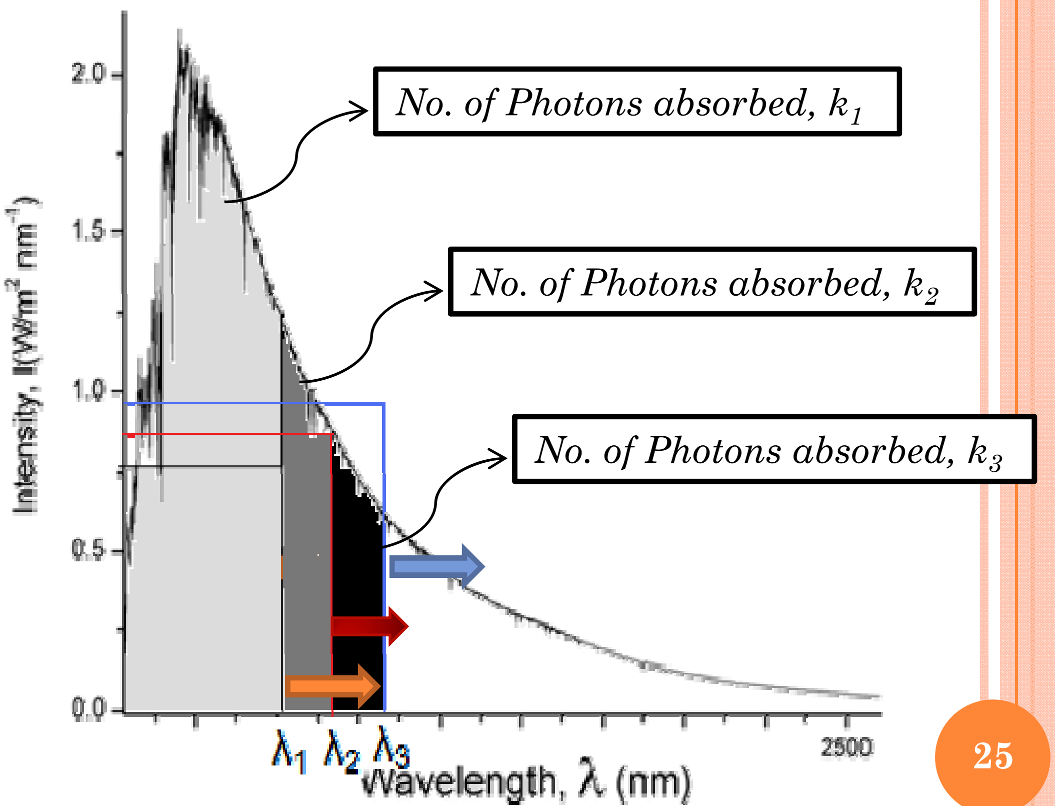
Excluding MISMATCH Losses

Efficiency,η = 75.79%

Eg_1 = 1.830 eV/680nm

Eg_2 = 1.268 eV/980nm

Eg_3 = 0.730 eV/1700nm



Comparison of efficiencies
(with/without considering Mismatch Losses)

Complete absorption by 2 jn. Solar Cells

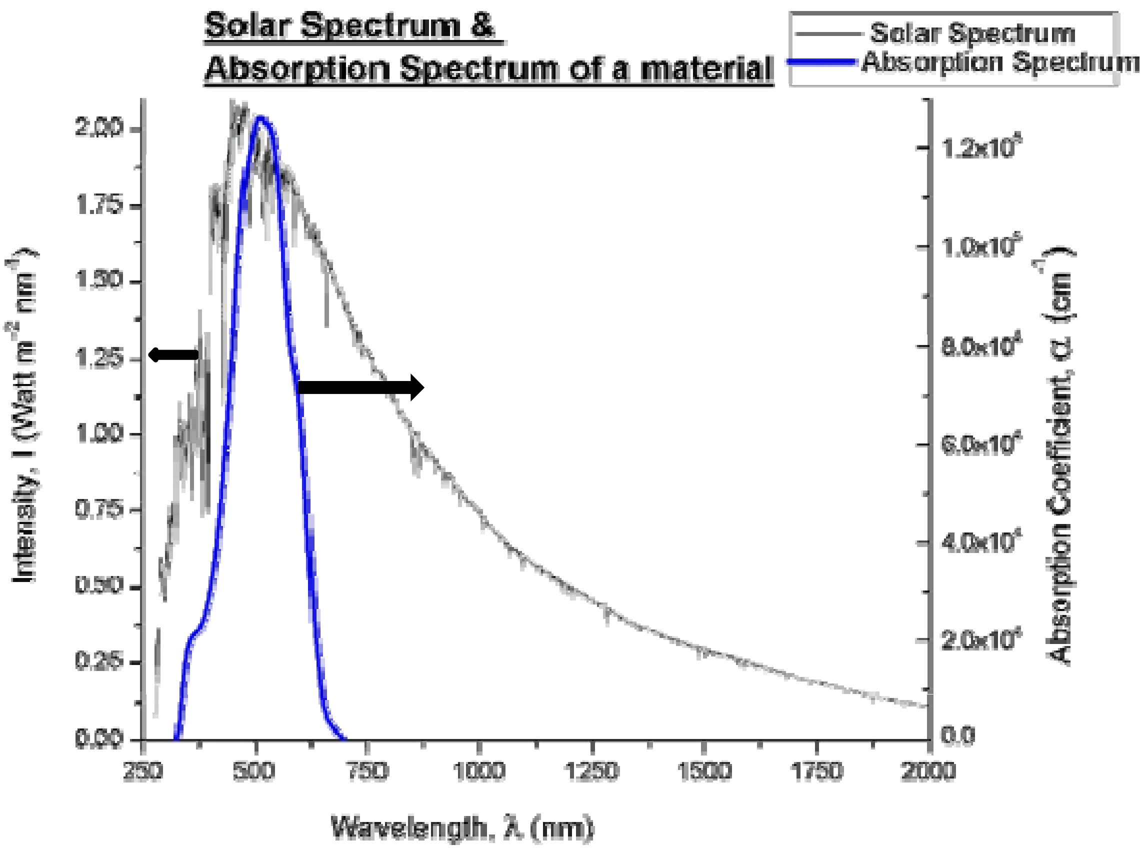
Parameters	Model does not include MISMATCH Losses	Model include MISMATCH Losses
Efficiency (in %)	66.85%	66.20%
Eg_1 / λ_1	1.5995 eV/ 780nm	1.444 eV/ 860nm
Eg_2 / λ_2	0.7339 eV/ 1700nm	0.734 eV/ 1692nm
Current Ratio, n	1.3627	1.0003

Complete absorption by 3 jn. Solar Cells

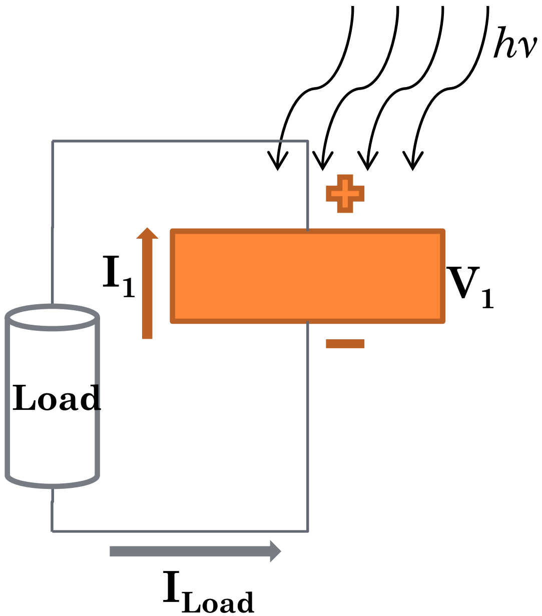
Parameters	Model does not include MISMATCH Losses	Model include MISMATCH Losses
Efficiency (in %)	75.79%	73.58%
Eg_1 / λ_1	1.830 eV/ 680nm	1.830 eV/ 680nm
Eg_2 / λ_2	1.268 eV/ 980nm	1.205 eV/ 1031nm
Eg_3 / λ_2	0.730 eV/ 1700nm	0.761 eV/ 1632nm

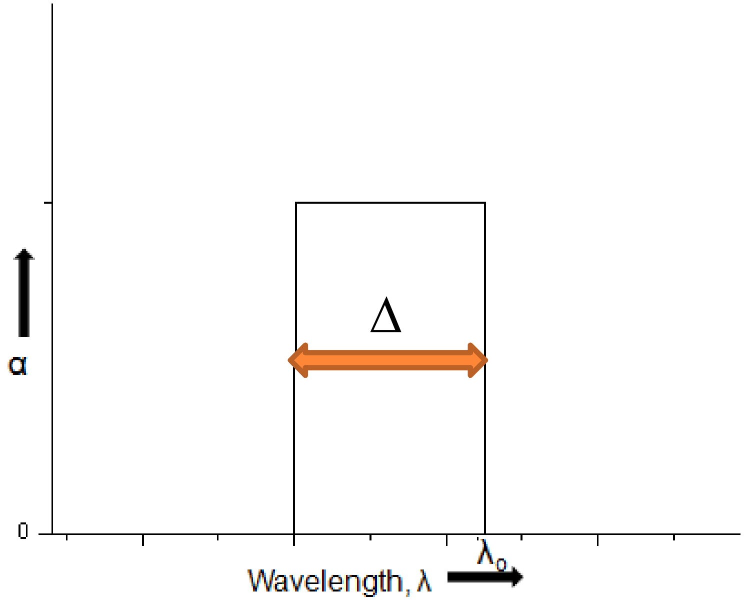
REALISTIC ABSORPTION SPECTRUM

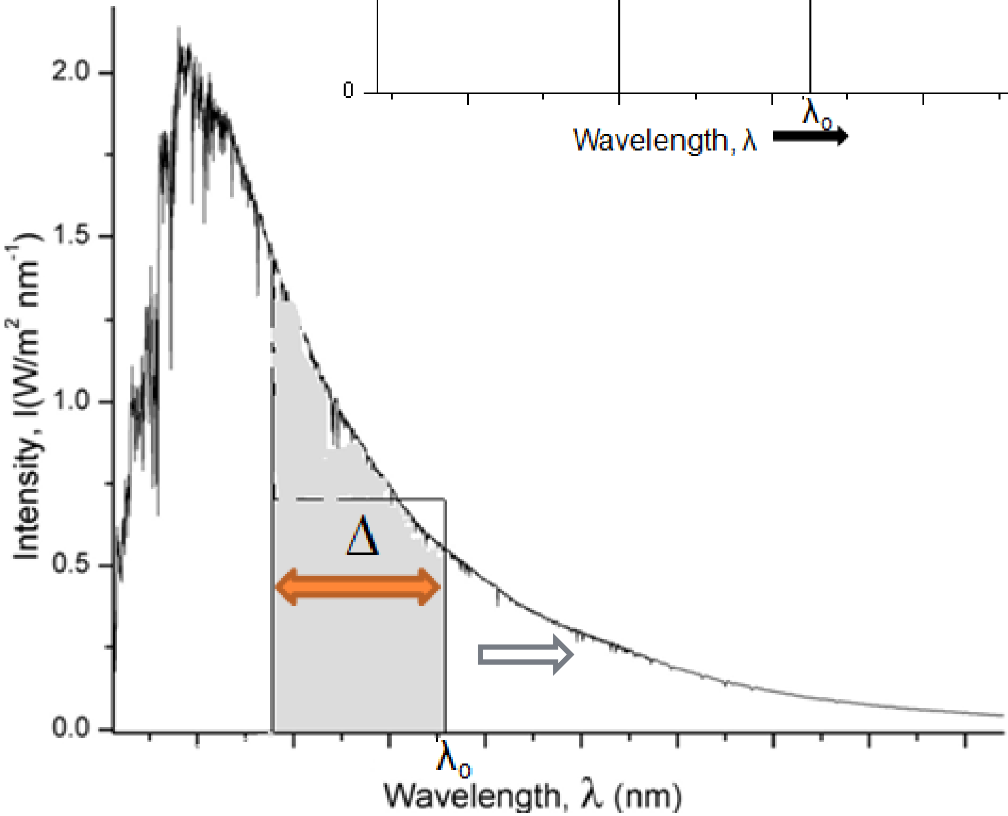
- Materials do not absorb for complete energy spectrum (> E_g).
- ***Inorganic materials*** have typically ***wide absorption spectrum***.
- However, ***organic materials*** have ***narrow absorption spectrum***.
- Hence, ***box type absorption spectrum(Δ)*** has been taken as 1st approximation for further simulations.



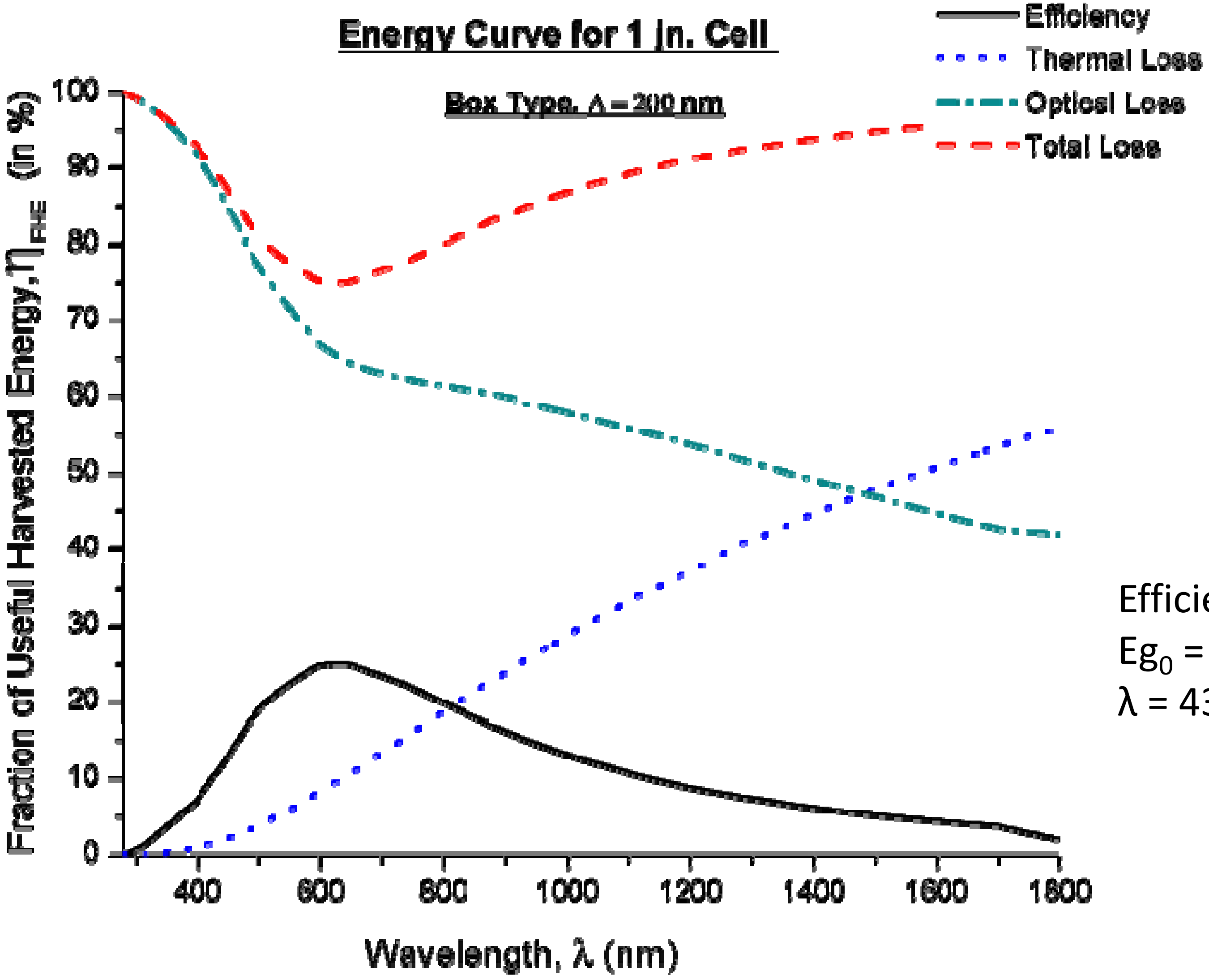
Single Junction Cells (box type)

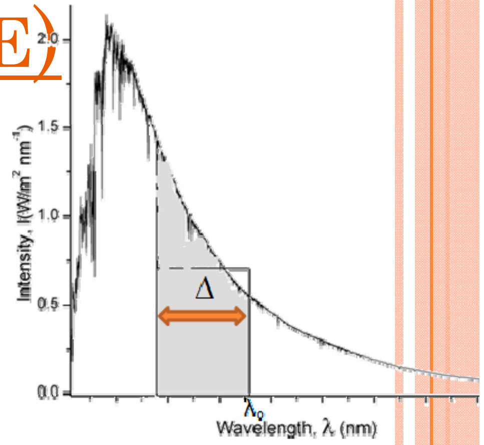






1 Junction Solar Cells (Box Type)



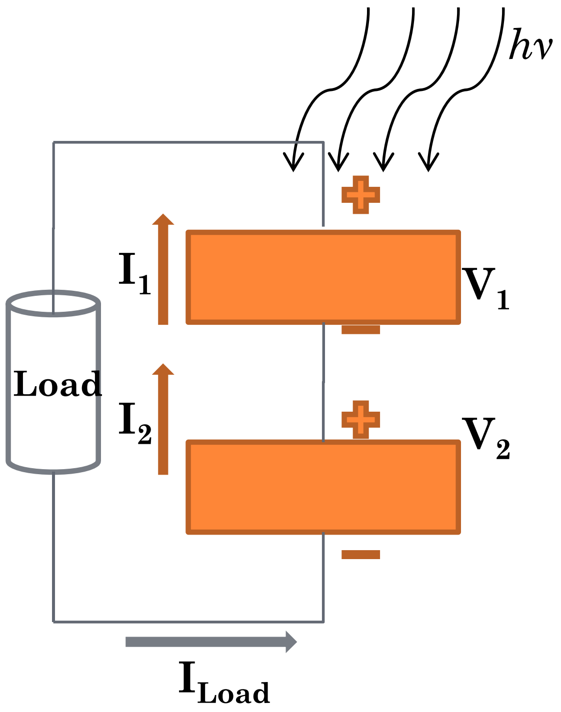


Efficiency,η = 24.98%

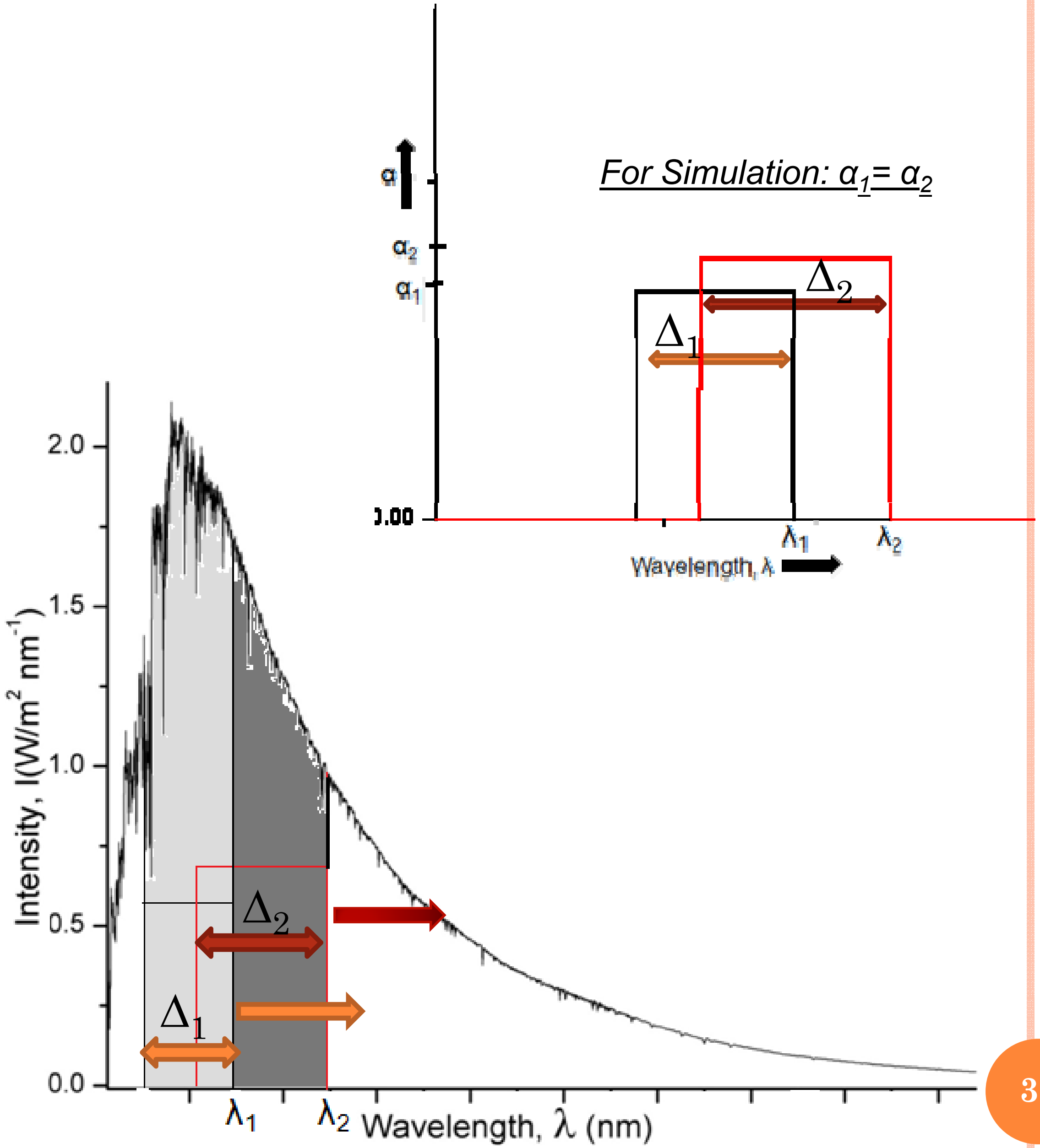
Eg_0 = 1.9648 eV

λ = 435nm-635nm

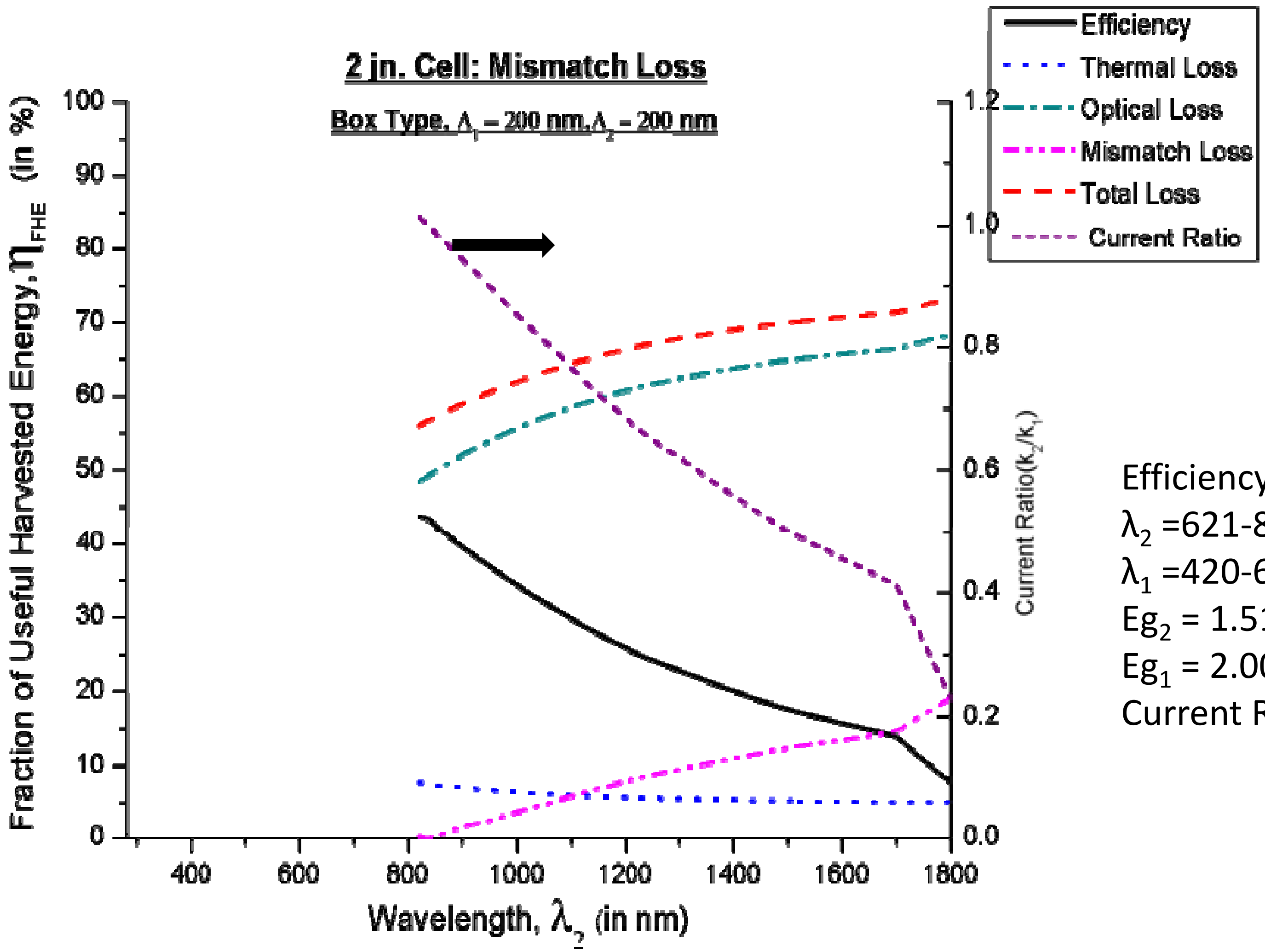
DOUBLE JUNCTION CELLS (BOX TYPE)

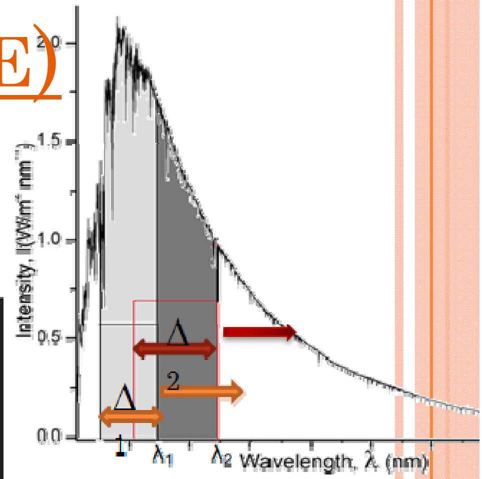


$V_{Load} = V_1 + V_2$



2 JUNCTION SOLAR CELLS (BOX TYPE)





Efficiency = 43.70%

λ_2 =621-821nm

λ_1 =420-620nm

Eg_2 = 1.513 eV

Eg_1 = 2.000 eV

Current Ratio,n = 1.0138

Summary
(Box type absorption spectrum)

Parameters		Single junction Solar Cells	2 junction Solar Cells
Efficiency (in %)		24.98%	47.00%
Eg_1 / λ_1	$\Delta\lambda_1$ = 200nm	1.9648 eV/ 435-635nm	2.000 eV/ 420-620nm
Eg_2 / λ_2	$\Delta\lambda_2$ = 200nm		1.513 eV/ 621-821nm

Maximized values for complete absorption spectrum

Parameters	Single junction Solar Cells	2 junction Solar Cells
Efficiency (in %)	47.63%	66.85%
Eg_1 / λ_1	1.0423 eV/ 1197nm	1.5995 eV/ 780nm
Eg_2 / λ_2		0.7339 eV/ 1700nm

OUTLINE

- Motivation
  - Overview of various Solar cell efficiencies.
- Background
  - Solar Spectrum
  - Efficiency of Solar cells and the parameters involved.
- Simulation/ Experimental Plan
  - Step Absorption Spectrum
    - Single junction Cells
    - 2 & 3 junctions Cells.
    - Mismatch Losses
  - Box Type Absorption Spectrum
    - Single junction Cells.
    - 2 junctions Cells.
  - Summary of Results
- **Summary**
- **Future Outlook**

Summary

- Very high efficiency achieved in Multijunction cells.

Complete Absorption (e.g. Inorganic Solar Cells)

Single junction Cell	2 junction Cell	3 junction Cell	…..
(47.63%)	(66.22%)	(73.58%)	
With Mismatch	(66.85%)	(75.79%)	

Fraction of Useful Harvested Energy, η_{HE}

Box Type Absorption Spectrum (Δ) (e.g. Organic Materials)

Single junction Cell	2 junction Cell	3 junction Cell	…..
(24.98%)	(43.60%)	…..	

Practically, 40.8% efficiency has been achieved by 3 junction Solar cell.

Future Outlook

- Using Gaussian absorption Spectrum ⟹ more realistic.
- Choice of Appropriate Materials ⟹ optimum value of η_{HE}.
- Include other loss parameters ⟹ more accurate efficiency.
- Thickness
  - To be adjusted to have same current
  - Lattice Mismatch
- Exploring Structure – Blend, Bilayer, Tandem further…

Questions???

Thank You !!

BAND GAP OF DIFFERENT MATERIALS