Application of the spectral response of photoluminescence in photovoltaics

Never Stand Still

Engineering

The Student:

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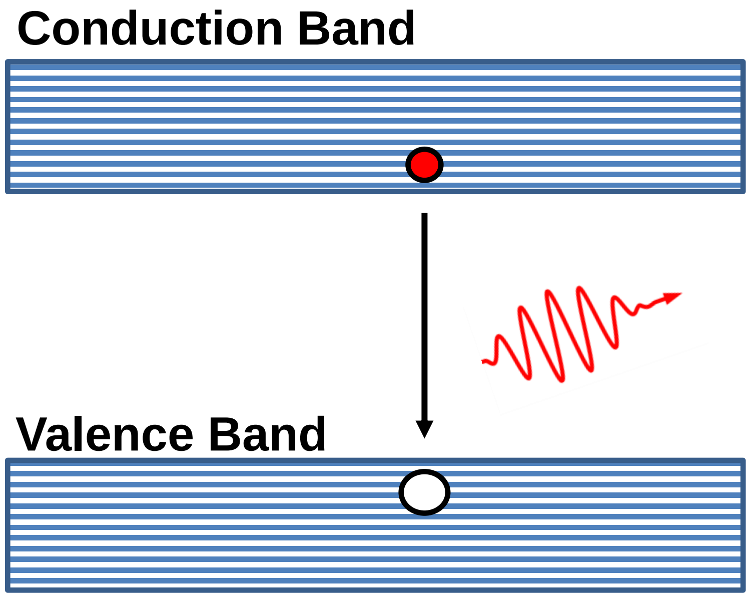
Scientia Profesor Martin Green

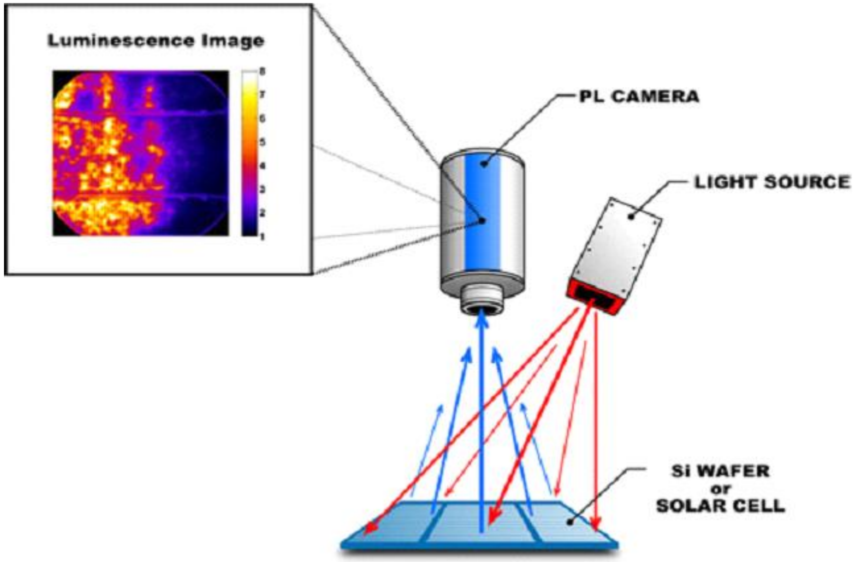
Photoluminescence?

- Luminescence: Radiative recombination of excess carriers
- Photo → generated by light
- Why photoluminescence?



Photoluminescence?

- Luminescence: Radiative recombination of excess carriers
- Photo → generated by light
- Why photoluminescence?
- How do I measure photoluminescence?
- What am I doing that's new?



1. Trupke, T., *et al*. (2006). *Applied Physics Letters*, *89*(4), 44107.

Spectral response

- The spectral response determines wavelength dependent properties
- That is a lot of Information
- Si's Photoluminescence only at 900 - 1300 nm

Lets change the illumination wavelength and measure photoluminescence

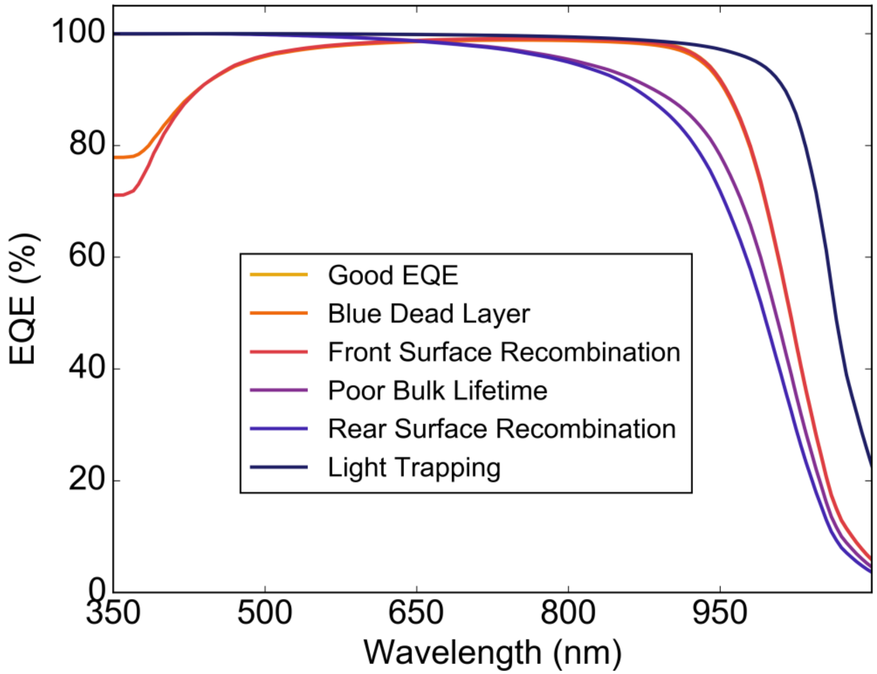


Fig: Simulated EQE in PC1D[1]

$$EQE_{Jsc} = \frac{I_{sc}}{qN_{ph}}$$

1. D.A. Clugston and P.A. Basore, Conf. Rec. Twenty Sixth IEEE Photovolt. Spec. Conf.-1997

Application 1: Band-to-band absorptance

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$$I_{PL} \propto \Delta n N_d \qquad \tau = \frac{\Delta n}{G}$$

$$I_{PL} \propto G\tau$$

For a constant effective lifetime

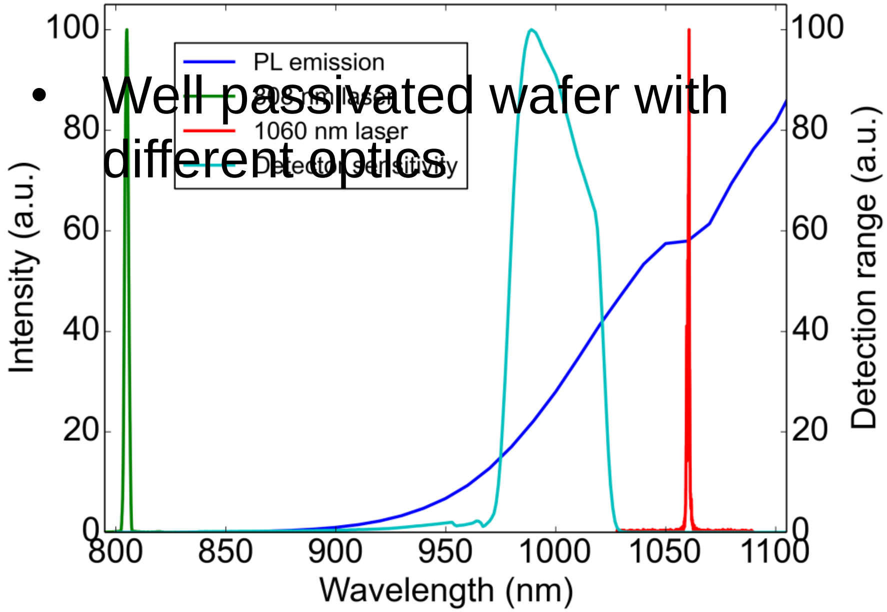
$$I_{PL} \propto G$$

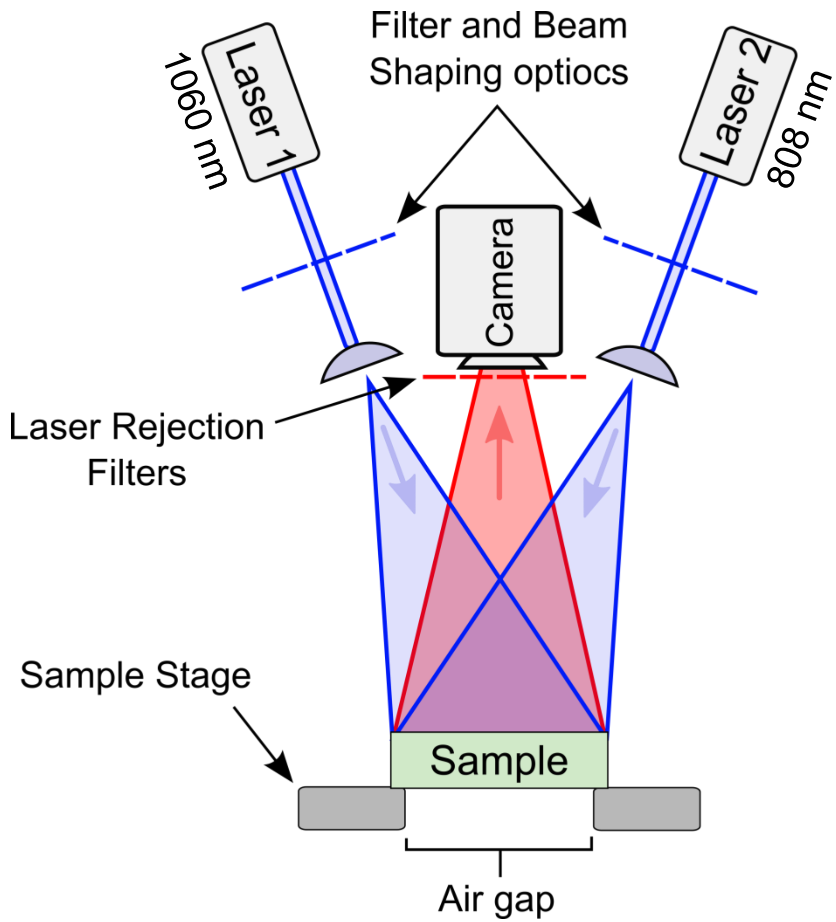
$$\propto AN_{ph}$$

$$\boxed{\frac{I_{pl}}{N_{ph}} \propto A}$$

Application 1: Band-to-band Absorptance

- Well passivated wafer with different optics



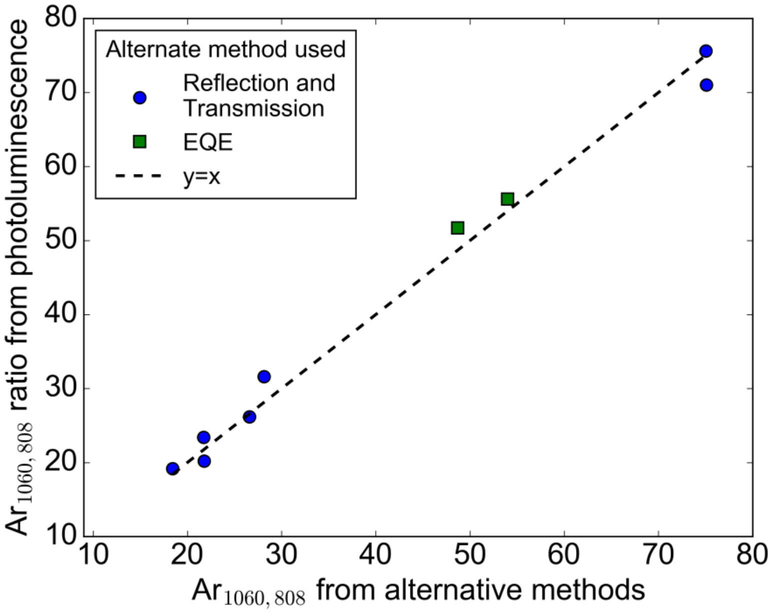


$$A \propto \frac{I_{pl}}{N_{ph}}$$

[1] Juhl, M. K., Trupke, T., Abbott, M., & Mitchell, B. (2015). *IEEE Journal of Photovoltaics*, *5*(6), 1840–1843.
[2] Juhl, M. K., et at. (2015) *31st European Photovoltaic Solar Energy Conference* Hamburg.

Application 1: Band-to-band Absorptance

- Well passivated wafer with different optics
- Compared to:
  1. Optical measurements
  2. EQE measurements



Comparison of Ar from our system to other measurement techniques

$$A \propto \frac{I_{pl}}{N_{ph}}$$

$$Ar_{1060,808} = \frac{A_{1060}}{A_{808}}$$

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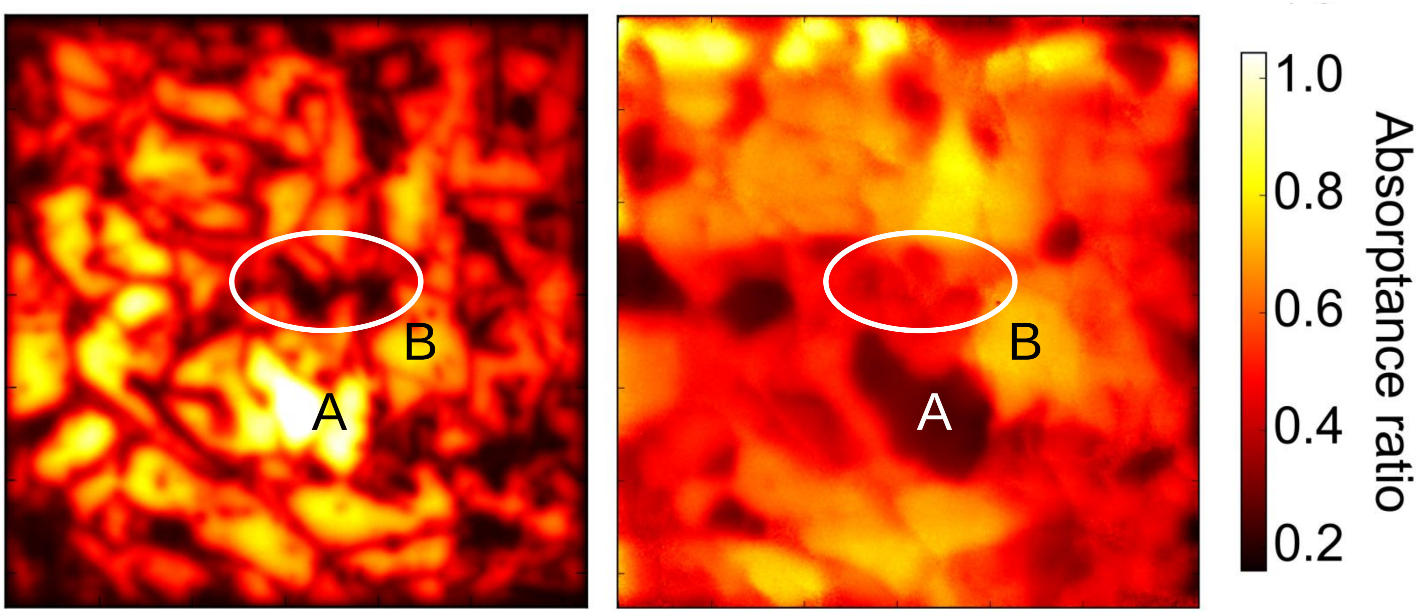
[2] Juhl, M. K., et.at. (2015) *31st European Photovoltaic Solar Energy Conference* Hamburg.

Application 1: Absorptance imaging!



(a) 808 nm illumination (b) 1060 nm illumination

$$A \propto \frac{I_{pl}}{N_{ph}}$$

Application 1: Band-to-band Absorptance

- Well passivated wafer with different optics
- Compared to:
  1. Optical measurements
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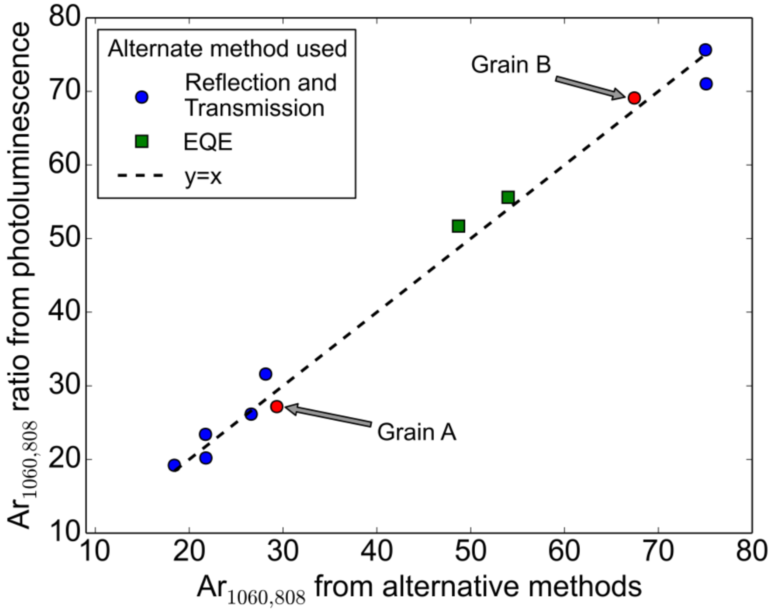

It works!!

$$A \propto \frac{I_{pl}}{N_{ph}}$$

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Application 2: External Quantum Efficiency

Application 2: External Quantum Efficiency

$$EQE_{Jsc} = \frac{I_{sc}}{qN_{ph}}$$

$$EQE_{jsc} \propto \frac{e^{\frac{V_{oc}}{Vt}}}{N_{ph}} \qquad I_{PL} \propto e^{\frac{iV_{oc}}{Vt}}$$

In low injection:

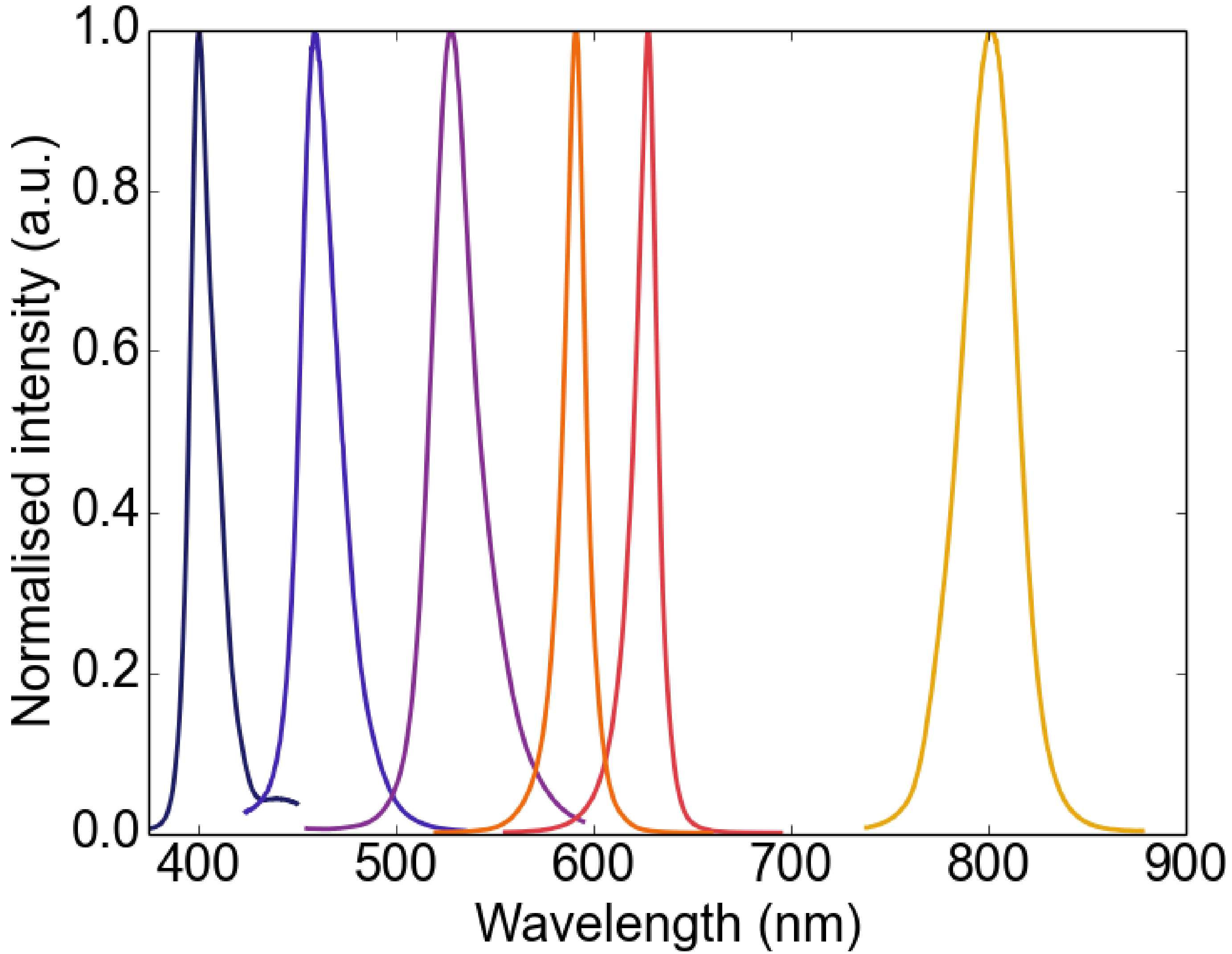
$$EQE_{Jsc} \propto \frac{I_{pl}}{N_{ph}}$$

$\frac{I_{pl}}{N_{ph}}$ is proportional to the EQE

The Experimental Setup

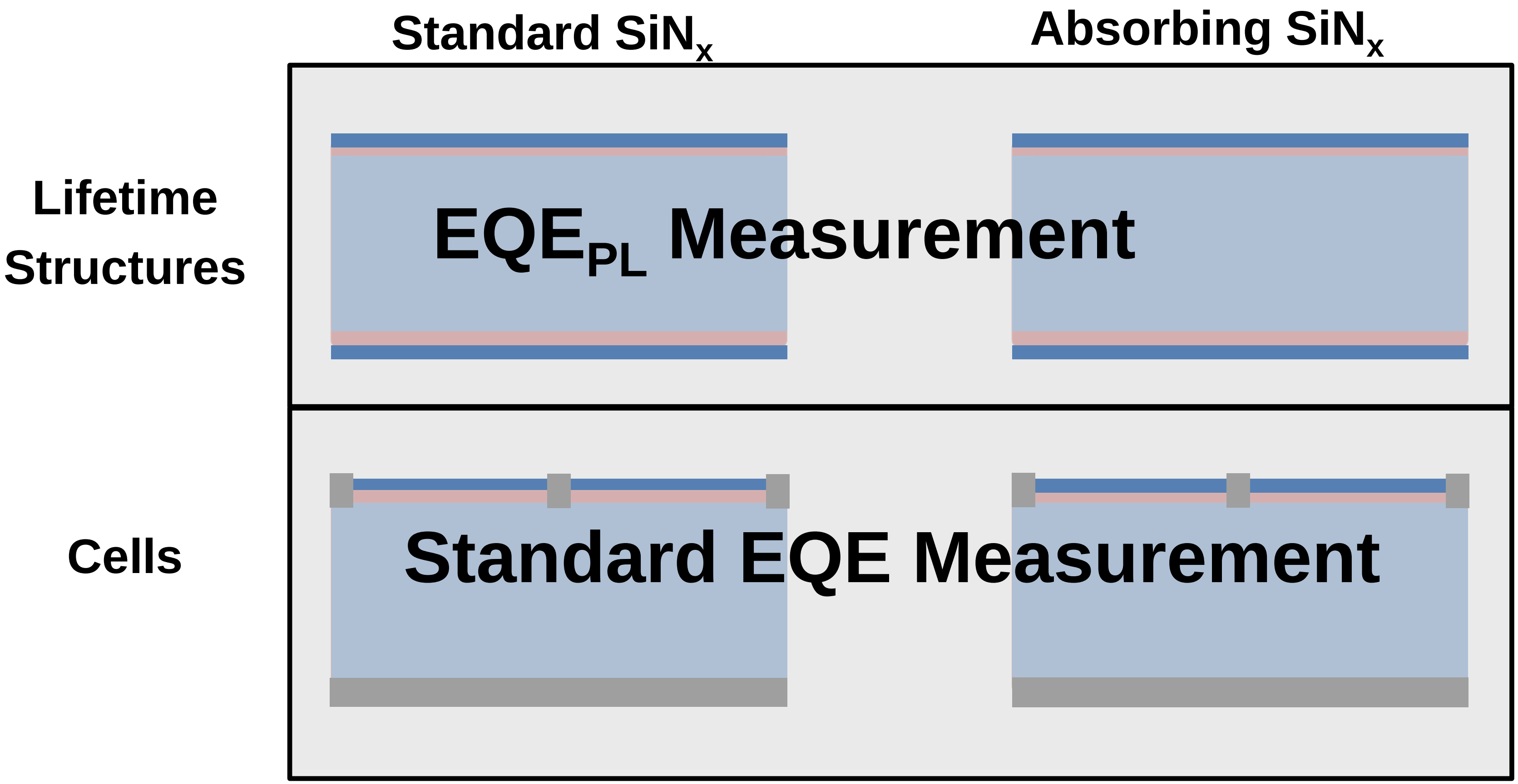
Bea

Sam



$$EQE \propto \frac{I_{pl}}{N_{ph}}$$

The Experiment



$$EQE \propto \frac{I_{pl}}{N_{ph}}$$

The Result

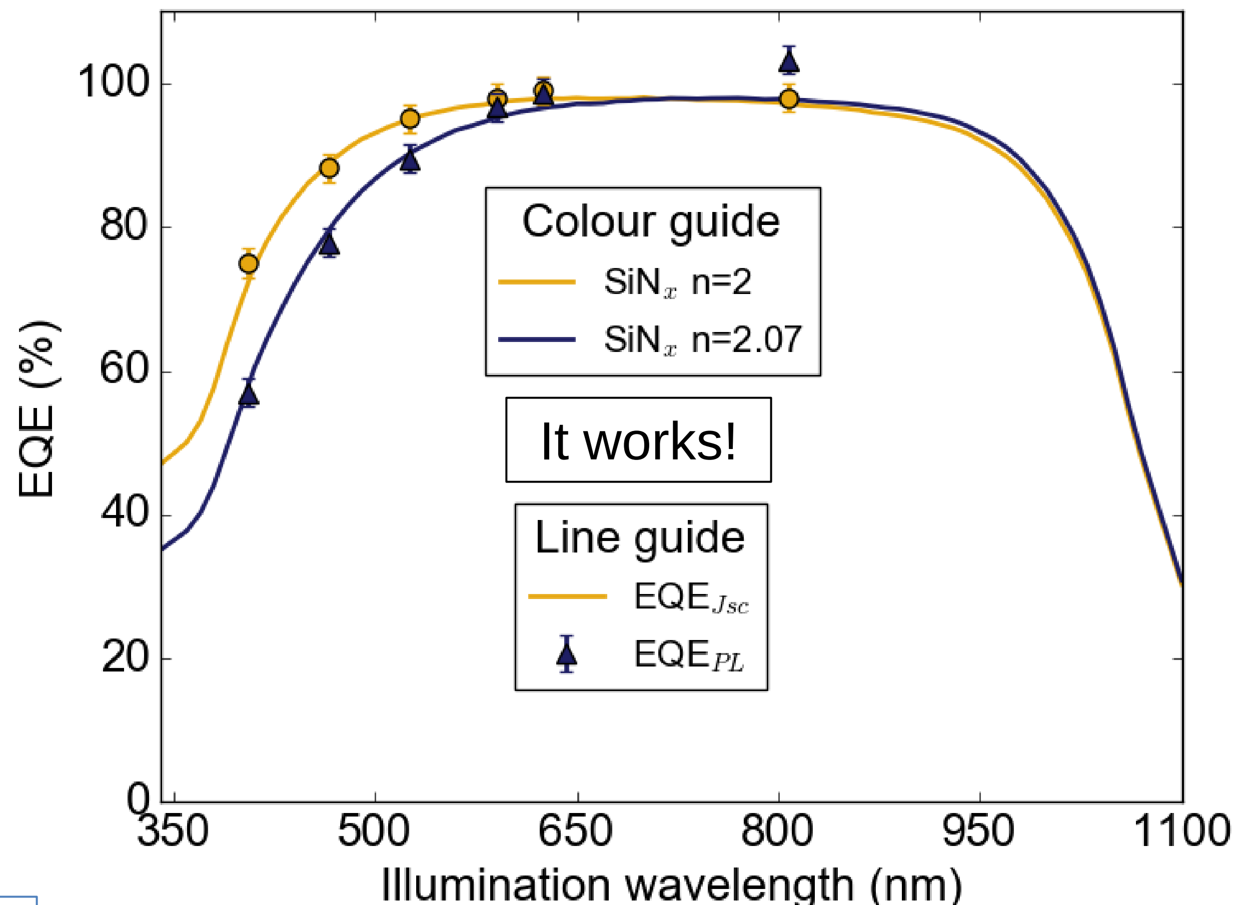


Figure: Our results,

$$EQE \propto \frac{I_{pl}}{N_{ph}}$$

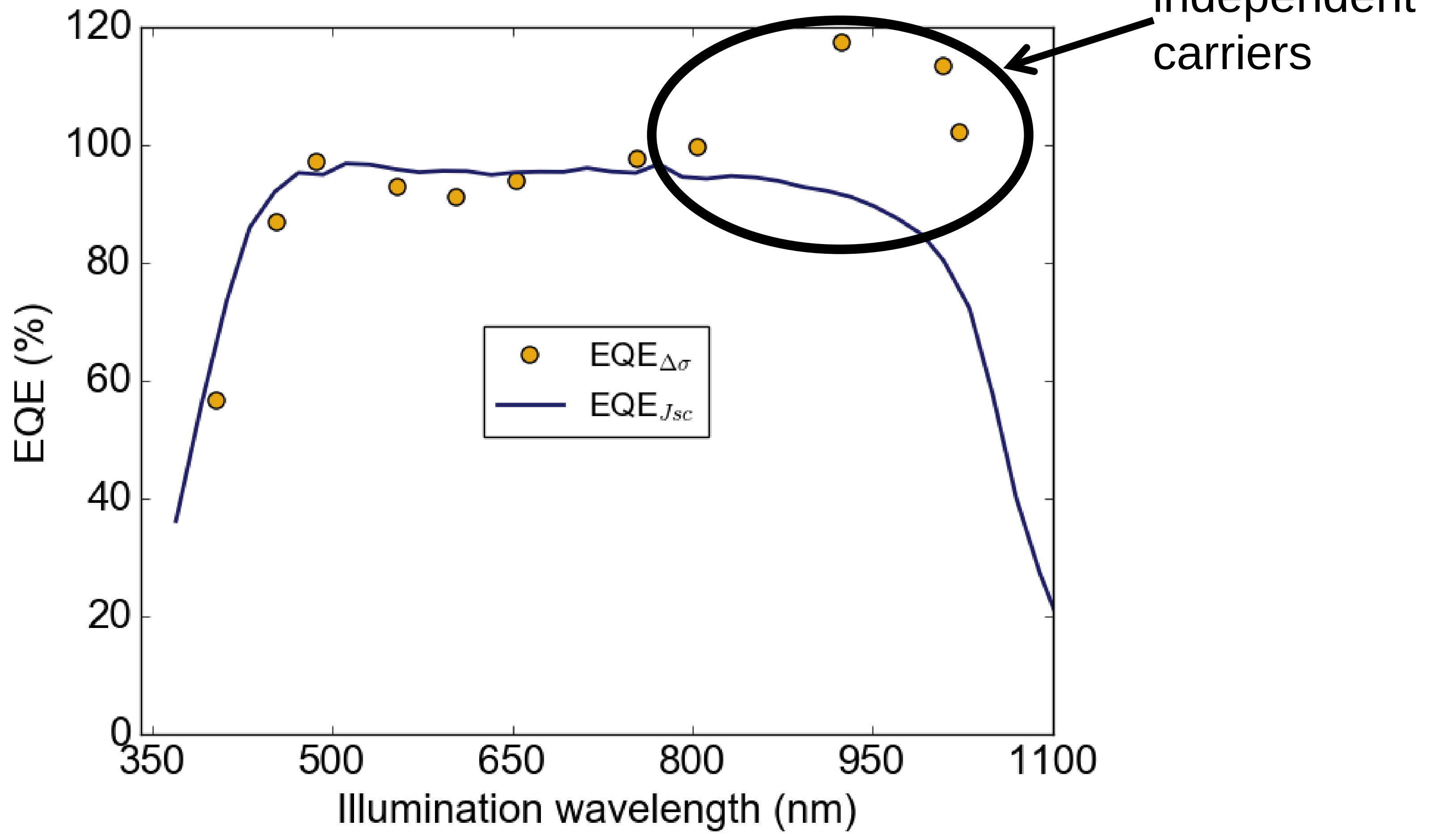
Conclusions for applications!

Can determine:

- The band-to-band absorptance, with imaging!
- The external quantum efficiency

But EQE_{PL} didn't match with EQE_{jsc} at ≈ 800 nm.

Results



Similar results from literature [1]

[1] Mäckel, H., & Cuevas, A. (2001). In *International Solar Energy Society Solar World Congress*. Adelaide,

Voltage independent what?

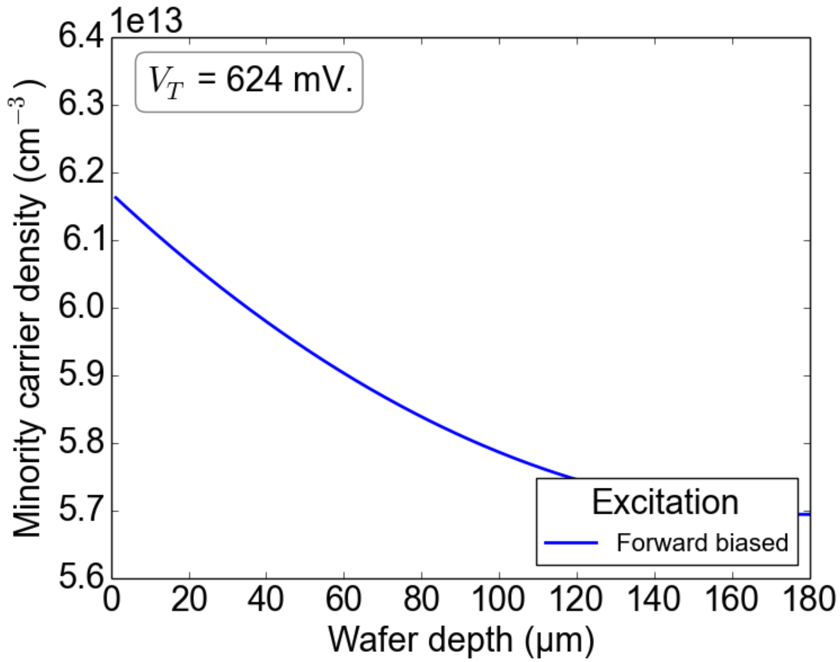
It wasn't me![1]

Voltage dependent carriers:

- Depend on the junction voltage

Voltage independent carriers:

- Do not depend on the junction voltage



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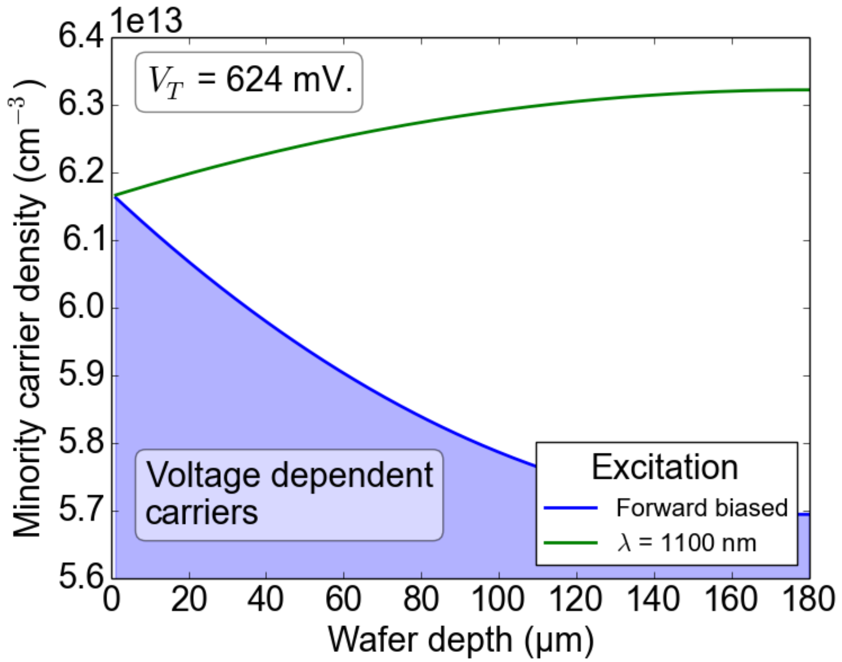

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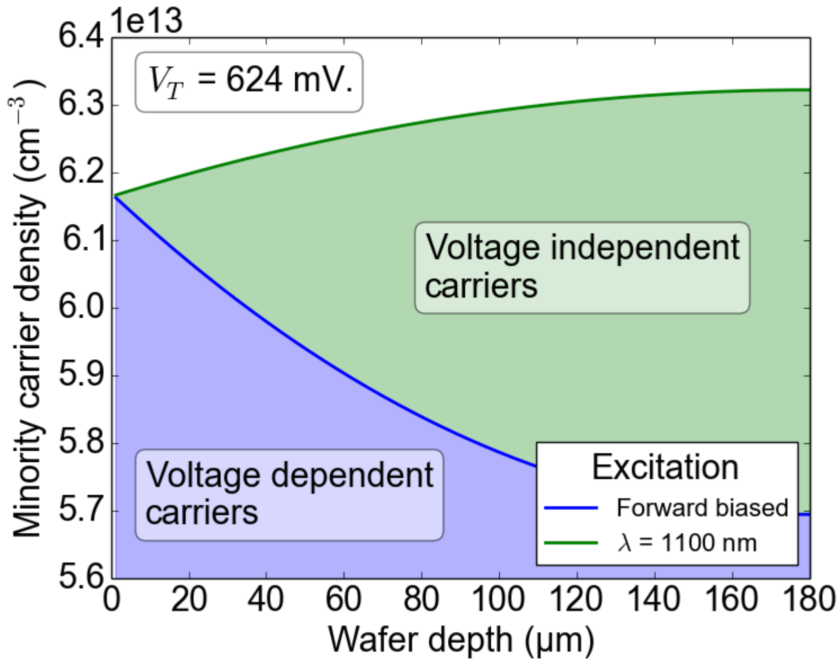

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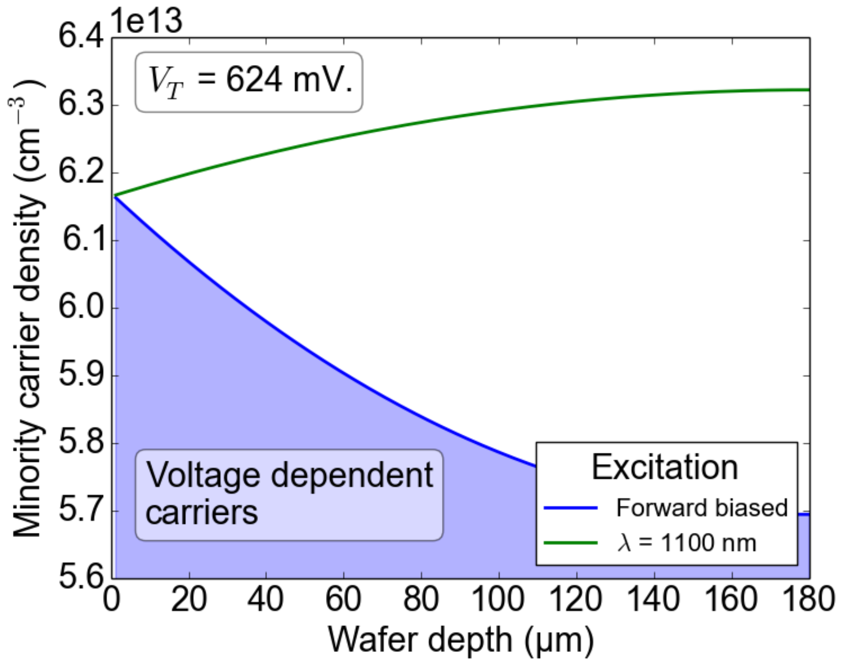

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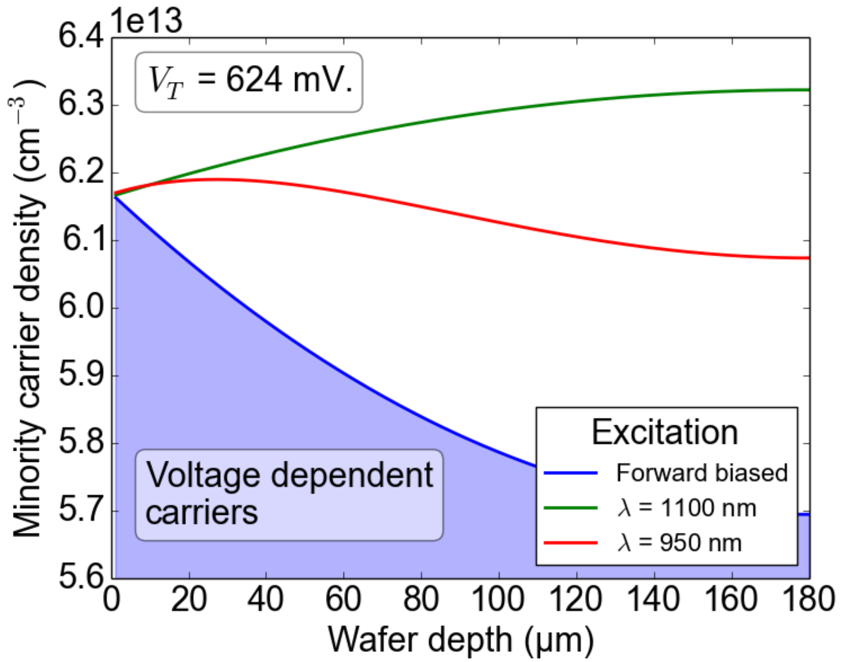

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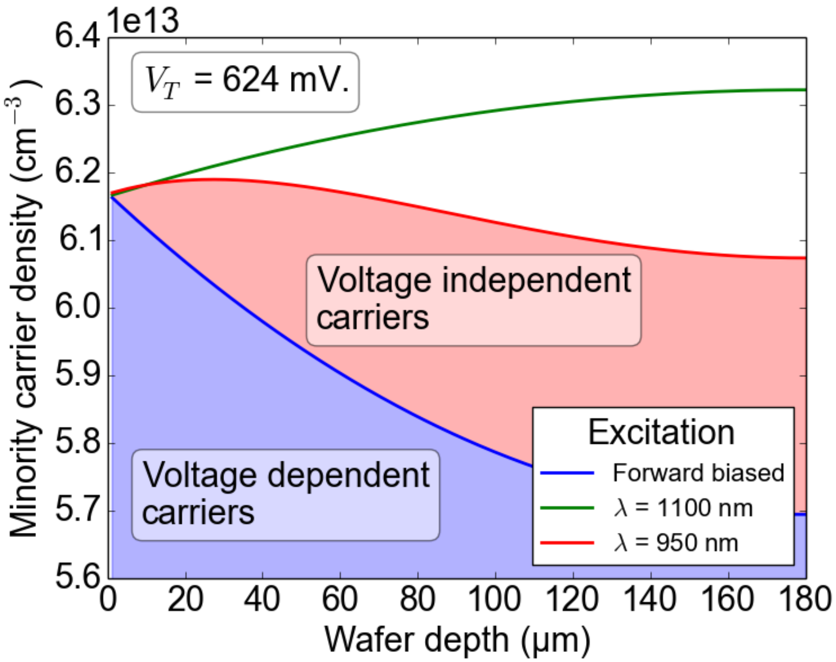

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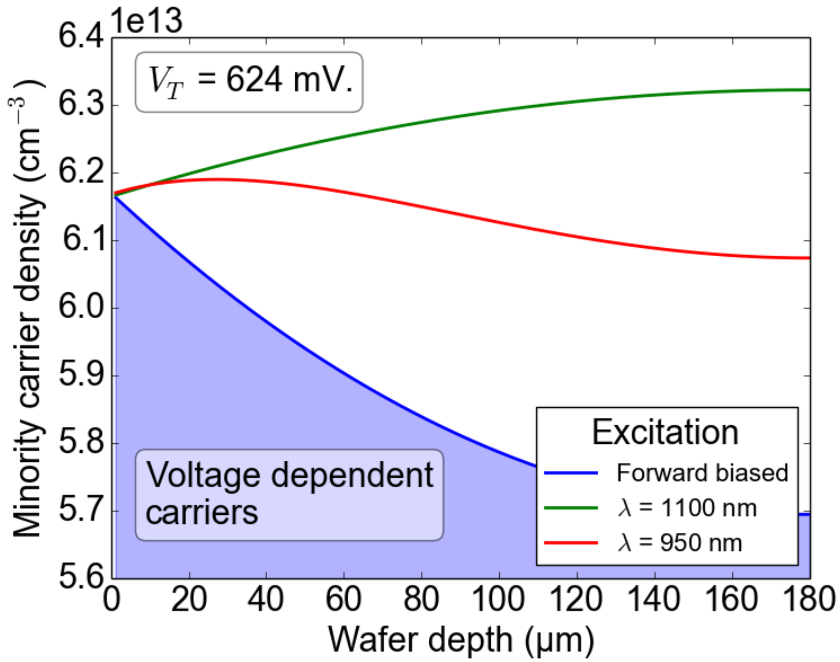

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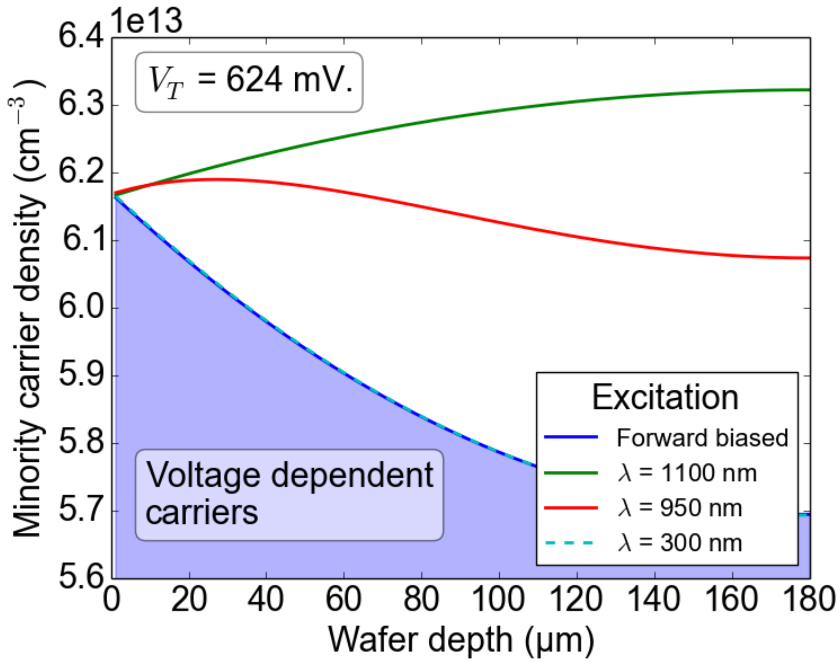

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Voltage independent carriers

Steady State Continuity Equation!

$$\frac{d^2 n[x]}{dx^2} = \frac{n[x]}{L^2} - \frac{\alpha N_\gamma e^{-\alpha x}}{D}$$

$$n = C_a e^{\frac{x}{L}} + C_b e^{-\frac{x}{L}} + C_c e^{-\alpha x},$$

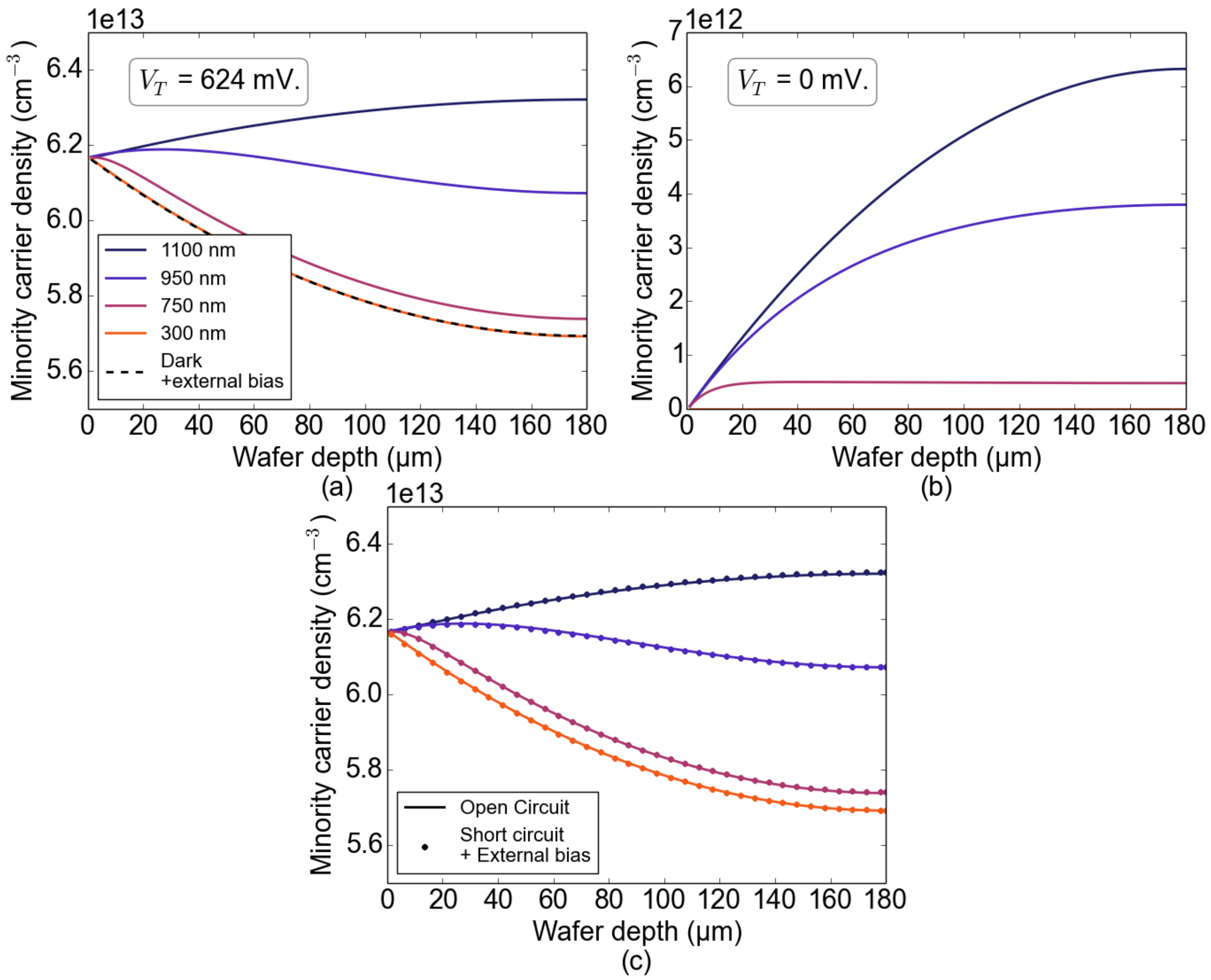
Inhomogeneous differential equation!:

$$n = n_{vd} + n_{vid},$$

$$n_{vd} = \left(C_{a-vd} e^{\frac{x}{L}} + C_{b-vd} e^{\frac{-x}{L}}\right) e^{\frac{qV}{kT}},$$

$$n_{vid} = \left(C_{a-vid} e^{\frac{x}{L}} + C_{b-vid} e^{\frac{-x}{L}} + C_{c-vid} e^{-\alpha x}\right) N_\gamma.$$

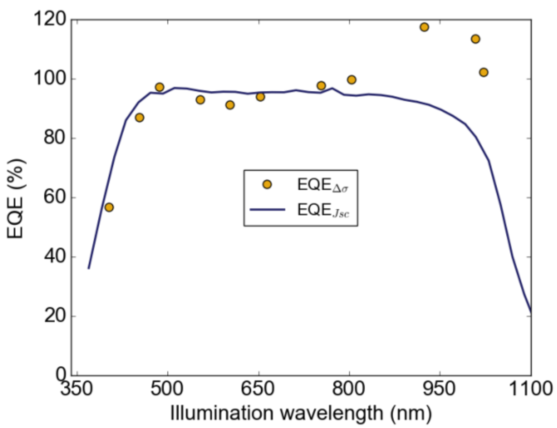
Voltage independent carriers



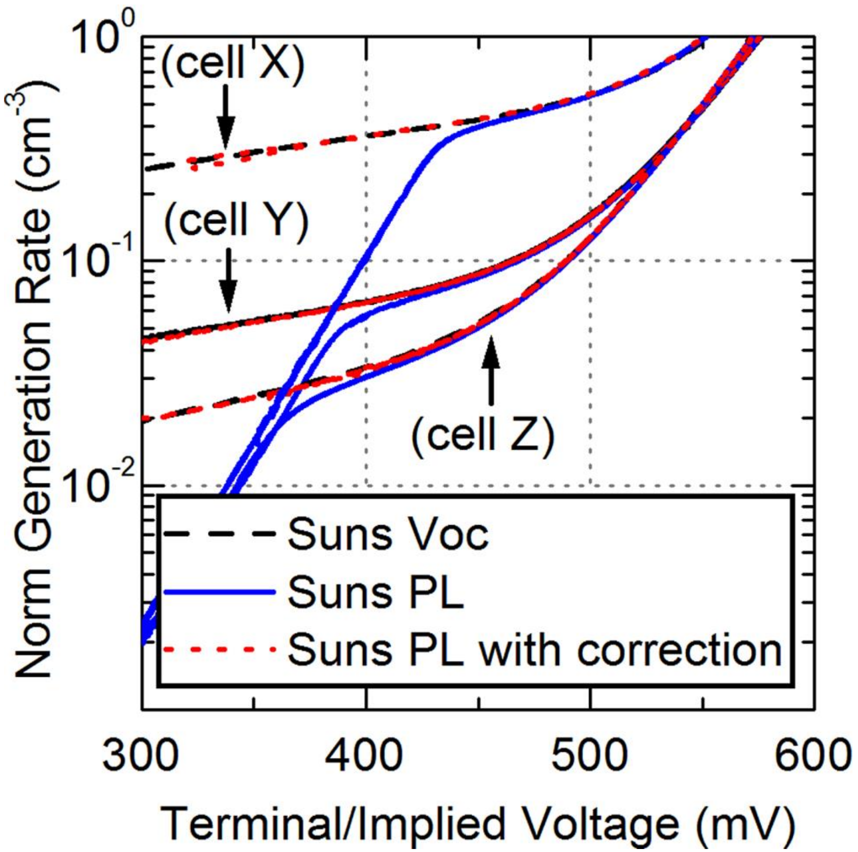
The impact

Cause's error when caculating

- Implied voltage from lifetime
- Lifetime from voltage
- Absorptance from average excess carrier density



Comparison of EQE_{Jsc} to EQE from photoconductance [1]



Comparison of Sun's PL with Suns Voc [2]

[1] Mäckel, H., & Cuevas, A. (2001). In *International Solar Energy Society Solar World Congress*. Adelaide
[2] Abbott, M. D., Bardos, R. A., Trupke, *et.al.* (2007). *Journal of Applied Physics*, *102*(4), 44502.

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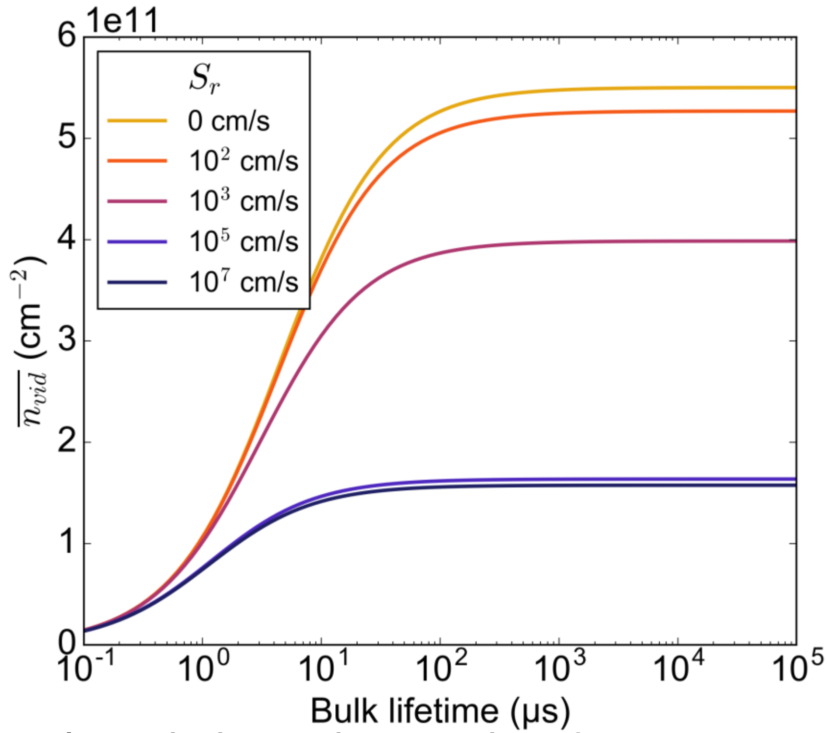
The impact: When does it happen

- It's complicated

$$n = n_{vd} + n_{vid},$$

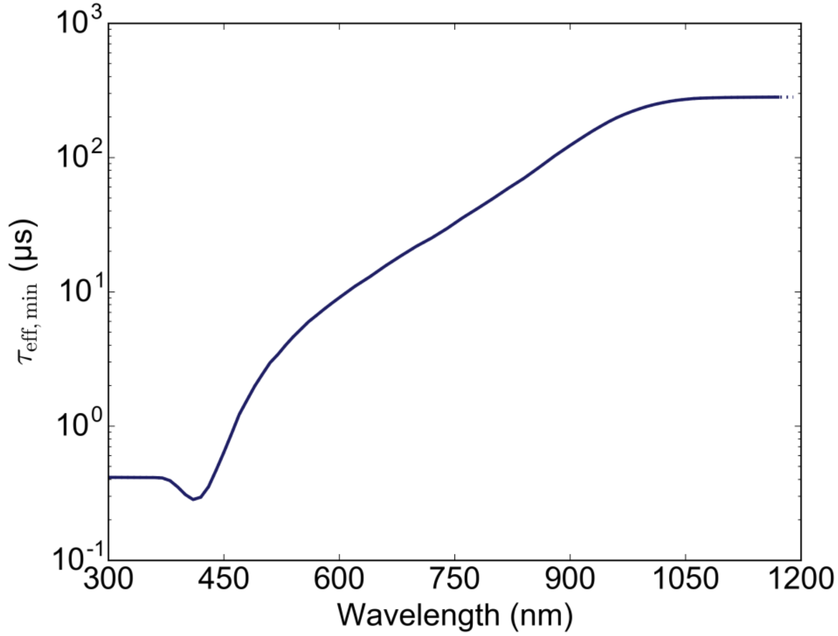
- So how do the n_{vid} behave?

$$\tau_{eff,min} = \frac{100 \times \overline{n_{vid}}}{G}$$

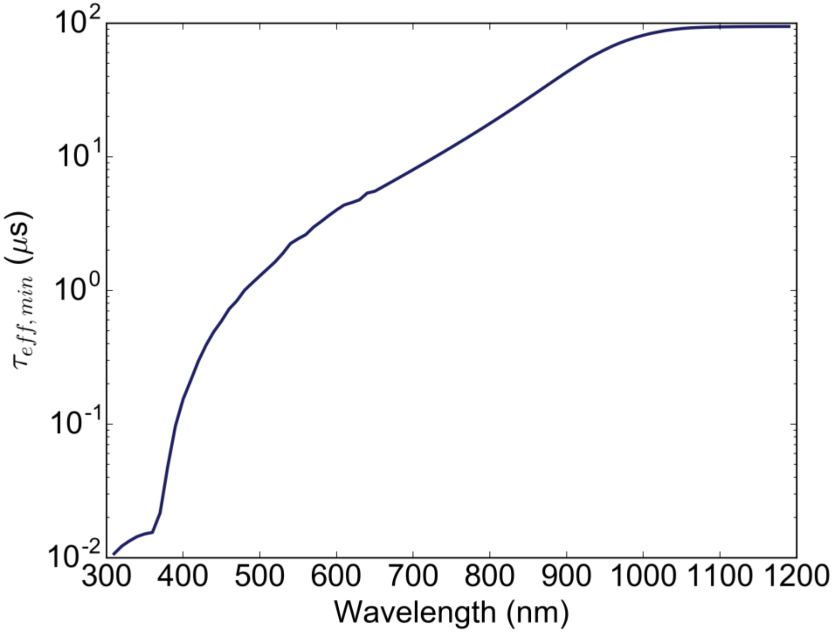


Voltage independent carriers for a 180 um cell under an illumination wavelength of 1000 nm.

The impact: When does it happen



Lifetime for which $100 \times \bar{n} > \overline{n_{vid}}$

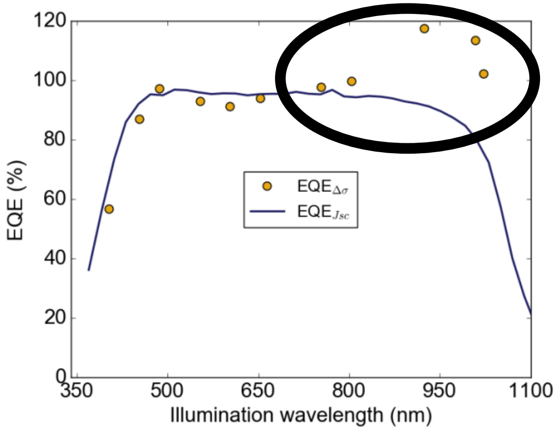


Lifetime for a less than 1% deviation between Voc and iVoc

The impact

Cause's error when caculating

- Implied voltage from lifetime
- Lifetime from voltage
- Absorptance measurements



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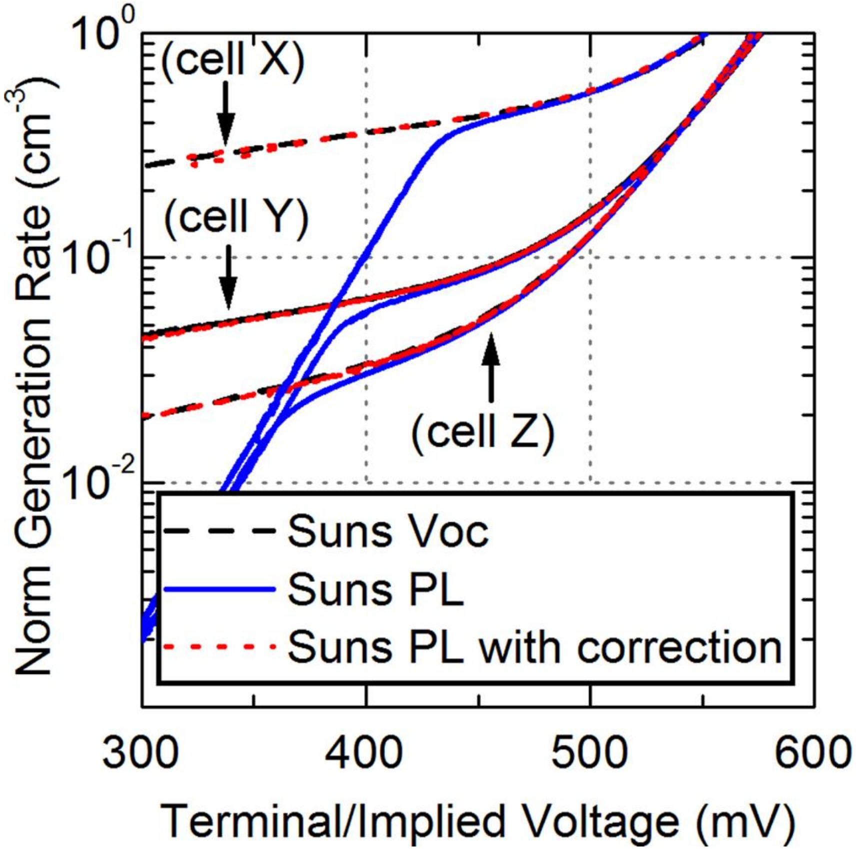

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Conclusions

- PL → well passivated samples → Band-to-band absorptance
- PL → no voltage independent carriers→ EQE
- The carrier density can be described in terms of a voltage dependent and independent term.
- Conversion from Voltage to lifetime does not always work.

Thank You!