Application of the spectral response of photoluminescence in photovoltaics

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Photoluminescence?

- Luminescence: Radiative recombination of excess carriers
- Photo $\rightarrow$ 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?

Spectral response

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

Fig: Simulated EQE in PC1D[1]

\[
EQE_{Jsc} = \frac{I_{sc}}{qN_{ph}}
\]

Application 1: Band-to-band absorptance
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\[ I_{PL} \propto \Delta n N_d \quad \tau = \frac{\Delta n}{G} \]

\[ I_{PL} \propto G \tau \]

For a constant effective lifetime

\[ I_{PL} \propto G \]

\[ \propto AN_{ph} \]

\[ \frac{I_{pl}}{N_{ph}} \propto A \]
Application 1: Band-to-band Absorptance

- Well passivated wafer with different optics

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

Application 1: Band-to-band Absorptance

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

\[ A \propto \frac{I_{pl}}{N_{ph}} \]

Comparison of Ar from our system to other measurement techniques

\[ Ar_{1060,808} = \frac{A_{1060}}{A_{808}} \]

Application 1: Absorptance imaging!

\[ A \propto \frac{I_{pl}}{N_{ph}} \]

(a) 808 nm illumination  
(b) 1060 nm illumination
Application 1: Band-to-band Absorptance

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

\[ A \propto \frac{I_{pl}}{N_{ph}} \]

It works!!

Application 2: External Quantum Efficiency
Application 2: External Quantum Efficiency

\[ EQE_{Jsc} = \frac{I_{sc}}{qN_{ph}} \]

\[ EQE_{Jsc} \propto \frac{V_{oc}}{N_{ph}} \quad I_{PL} \propto e^{\frac{iV_{oc}}{\nu t}} \]

In low injection:

\[ EQE_{Jsc} \propto \frac{I_{pl}}{N_{ph}} \]

\[ \frac{I_{pl}}{N_{ph}} \] is proportional to the EQE
The Experimental Setup

\[
EQE \propto \frac{I_{pl}}{N_{ph}}
\]
The Experiment

Lifetime Structures

Cells

Standard SiN$_x$

Absorbing SiN$_x$

$\text{EQE}_{\text{PL}}$ Measurement

Standard EQE Measurement

$\text{EQE} \propto \frac{I_{\text{pl}}}{N_{\text{ph}}}$
The Result

It works!

\[ EQE \propto \frac{I_{pl}}{N_{ph}} \]

Figure: Our results,
Conclusions for applications!

Can determine:

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

But $\text{EQE}_{\text{PL}}$ didn’t match with $\text{EQE}_{\text{jsc}}$ at $\approx 800$ nm.
Results

Impact of voltage independent carriers

Similar results from literature [1]

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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Voltage independent carriers

Steady State Continuity Equation!

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

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

Inhomogeneous differential equation!:

\[
n = n_{vd} + n_{vid},
\]

\[
n_{vd} = \left( (C_{a-vd} e^{\frac{x}{L}} + C_{b-vd} e^{-\frac{x}{L}}) \right) \frac{qV}{e k T},
\]

\[
n_{vid} = \left( (C_{a-vid} e^{\frac{x}{L}} + C_{b-vid} e^{-\frac{x}{L}} + C_{c-vid} e^{-\alpha x}) \right) N_y.
\]
Voltage independent carriers

\( V_T = 624 \text{ mV.} \)

\( V_T = 0 \text{ mV.} \)

(a)

(b)

(c)
The impact

Cause’s error when calculating
- Implied voltage from lifetime
- Lifetime from voltage
- Absorptance from average excess carrier density

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

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

The impact: When does it happen

- It’s complicated
  \[ n = n_{vd} + n_{vid}, \]
- So how do the \( n_{vid} \) behave?

\[ \tau_{eff,min} = \frac{100 \times n_{vid}}{G} \]

Voltage independent carriers for a 180 um cell under an illumination wavelength of 1000 nm.
The impact: When does it happen

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

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

Cause’s error when calculating
- Implied voltage from lifetime
- Lifetime from voltage
- Absorptance measurements

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

- PL $\rightarrow$ well passivated samples $\rightarrow$ Band-to-band absorptance
- PL $\rightarrow$ no voltage independent carriers $\rightarrow$ 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!