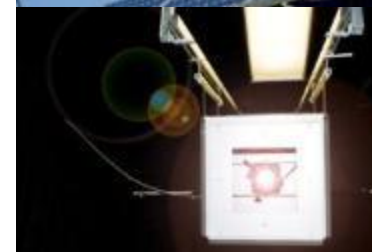
SPECTRALLY DEFINED ELECTROLUMINESCENCE IMAGING OF PHOTOVOLTAIC MODULE



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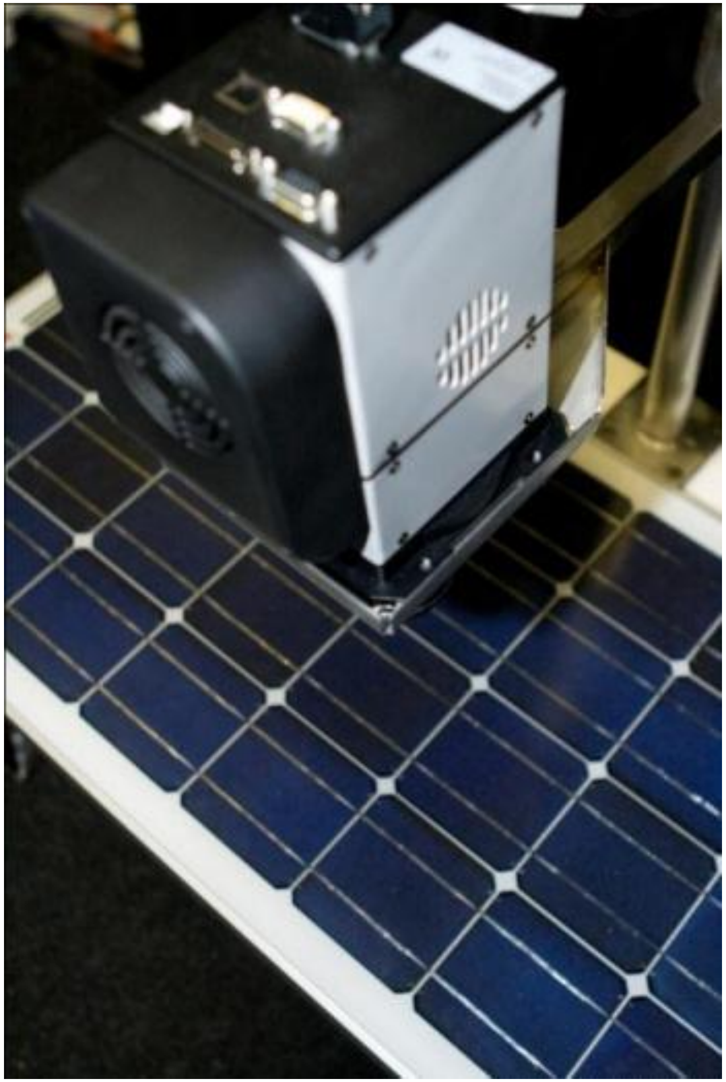
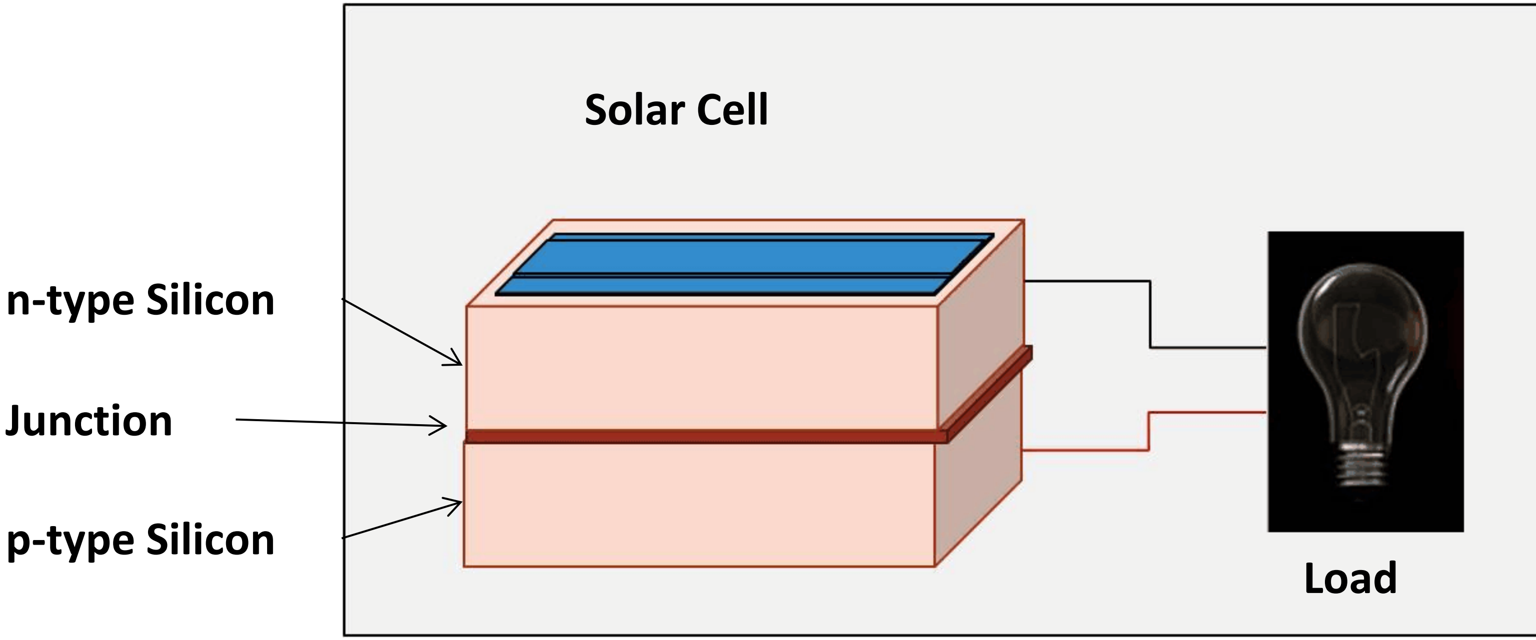
Outline:

- Introduction to Electroluminescence (EL) imaging
- EL Intensity
- EL Spectrum
- Results: Modelling of EL Spectrum
- Conclusions and Future Work

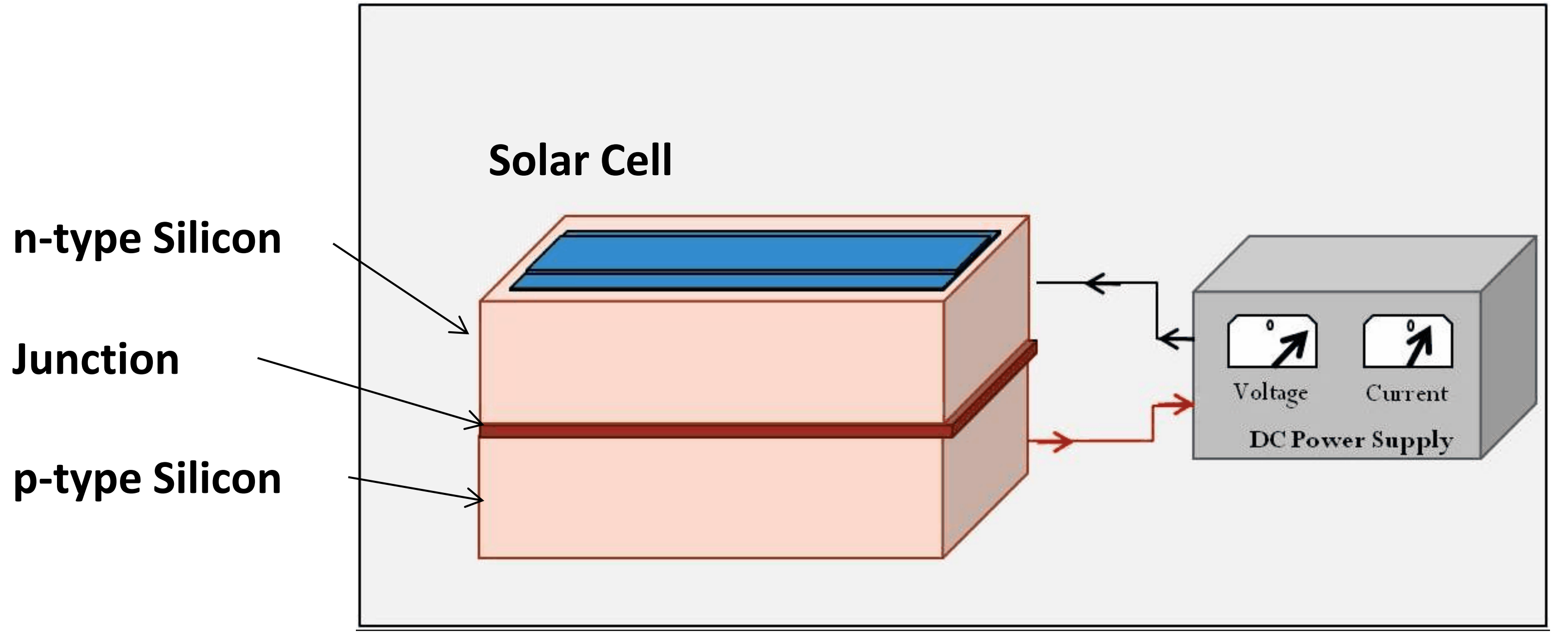


Solar Current Generation



- Sunlight is made up of photons
- The energy of photons excite carriers in the material
- The carriers move through the material
- Current flows through the circuit

What causes Electroluminescence (EL) in a solar cell?



Step 1: The solar cell is forward biased.

Applied current > Short circuit current (Isc)

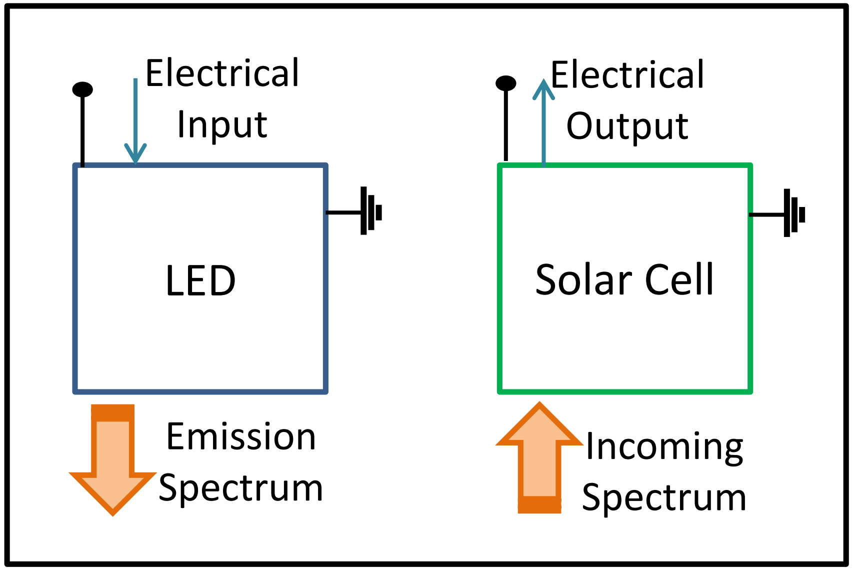
Step 2: Carriers are generated in the cell material

Step 3: The carriers move through the material

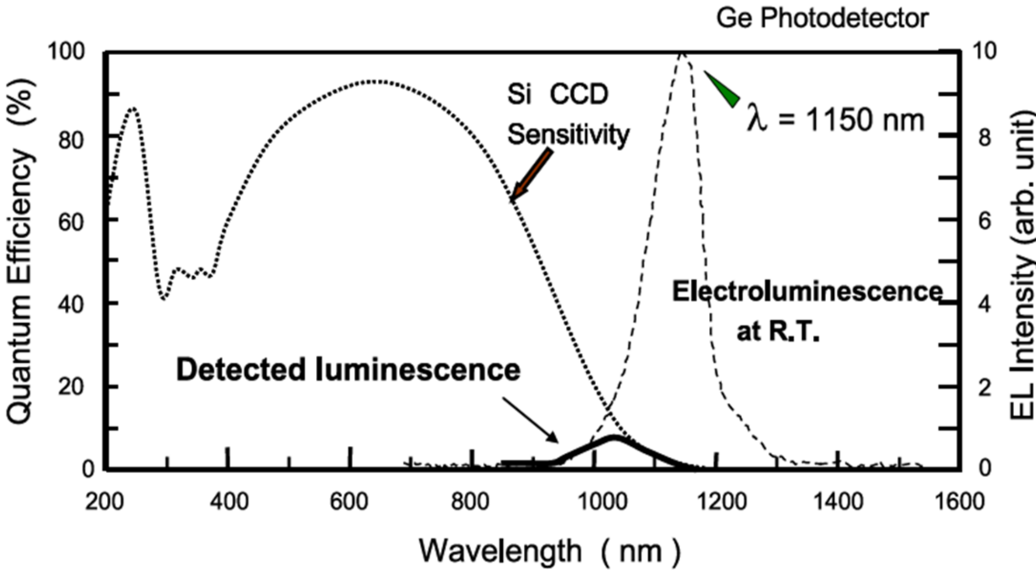
Step 4: Electron and hole recombine releasing energy in the form of light

Electroluminescence (EL)

- Solar cell receives Optical Input -> Electrical output
- LED receives Electrical input -> Optical output
- When a Solar Cell is forward biased, carriers are injected at the junction.
- Spontaneous radiative recombination of electron-hole pairs results in the generation of photons.
- The spectrum of the EL from silicon is out of the visible range and thus can only be detected with a silicon CCD camera with appropriate infrared filters.



(Kirchartz et al., 2009).



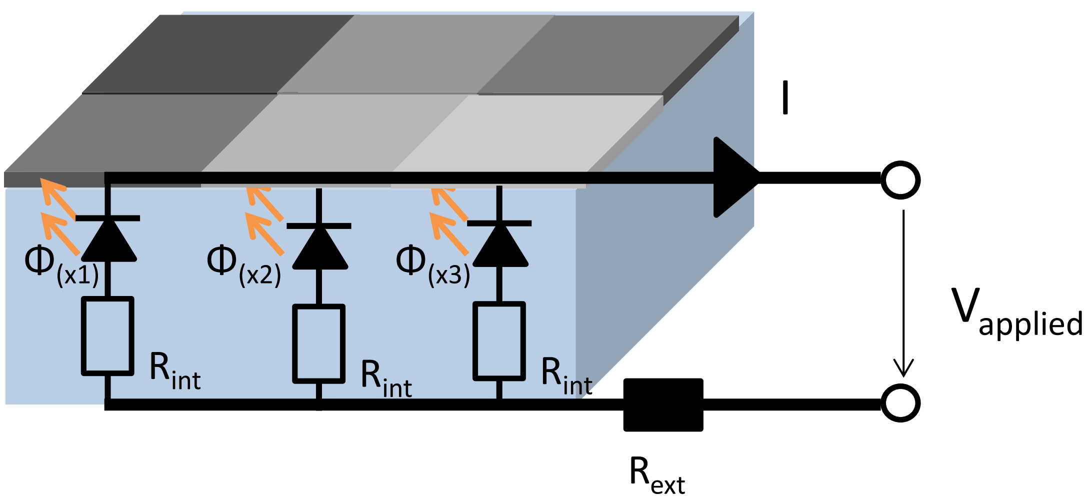
EL Intensity

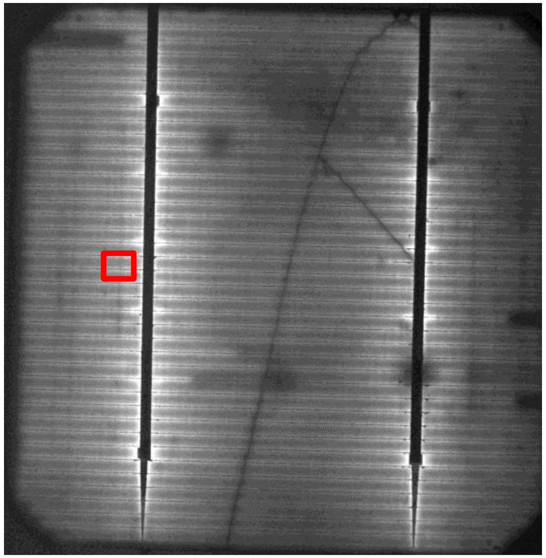
- A solar cell can be considered a spatially extended device where each point of the surface has its own local quantum efficiency and local junction voltage
- The excess photon density at position *x* on the surface, $\phi_{em}(E,x)$ is given by:

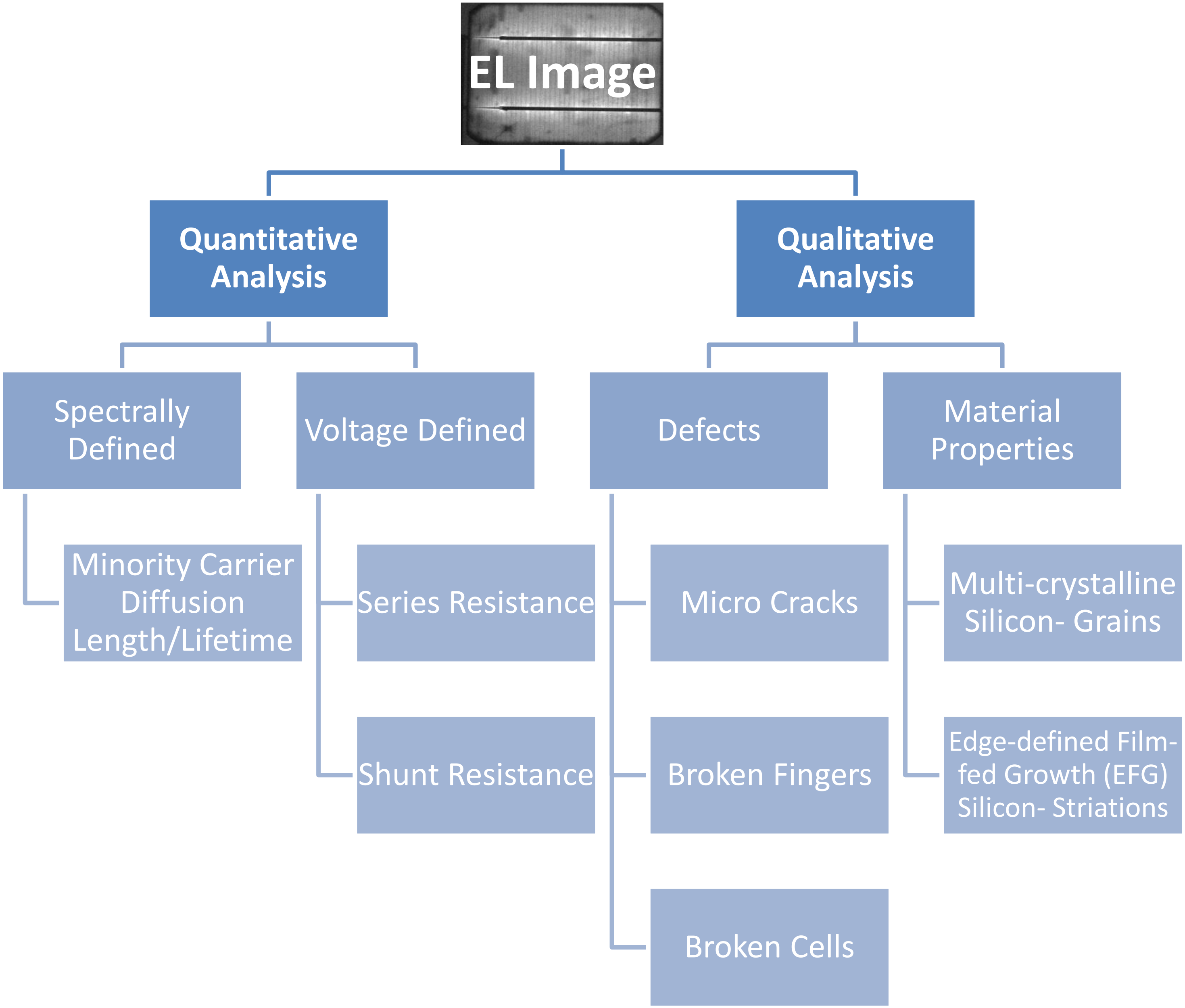
$$\phi_{em}(E,x) = [1 - R(E,x)]Q_i(E,x)\phi_{bb}(E)\left(exp\left(\frac{qV(x)}{kT}\right) - 1\right)$$

- The intensity of the emitted photons is related to
  - recombination mechanisms,
  - material properties
  - optical properties
  - junction voltage.
- The junction voltage varies across the surface of the cell but is not wavelength dependant so can be determined from a spatial EL intensity image.

* Uwe Rau, Physical Review B **76** (8) (2007).






EL Image
Quantitative Analysis
Qualitative Analysis
Spectrally Defined
Voltage Defined
Defects
Material Properties
Minority Carrier Diffusion Length/Lifetime
Series Resistance
Shunt Resistance
Micro Cracks
Broken Fingers
Broken Cells
Multi-crystalline Silicon- Grains
Edge-defined Film-fed Growth (EFG) Silicon- Striations

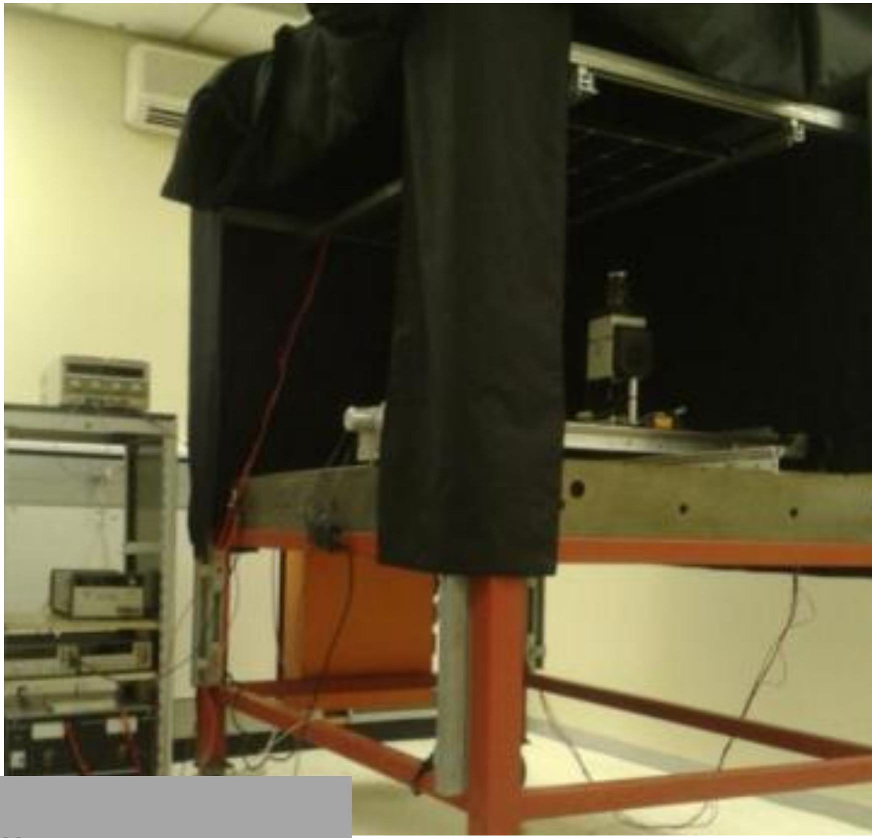
Experimental Setup: High Resolution EL Imaging

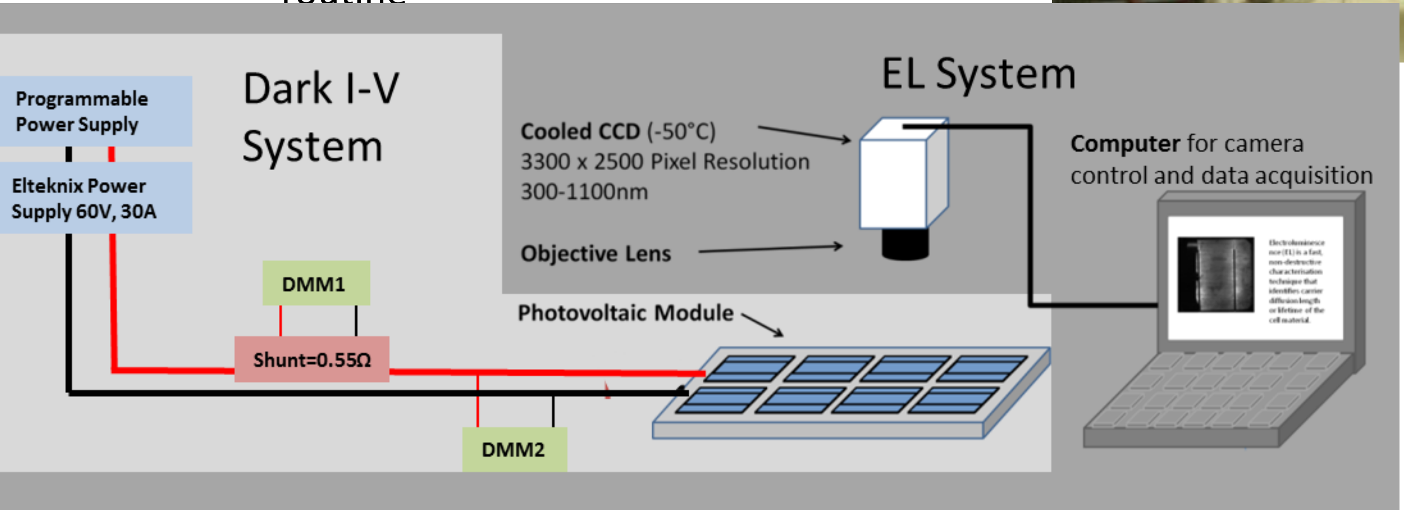
Dark I-V System

- Programmable power supply forward biases module.
- Applied current and voltage are measured by digital multi-meters.

EL System

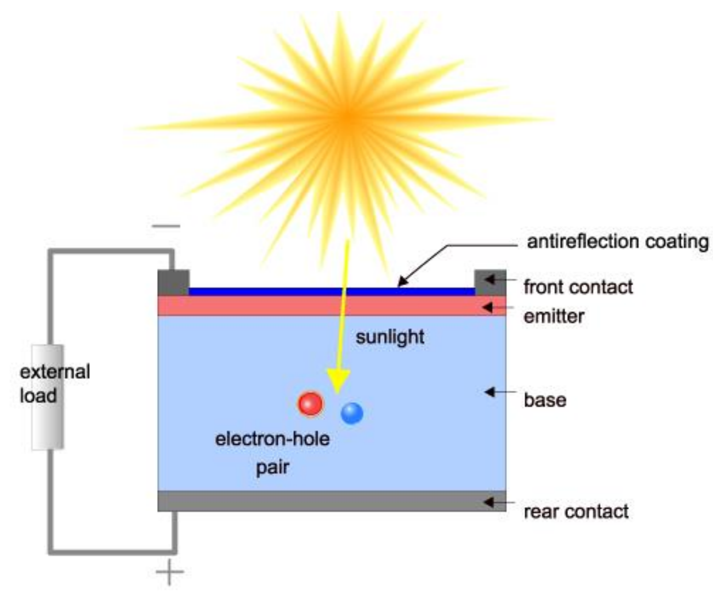
- Uses the same equipment to apply and measure the bias conditions.
- Images taken with cooled CCD camera.
- Camera mounted on x-y stage in order to image entire module.
- Images processed using a Mathematica routine



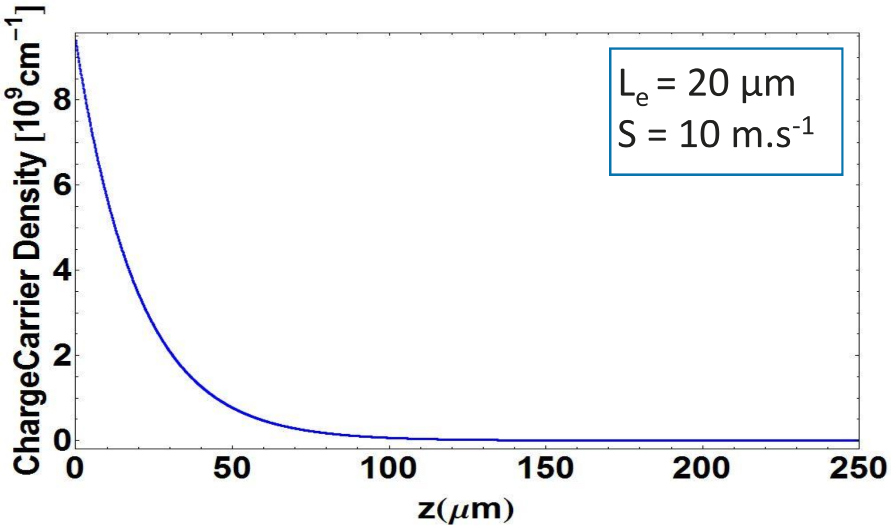


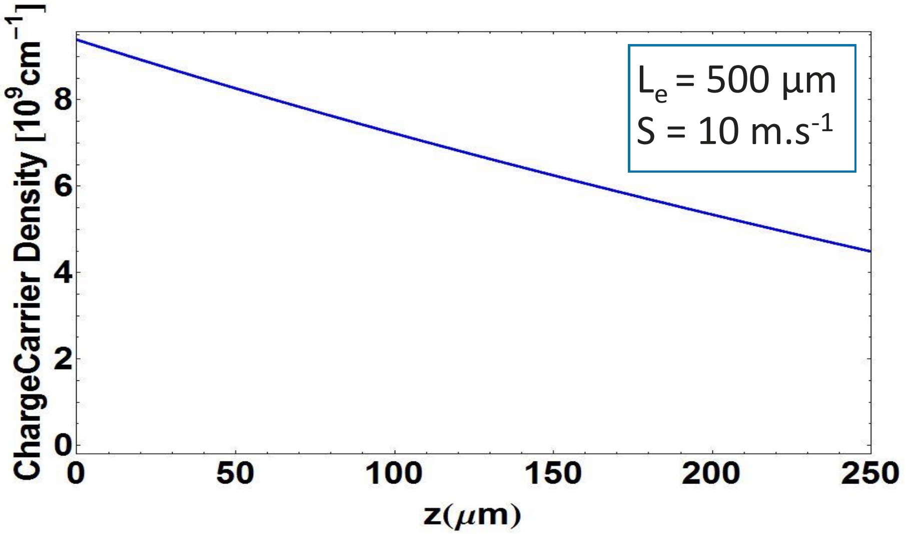
Minority Carrier Concentration

- The spectrum of the emitted EL is simulated using semiconductor theory. The effects of recombination properties such as minority carrier diffusion length and surface recombination on the spectrum of the emitted EL are examined.
- The excess charge carrier concentration distribution, n(z), of electrons in the p-layer of the solar cell is determined by solving the continuity equation for electrons in solid state.



$$n_e(0) = \frac{n_i^2}{N_A}\exp\left(\frac{eU}{k_B T}\right) \qquad j_e(d) = -D_e \frac{dn_e}{dx}(d) = S n_e(d)$$





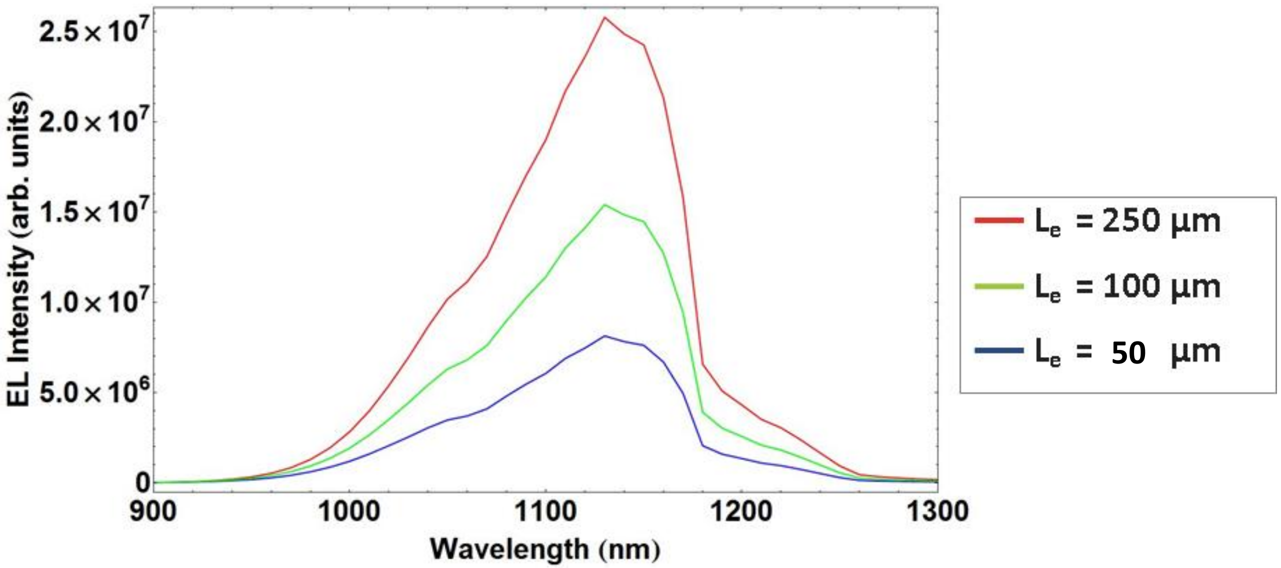
Modelled EL Spectrum

- The rate of spontaneous emission of photons of energy, E_γ, is determined with respect to the absorption coefficient, $\alpha(E_\gamma)$, the carrier concentration and doping levels of the material.

$$r_{sp}(E_\gamma, z) \approx \alpha(E_\gamma)\frac{{E_\gamma}^2}{\pi^2\hbar^3c^2}exp\left(-\frac{E_\gamma}{k_BT}\right)\frac{N_{\frac{A}{D}}n(z)}{n_i^2}$$

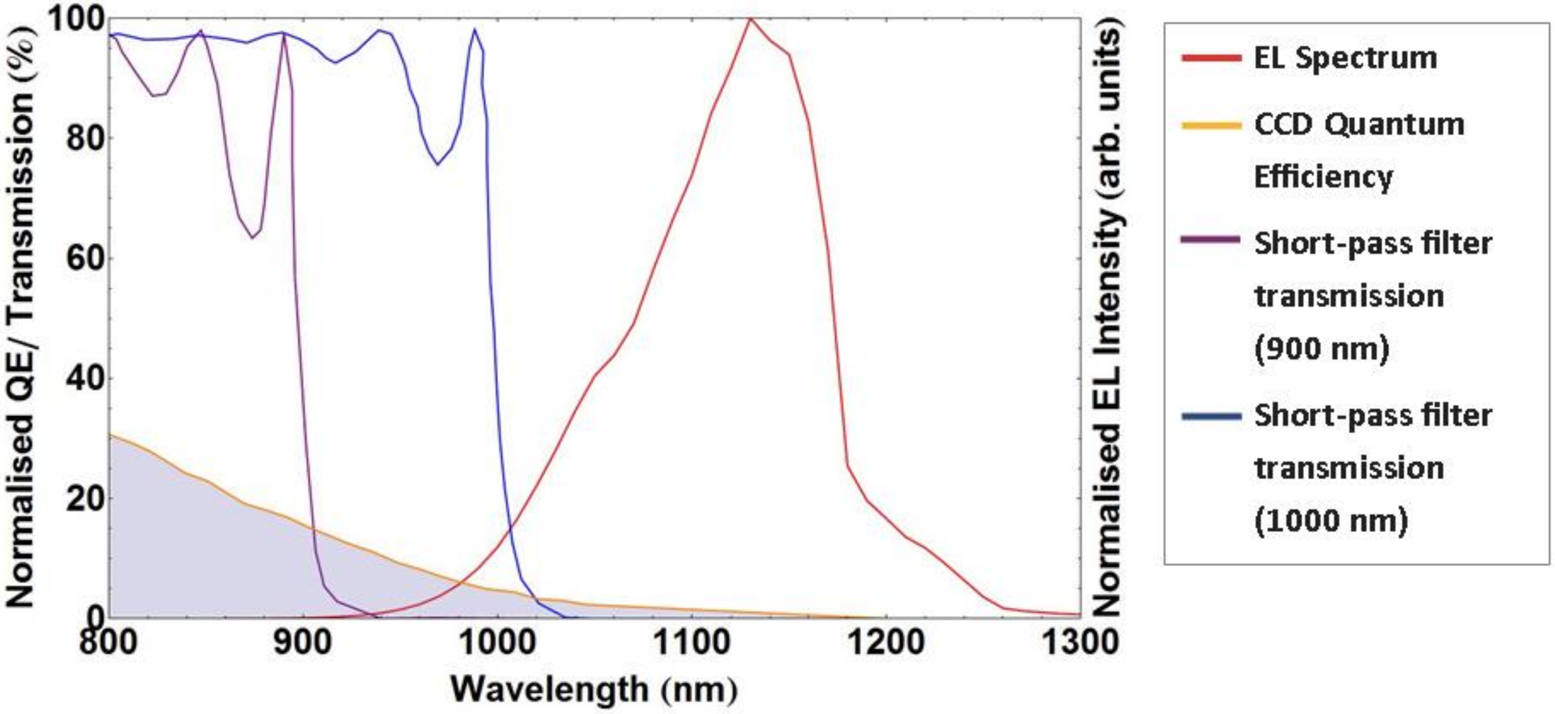
- Varying the diffusion length of the carriers has a significant effect on the short wavelength region of the spectrum as photons in this region have a higher absorption coefficient.
- The longer diffusion length means carriers can recombine closer to the surface and the photons emission from the surface is greater.

$$I(E_\gamma) = [1 - R_f(E_\gamma)]\int_0^d (r_{sp}(z, E_\gamma)\{exp[-\alpha(E_\gamma)z] + R_r(E_\gamma)\exp[-\alpha(E_\gamma)(2d-z)]\})dz$$



Detected EL Spectrum

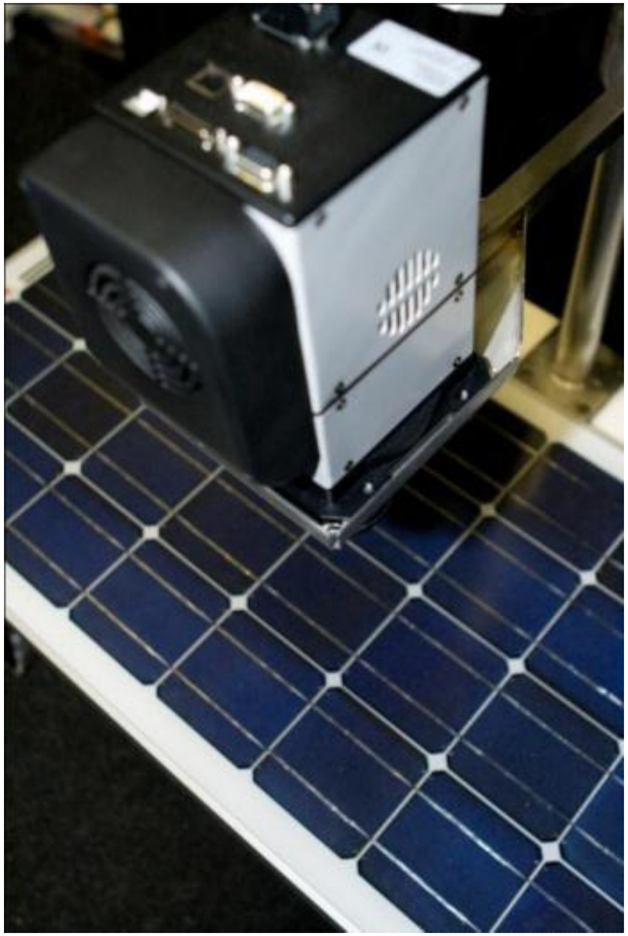
- The figure shows the EL spectrum and the CCD sensitivity. Only short wavelength EL is detected and it is only a small percentage of the total EL.
- Short-pass filters cut-off at 900 and 1000 nm. The ratio of images with these filters allows the effects of diffusion length (see fig. 3) to be isolated.



The EL spectrum overlaid with the CCD camera sensitivity and the transmission of the short-pass filters.

Summary

- A solar cell can be visualised as a spatially extended device where light is emitted at different points on the surface, each with their own local quantum efficiency and local junction voltage.
- In order to spectrally define an EL image, appropriate filters can be used for spectral analysis.
- Simulated EL shows the effect of diffusion length in the short wavelength region.
- Future work includes integration of filters into experimental set-up and correlation between experimental and simulated results.



Acknowledgements

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