Solar PV Modules Optical Characterization

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OUTLINE OF TALK

a. Electroluminescence/ Photoluminescence

b. EL/PL Imaging

c. Spectral response measurement

Internal and External quantum Efficiency.

d. Thermography

Luminescence

- Electroluminescence:

  Light emitted under electrical excitation, such as in a light emitting diode

- Photoluminescence:

  Light emitted under optical excitation, such as in

  Fluorescent Lamp

Excess Carrier Density

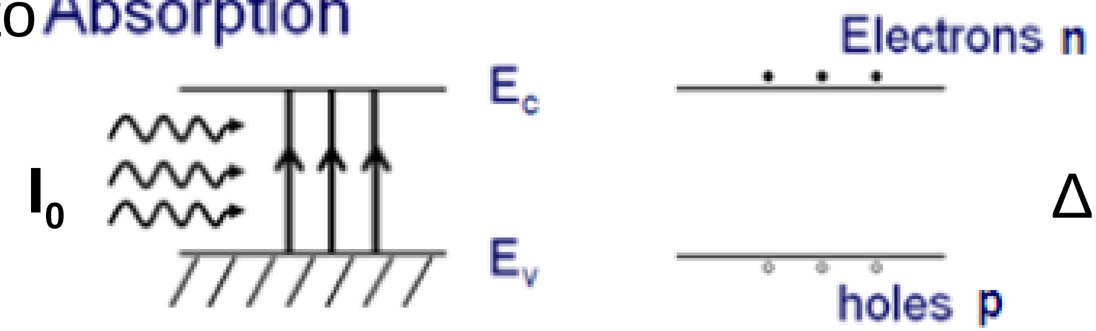
a. Excitation : Generation of Excess Electrons and Holes

$$n = n_0 + \Delta n,\ p = p_0 + \Delta p$$

i) Electrical Injection :

$$\Delta n = \Delta p = (\,I/\,qA\,W)\,.\,\tau_{eff}$$

ii) Photo Absorption



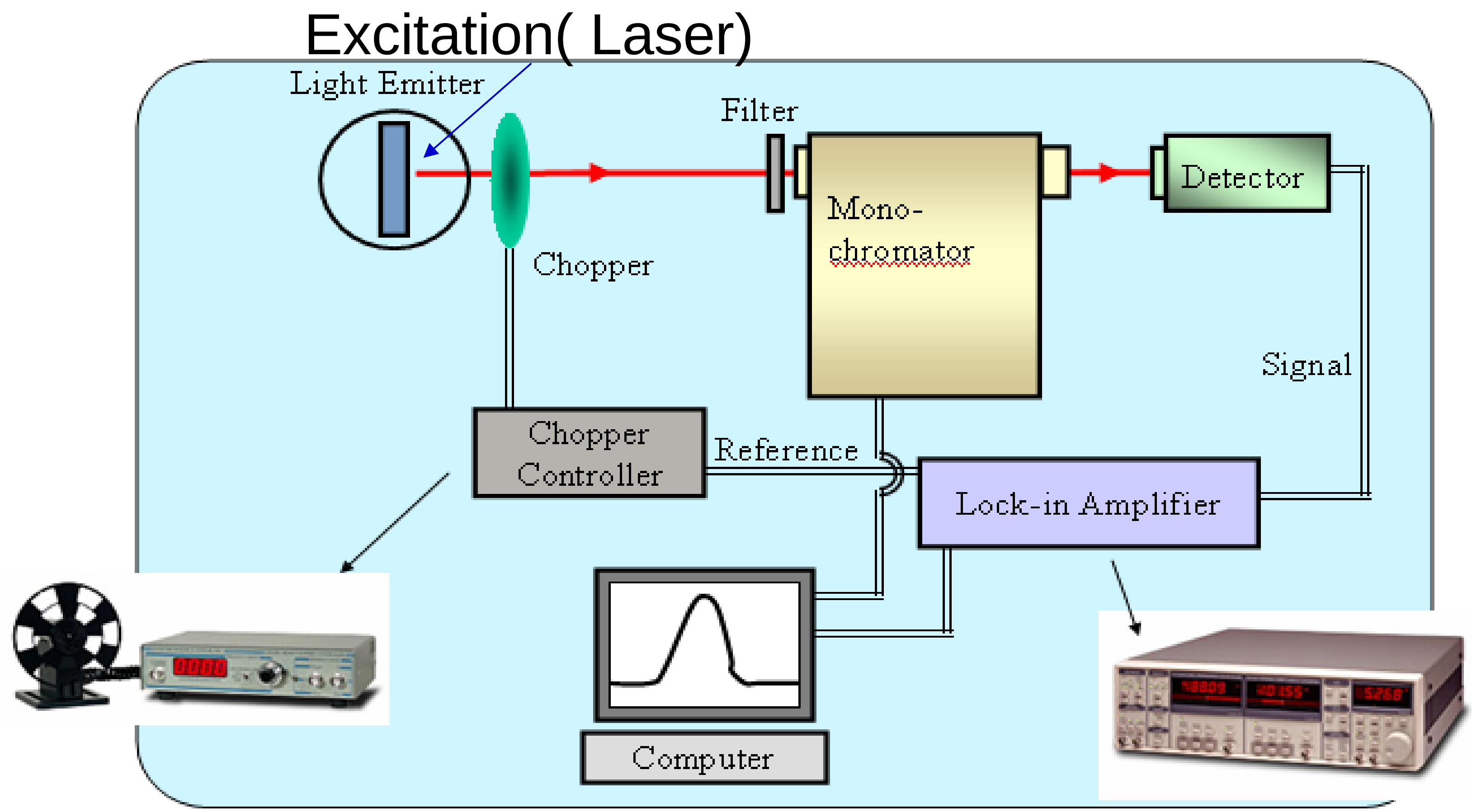
$$\Delta n = \Delta p = G\,\tau = (\alpha I_0/h\nu)\tau$$

b) Recombination (Spontaneous emission)

Luminescence

Light emitting diodes

Luminescence Spectrum measurement



Monochromator : To separate the different wavelength components in the light beam
Detector : To convert the light into an electrical signal
Lock-in amplifier : To detect the signal while rejecting noise

Spectrum of Light Emitted by Silicon Solar Cell

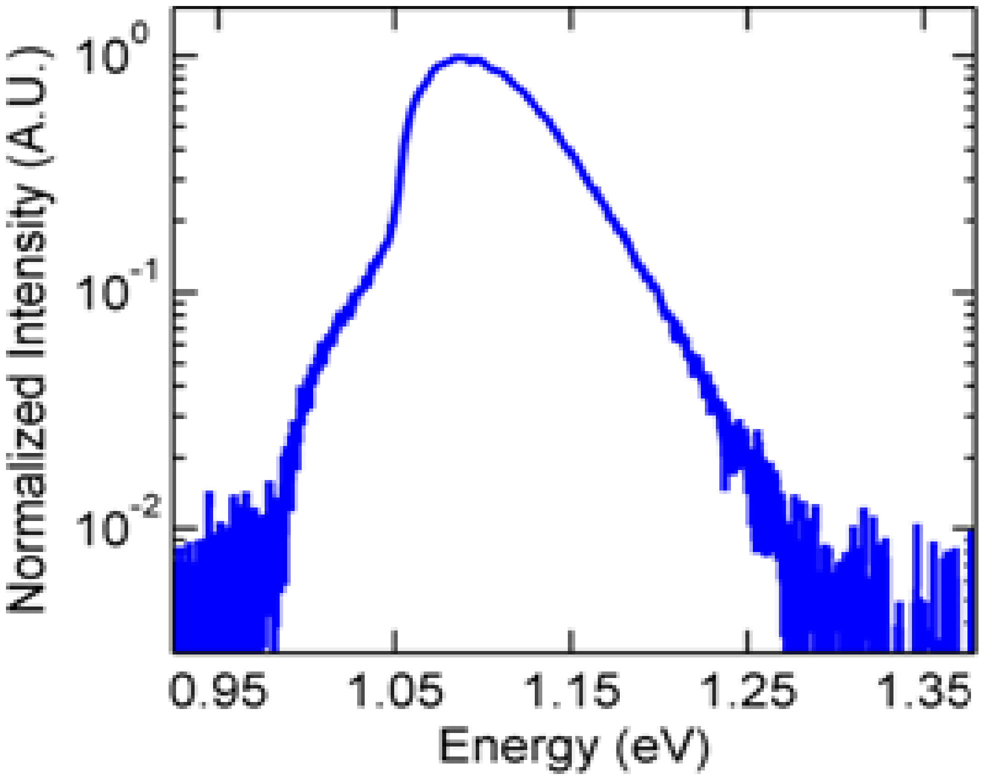


Fig.3. Intensity of the EL signal normalized to the peak value and plotted as a function of energy.

Band to Band Recombination Processes

RADIATIVE NON RADIATIVE

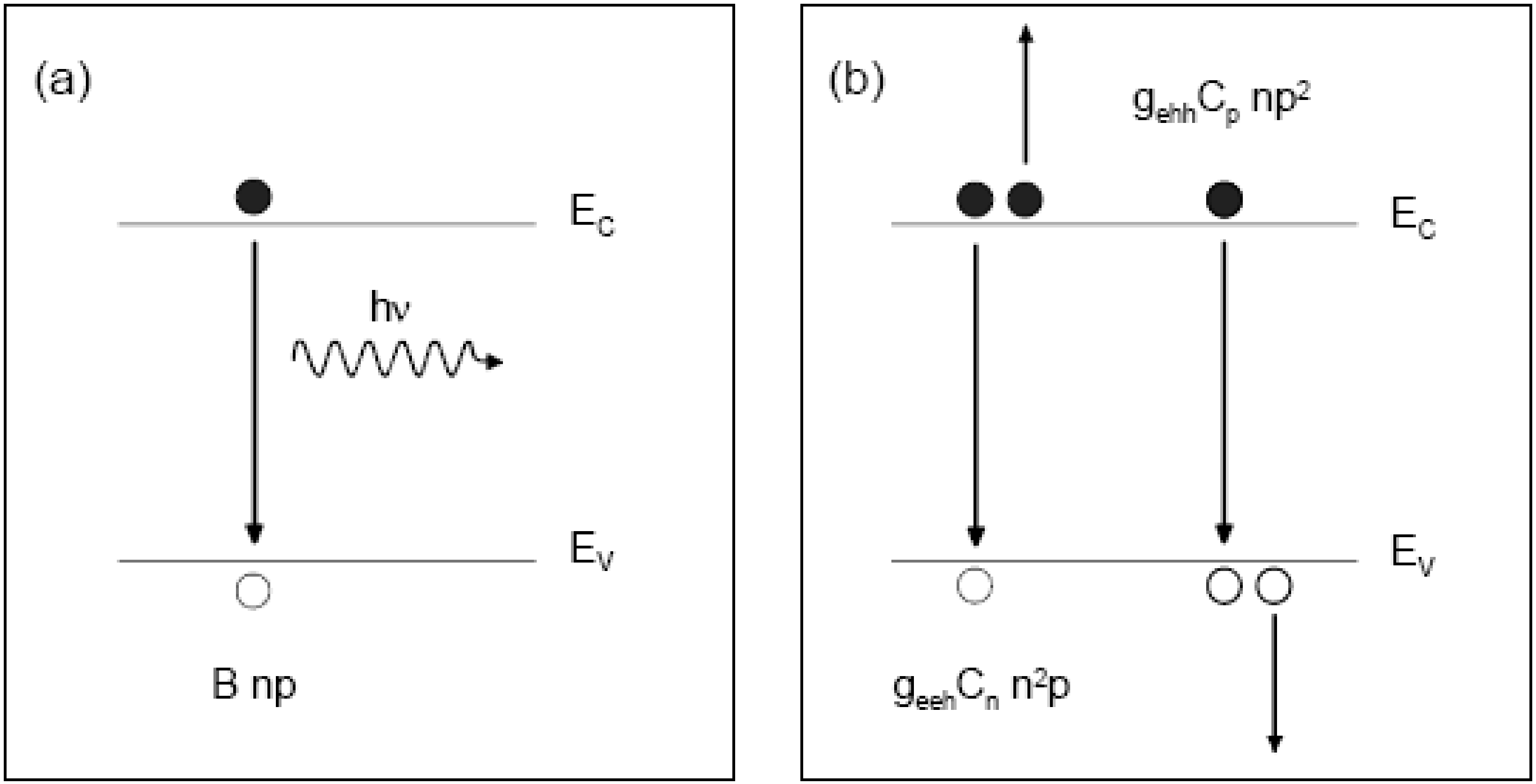
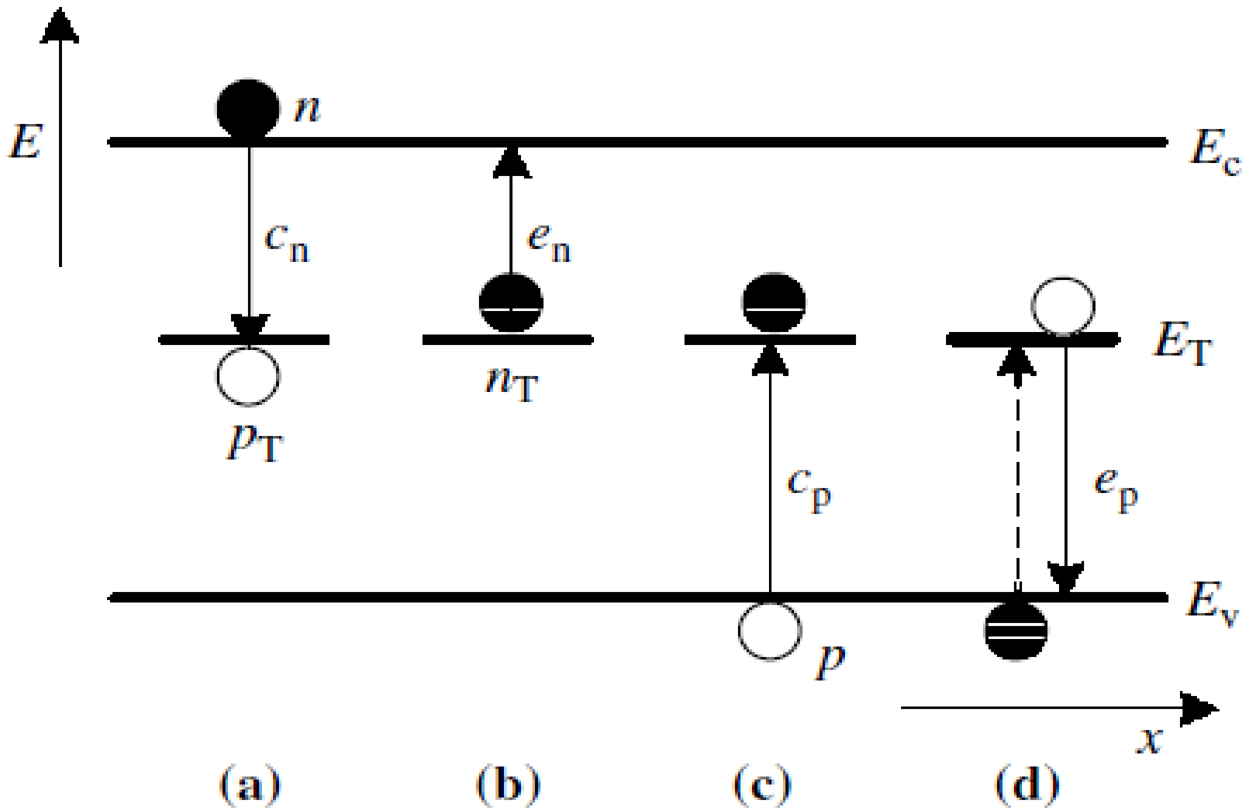


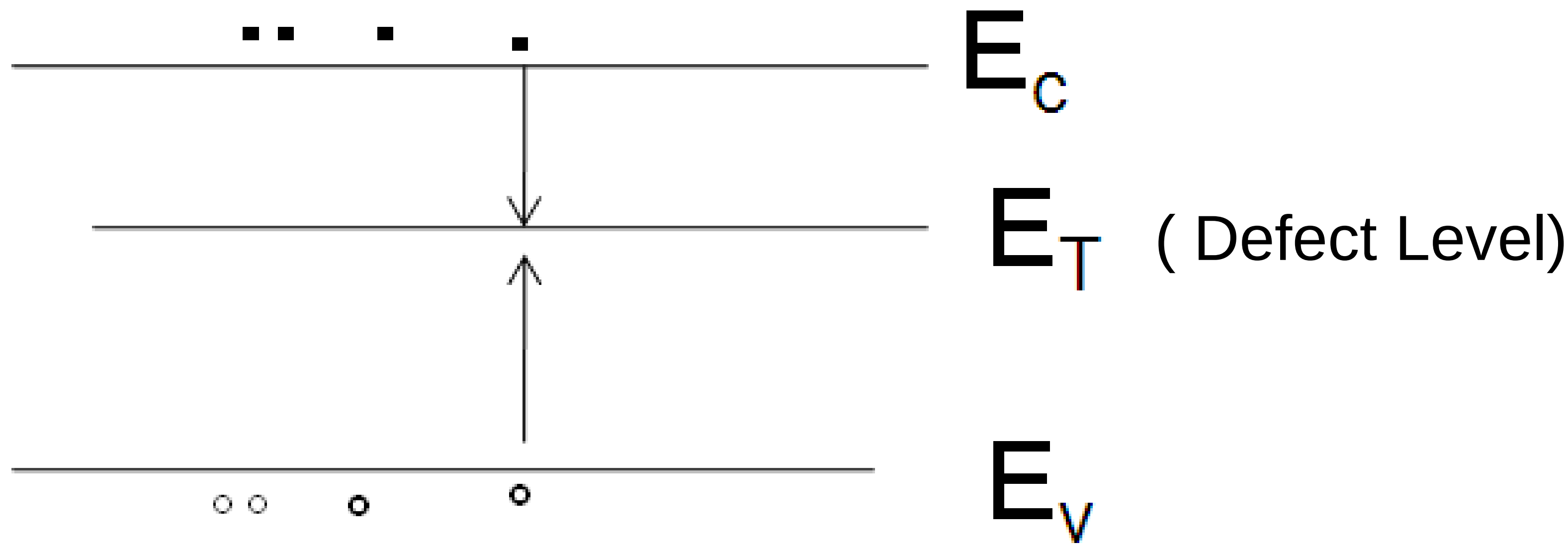
Fig. 1.12. Schematic diagram of intrinsic recombination mechanisms: (**a**) radiative band-band recombination and (**b**) Auger band-band recombination.

Interactions between Bands and Defect Level E_T



Recombination via Defect Level

Non – Radiative Recombination at bulk defects, surfaces
Shockley-Read-Hall (SRH)



$$R = \frac{\left(np - n_i^2\right)}{\tau_{po}\left(n + n_1\right) + \tau_{no}\left(p + p_1\right)} \qquad \tau_{po} = \frac{1}{c_p N_t} \qquad \tau_{no} = \frac{1}{c_n N_t}$$

Emission Efficiency of Silicon

- Radiative Recomb Rate = $\Delta n / \tau_R$

  For Silicon $\tau_R \sim 20$ msec
- Total Recombination Rate = $\Delta n / [\, 1/\tau_R + \tau_{NR}]$
- Emission Efficiency = $\tau_{NR} / \tau_R + \tau_{NR}$

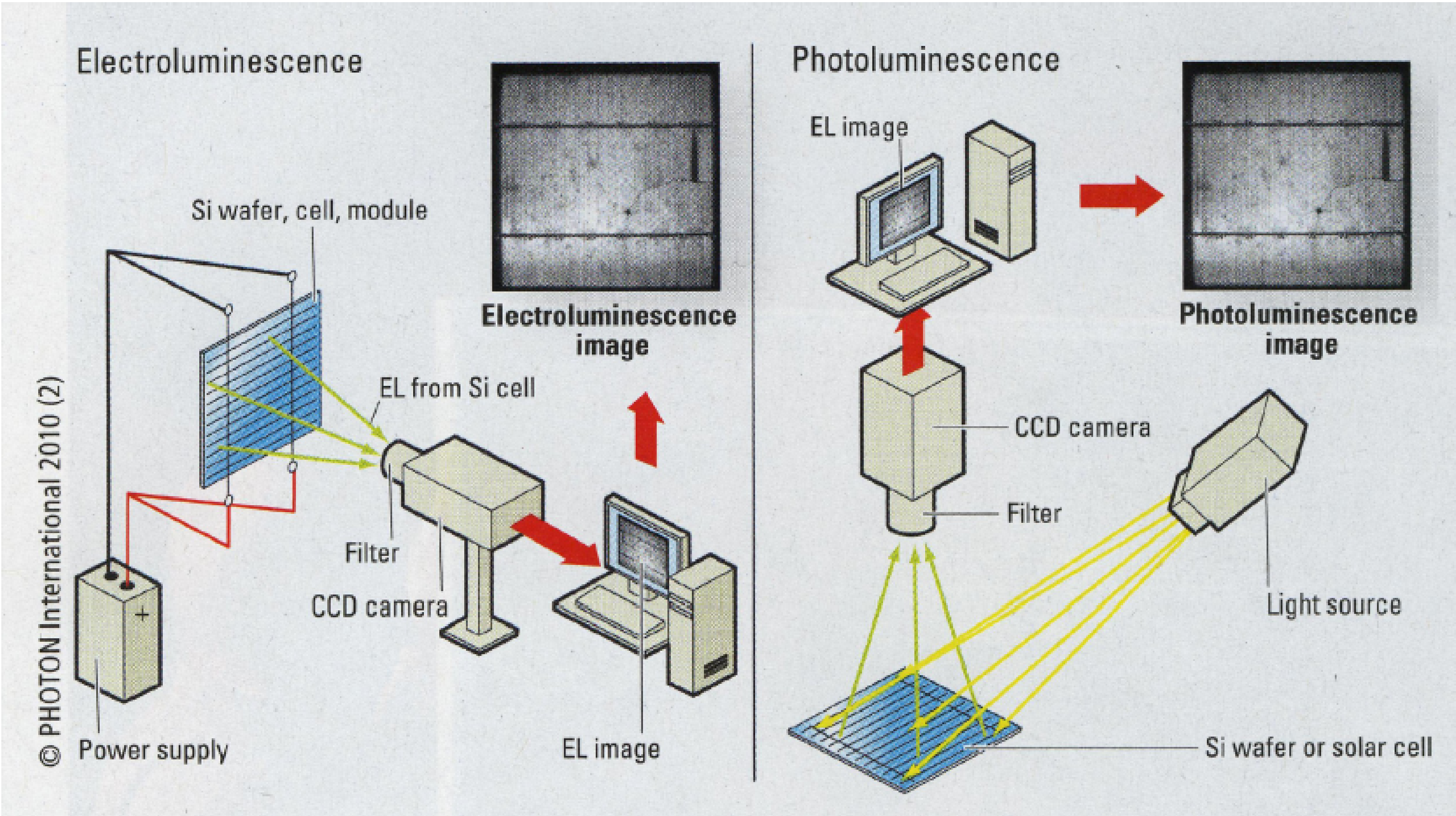
  $= 10^{-3}$ for Si

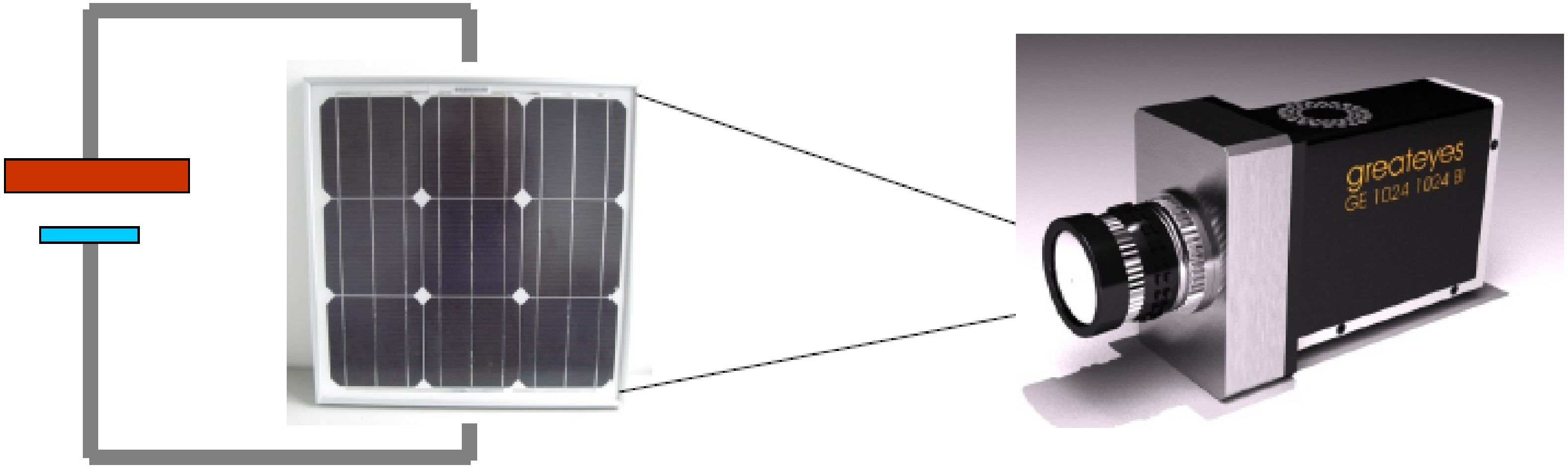
depending on $\tau_{NR.}$ (If there are defects, τ_{NR} will be

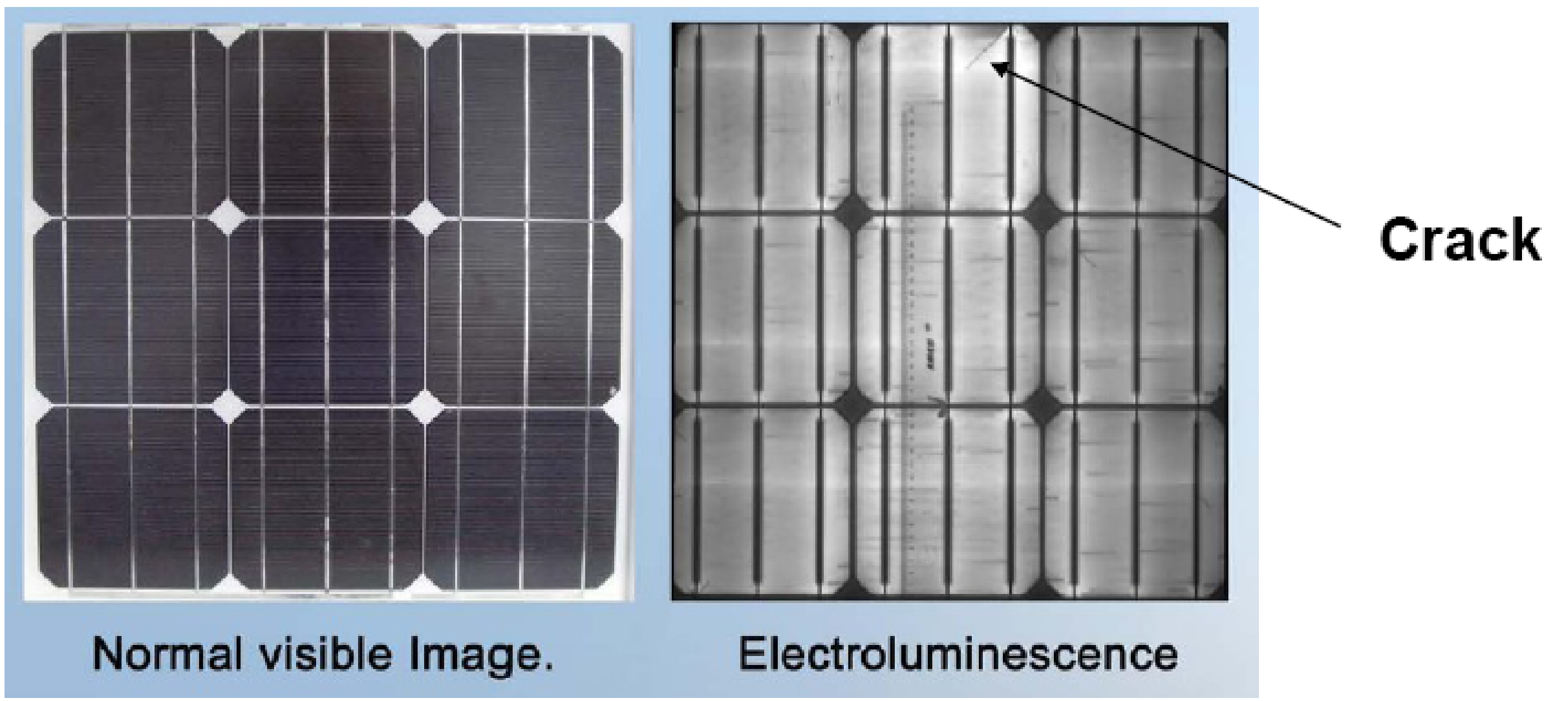
smaller and emission will reduce)

EL/PL Imaging

Measurement Principle – How does it work ?




greateyes
GE 1024 1024 BI


Crack
Normal visible Image.
Electroluminescence

PL Imaging : Cell Fabrication Monitoring

1 ohm-cm FZ Silicon
4 inch wafer Quarters
Trupke et al
2006 IEEE PVSC

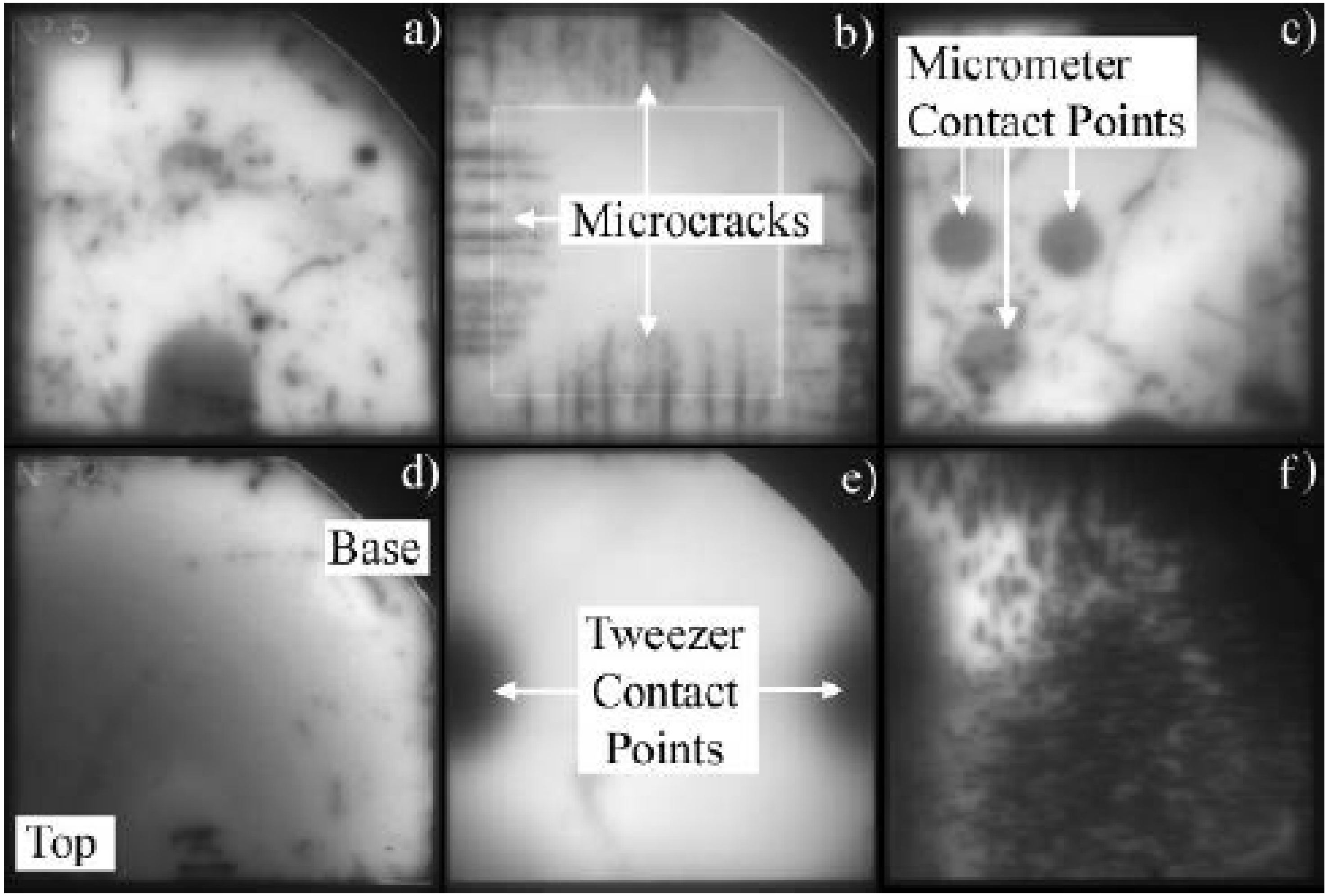
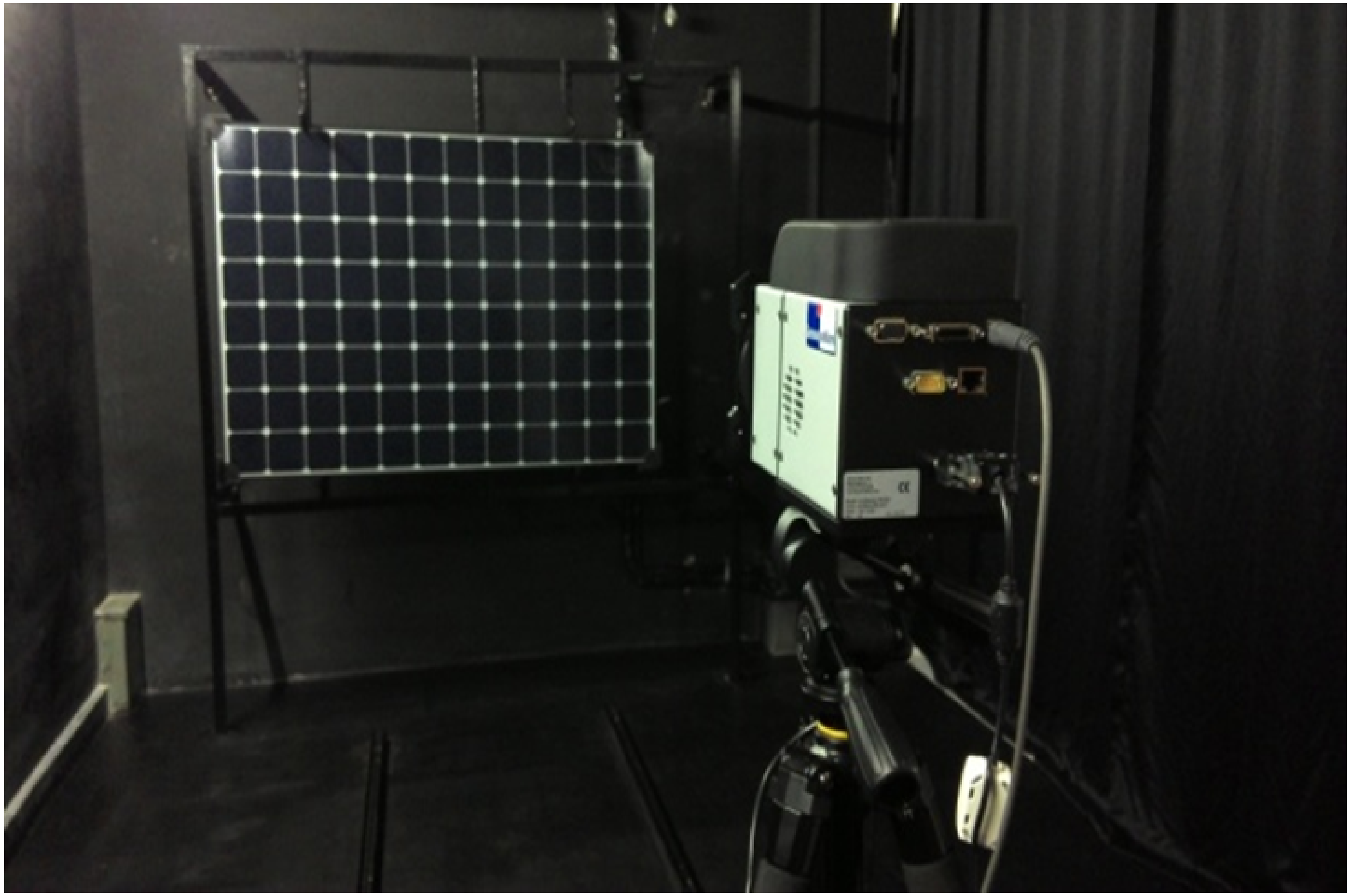


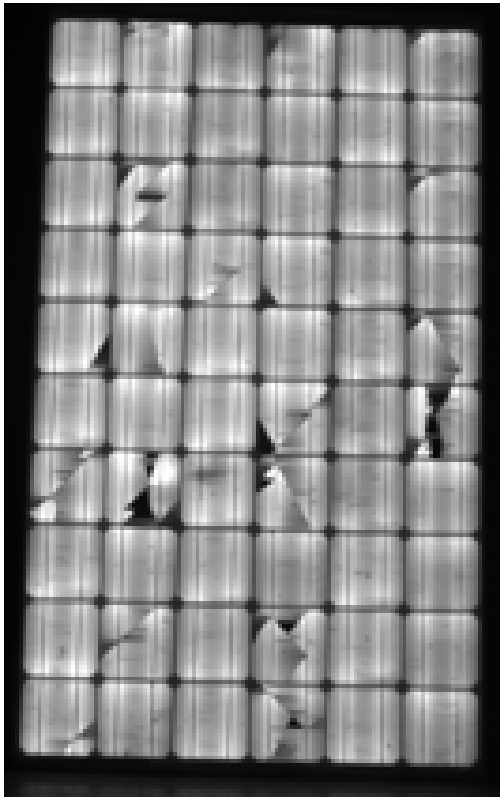
Fig.1 *Various examples of process induced defects*

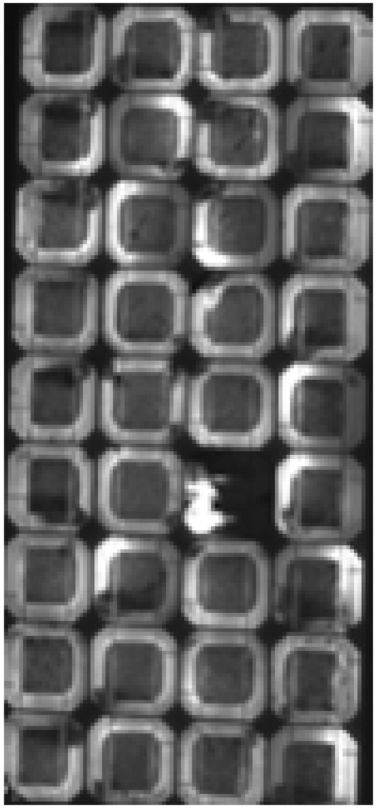
a) Effect of a dent in substrate holder , b) Poor Laser Scribing and cleaving , c) Effect of measurement by micrometer, d) Effect of temperature gradient across wafer during furnace anneal
e) Wafer handling with clean plastic tweezers , f) unintentionally contaminated wafer

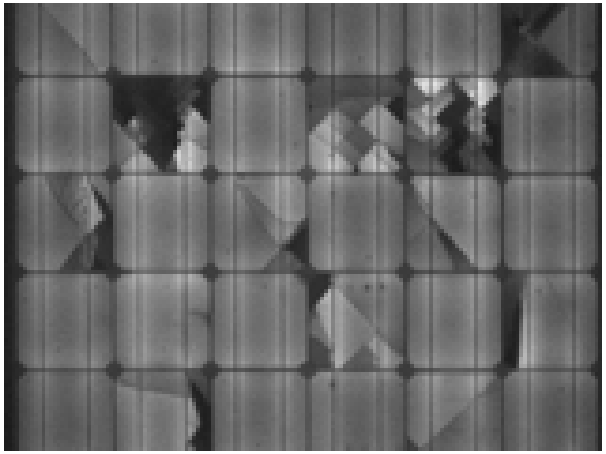
Standard method OF EL Imaging Measurement of Module



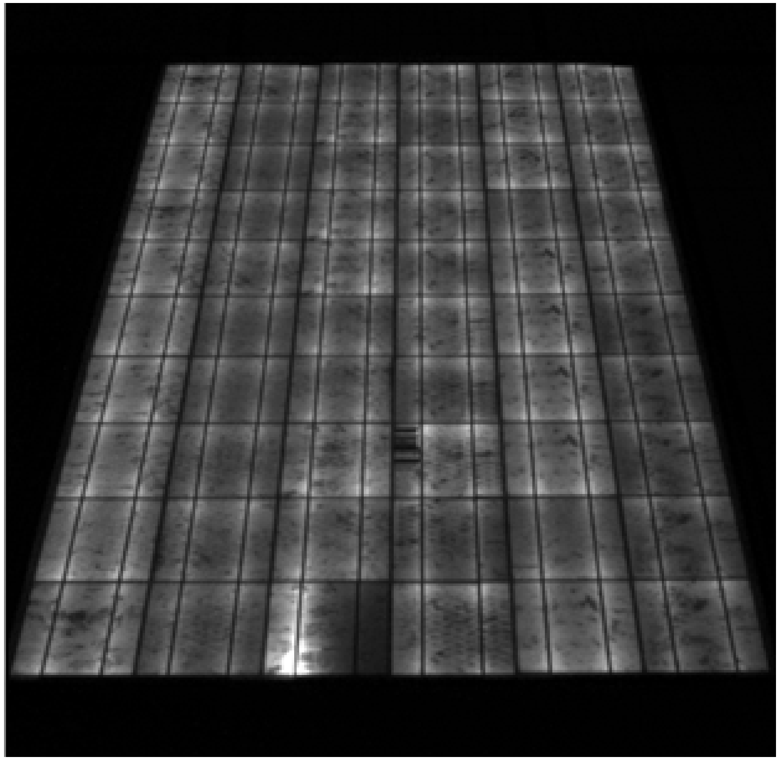
- Importance of Electroluminescence image
  - Quick method to find out the latent defects in the solar cells, particularly cracks and inactive regions







EL Image C-Si Module



6 in x 6 in cell
Jsc ~ 36.8 mA/cm^2

EL with
I_F ~ 1.3 Isc

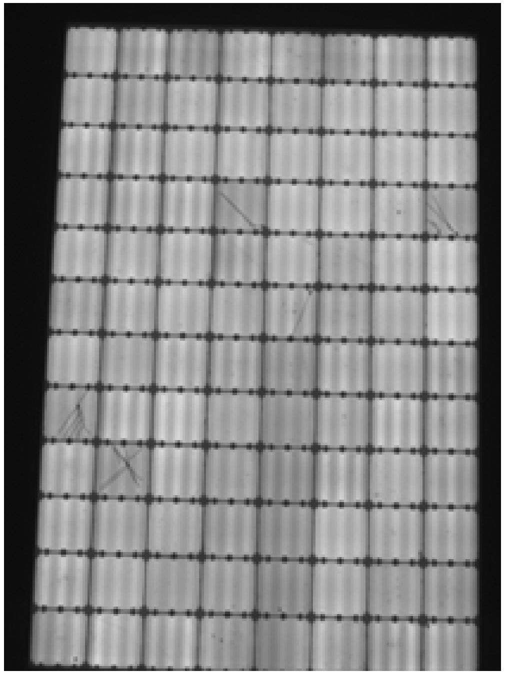
Av Voc per cell
0.615 V

Exposure time 180 sec

Name plate Data

Pmax (Watts): 230 W, Voc (Volts): 36.9 V (60 Cells)
Isc (Amp): 8.56 A, Imax (Amp): 7.52 A,
Vmax (Volts):30.60 V

EL Image Sun Power Module

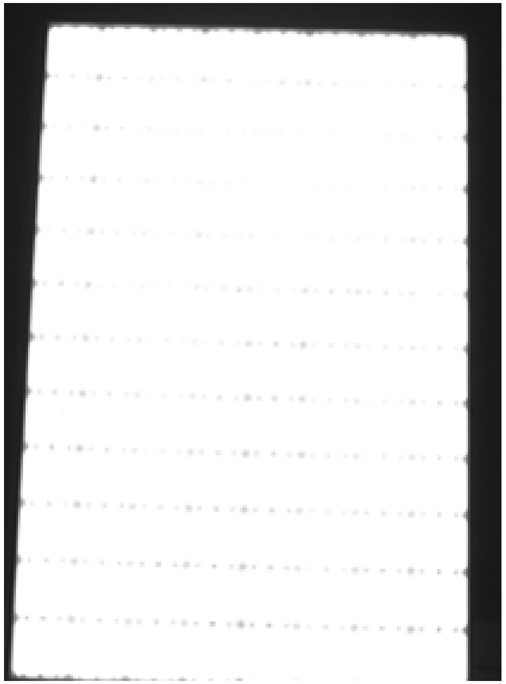


Exposure time 20 sec

5 in x 5 in cell
Jsc ~ 40 mA/cm^2

EL with
I_F = 1.3 Isc

Av Voc per cell
0.676 V

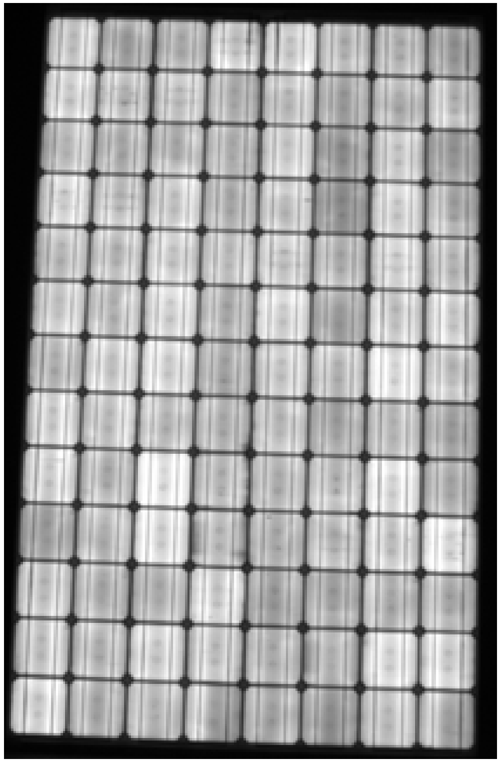


Exposure time 60 sec

Name plate Data

Pmax (Watts): 327 W, Voc (Volts): 64.9 V (96 cells)
Isc (Amp): 6.46 A, Imax (Amp): 5.98 A,
Vmax (Volts):54.7 V

EL Image HIT Module

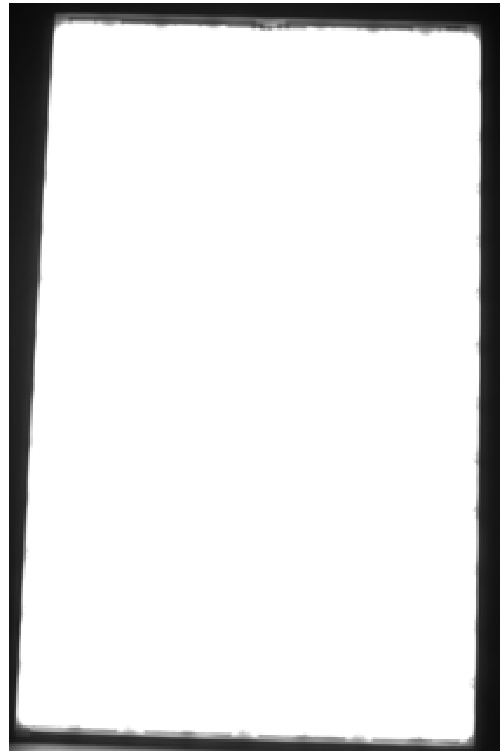


Exposure time 6 sec

10cmx10cm cell
Jsc ~ 37.9 mA/cm²

EL with
I_F =1.3 Isc

Av Voc per cell
0.708 V



Exposure time 60 sec

Name plate Data

Pmax (Watts): 210 W, Voc (Volts): 73.6 V (104 Cells)
Isc (Amp): 3.79 A, Imax (Amp): 3.52 A,
Vmax (Volts):59.7 V

Rajeev, IIT Bombay

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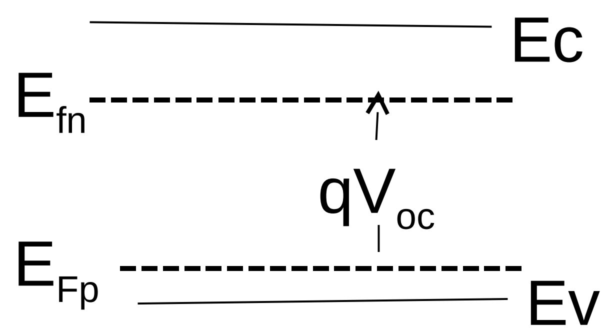
V_{oc} is governed by Excess Carrier Density Generated by Light

$$V_{oc} = E_{Fn} - E_{Fp} \; ,$$

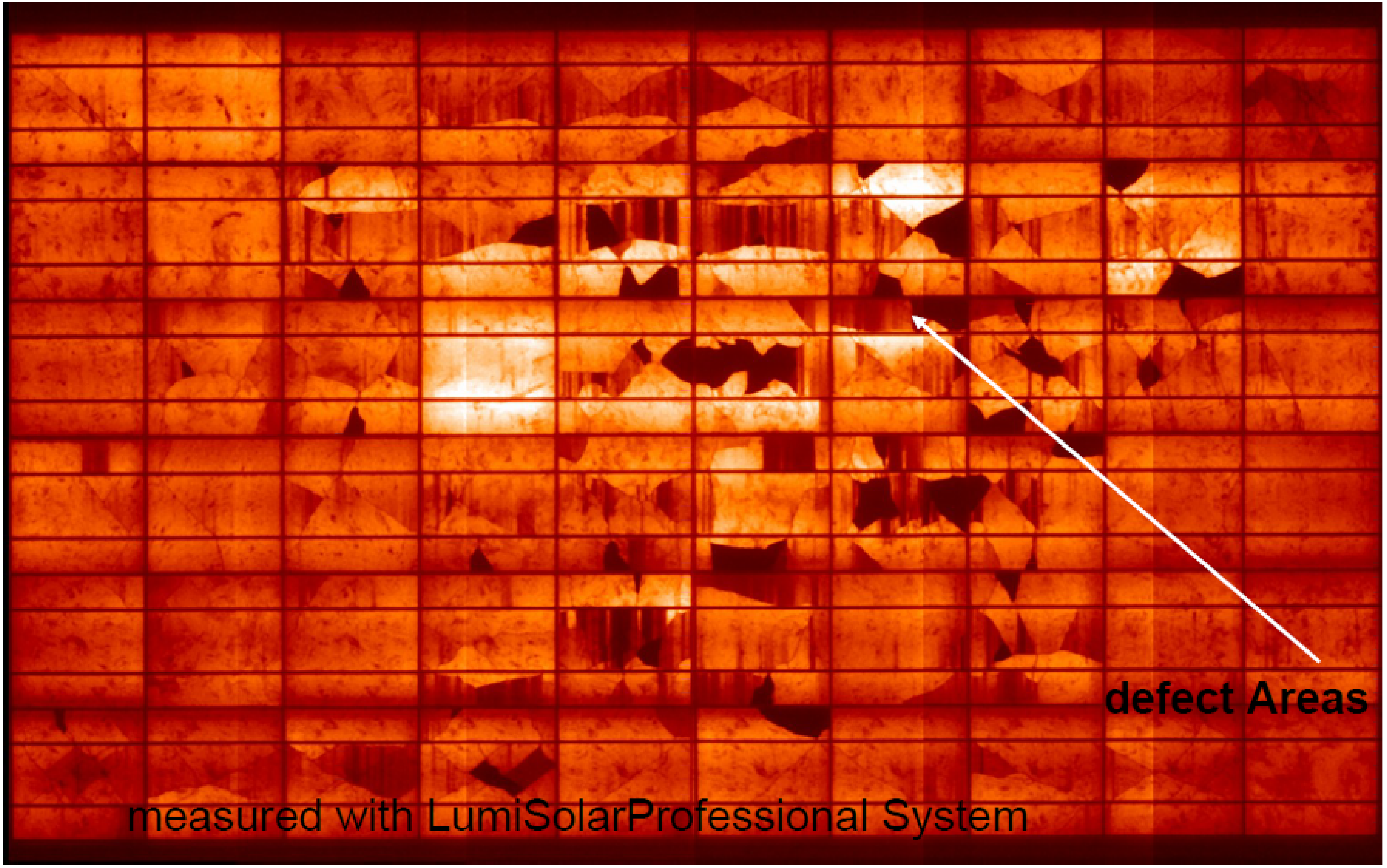
$$E_C - E_{Fn} = kT\ln(N_c/(\Delta n + n_0) \; ,$$

$$E_{Fp} - E_v = kT\ln(N_v/(N_a + \Delta p)$$

$$(\Delta n + n0)\,(Na + \Delta p) = ni2 \exp[\,qVoc/kT]$$
$$= ni2 \exp[(Efn - Efp)/kT]$$
$$Voc \sim kT/q\,[\ln(\Delta n\,.\,Na)/ni2]$$
$$\sim kT/q\,[\ln(G\tau\,.\,Na)/ni2]$$



Electroluminescence of poly-Si Solar Module



greateyes

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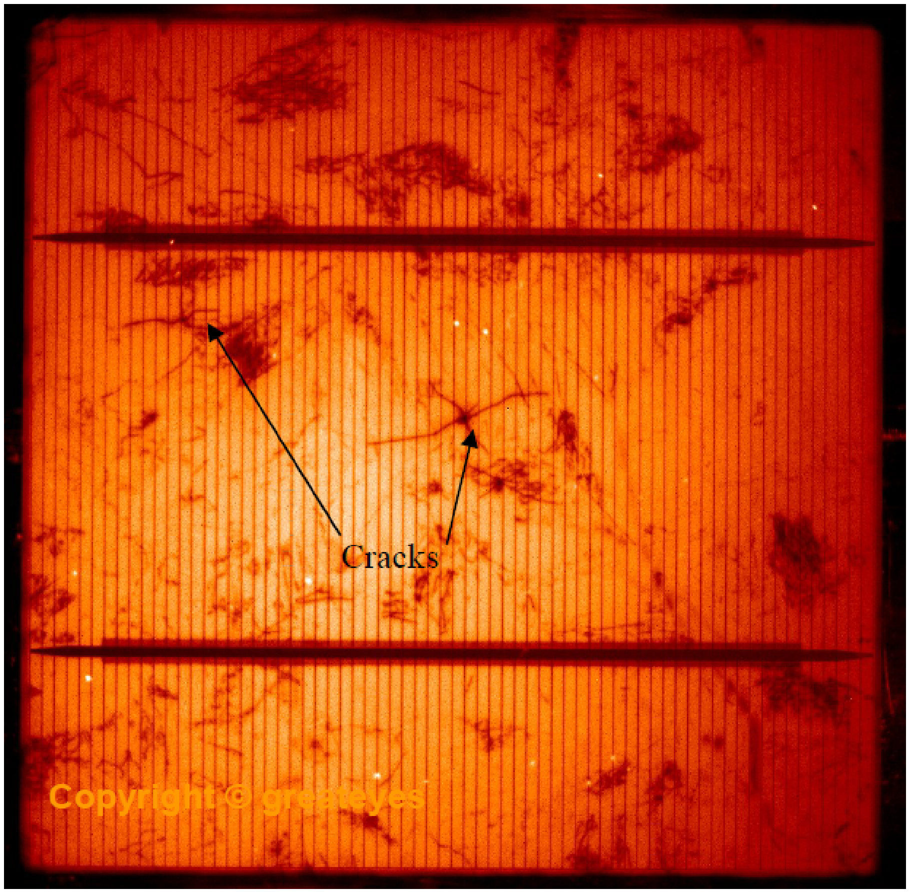
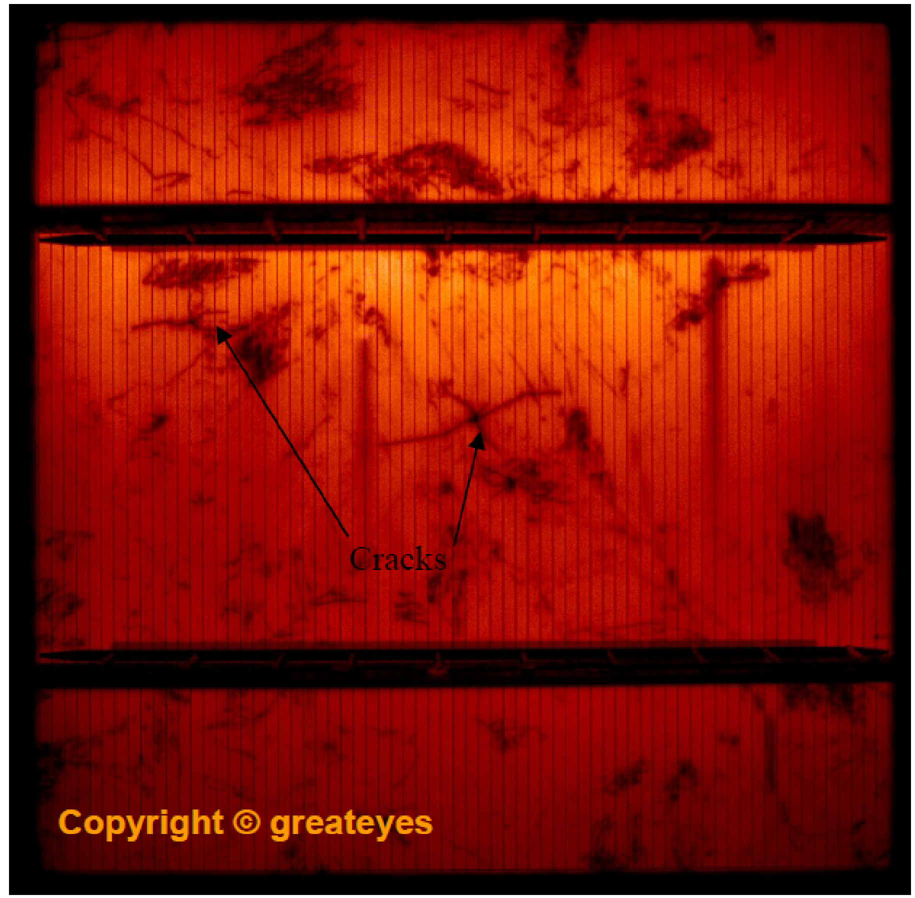
Comparison of PL and EL Images

greateyes





Application of EL and PL Inspection

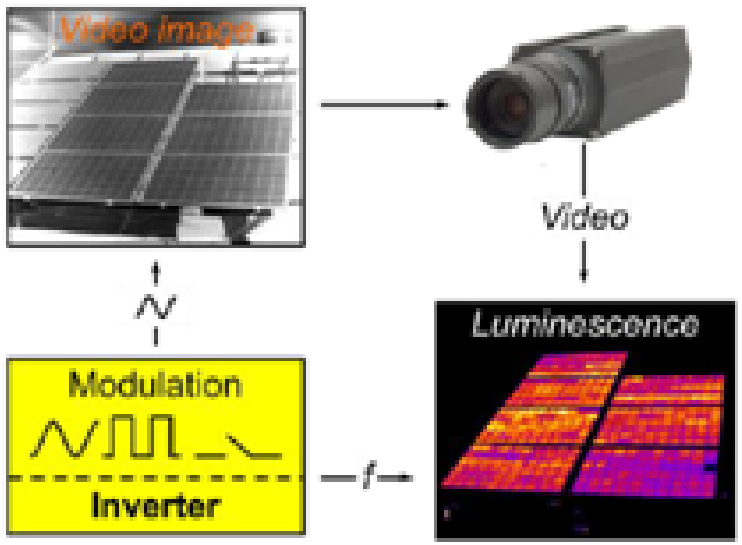
- For R&D and Production of Wafers & Solar Cells & Solar Modules
- Inspect c-Si, a-Si, CIGS, CIS, CdTe, ... photovoltaic devices
- High Informative Value (Micro Cracks, Finger defects and many more)
- Quick Measurement, Inline Process Control is possible

⇨ Enhance Efficiency of Cell / Module

⇨ Optimize Production Efficiency

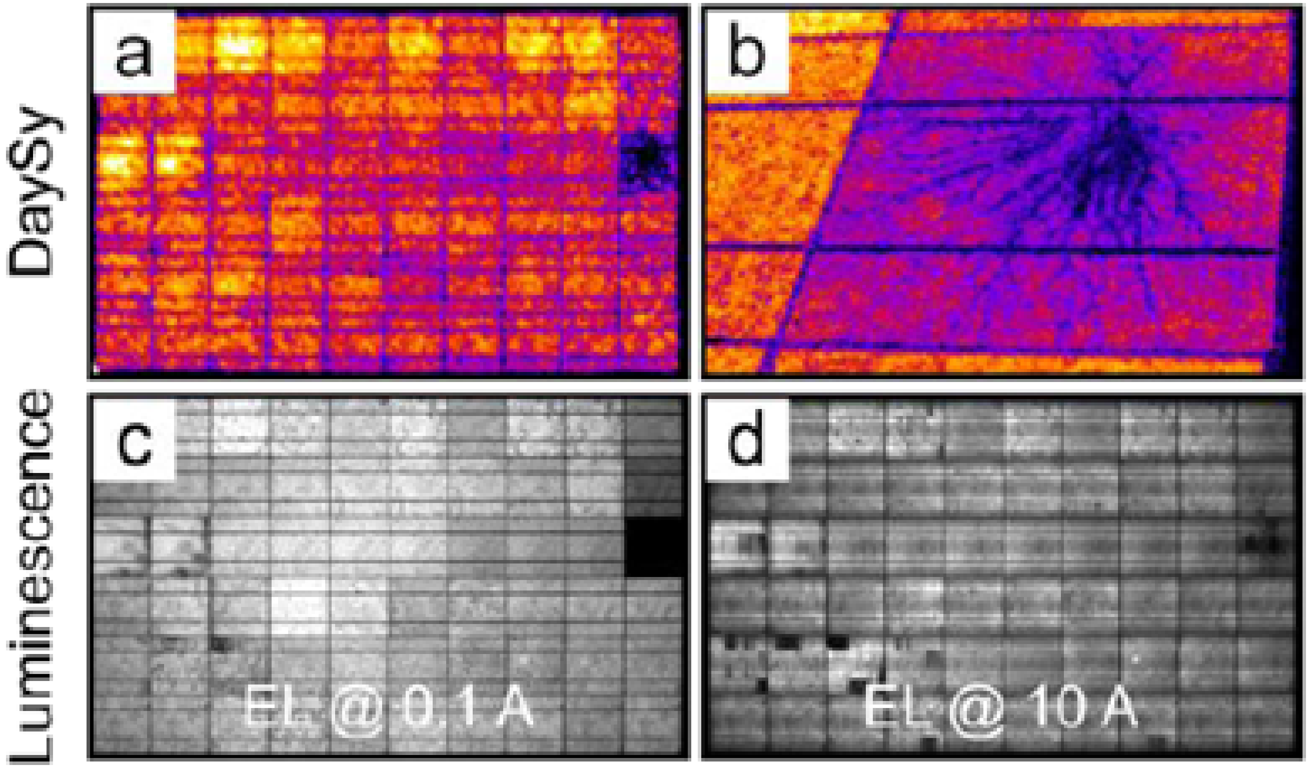
Daylight PL Imaging

- Need for lighted (daylight or artificial lighting) EL
  - Eliminates the need of a dark room.
  - Allows to capture the EL image of modules without transporting it to the lab.
- Day light Luminescence System (DaySy) method



Ref: L. Stoicescu *et al*. "Daylight Luminescence for Photovoltaic System Testing", in Proc. 22nd International Photovoltaic Science and Engineering Conference, Hangzhou, China, 2012.

Comparison of Different Imaging Techniques



Photoluminescence

Electroluminescence

- Spectral response Measurement
- External and Internal Quantum Efficiency

Spectral Response and QE

- Spectral Responsivity (SR) : Amperes per Watt

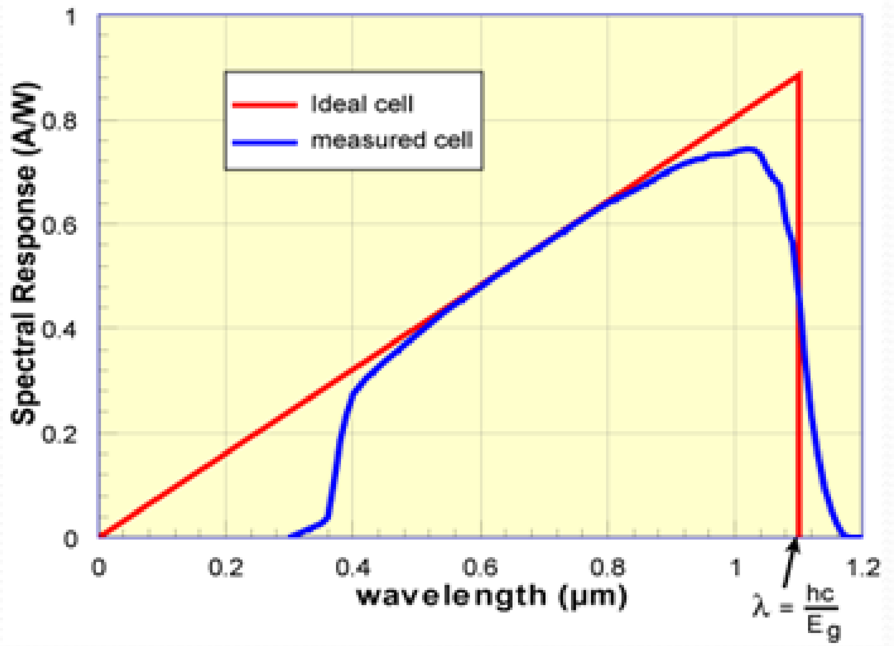
$$SR(\lambda) = I_{sc} / P_{in} \text{ (A/W)}$$

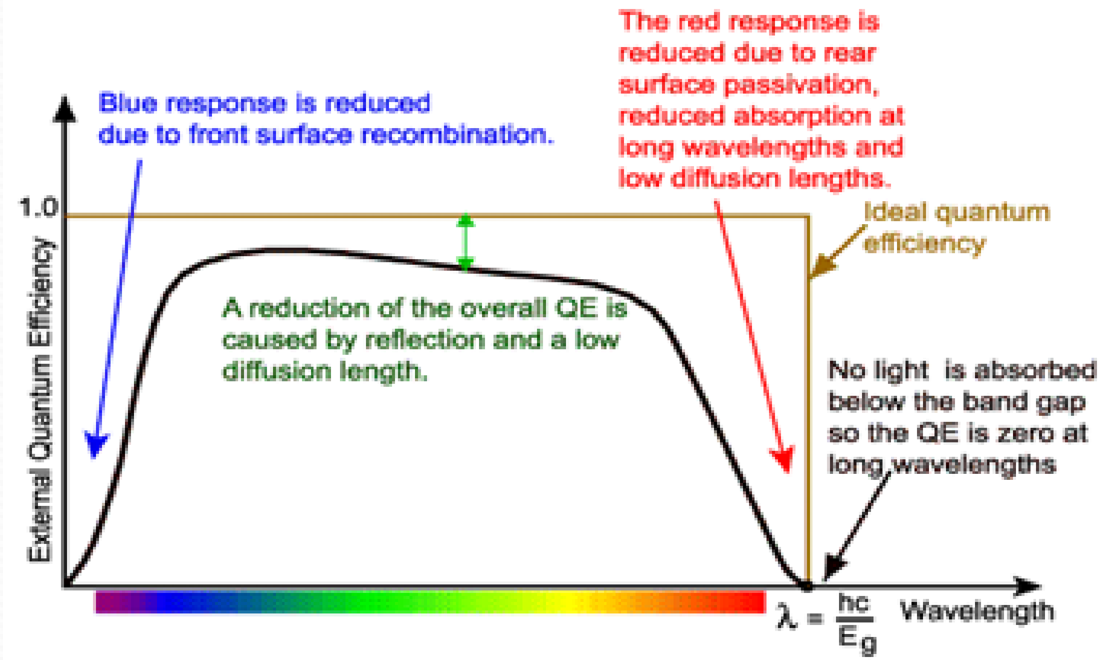
- External Quantum Efficiency (EQE) : Electrons per photon

$$\eta_{ext} = [\, I_{sc} / q] / [\, P_{in} / (hc/\lambda)] = (I_{sc}/Pin) [\, hc / \lambda q \,]$$

$$= SR(\lambda) [\, hc / q \lambda \,]$$

$$SR(\lambda) = (q\lambda / hc)\, \eta_{ext}$$


Ideal cell
measured cell
Spectral Response (A/W)
wavelength (μm)
λ = hc/Eg


Blue response is reduced due to front surface recombination.
The red response is reduced due to rear surface passivation, reduced absorption at long wavelengths and low diffusion lengths.
Ideal quantum efficiency
A reduction of the overall QE is caused by reflection and a low diffusion length.
No light is absorbed below the band gap so the QE is zero at long wavelengths
External Quantum Efficiency
Wavelength
λ = hc/Eg

Spectral Response Measurement

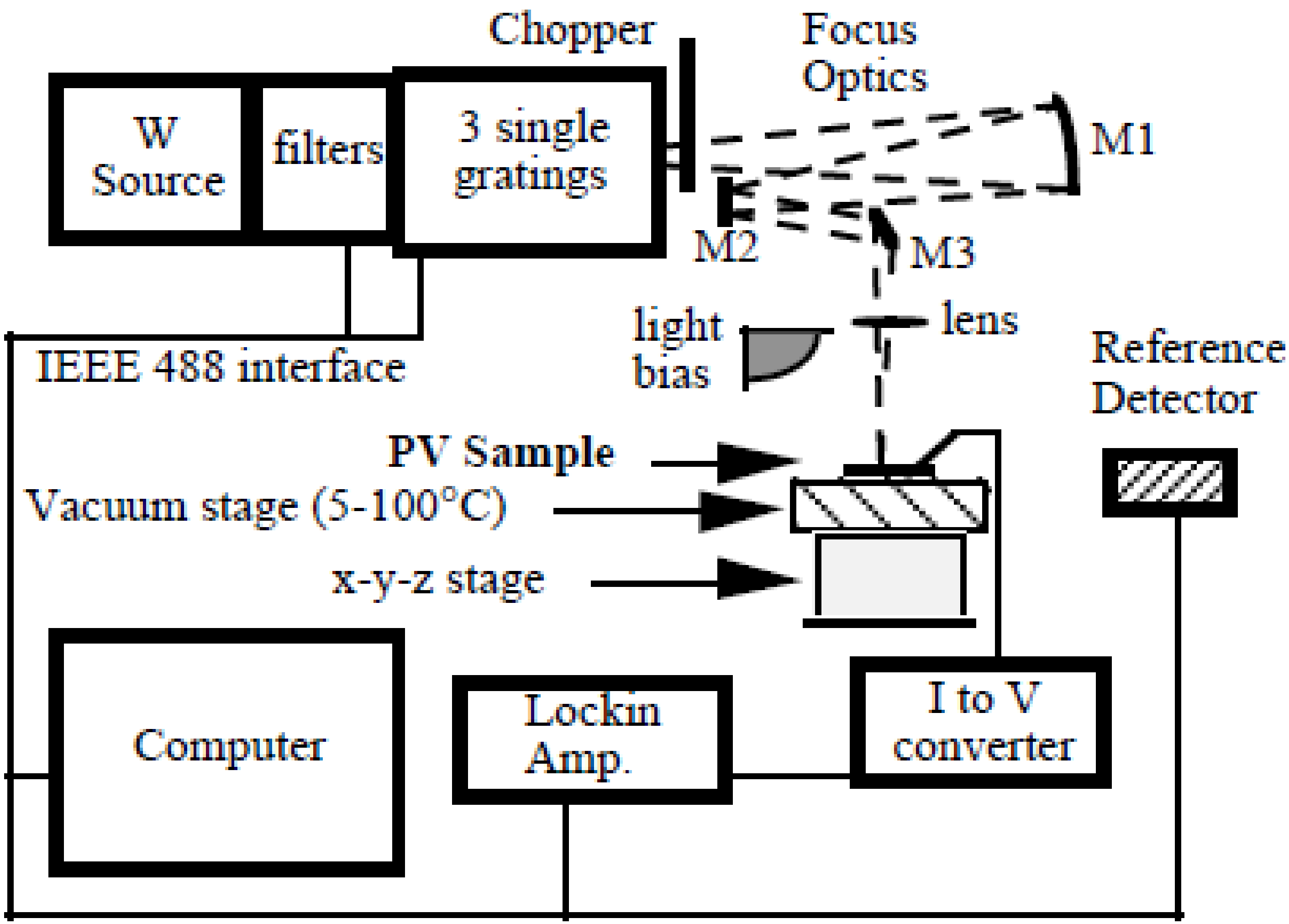


Figure 2: NREL grating monochrometer QE system

K Emery et al, NREL , July 1998

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Spectral Response Measurement

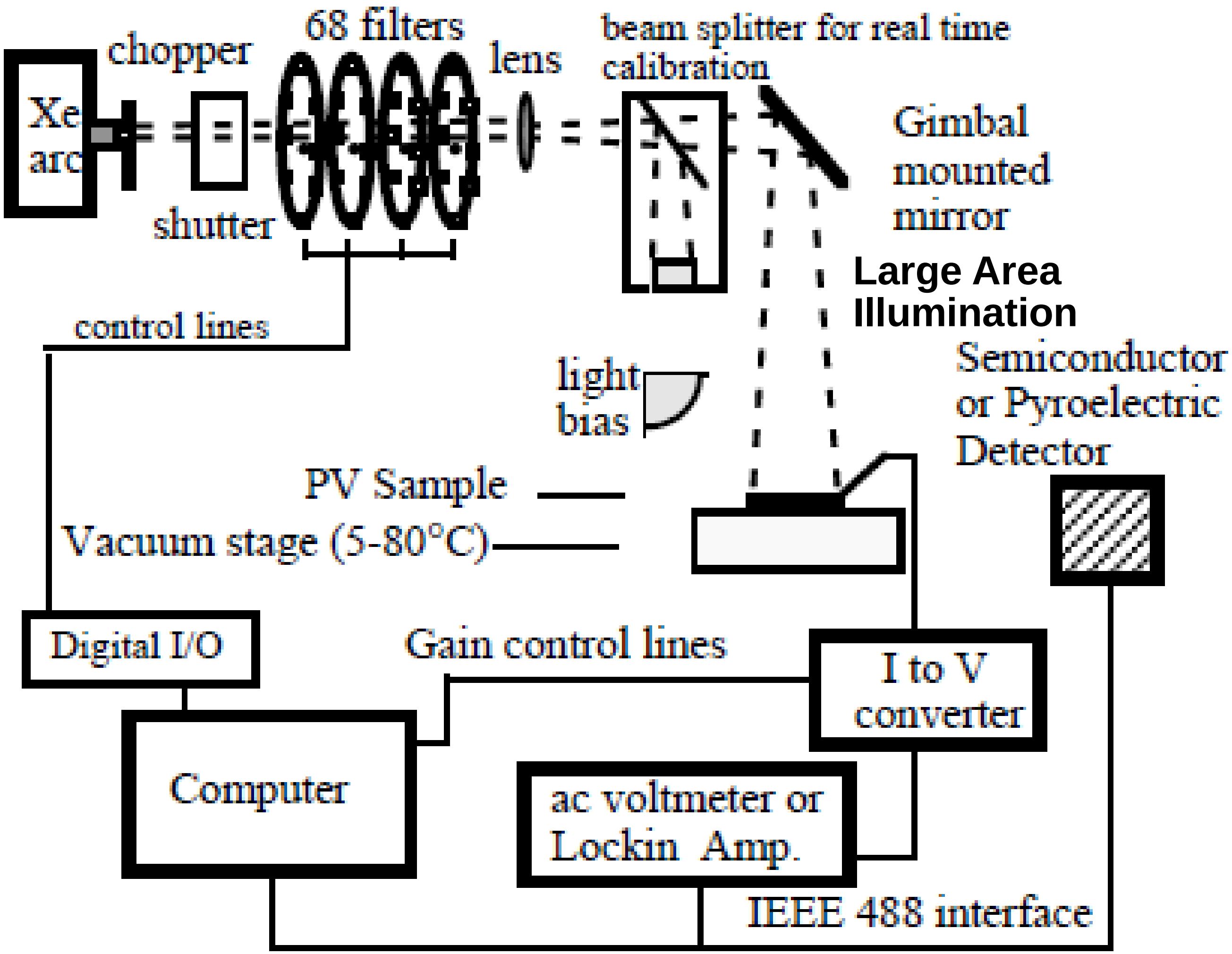

Figure 1: NREL filter QE system with a 280-2000 nm wavelength range.

Grating Based Vs Filter Based

Grating Based	Filter Based
Small Beam Size/ Small Area Illumination	Large Area illumination
Less Spatial Uniformity over large Area	Better Spatial Uniformity over large Area
Narrow Bandwidth Possible	Wider Bandwidth
Low Radiant Power	High Radiant Power

Quantum Efficiency

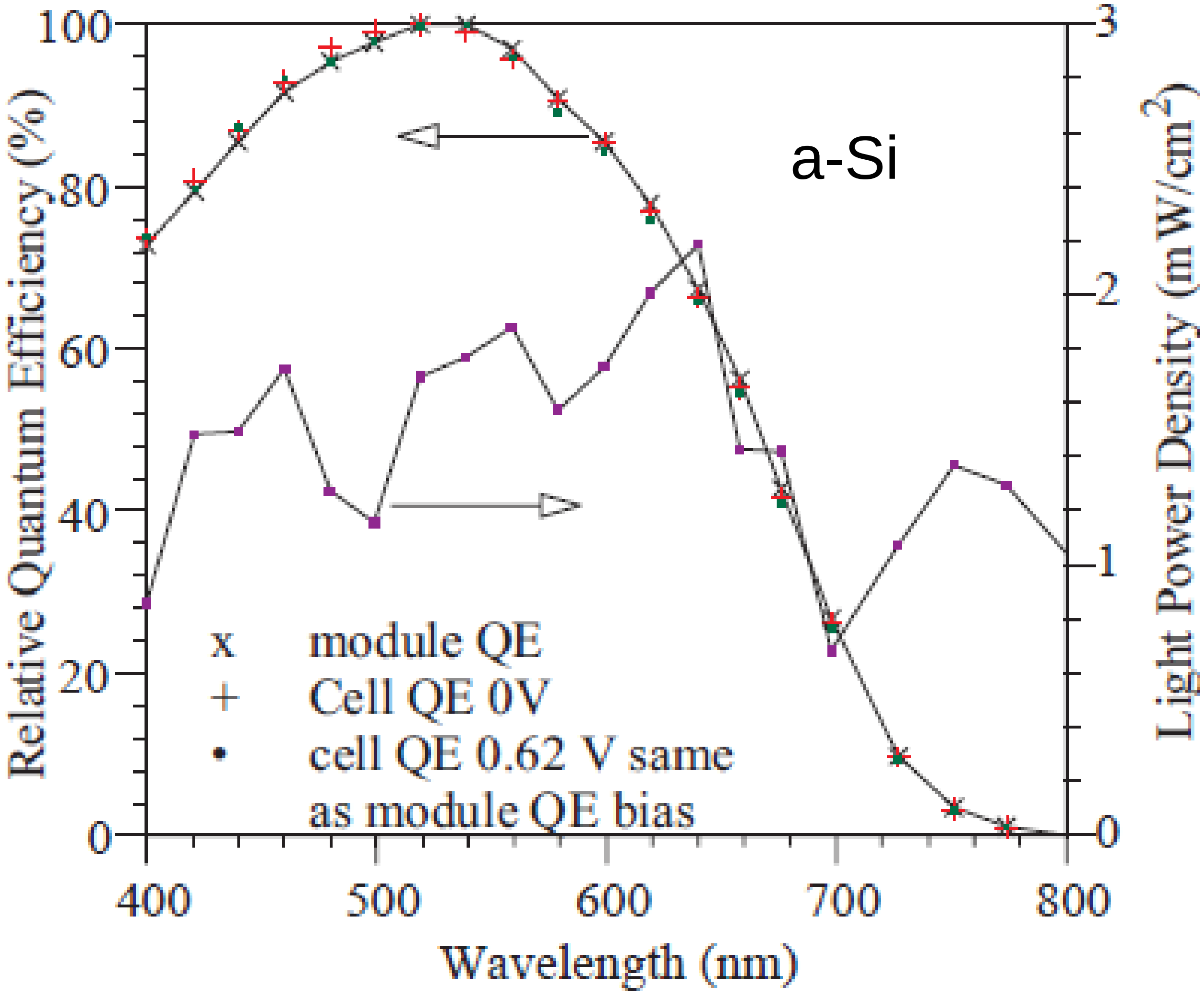

Figure 3: Module *vs.* cell QE measured with the filter system on a Solarex SA5 module.

Equivalent Circuit of a 2 Junction Tandem Cell

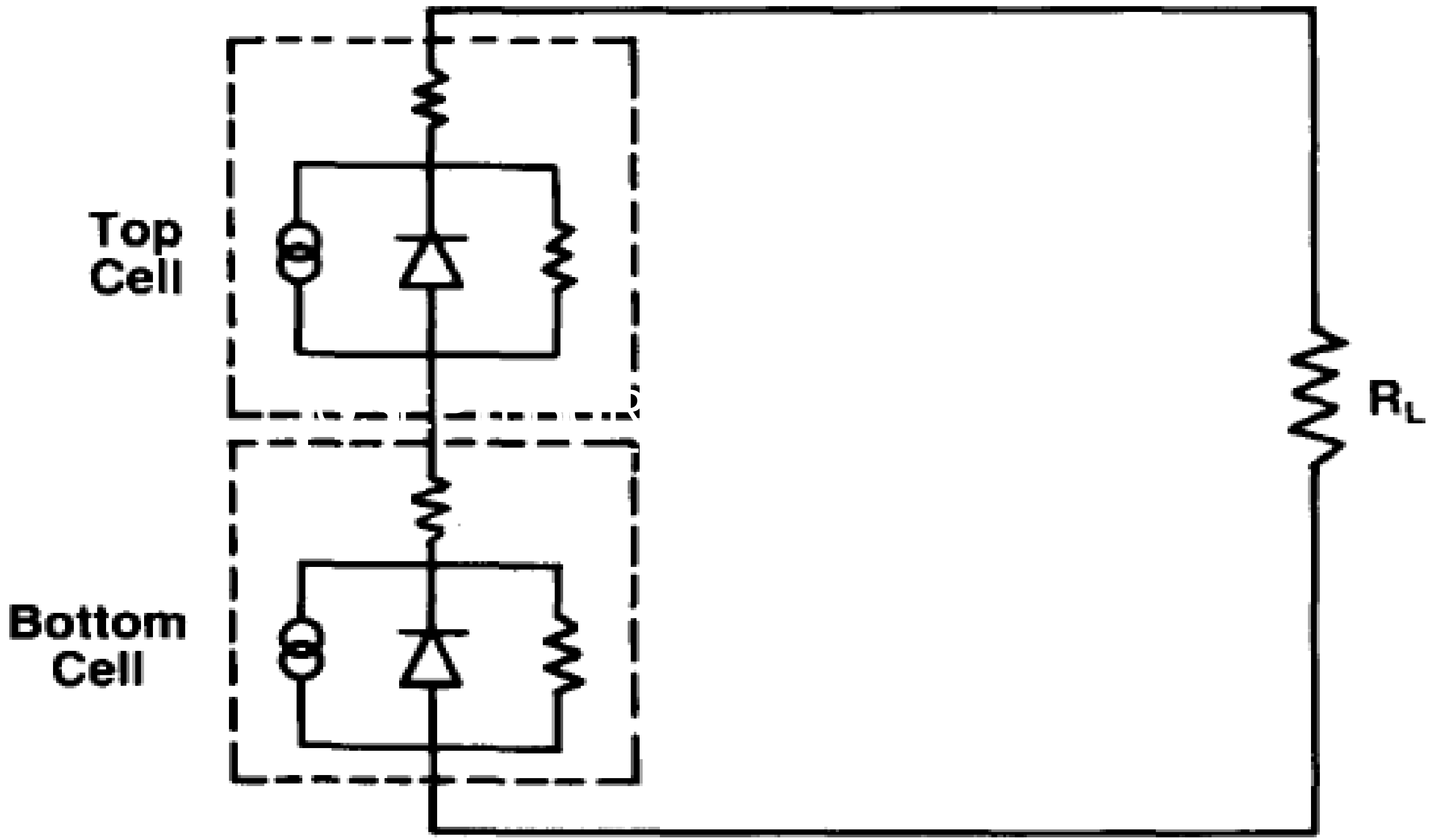

Fig. 2. Equivalent circuit of a two-cell tandem device.

Short circuit condition

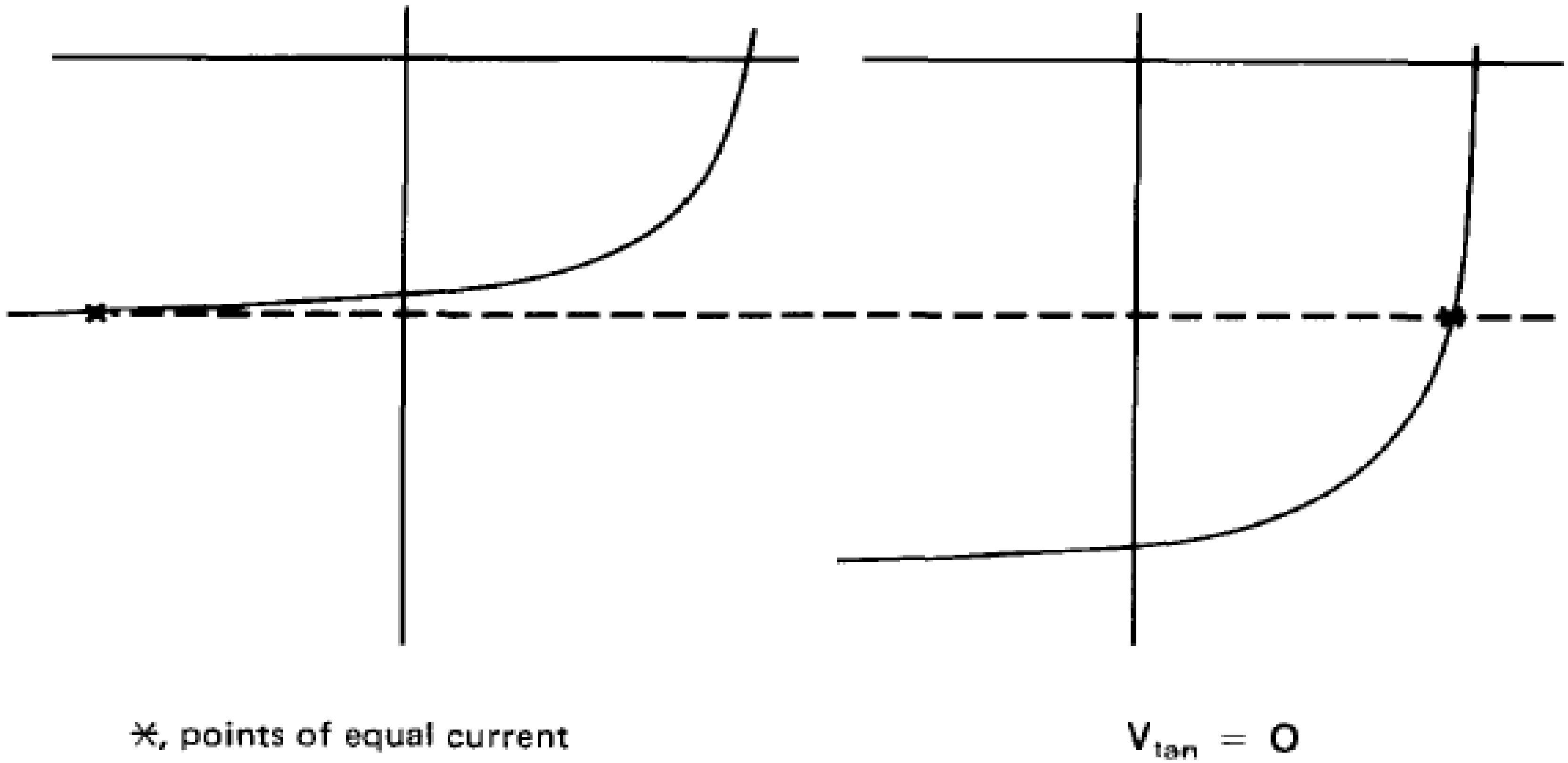

Fig. 3. Typical single-cell component I–V curves for the top and bottom cells of a tandem under illumination and at short-circuit ($V_{tan} = 0$). The individual-cell operating points are indicated by the crosses ×.

Light Biasing Top Cell (Blue Light) and Red Probe Light (Bottom Cell)

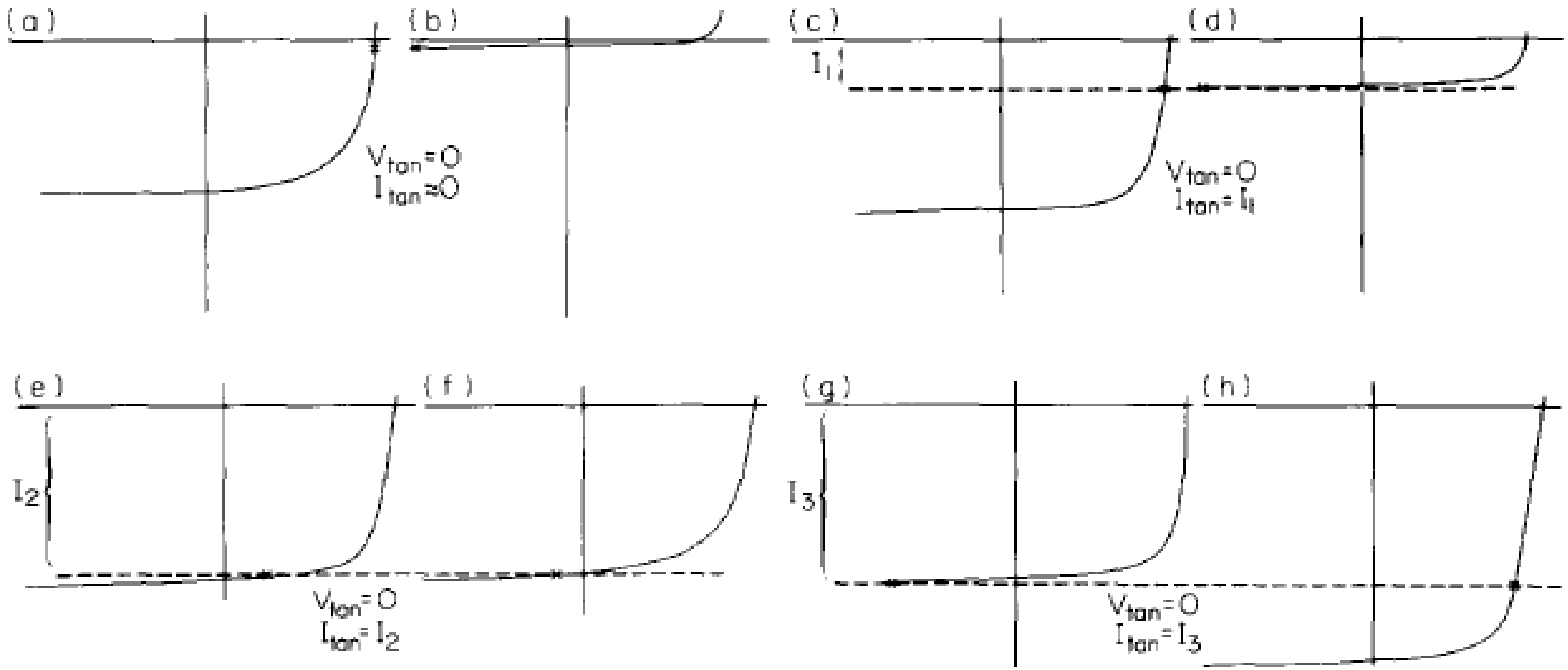

Fig. 6. Single-cell component *I–V* curves under blue-light bias with $V_{tan} = 0$: (a) top cell; (b) bottom cell; (c) top cell with red probe light; (d) bottom cell with red probe light; (e) top cell after increasing the red light intensity; (f) bottom cell after increasing the red light intensity; (g) top cell after further increasing the red light intensity; (h) bottom cell after further increasing the red light intensity.

Light Biasing arrangement

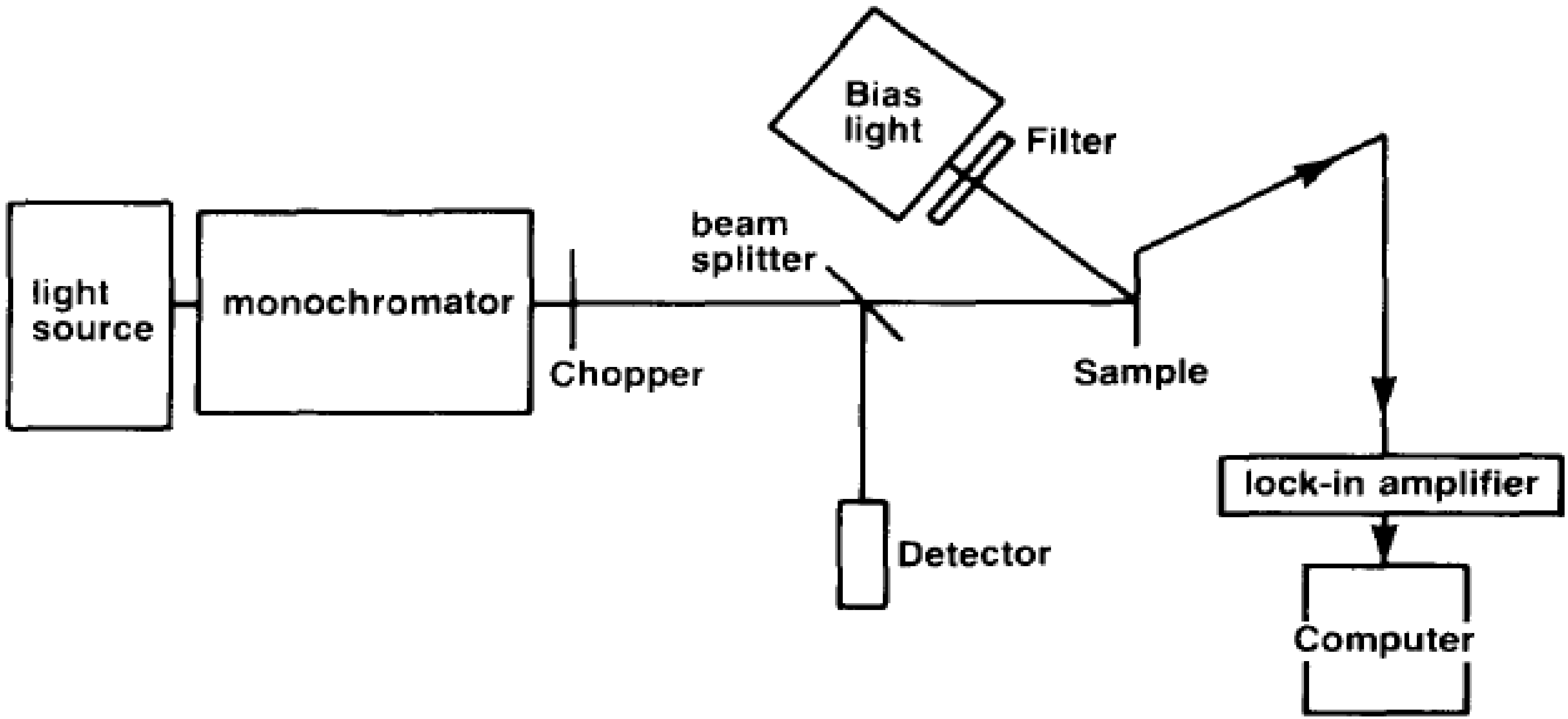

Fig. 10. Experimental setup for the quantum efficiency measurement with voltage and light biasing.

Solar Cells, 18 301-314 (1986)

- Thermography

Shunts in Solar Cells

- The most important process-induced shunts are residues of the emitter at the edge of the cells, cracks, recombination sites at the cell edge, Schottky-type shunts below grid lines,scratches, and aluminum particles at the surface. The material-induced shunts are strong recombination sites at grown-in defects (e.g., metal-decorated small-angle grain boundaries), grown-in macroscopic Si3N4 inclusions, and inversion layers caused by microscopic SiC precipitates on grain boundaries crossing the wafer.

O Breitenstein et al, Progress Photovoltaic Res Appl 12, 529 (2004

- The temperature in the shunted region is higher than in the non-shunted regions, which can be detected by Infra-red Imaging

- This technique detects the periodic local surface temperature modulation in the positions of local shunts with a sensitivity below 100 μK by applying a pulsed bias to the cell in the dark

system based on a 128128 pixel InSb focal plane array thermocamera

O Breitenstein et al, Progress Photovoltaic Res Appl 12, 529 (2004

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Lock-in Image

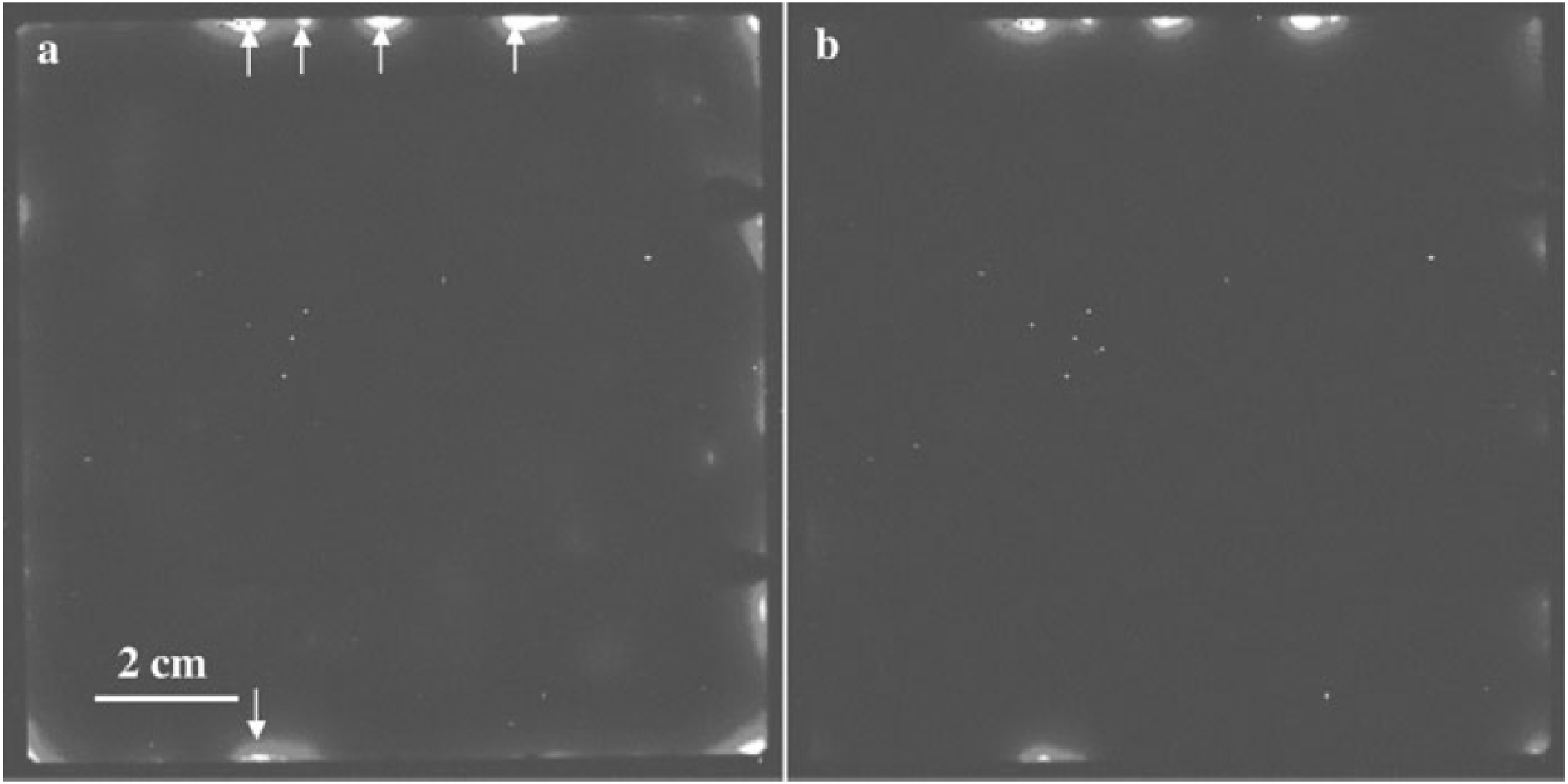

Figure 1. Lock-in thermogram of a cell containing edge shunts, measured under: (a) +0·5 V; (b) −0·5 V bias

O Breitenstein et al, Progress Photovoltaic Res Appl 12, 529 (2004)

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Lock-in Image

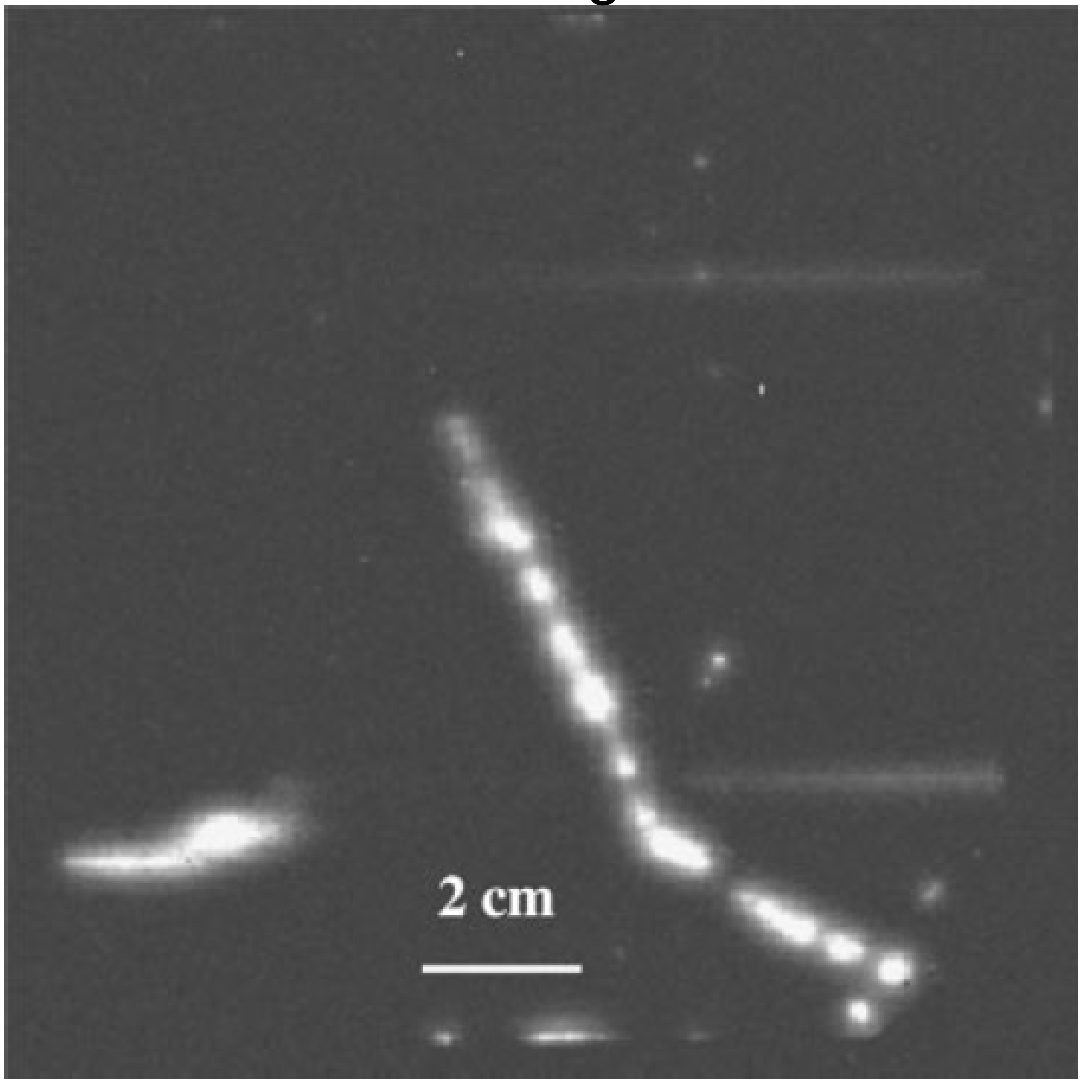

Figure 5. Lock-in thermogram of a cell with two scratches

O Breitenstein et al, Progress Photovoltaic Res Appl 12, 529 (2004

Imaging without Lock-in

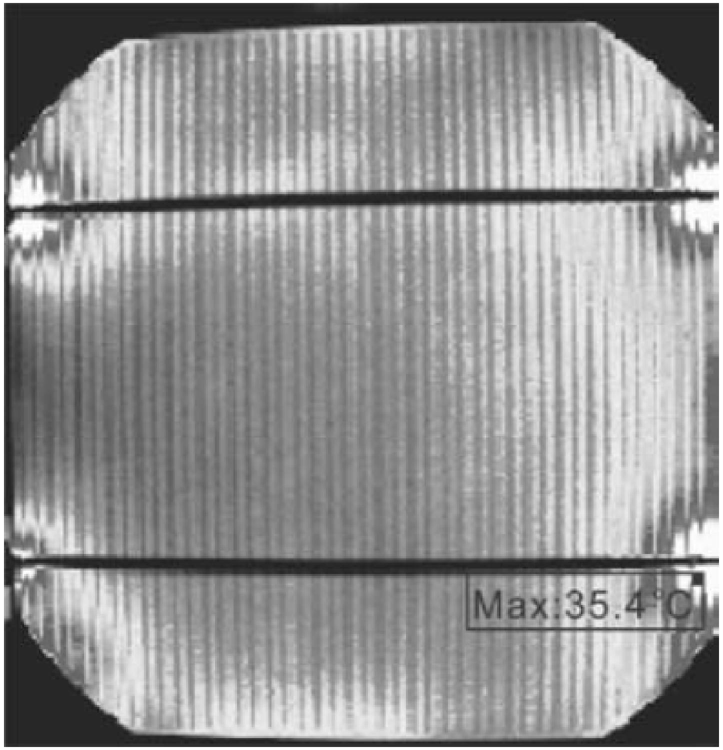

Fig. 4. Shunts caused by PECVD hooks under the four ends of bus bars.

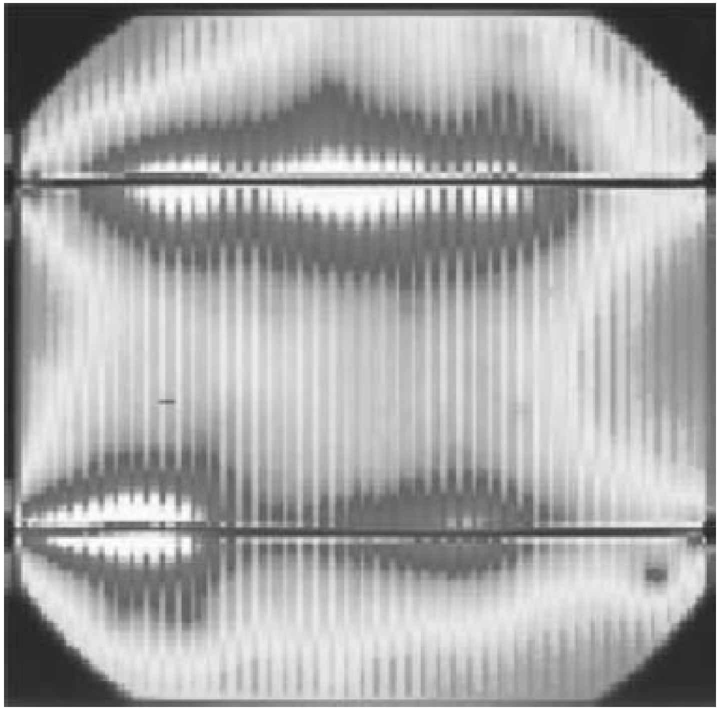

Fig. 8. Shunts caused by over sintering under the bus bars.

Z Lucheng et al, J Semiconductors 30, 076001-1 (2009)