A New Real-Time Quantum Efficiency Measurement System

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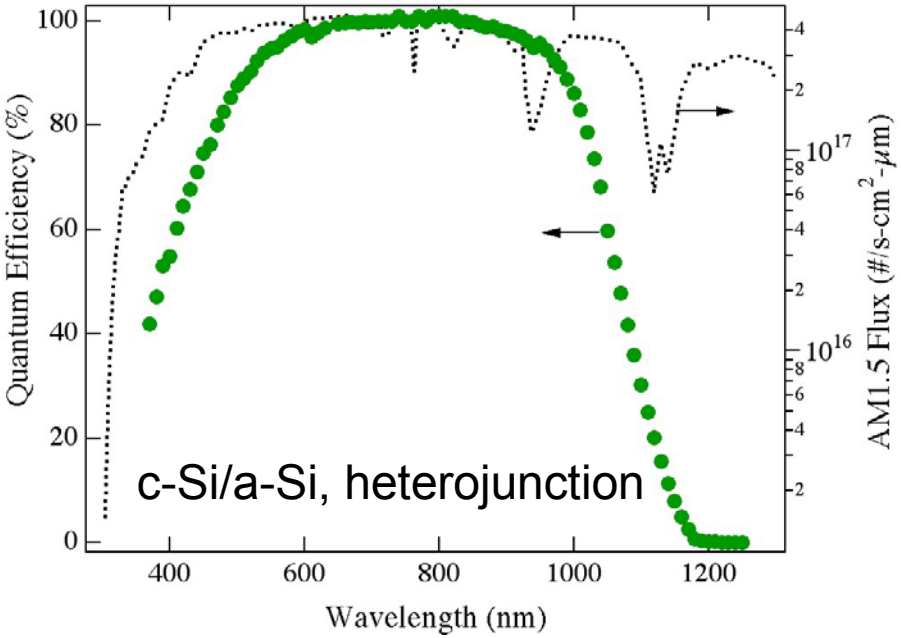
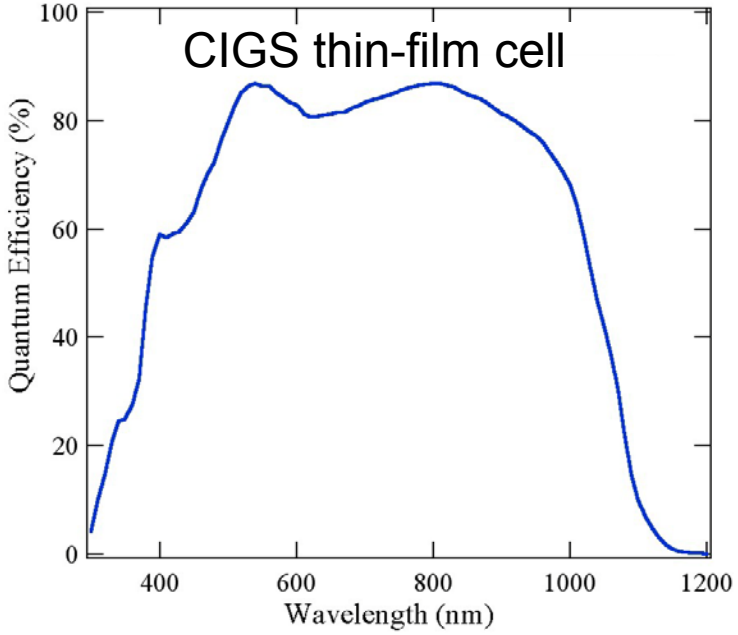
Information-Rich Quantum Efficiency Graphs





- Spectral response (current loss)
- Spatial response
  - "Blue" – front, "Red" - back surfaces, bulk
  - thin-film layers (thickness, composition, Bandgap)
- Diffusion length (modeling) (Kieliba, JAP 2006)
- Recombination centers (QE(T)) (Wagner,APL 2003)
- Junction physics, impurity diffusion (QE(V)) (Batzner TSF 2003),(a-Si:H cells)

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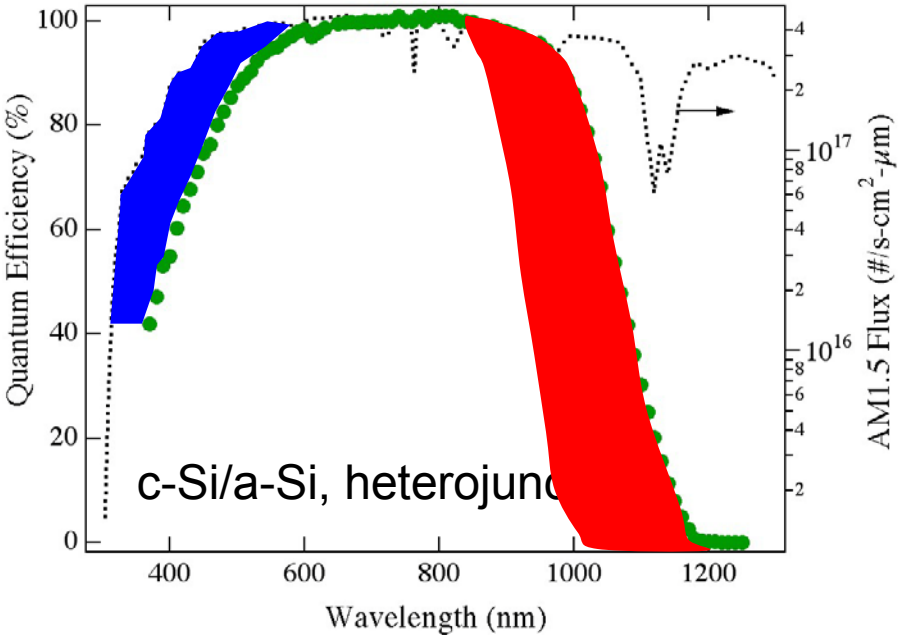

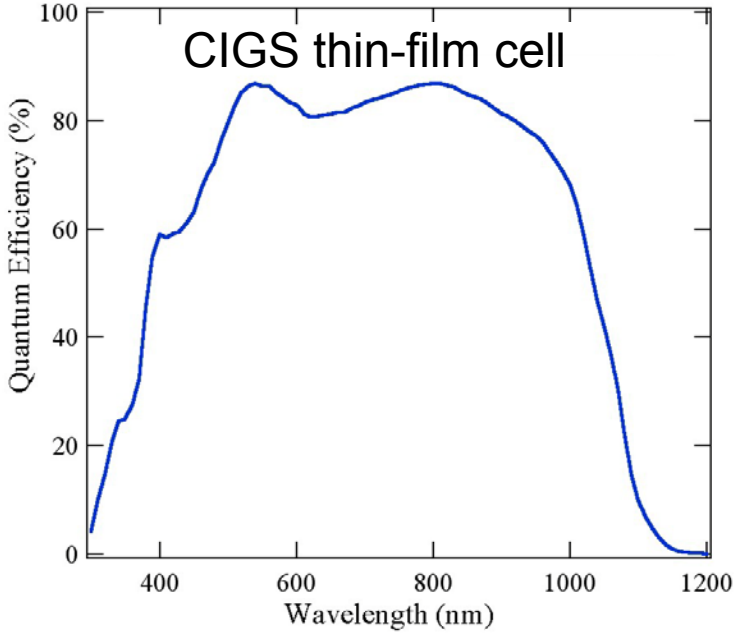

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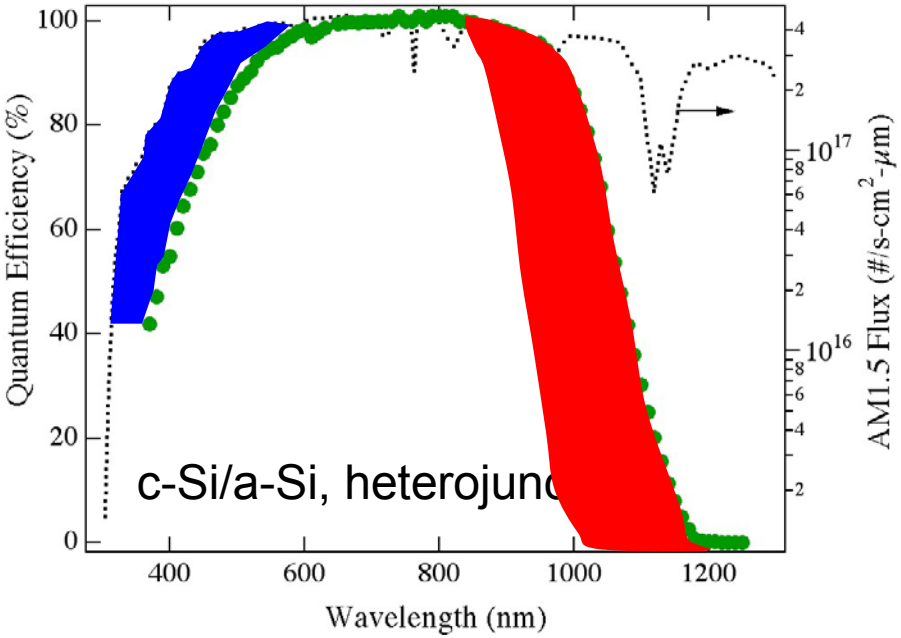

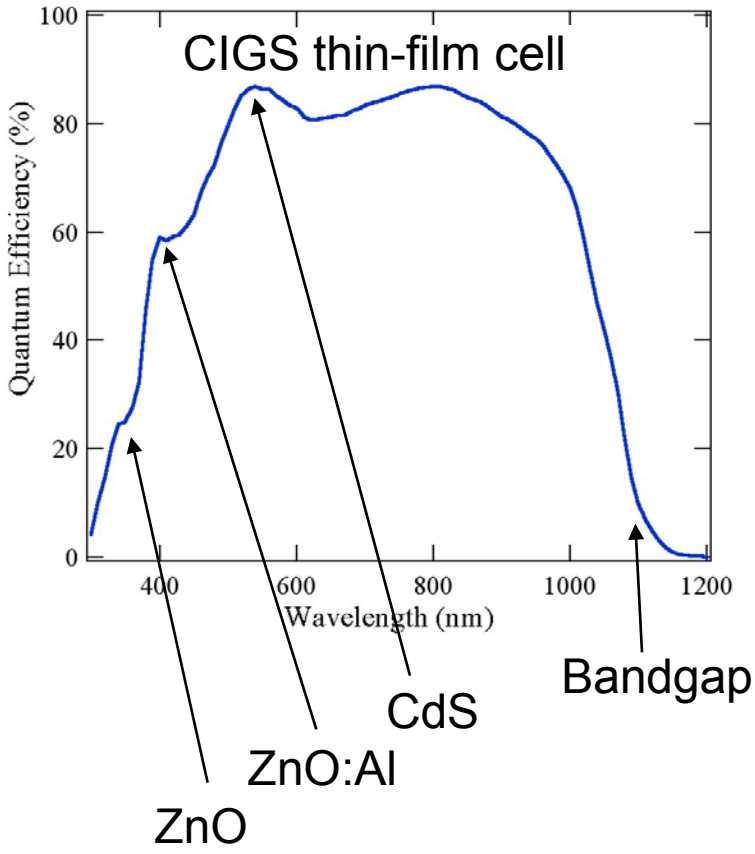

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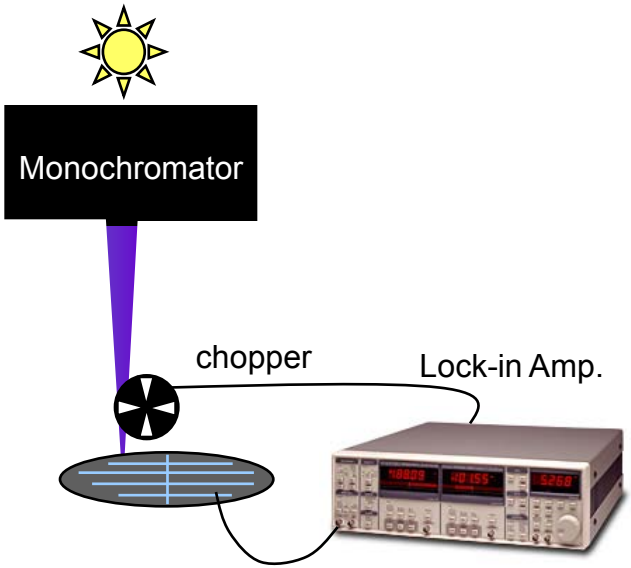
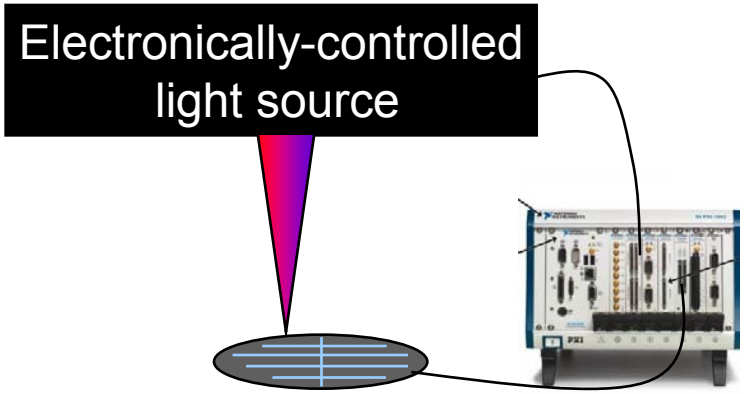
So, why don't we use QE graphs more in research and industry?

Traditional QE method

Time! (money, lack of graduate students)

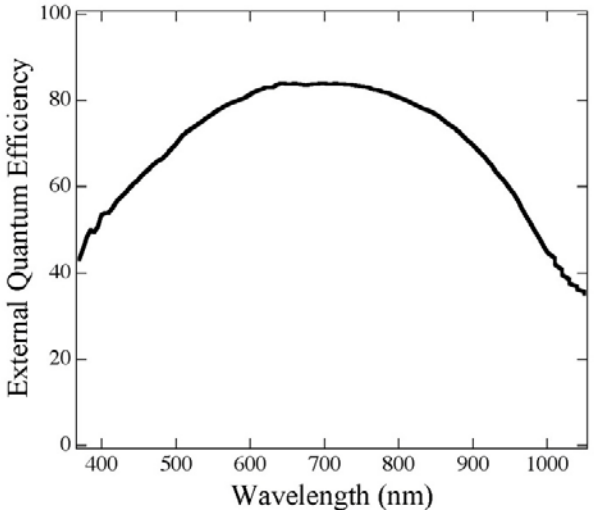
New method

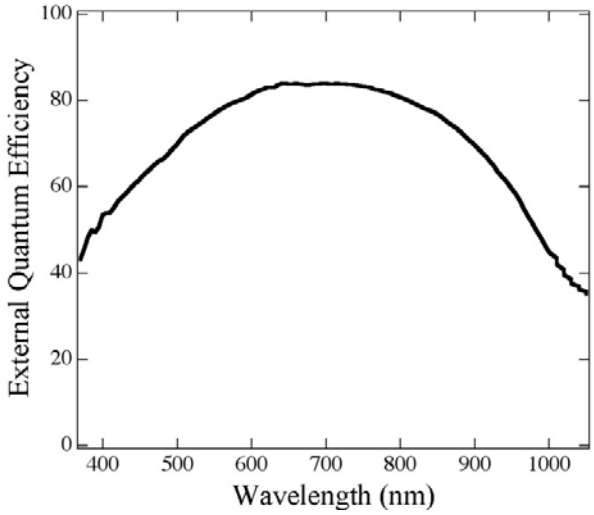




Parallel measurement ~ 0.1 sec

Serial measurement ~ 5-20 mins



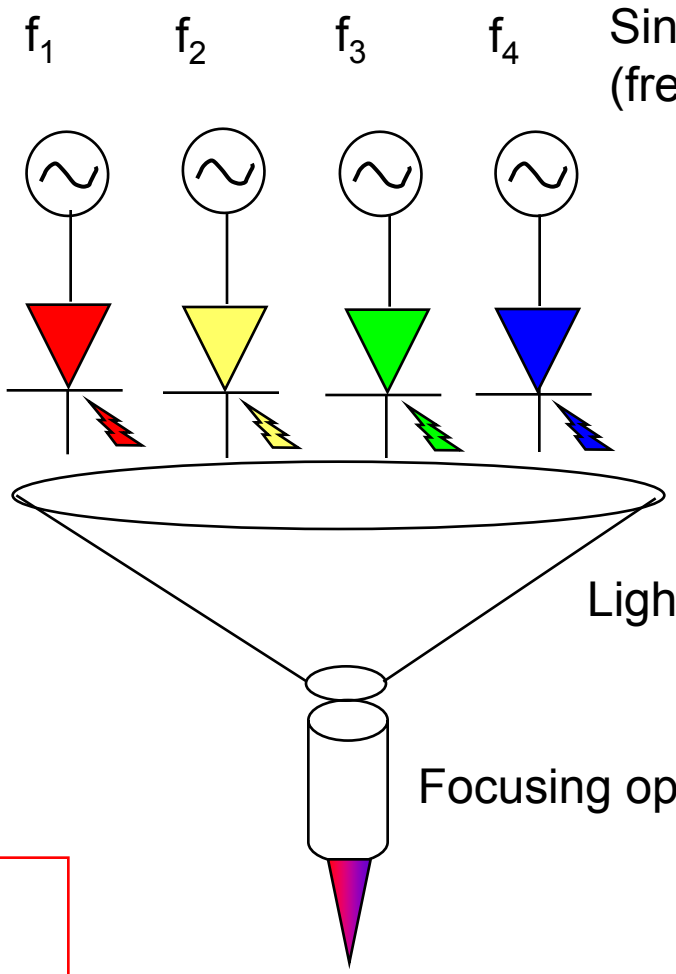


1000x decrease in time

New method: Real –Time Quantum Efficiency measurement system (RTQE)

Electronically-Controlled LED light source

LED (#, color)	λ_{peak} (nm)	Drive-frequency (Hz)
1, Red	700	1000
2, Yellow	600	1153
3, Green	550	1262
4, Blue	470	875
…	-	-



Parallel processing of information from an array of spectral channels encoded in modulated frequency bands

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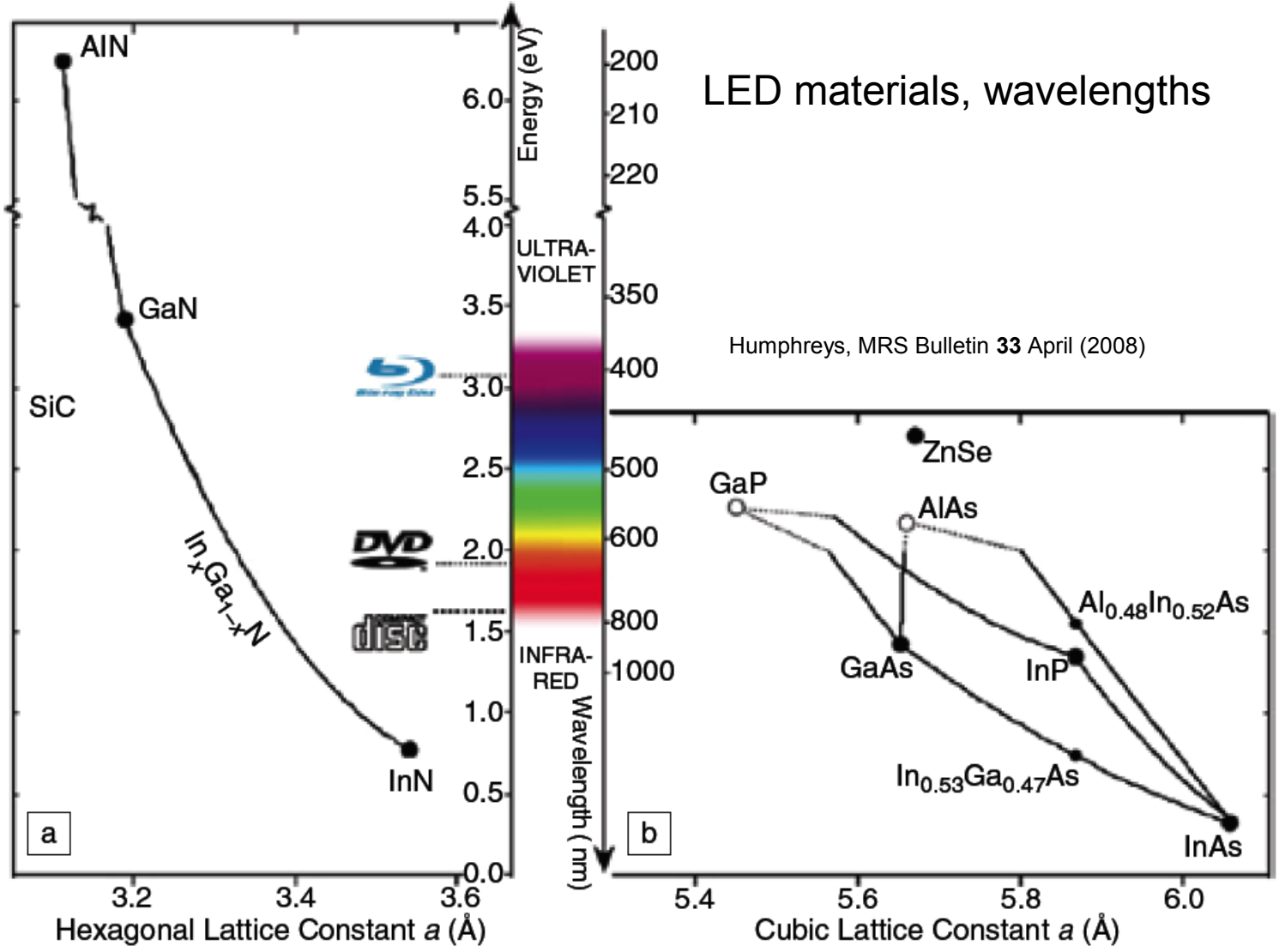


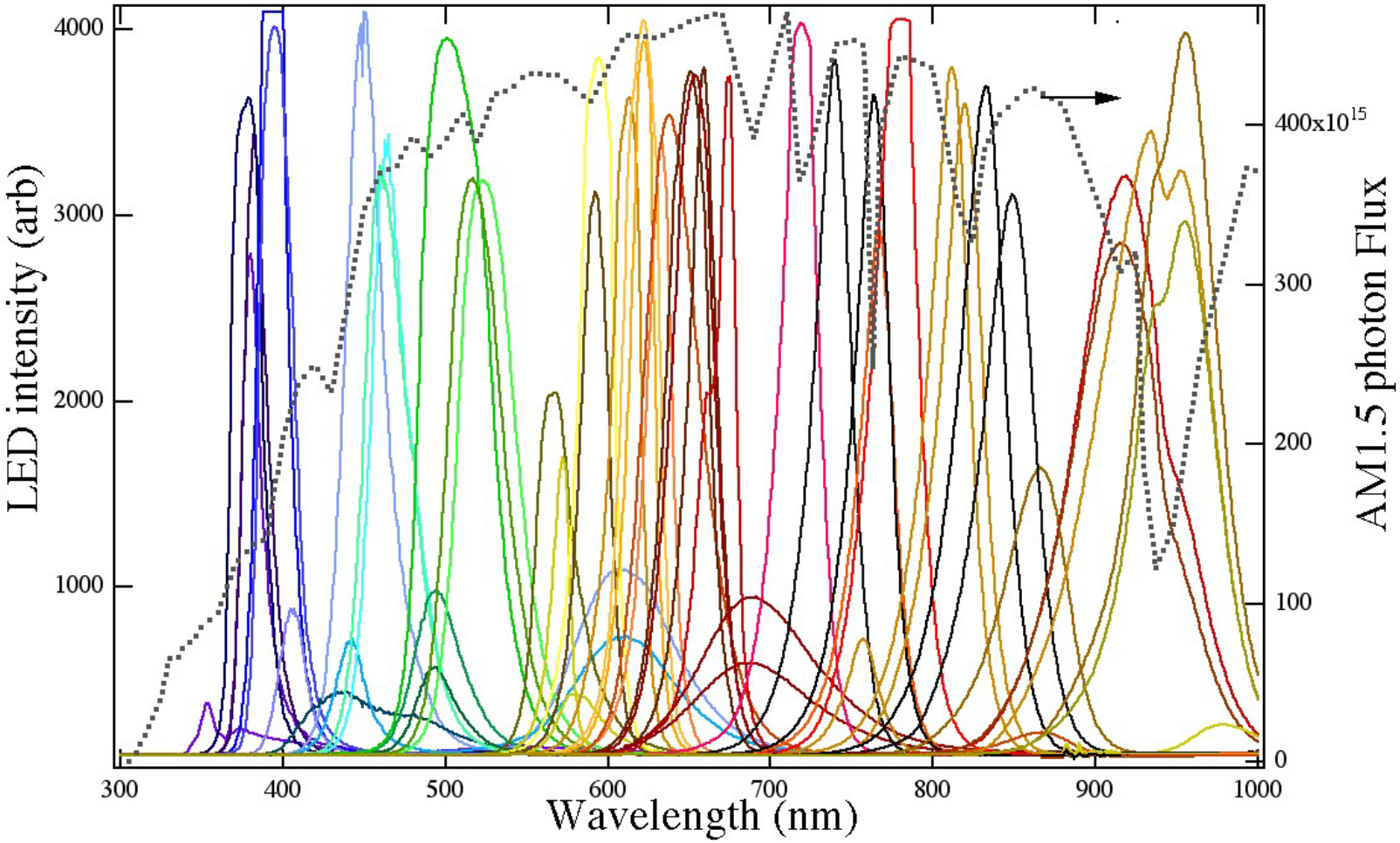
LED materials, wavelengths

Humphreys, MRS Bulletin **33** April (2008)

New method: Real –Time Quantum Efficiency measurement system (RTQE)

Electronically-Controlled LED light source

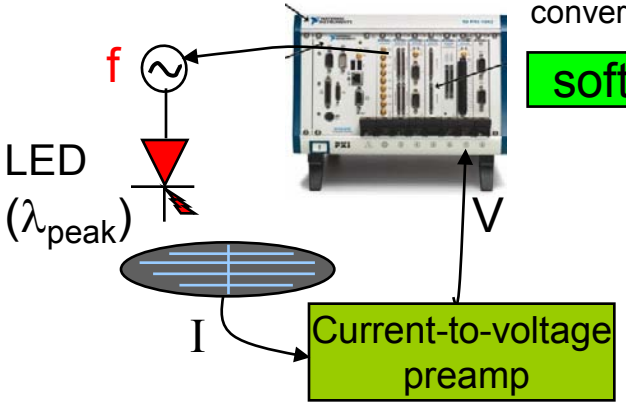
58-color LED array (2004)



Principle of operation

f, Sine wave drive frequency

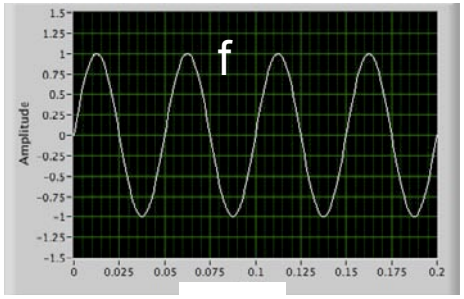
λ, LED emission wavelength



analog-to-digital converter DAQ card

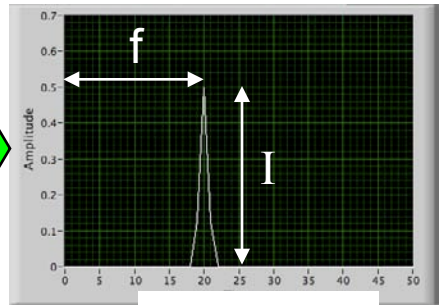
software

voltage vs time

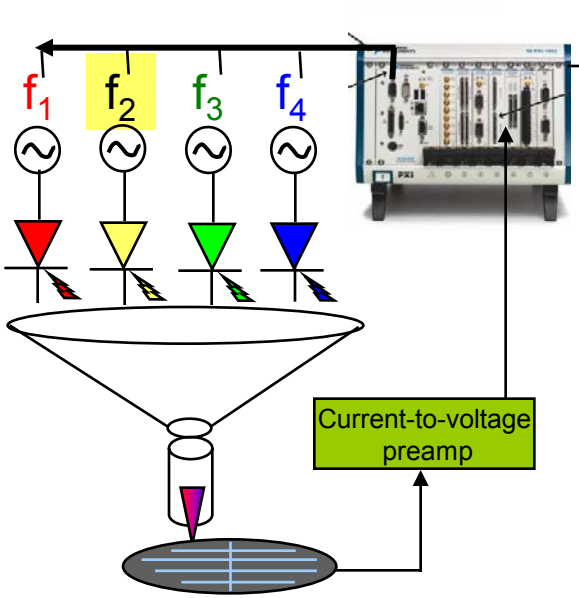


FFT

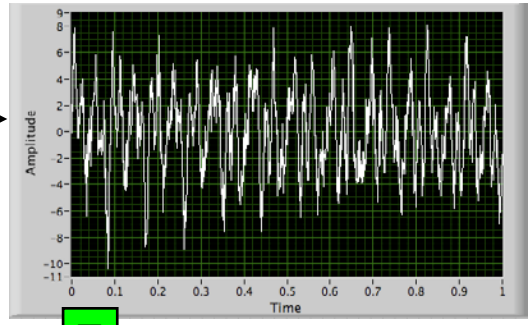
power spectrum



f_λ, $QE=K(I(f_\lambda))$



voltage vs time



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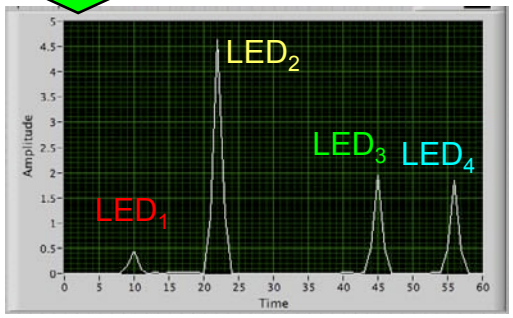
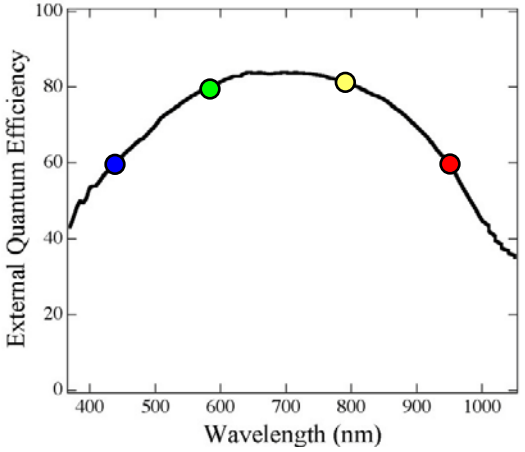




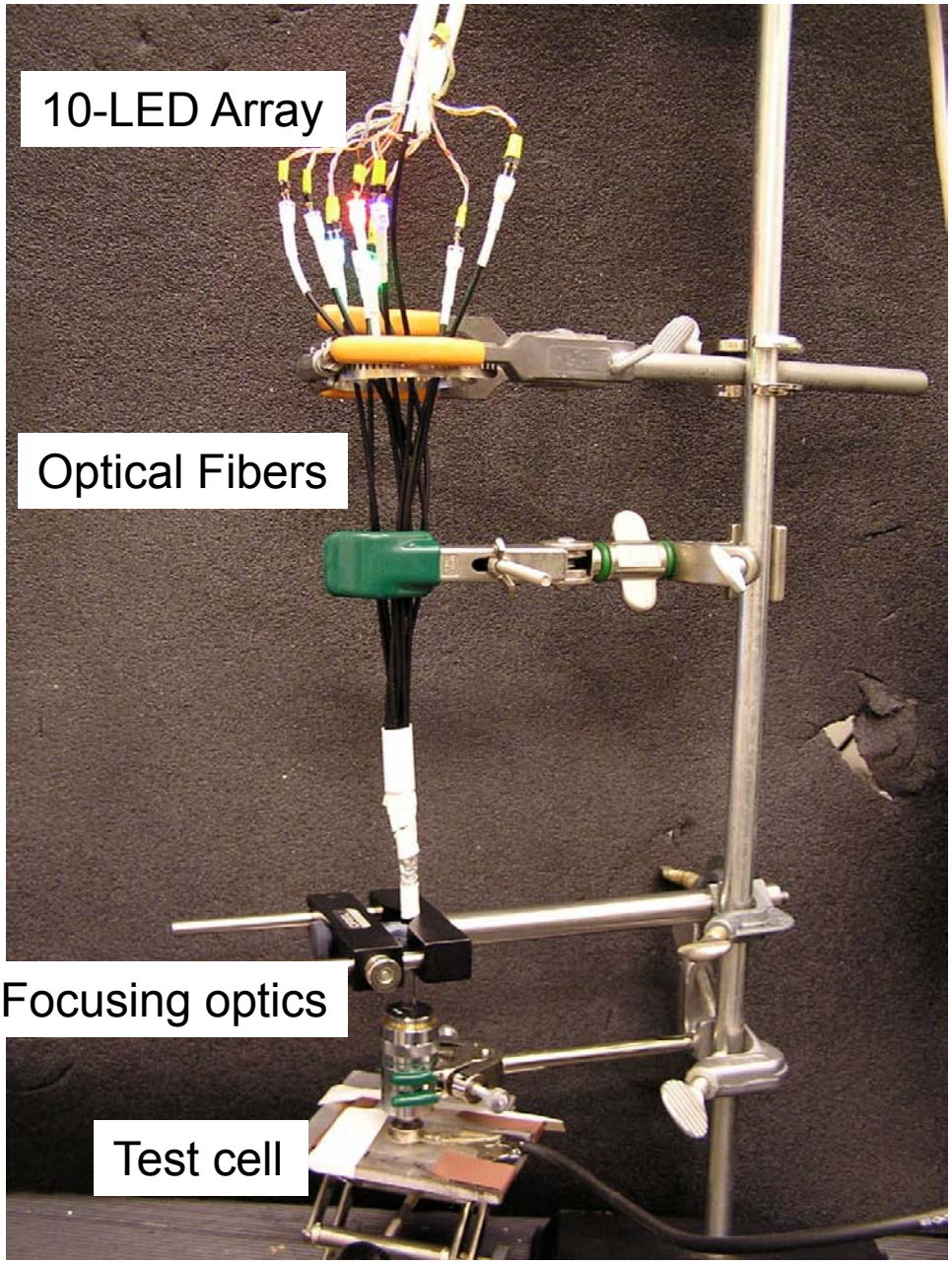
$f_{\lambda 1}$, $QE_1=K_1(I(f_{\lambda 1}))$

$f_{\lambda 2}$, $QE_2=K_2(I(f_{\lambda 2}))$

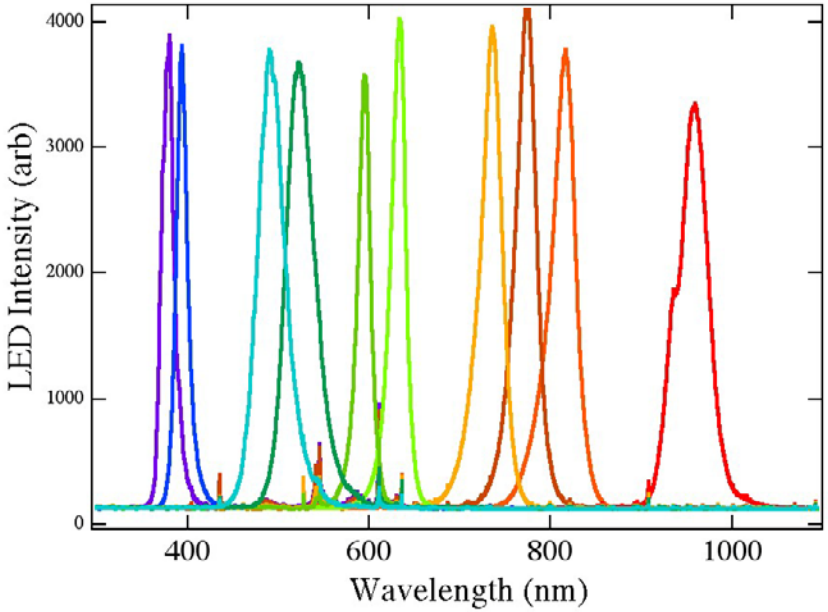
$f_{\lambda 3}$, $QE_3=K_3(I(f_{\lambda 3}))$

$f_{\lambda 4}$, $QE_4=K_4(I(f_{\lambda 4}))$

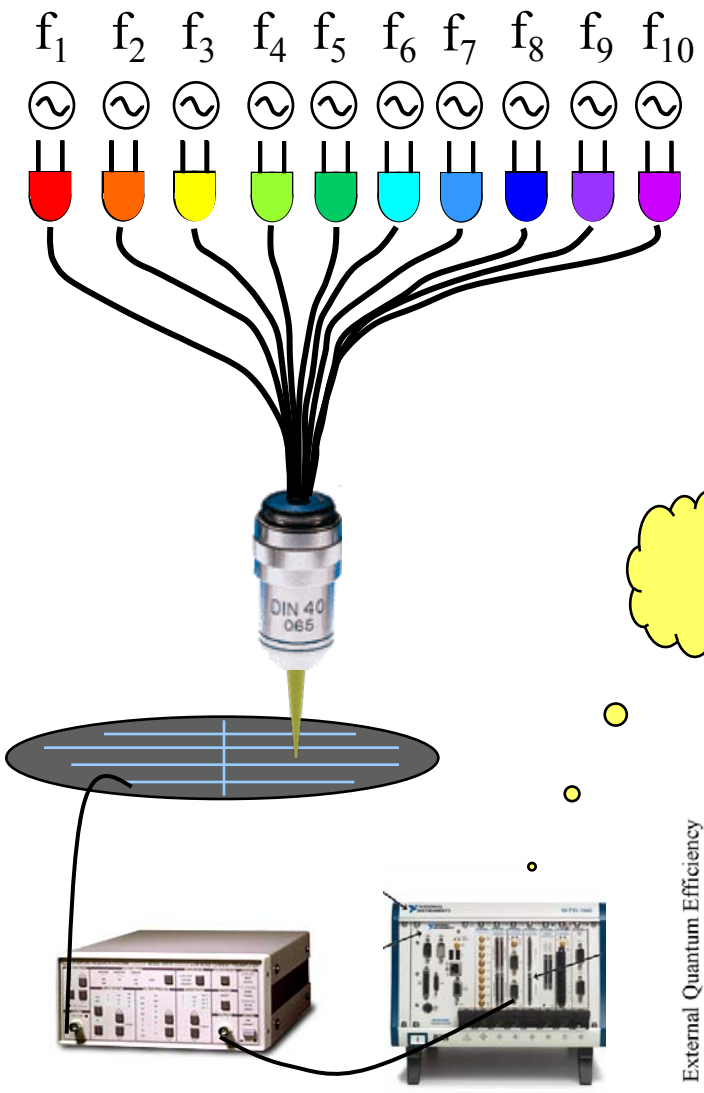
Proof of concept: 10-LED Real-Time QE system prototype

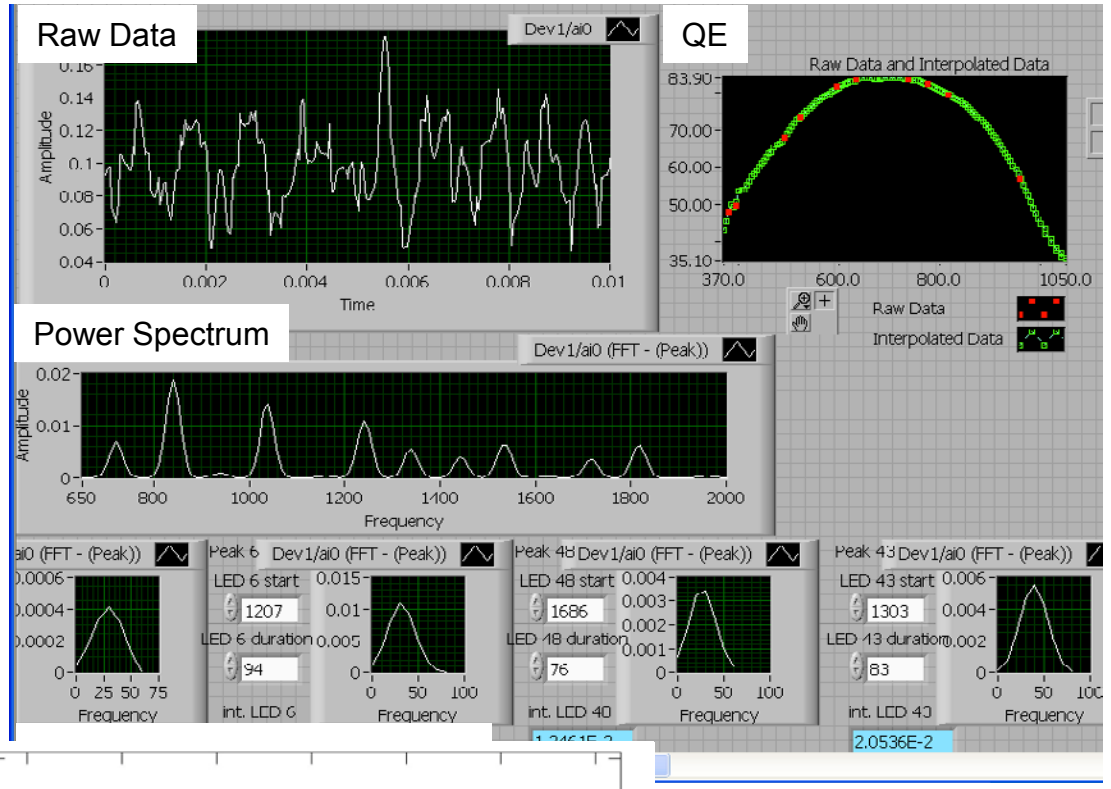


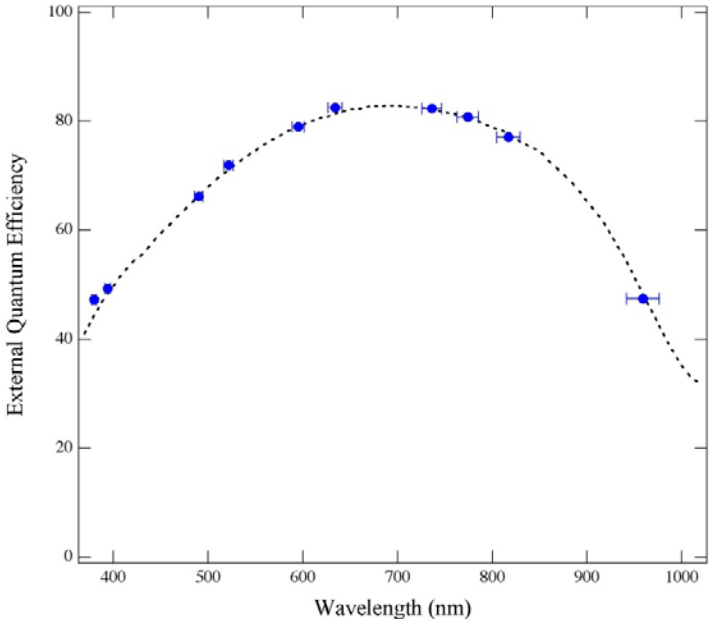
10 LEDs were chosen to span the Spectral response range of C-Si.



10-LED array prototype







LED QE (real-time)

Standard QE (20 mins)

Technical Considerations:

1) LED emission: Spectral width, Asymmetric spectra, Spectral overlap
Calibration accounts for LED spectra using Singular Value Decomposition mathematics

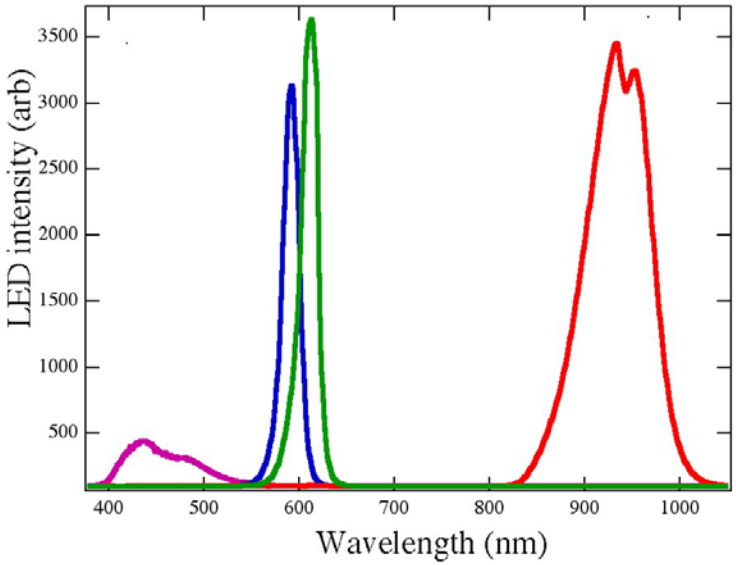
Singular Value Decomposition (SVD)
"least-squares-fit" for matrices

Current (LED) = Illumination (LED,λ) * QE(λ)

$$\begin{pmatrix} I_1 \\ I_2 \\ I_3 \\ . \\ . \\ . \end{pmatrix} = \begin{pmatrix} \lambda_{11},\lambda_{12},\lambda_{13},\ldots \\ \lambda_{21},\lambda_{22},\lambda_{23},\ldots \\ \lambda_{31},\lambda_{31},\lambda_{33},\ldots \\ \ldots\ldots\ldots \end{pmatrix} * \begin{pmatrix} QE_1 \\ QE_2 \\ QE_3 \\ . \\ . \\ . \end{pmatrix}$$

LED spectrum (→) ; LED # (↑)

$$(QE\ (\lambda)) = (V)(S)(U^T)(\text{current(LED)})$$



2) LED drive signal: sinusoidal LED emission, non-multiple drive frequencies.
high data acquisition < drive frequency < 1/response time

3) Data acquisition rate: 2x highest LED drive frequency (avoid aliasing)

The Real-Time QE system is:

Parallel processing of information
from an array of spectral channels
encoded in modulated frequency bands

- fast
- inexpensive
- all solid-state
- robust

- Replace traditional lab-based QE systems

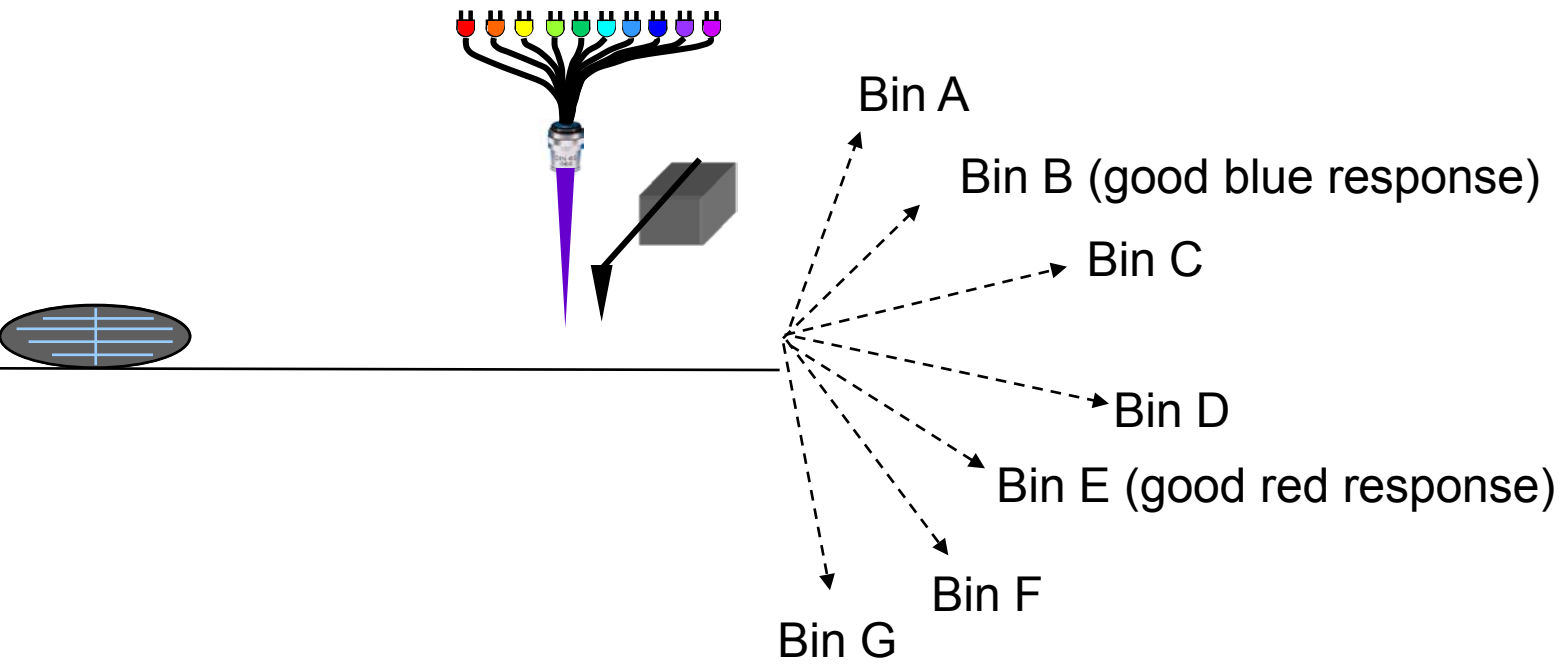
Expanded Applications

- In-line diagnostics
- Spatial QE mapping
- Multi-junction QE measurements

In-line QE for solar cell manufacturing

Benefits:

- In-line diagnostics for process control
- Device physics feedback
- Spectral-matching cell binning to maximize module KW-hr output



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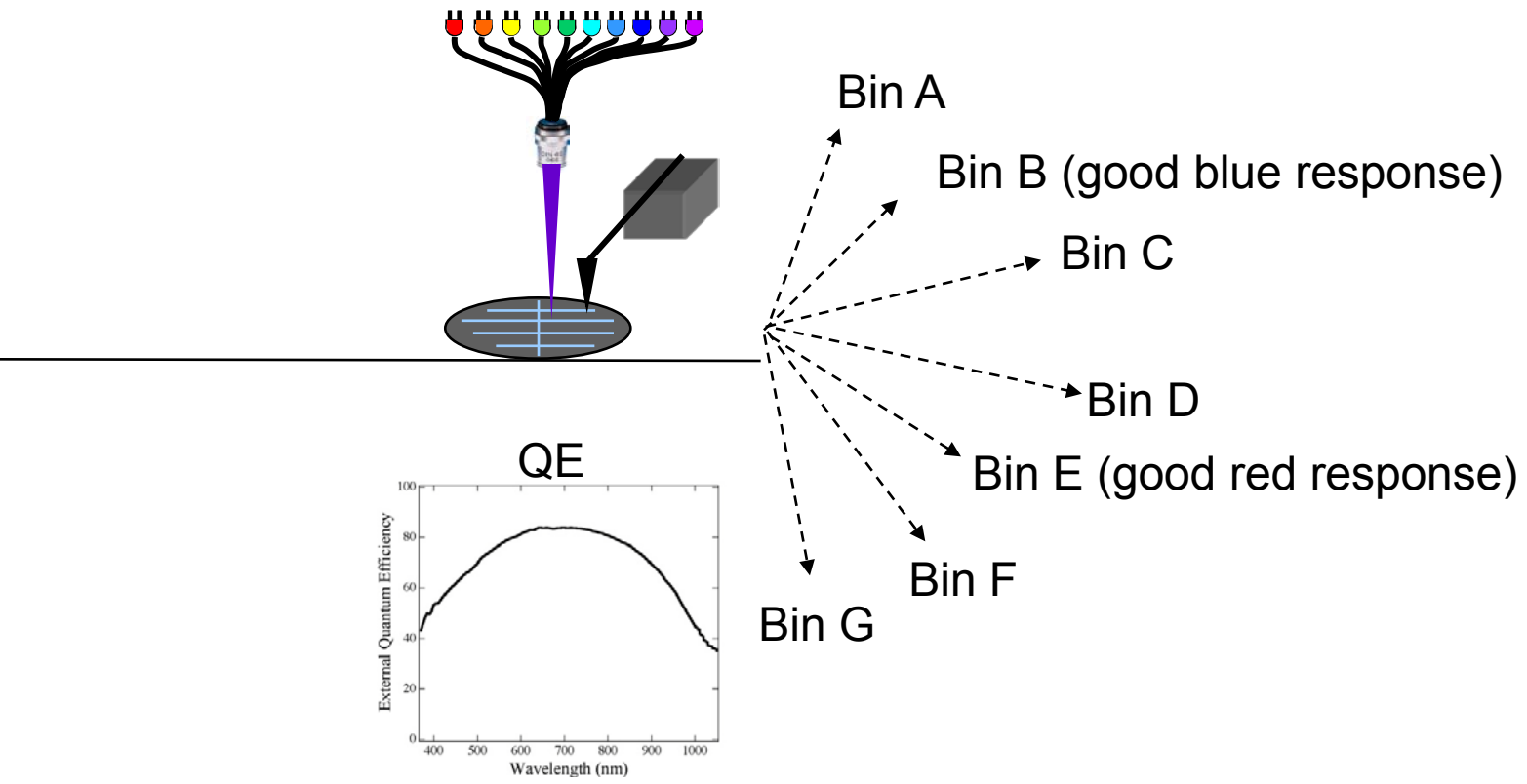

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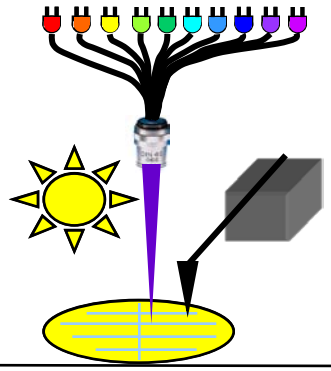


Bin A

Bin B (good blue response)

Bin C

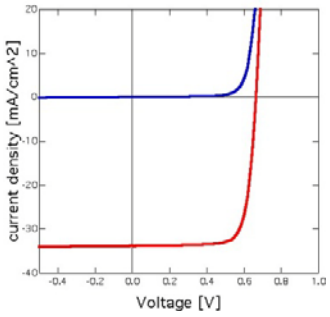
Bin D

Bin E (good red response)

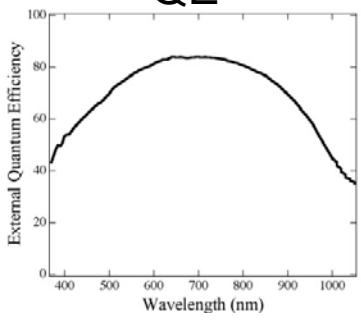
Bin F

Bin G

JV



QE



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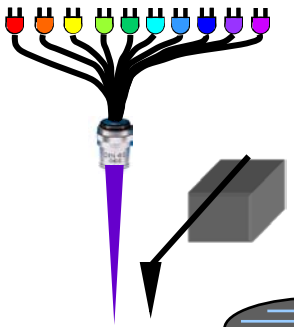

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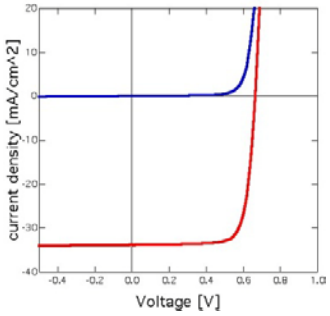

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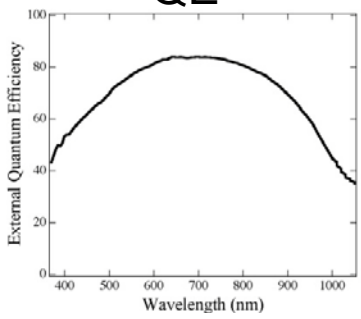

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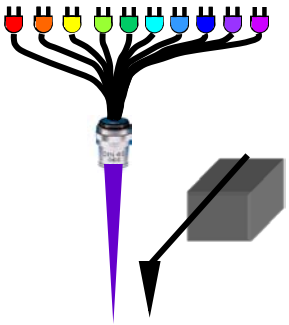

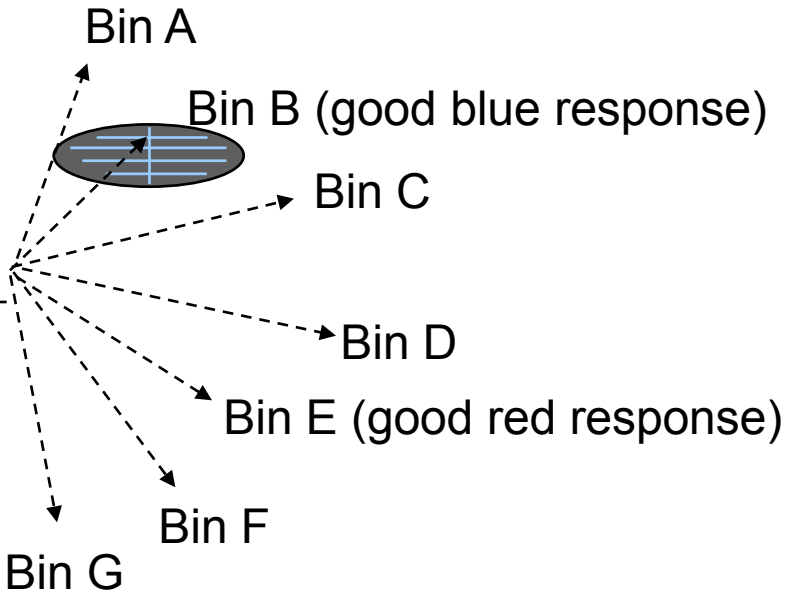

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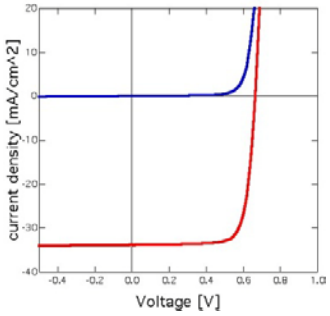

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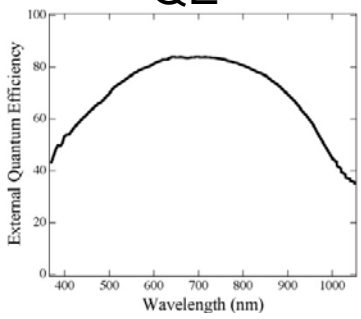

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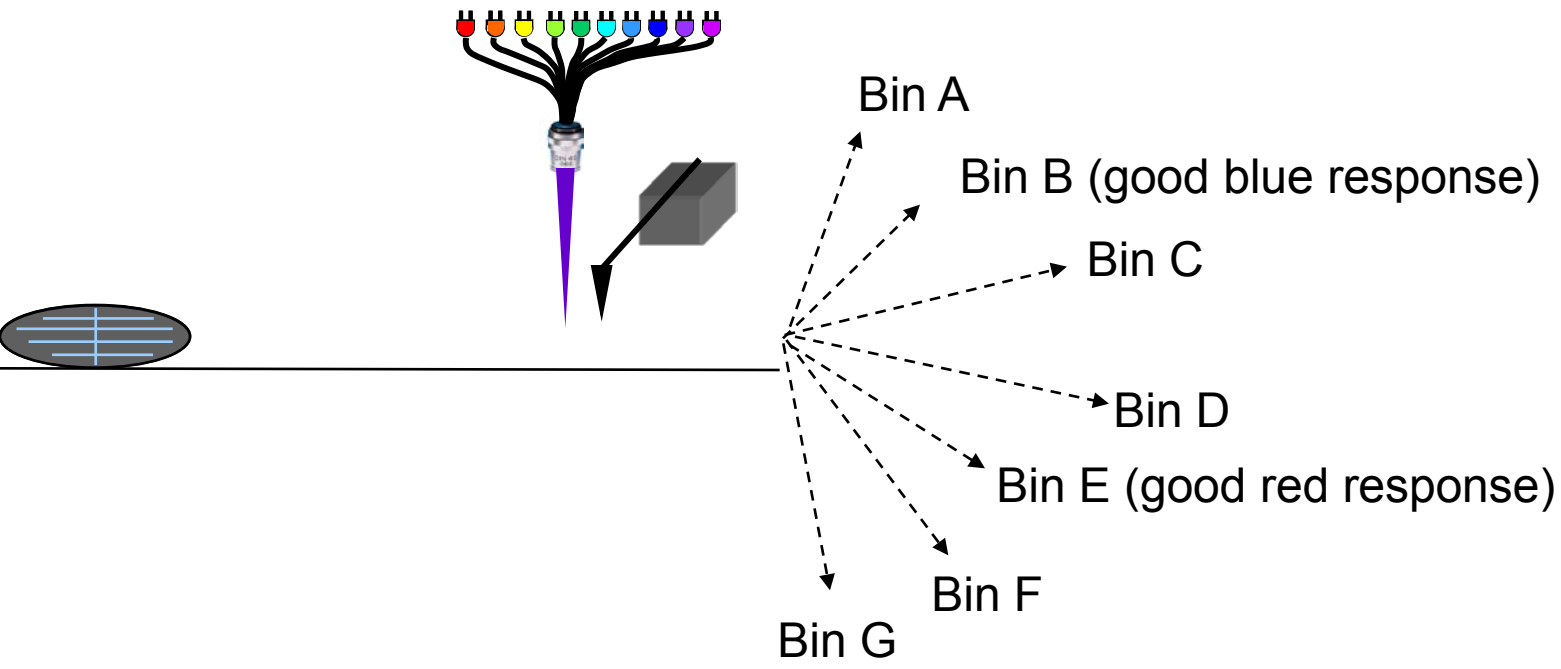

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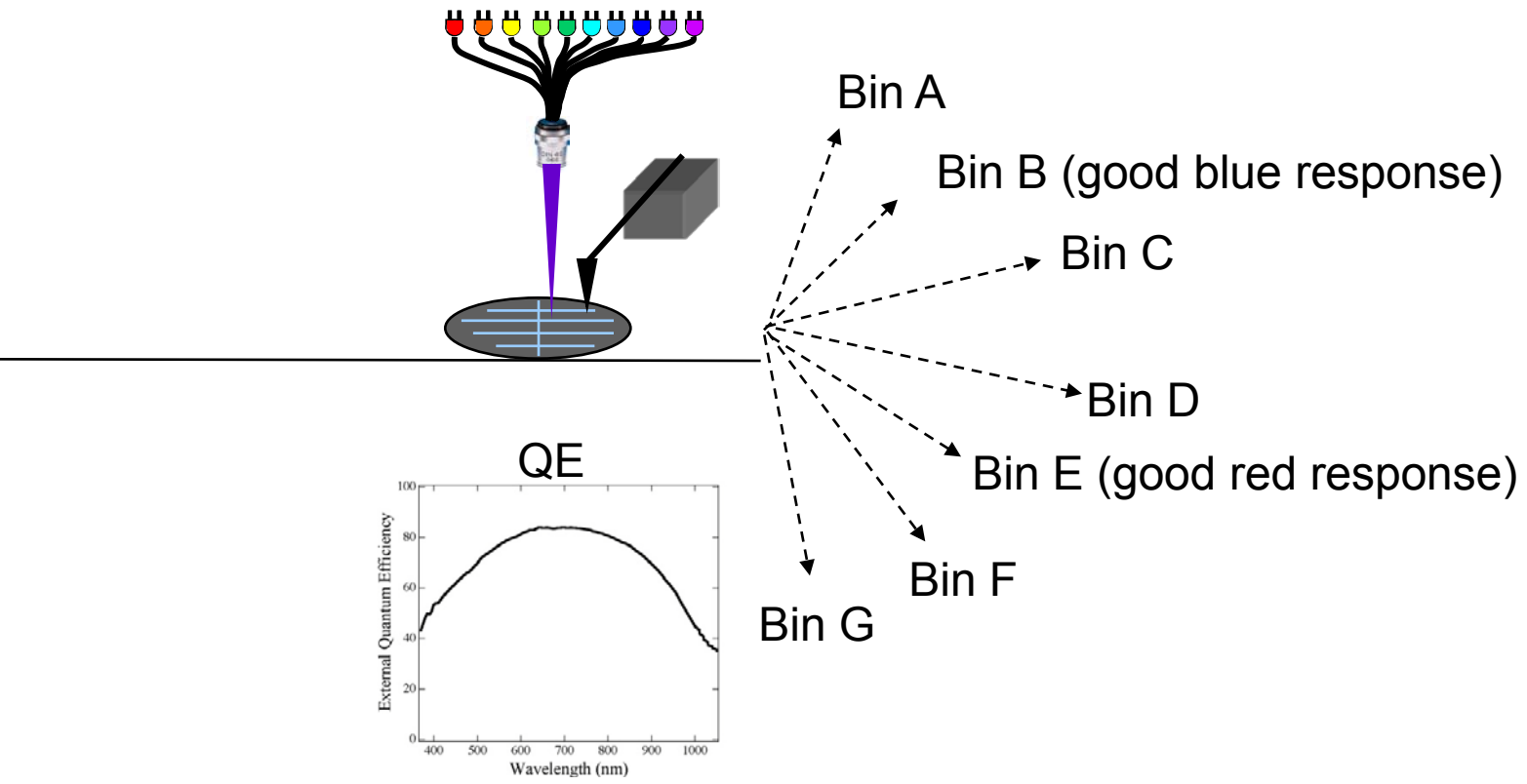

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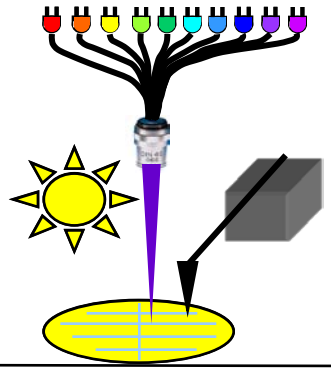

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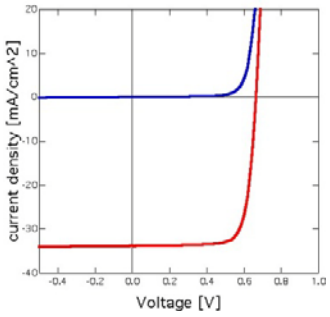

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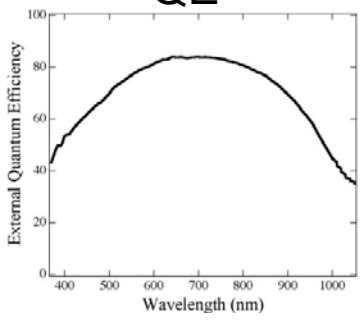

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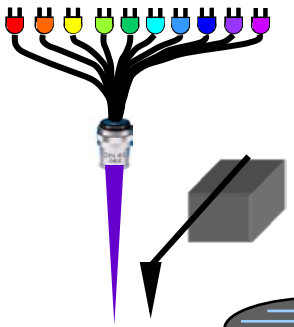

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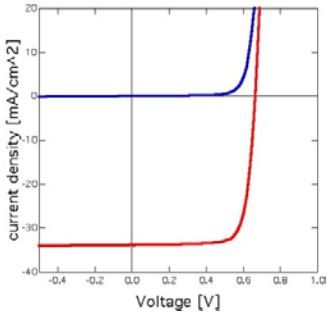

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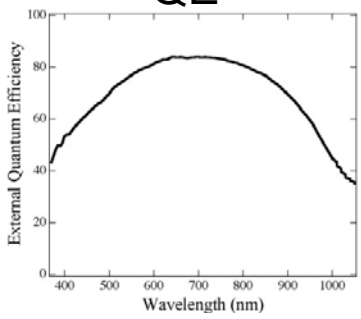

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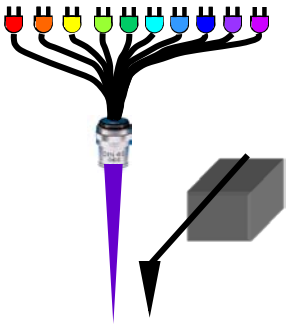
- Device physics feedback
- Spectral-matching cell binning to maximize module KW-hr output



Bin A

Bin B (good blue response)

Bin C

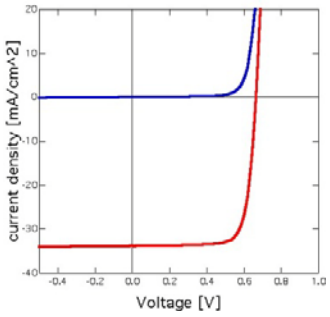
Bin D

Bin E (good red response)

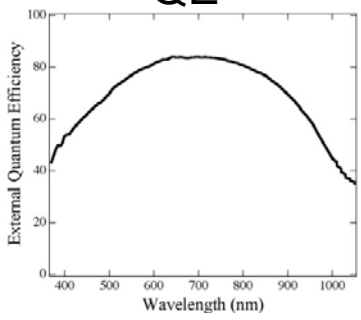
Bin F

Bin G

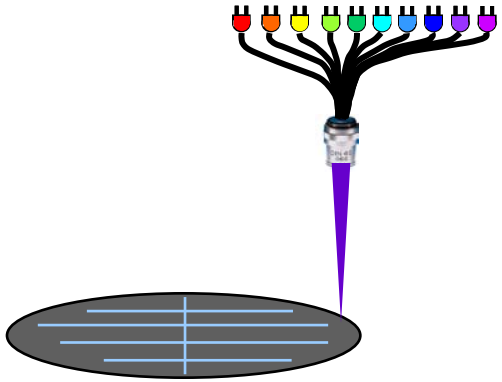
JV

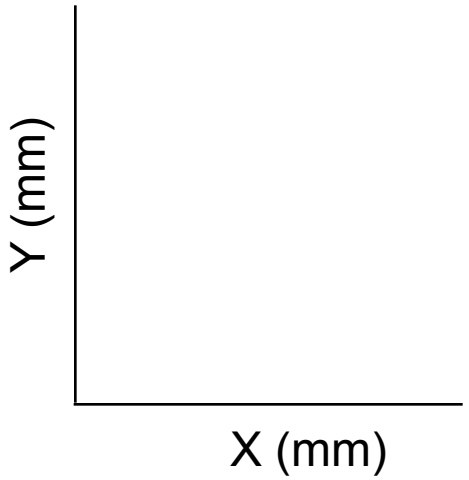


QE



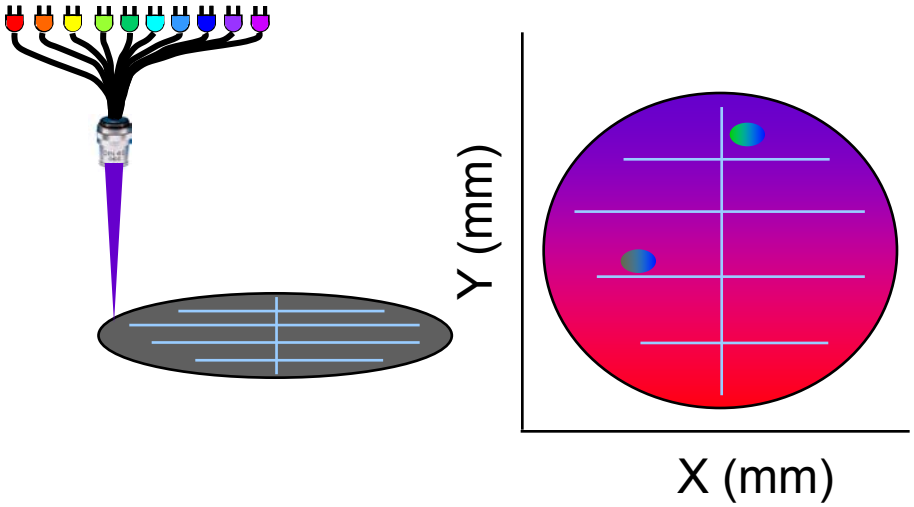
Spatial spectral-response Mapping (cells, modules)



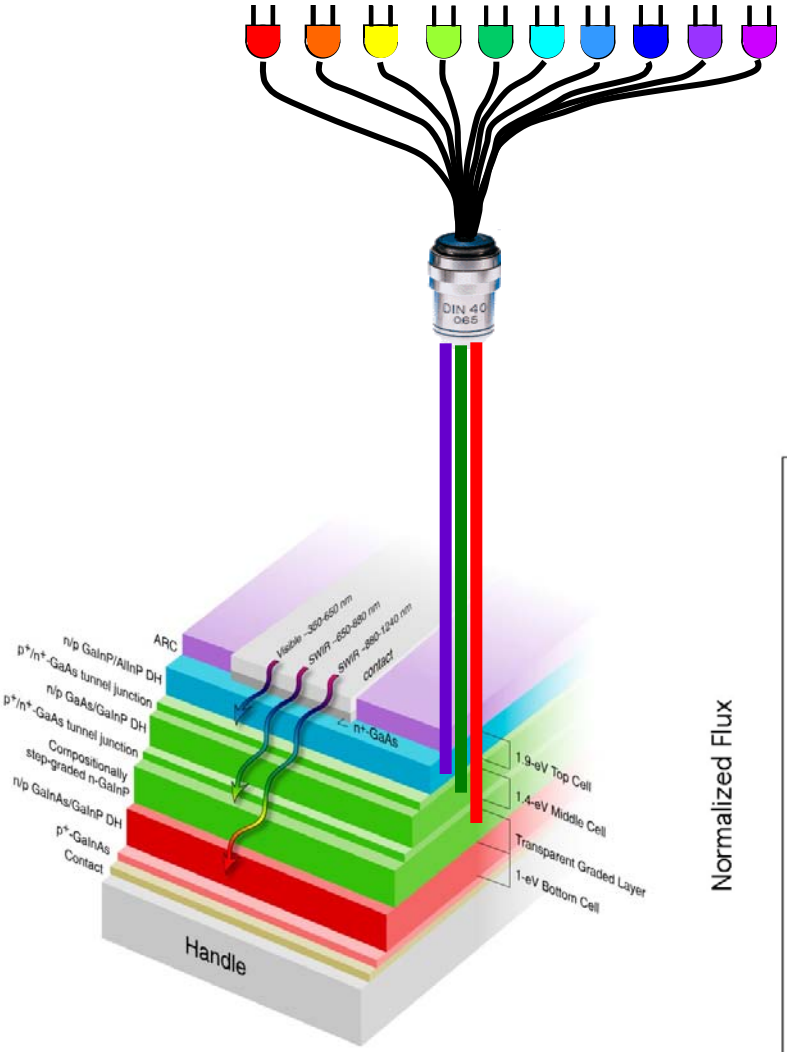


Spatial spectral-response Mapping (cells, modules)

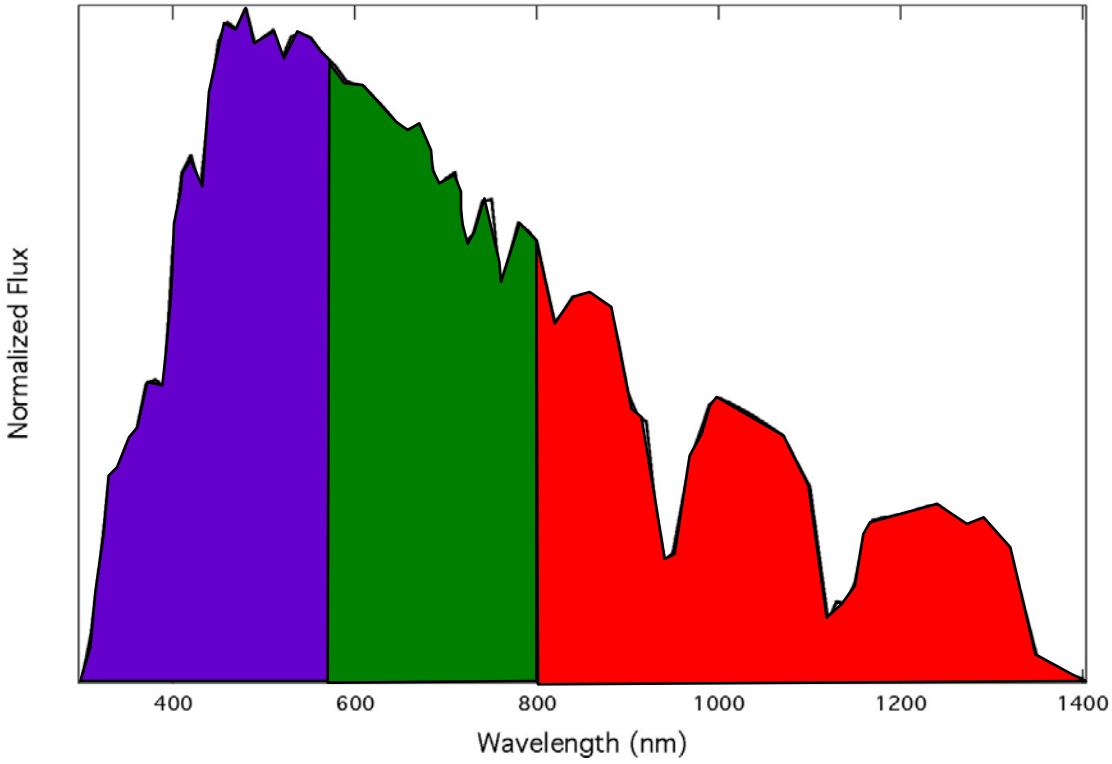
Cell and module uniformity
Defects
Process control



Electronic control of light spectrum
Multi-junction solar cell QE measurements



- RTQE measurement on subcell under test
- Light bias other subcells to allow transport



Real Time Quantum Efficiency Technique

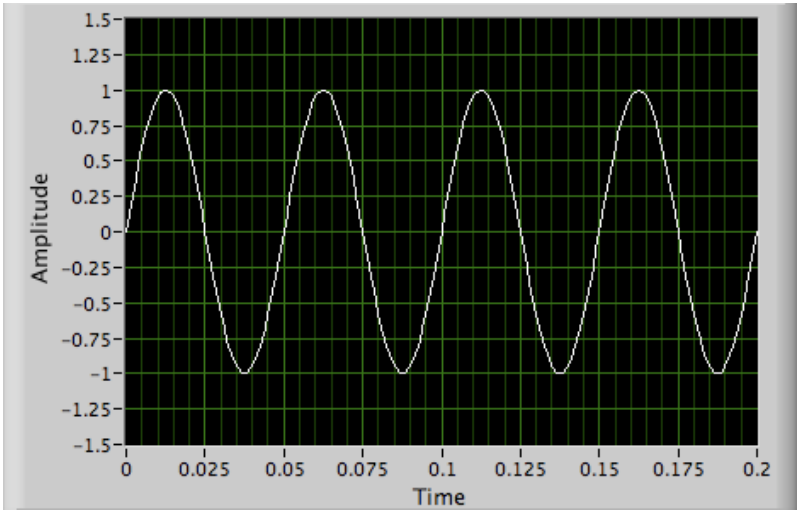
- Electronically controlled full-spectrum LED light source
- Parallel data processing
- Simple, robust, "inexpensive", solid-state, FAST (~1000 vs 1 QE Measurement during this talk)

Expanded Applications

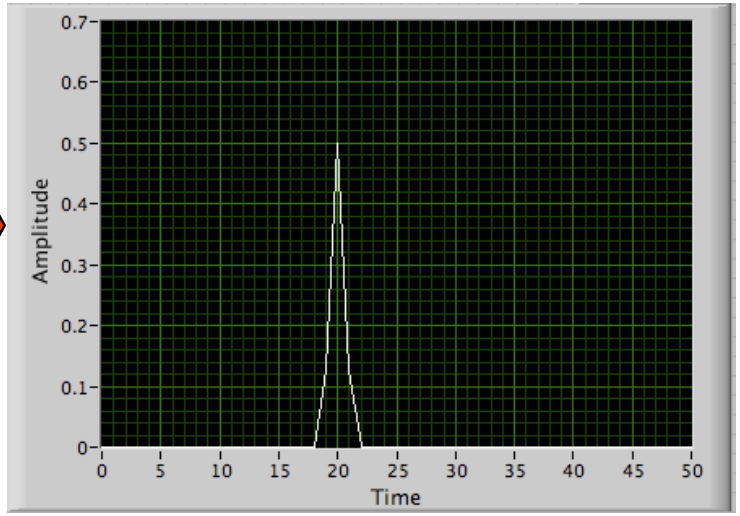
- Industrial In-line diagnostics, spectral-matching cell sorting
- Spatial spectral response mapping
- Electronic filtering – tandem solar cell QE measurements
- Technique applicable to other spectroscopy techniques

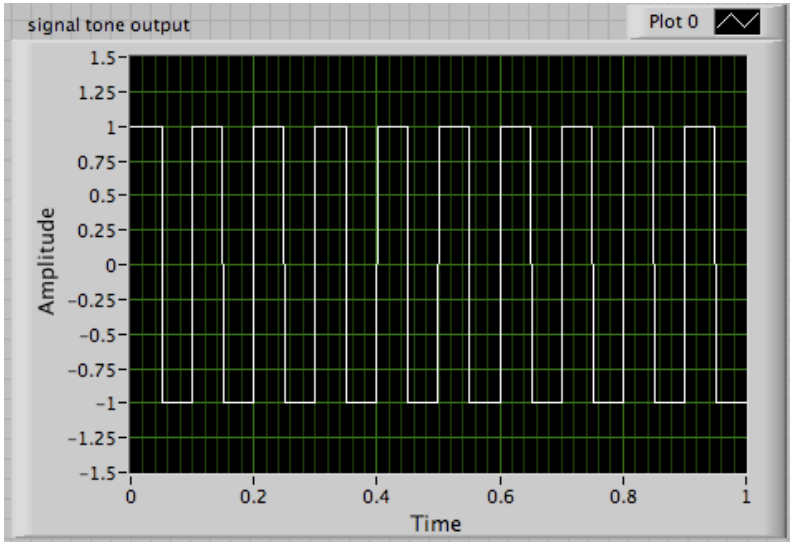
Further information:
Technical: david_young@nrel.gov
Technology Licensing: david_christensen@nrel.gov

Pure sine wave drive voltage:



FFT





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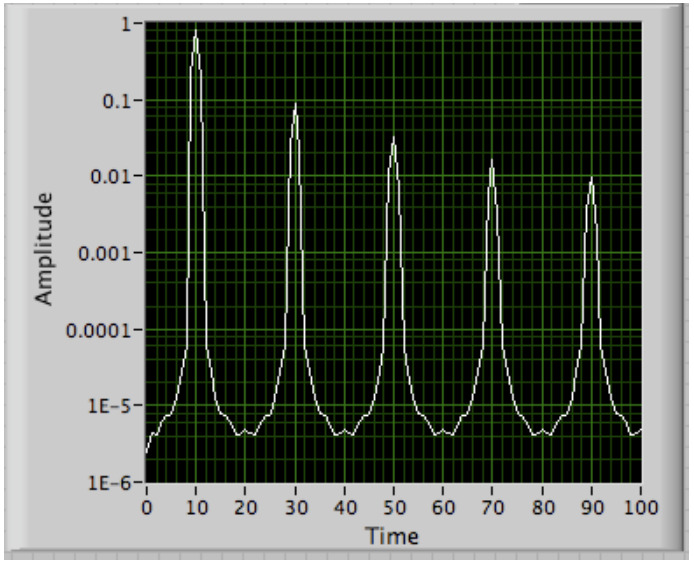

No multiple frequencies

fast data acquisition rate <Drive frequencies < 1/minority life time, acquisition/2

LED spectral width