

Characterization of 19.9% Efficient CIGS Absorbers

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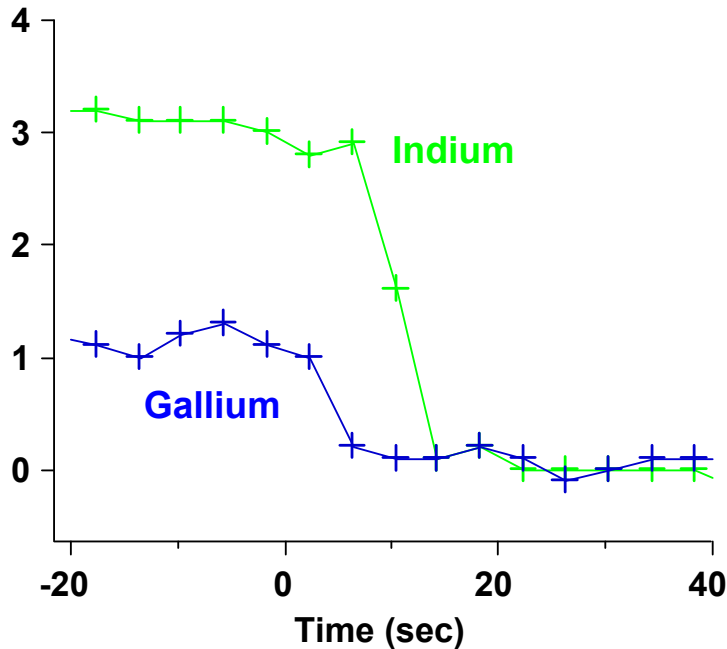
National Renewable Energy Laboratory

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Device	Area (cm ²)	Efficiency (%)	V _{oc} (mV)	J _{sc} (mA/cm ²)	Ff (%)	R (Ω-cm ²)	A	J ₀ (mA/cm ²)
C1068-2	0.450	18.8	678	35.2	78.7	0.41	1.30	5.3 x 10 ⁻⁸
S2051-A1	0.408	19.2	689	35.7	78.1	0.27	1.48	5.2 x 10 ⁻⁷
C1675-11	0.406	19.3	668	36.2	79.6	0.14	1.29	6.5 x 10 ⁻⁸
C1812-11	0.409	19.5	692	35.2	79.9	0.24	1.33	6.4 x 10 ⁻⁸
M2992-11	0.419	19.9	690	35.5	81.2	0.37	1.14	2.1 x 10⁻⁹

- 19.9% CIGS devices with improved fill factor, reduced recombination
- See Repins et al. *Progress in Photovoltaics* **16**, 2008



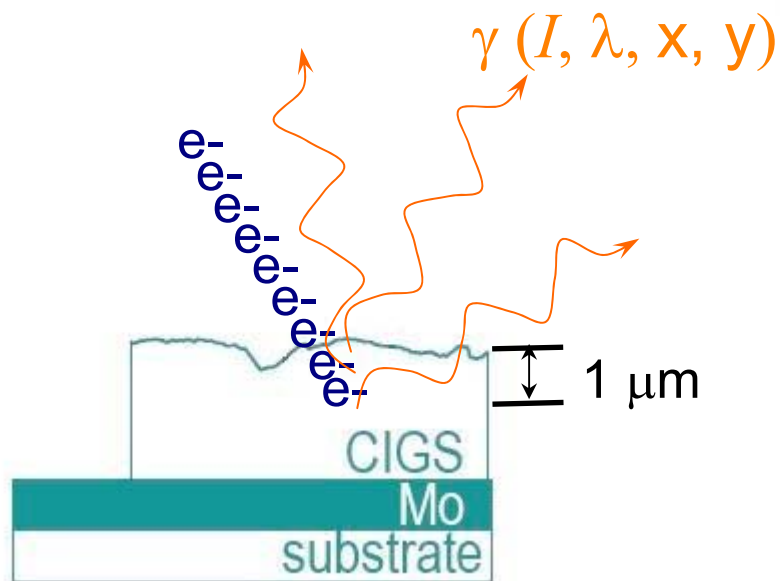
Device Name	Area (cm ²)	η (%)	Voc (mV)	FF (%)	Jsc (mA/cm ²)	Official Mst?
M2992-11#5	0.419	19.9	690	81.2	35.4	Yes
C2183-12#5	0.416	19.9	697	80.0	35.7	Yes
C2219-21#7	0.417	19.8	714	79.1	35.1	Yes
M2992-11#4	0.419	19.7	690	81.2	35.1	Yes
M2992-11#6	0.419	19.7	690	81.1	35.3	Yes
C2183-12#4	0.417	19.7	695	80.0	35.5	Yes
C2200-22#1	0.420	19.6	725	80.6	33.6	No
C2213-22#2	0.994	19.2	716	80.4	33.4	Yes

- Processing change: terminate three-stage CIGS deposition without Ga
- Improved device performance demonstrated in two different evaporators and by three different operators
- Why does this processing change improve device performance?

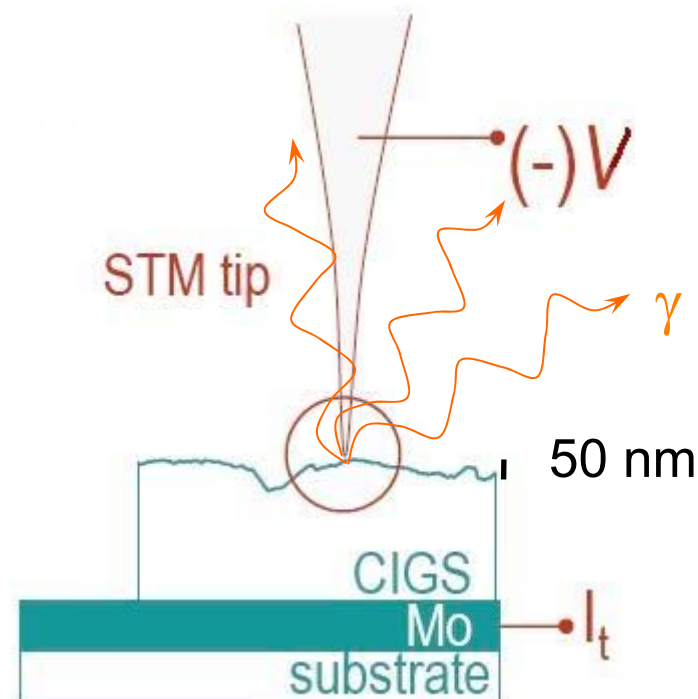
- Characterization:
 - Scanning tunneling luminescence (STL) mapping and cathodoluminescence (CL) mapping
 - Transmission electron microscopy (TEM)
 - Time-resolved photoluminescence (TRPL)
 - Capacitance-voltage (CV)
 - Grazing incidence x-ray diffraction (GIXRD)
- Note which results are typical of high-efficiency ($>18\%$) CIGS, and which results are particular to most recent ($>19.5\%$) CIGS.

STL and CL mapping

Measure intensity and wavelength of luminesced photons as a function of position



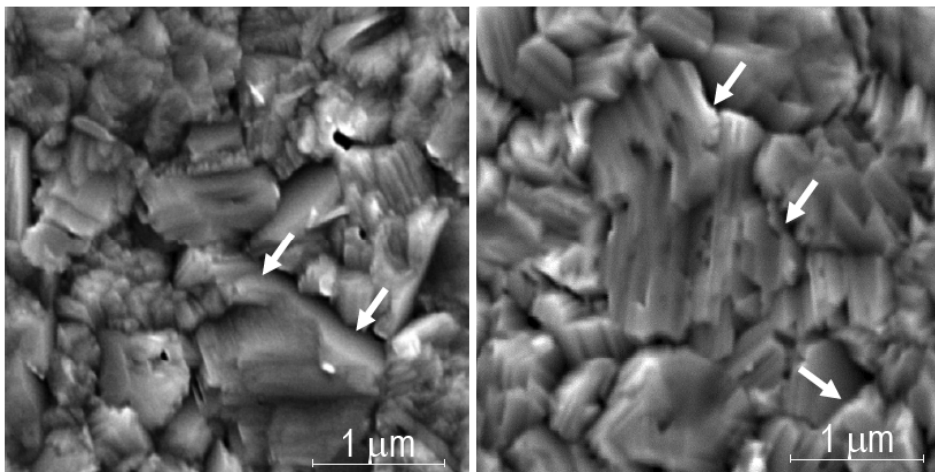
CL: electron beam excitation
 $\sim 1\ \mu\text{m}$ penetration depth



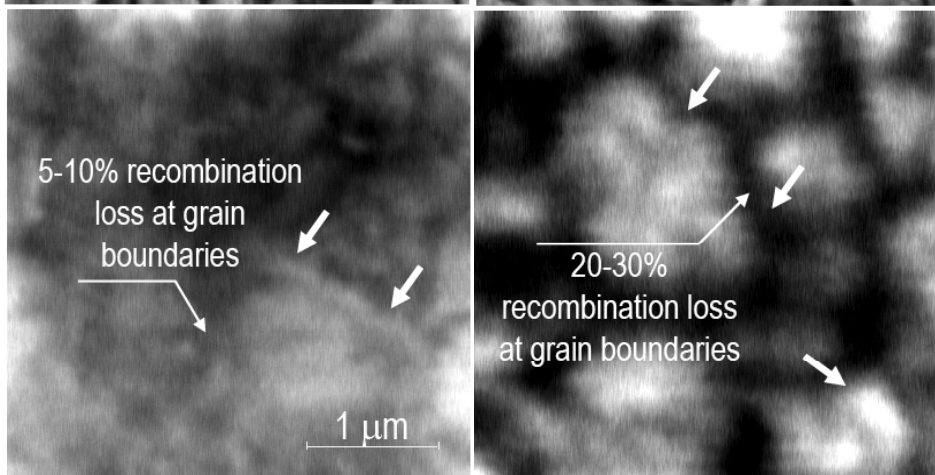
STL: excitation confined to
top $50\ \text{nm}$ or less

Example: CL intensity as a function of position

SEM



CL map

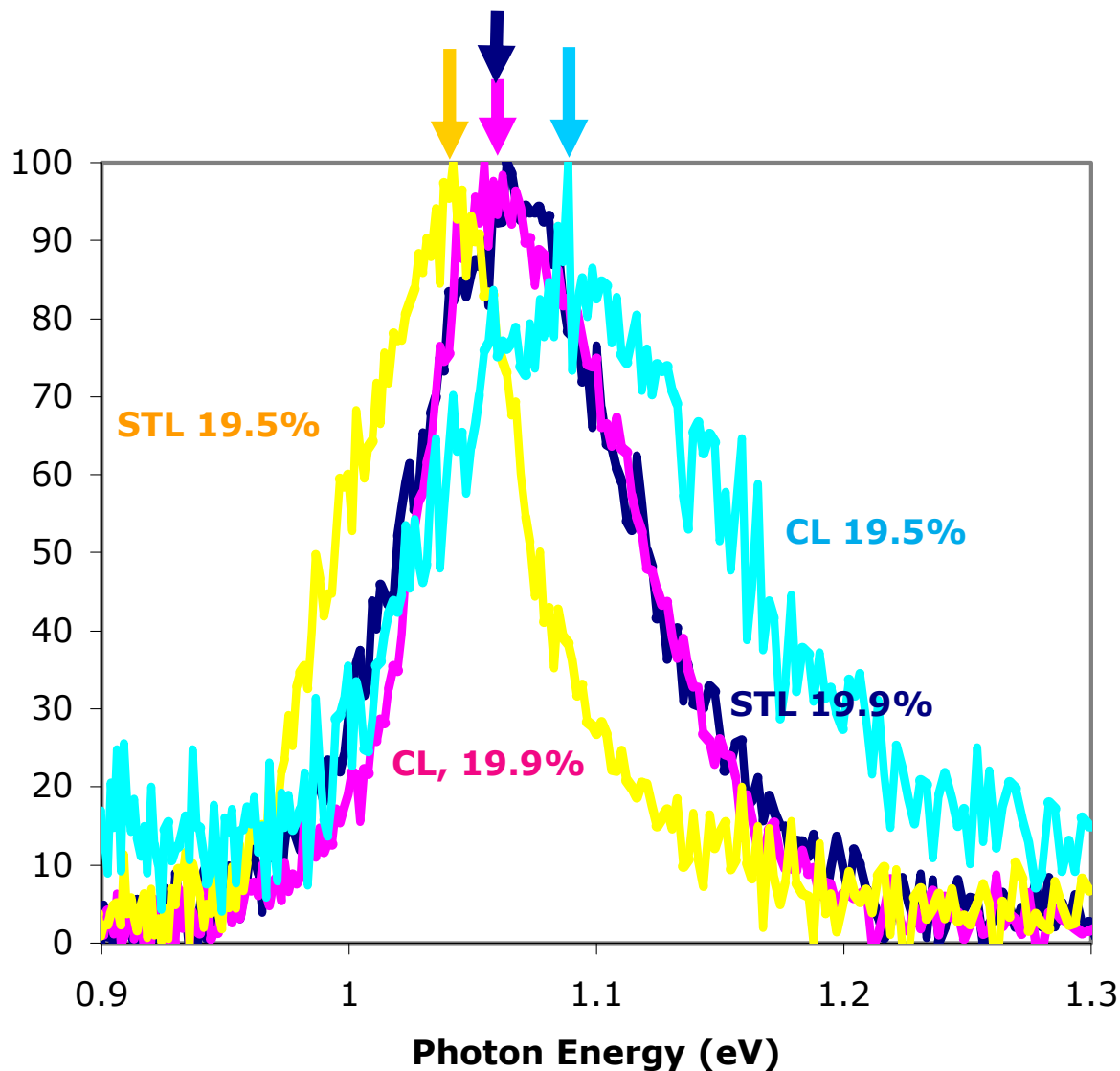


19.9% device

13.0% device

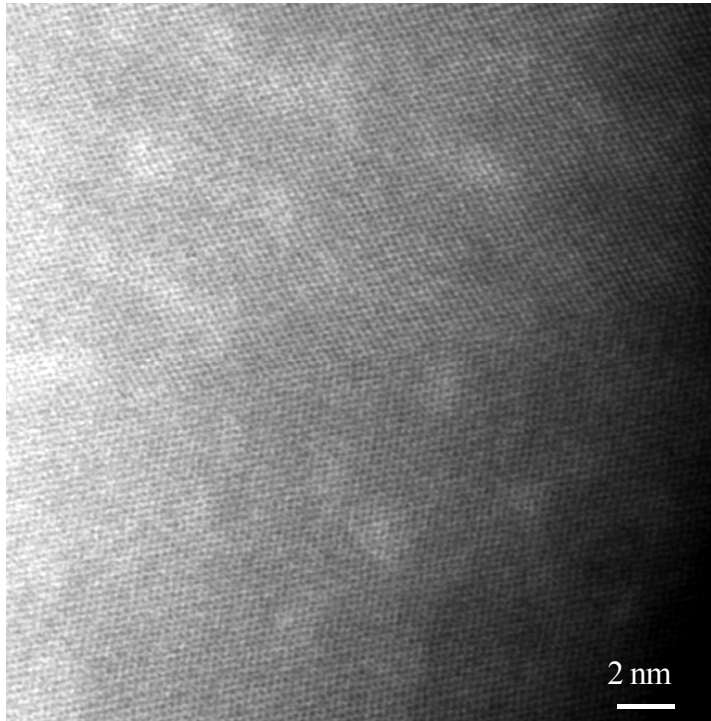
Relatively low non-radiative loss at grain boundaries is typical of >18% devices.

CL and STL comparison

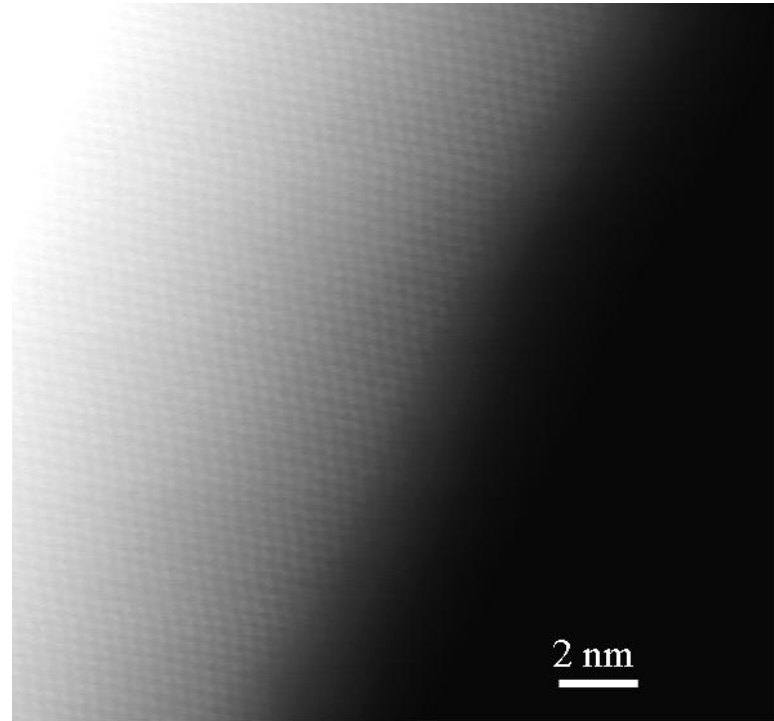


Lack of red shift between CL and STL is unique to 19.9% material

TEM: Atomic number (Z) contrast



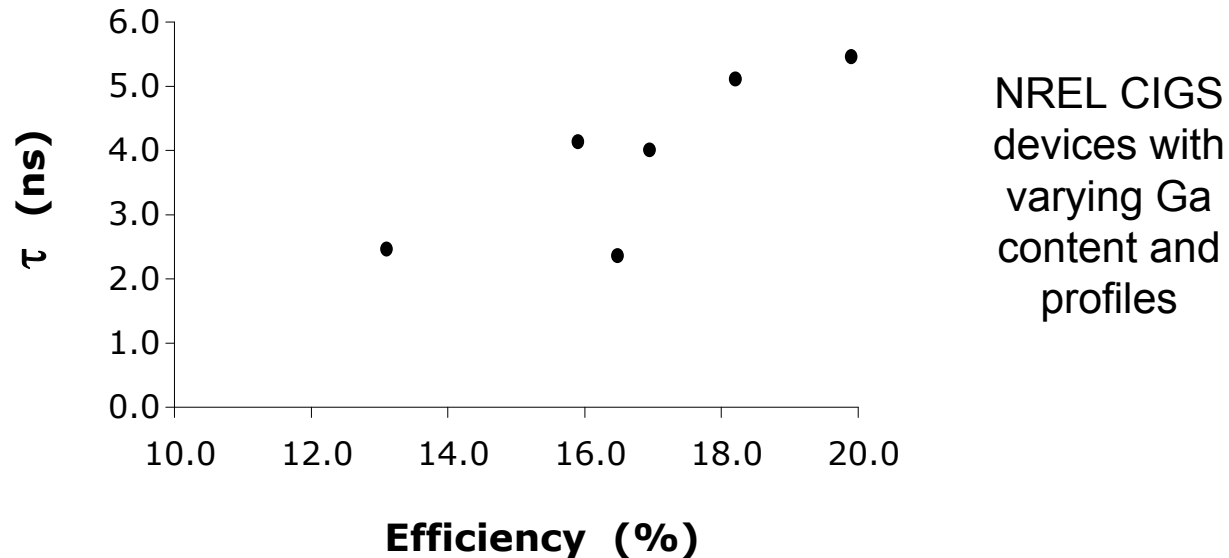
19.5%



19.9%

Decreased indication of nanodomains is unique to 19.9% material

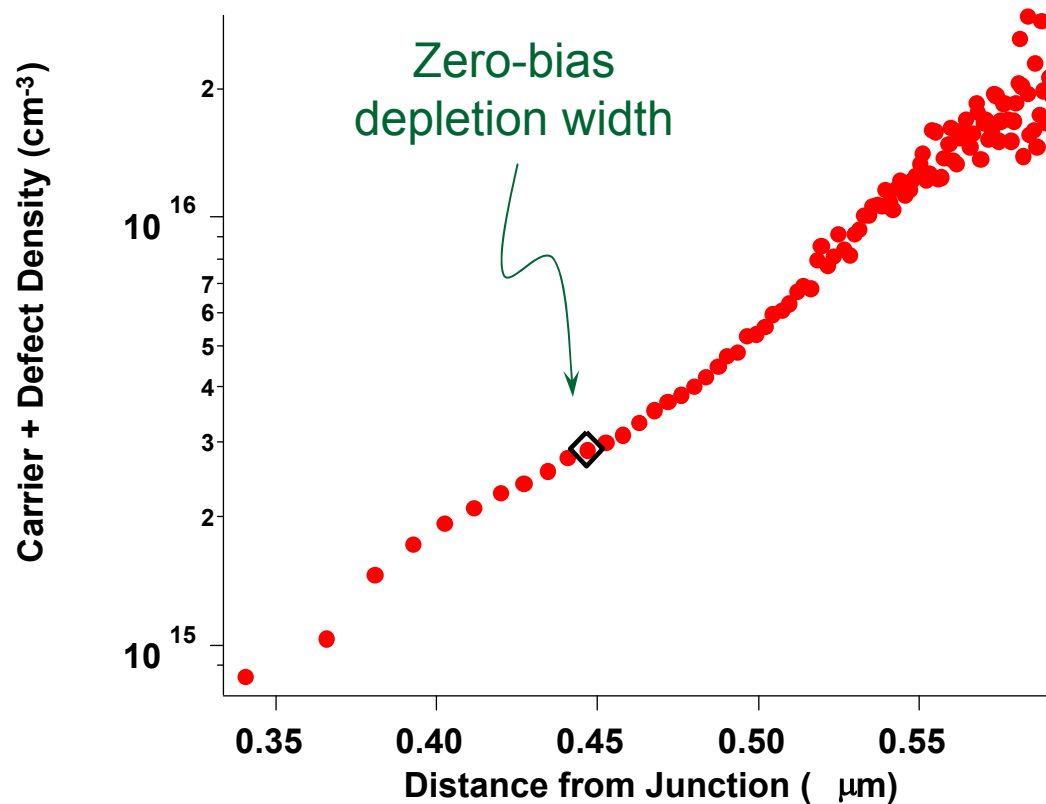
TRPL



Relatively long lifetime is consistent with high efficiency and low recombination

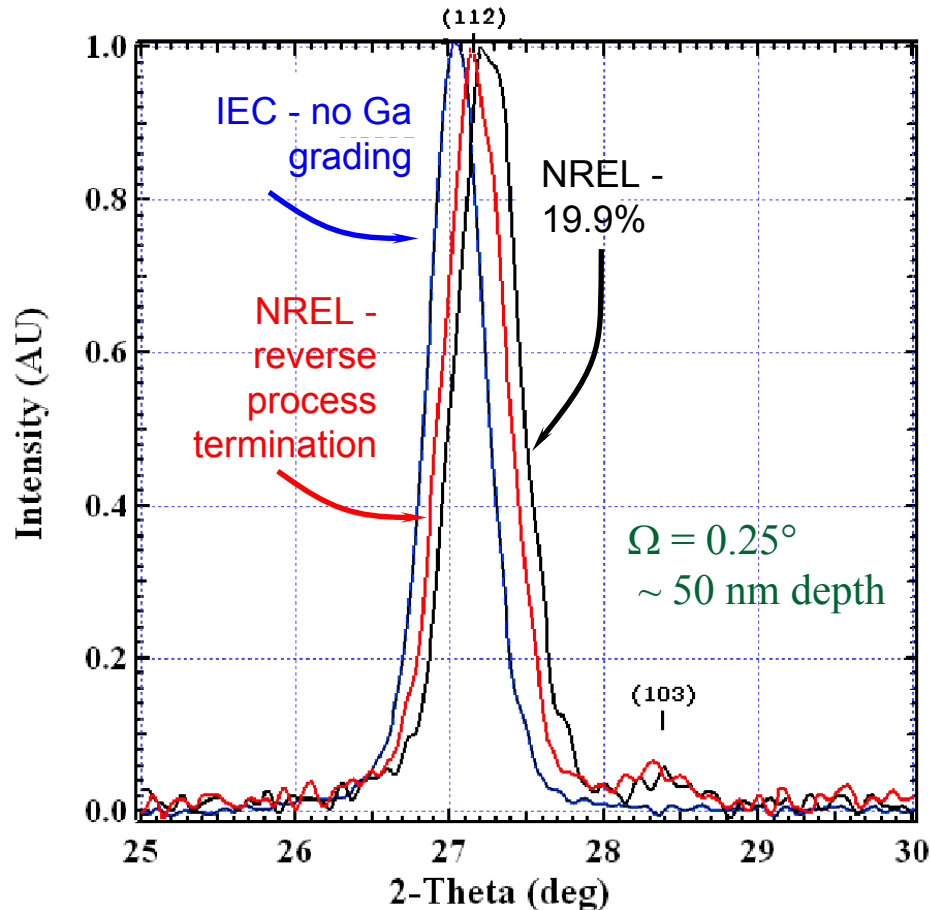
Factors other than recombination (charge separation, intensity, fitting algorithm) also influence apparent lifetime. *See Metzger et al, E-MRS, May 2008*

CV



Zero-bias depletion width less than 0.5 mm, doping density approaching $2 \times 10^{16} \text{ cm}^{-3}$, consistent with >19% devices.

GIXRD



- Compared three samples
- Narrow peaks are characteristic of high efficiency devices
- Record device has largest peak shift
- Not explained by Ga ratio (0.71 would be required)
- Instead, decreased Cu content near surface is implied.

Summary	Consistent with high η (>18%) devices	Unique to recent 19.9% CIGS
Modified process termination		✓
Low nonradiative loss at grain boundaries	✓	
No red shift between CL and STL		✓
Decreased evidence of nanodomains in TEM		✓
Long lifetime (TRPL)	✓	
High doping density / short depletion width (CV)	✓	
Larger shift of GIXRD peak to high angle		✓

- Techniques probing into the bulk are consistent with high efficiency devices.
- Shallow probes indicate a more perfect and Cu-poor formation of the near-surface region.
- Ga segregates preferentially to α -phase domains, Cu vacancies to β -phase domains (Stanbery et al.) Hypothesis: Denying Ga to surface encourages more perfect formation of Cu-deficient β -phase and thus the buried homojunction.