Characterization of 19.9% Efficient CIGS Absorbers

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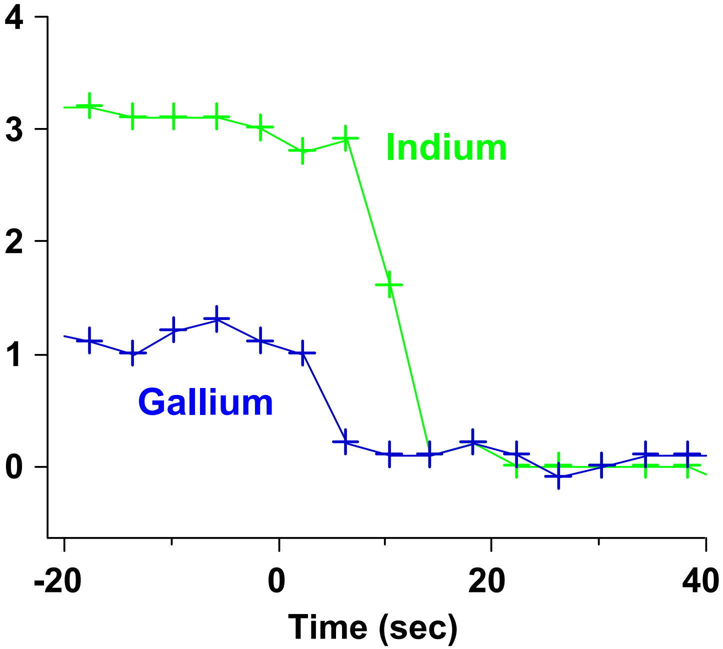
Device	**Area (cm^2)**	**Efficiency (%)**	**V_{oc} (mV)**	**J_{sc} (mA/cm^2)**	**Ff (%)**	**R (Ω-cm^2)**	**A**	**J_0 (mA/cm^2)**
C1068-2	0.450	18.8	678	35.2	78.7	0.41	1.30	5.3×10^{-8}
S2051-A1	0.408	19.2	689	35.7	78.1	0.27	1.48	5.2×10^{-7}
C1675-11	0.406	19.3	668	36.2	79.6	0.14	1.29	6.5×10^{-8}
C1812-11	0.409	19.5	692	35.2	79.9	0.24	1.33	6.4×10^{-8}
M2992-11	0.419	19.9	690	35.5	**81.2**	0.37	**1.14**	**2.1×10^{-9}**

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



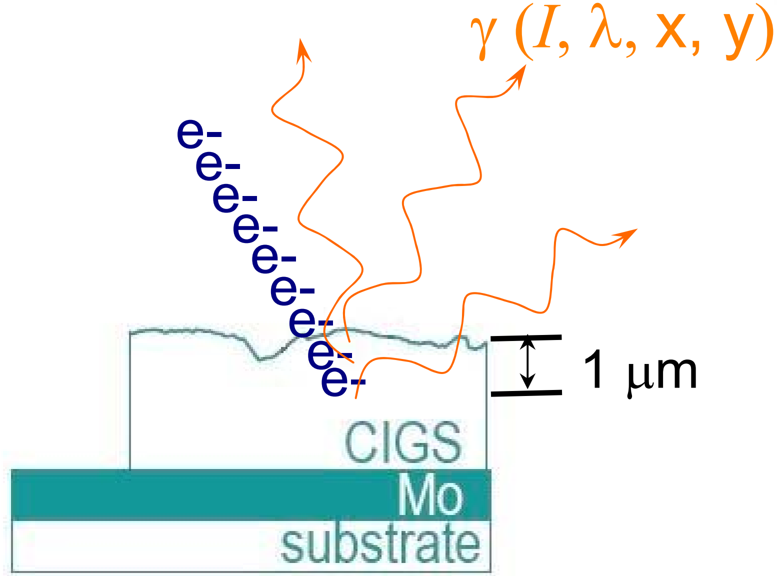
Device Name	Area (cm^2)	η (%)	Voc (mV)	FF (%)	Jsc (mA/ cm^2)	Official Mst?
M2992-11#5	0.419	19.9	690	81.2	35.4	Yes
C2183-12#5	0.416	19.9	697	80.0	35.7	Yes
C2219-21#7	0.417	19.8	714	79.1	35.1	Yes
M2992-11#4	0.419	19.7	690	81.2	35.1	Yes
M2992-11#6	0.419	19.7	690	81.1	35.3	Yes
C2183-12#4	0.417	19.7	695	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?

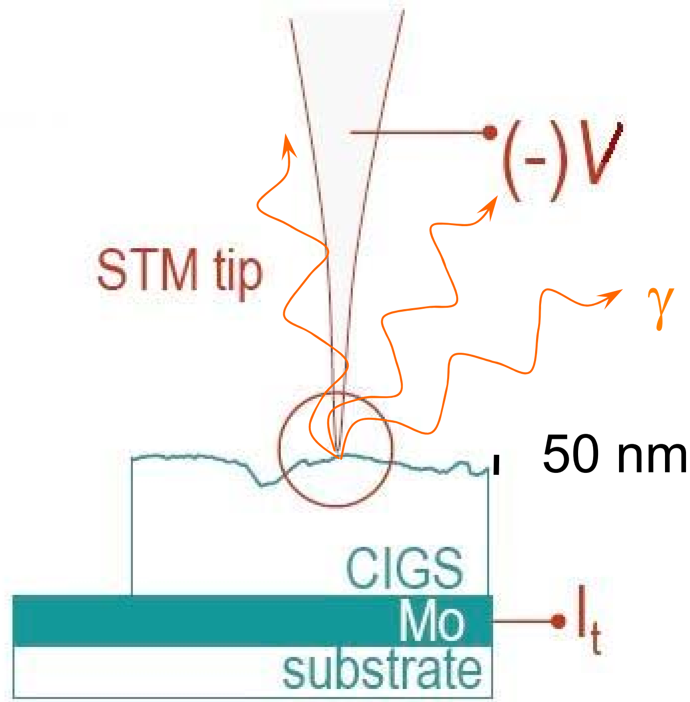
- Characterization:
  - Scanning tunneling luminescence (STL) mapping and cathodoluminescence (CL) mapping
  - Transmission electron microscopy (TEM)
  - Time-resolved photoluminescence (TRPL)
  - Capacitance-voltage (CV)
  - Grazing incidence x-ray diffraction (GIXRD)
- Note which results are typical 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
~ 1 μm penetration depth

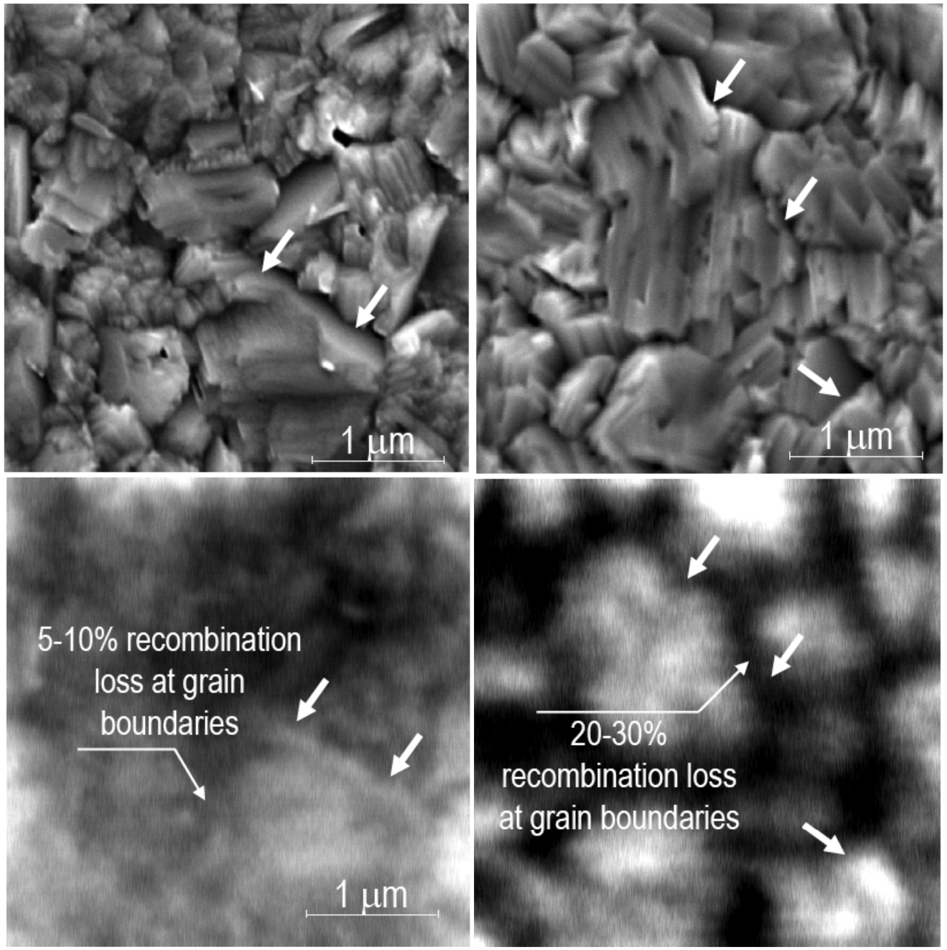


STL: excitation confined to top 50 nm or less

Example: CL intensity as a function of position

SEM

CL map

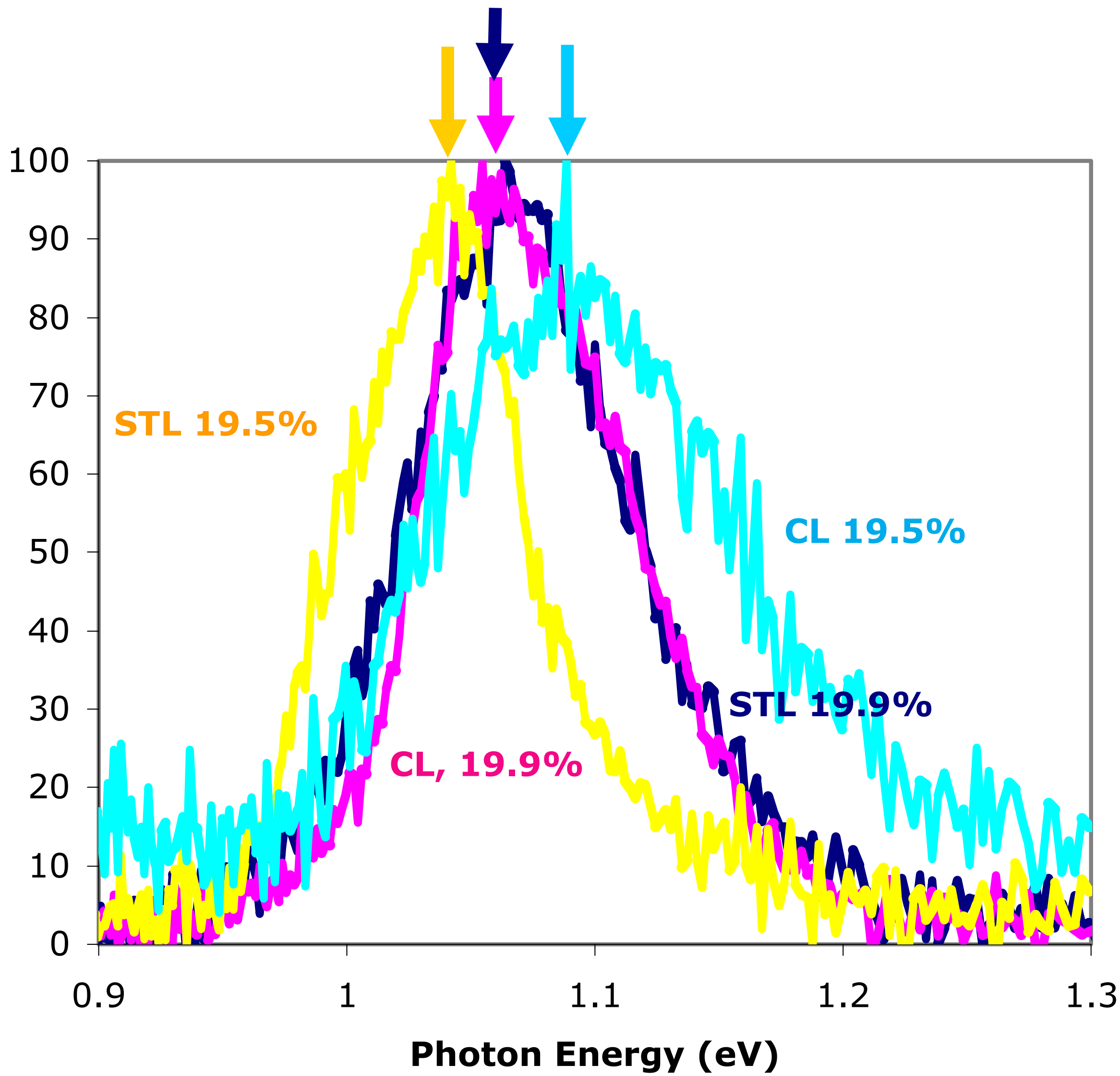


19.9% device

13.0% device

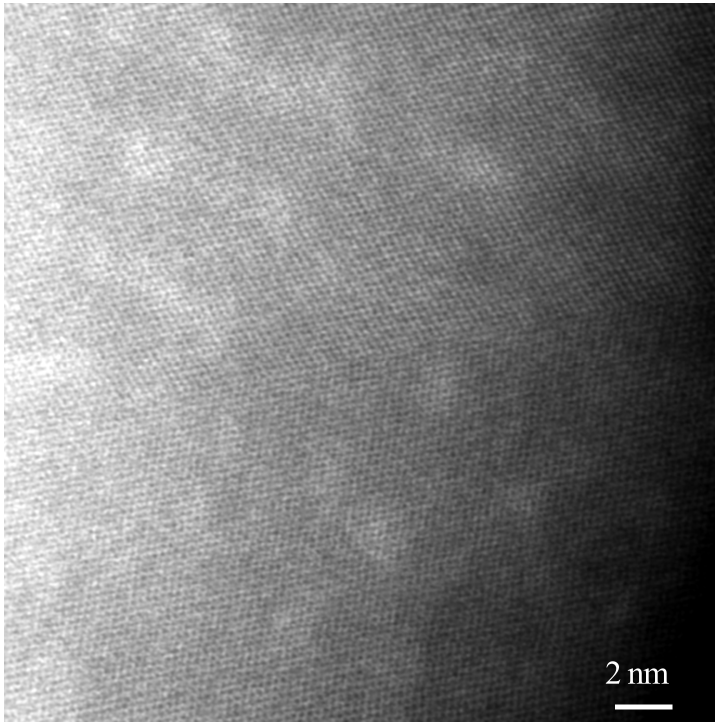
Relatively low non-radiative loss at grain boundaries is typical of >18% devices.

CL and STL comparison

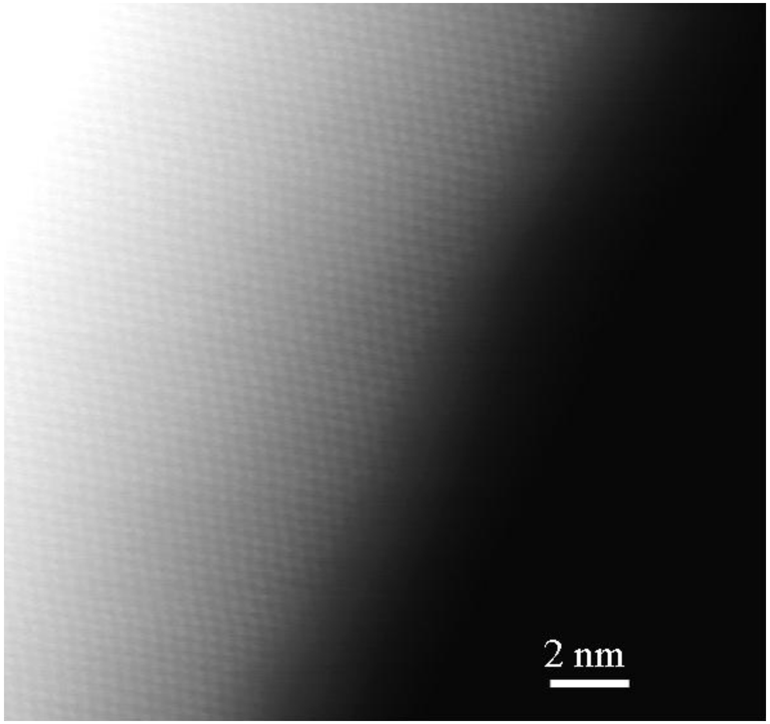


Lack of red shift between CL and STL is unique to 19.9% material

TEM: Atomic number (Z) contrast



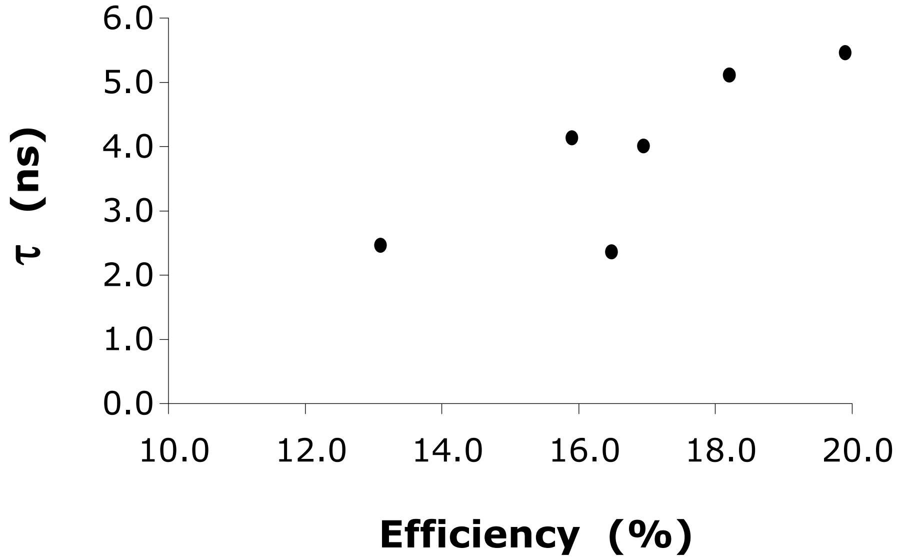
19.5%



19.9%

Decreased indication of nanodomains is unique to 19.9% material

TRPL

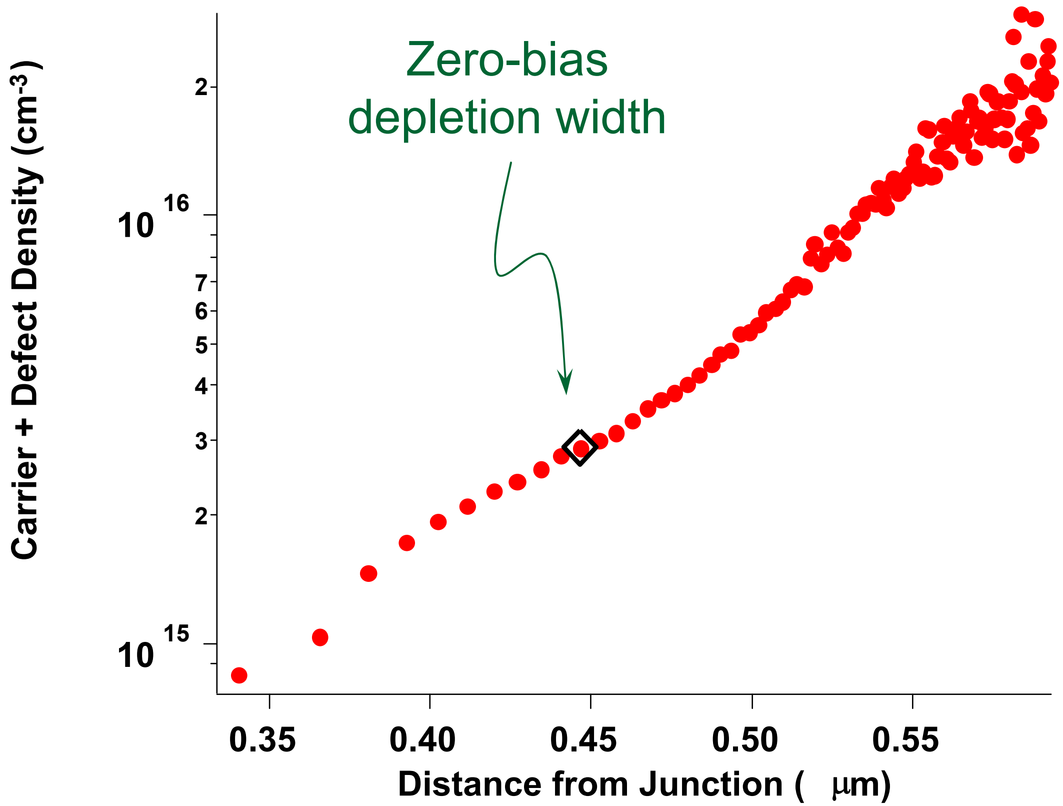


NREL CIGS devices with varying Ga content and profiles

Relatively long lifetime is consistent with high efficiency and low recombination

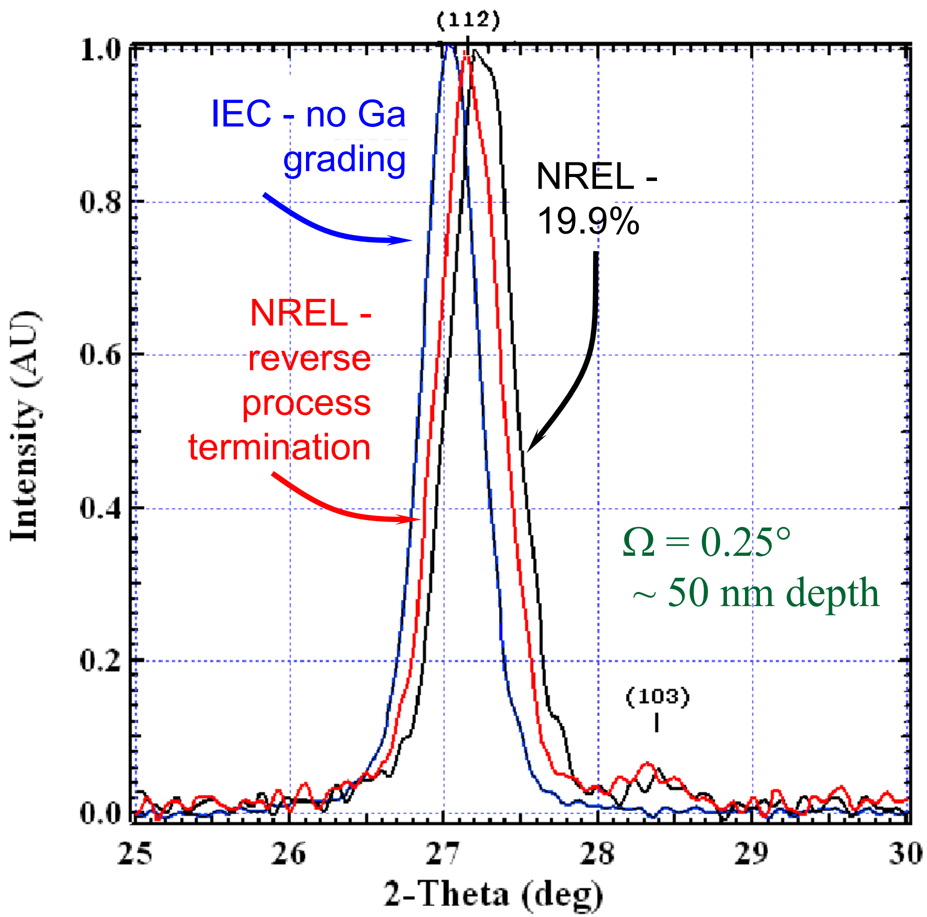
Factors other than recombination (charge separation, intensity, fitting algorithm) also influence apparent lifetime. *See Metzger et al, E-MRS, May 2008*

CV



Zero-bias depletion width less than 0.5 mm, doping density approaching 2×10^{16} 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.