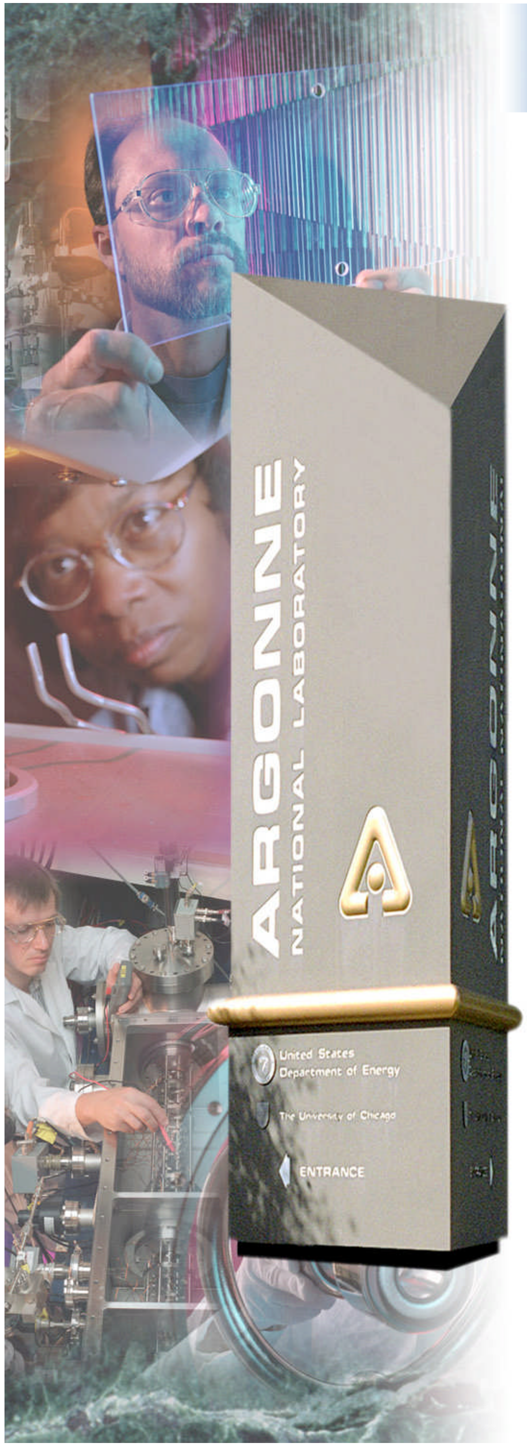
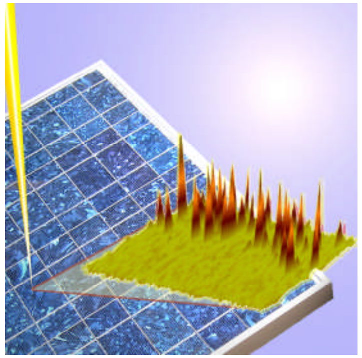


ARGONNE NATIONAL LABORATORY

Controlling metal-impurity nanodefects for low-cost solar cells (dirty silicon)



- Barry Lai, Zhonghou Cai, Steve Heald

THE UNIVERSITY OF CHICAGO

Office of Science
U.S. DEPARTMENT OF ENERGY

Argonne National Laboratory is managed by
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Status of Photovoltaic (PV) Industry

High-purity Semiconductor-grade Silicon Feedstock

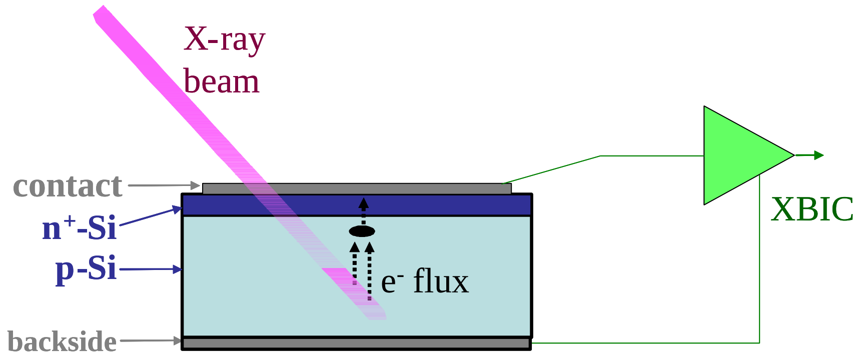
- 90% of PV devices used crystalline silicon
- Historically relied on scraps from semiconductor industry
- PV industry is growing at > 30% annually, now ~ 40% of the silicon market
- In 2004, demand exceeded supply for silicon feedstock $\Rightarrow$ higher price

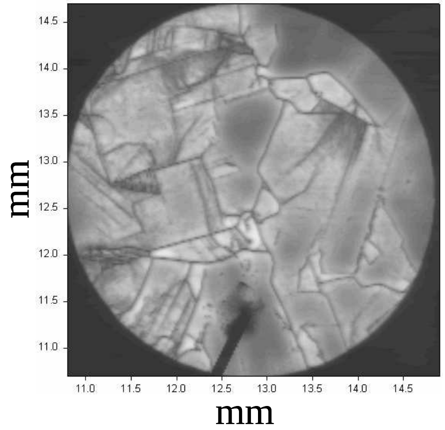
Low-cost Metallurgical-grade Silicon Feedstock

- High impurity (> 10^{15} cm^{-3}) $\Rightarrow$ high recombination activity $\Rightarrow$ low efficiency
- Removing metal impurities (gettering, passivation) is difficult and expensive
- Questions:
    1) What type of defect is most detrimental to device performance?
    2) Can one live with native metal impurities by defect engineering?

Characterization

- XBIC: X-ray Beam Induced Current
  Map recombination activity
  ALS 10.3.1, 10.3.2, APS 2-ID-D, 20-ID



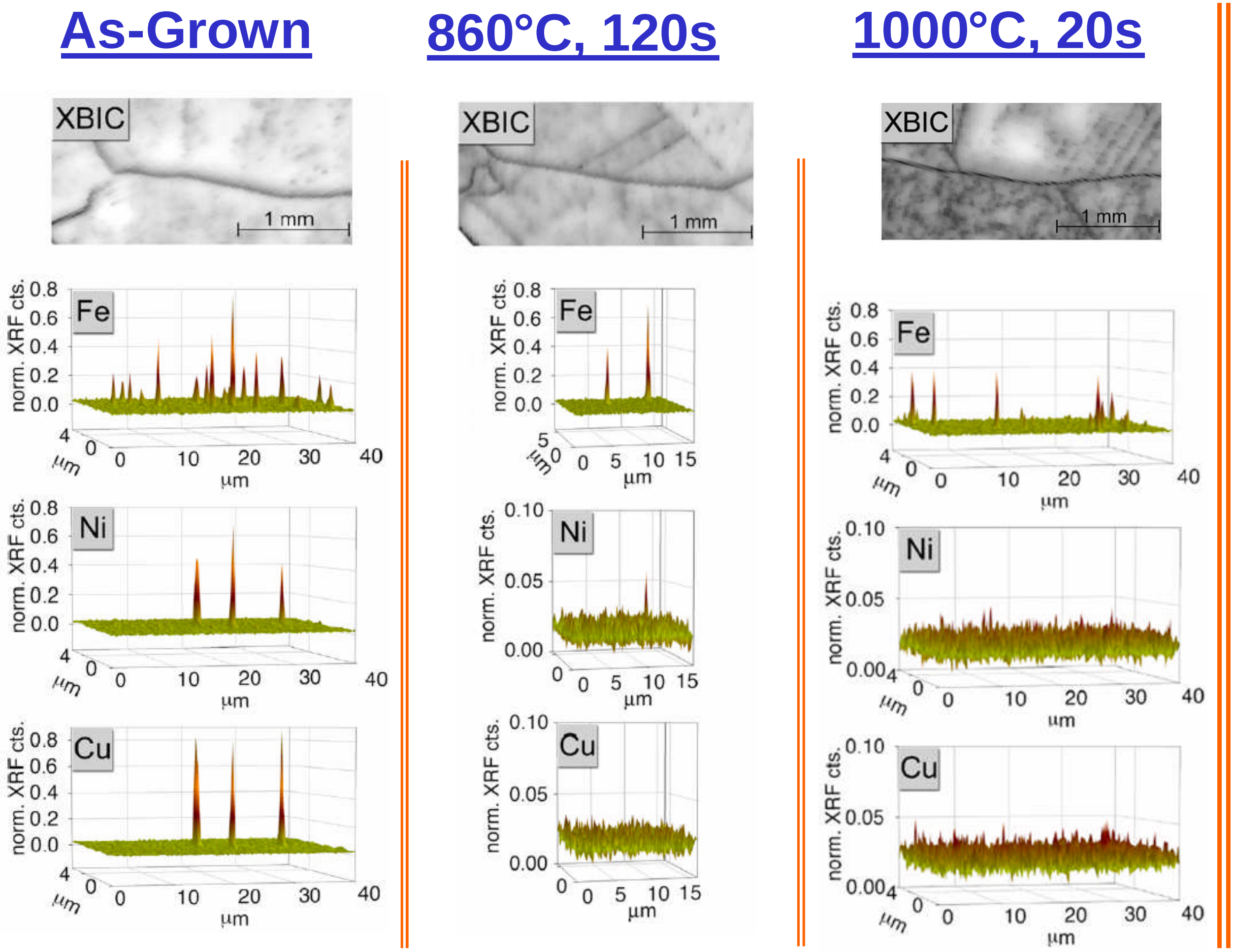


- μ-XRF: Map spatial distribution of metal precipitates
  Determine elemental composition of each precipitate
  APS 2-ID-D, 20-ID

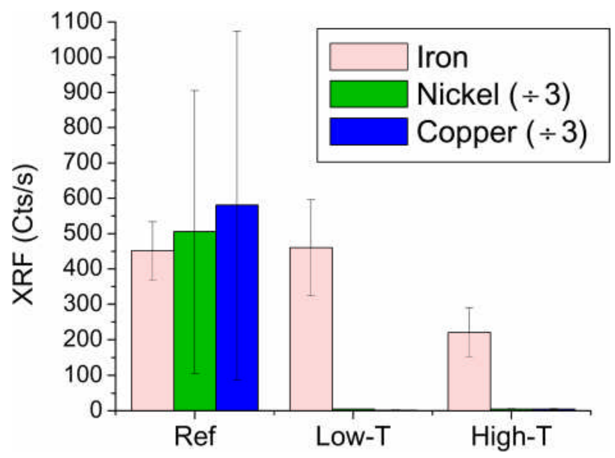
- μ-XAS: Determine chemical state of metals in the precipitates
  μ-XANES: 2-ID-D
  μ-EXAFS: 20-ID

High-T RTP dissolves metal silicide nanoprecipitates, leads to more recombination active sites (XBIC)

T.Buonassisi, A.A.Istratov, et al., Appl. Phys. Lett., in print

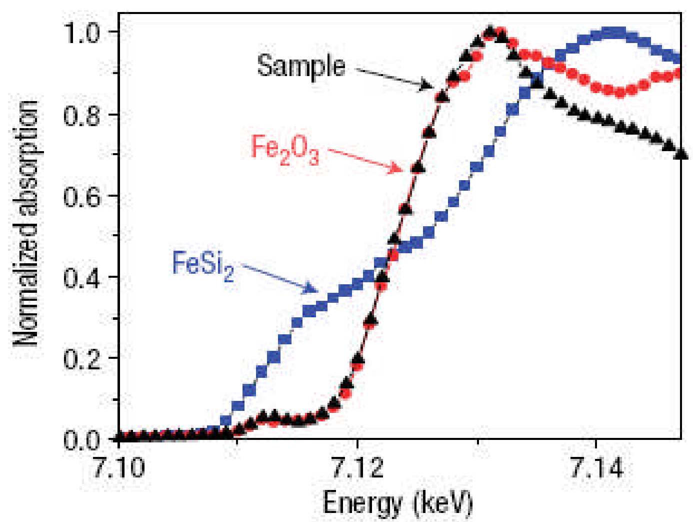


Average metal content per precipitate



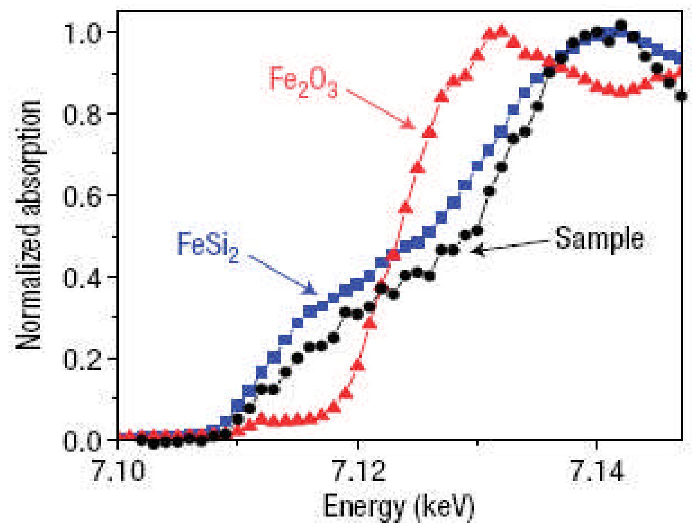
μ-XRF & μ-XANES revealed two types of metal clusters in mc-Si

*T.Buonassisi et al., J.Appl.Phys. **97**, 63503 (2005) and J.Appl.Phys. **97**, 74901 (2005).*



Large (up to 25 μm) inclusions

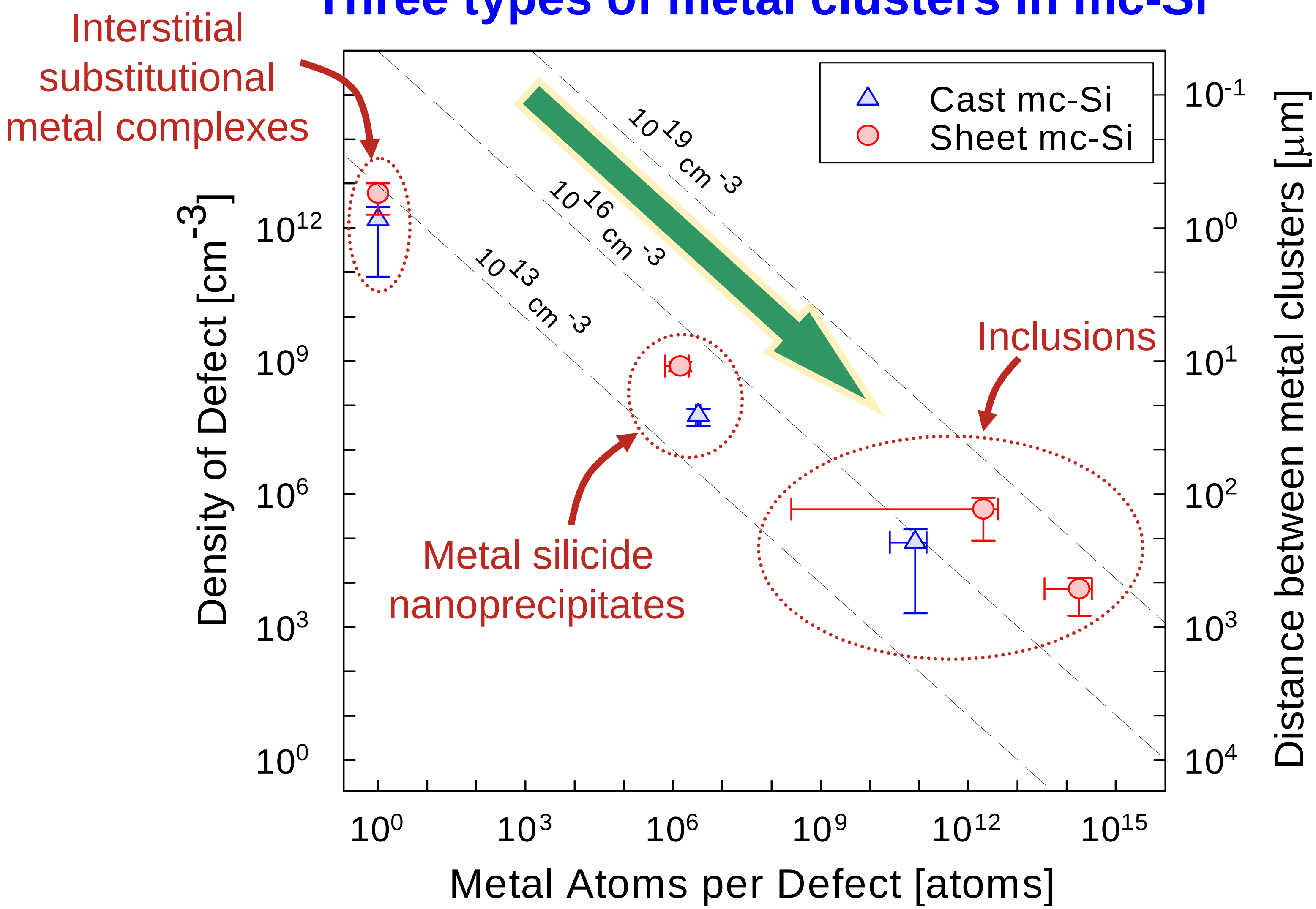
- Often found within grains.
- Found in low density.
- Fe is dominant, often with presence of other slowly diffusing metals (e.g., Cr, Mo, Ti).
- Fe is oxidized and is very similar to Fe_2O_3



Small (10's of nm) nanoprecipitates

- Typically accumulated along grain boundaries.
- Found in high density.
- No slowly diffusing metals detected.
- Consist of Fe, Cu, or Ni in a silicide form.

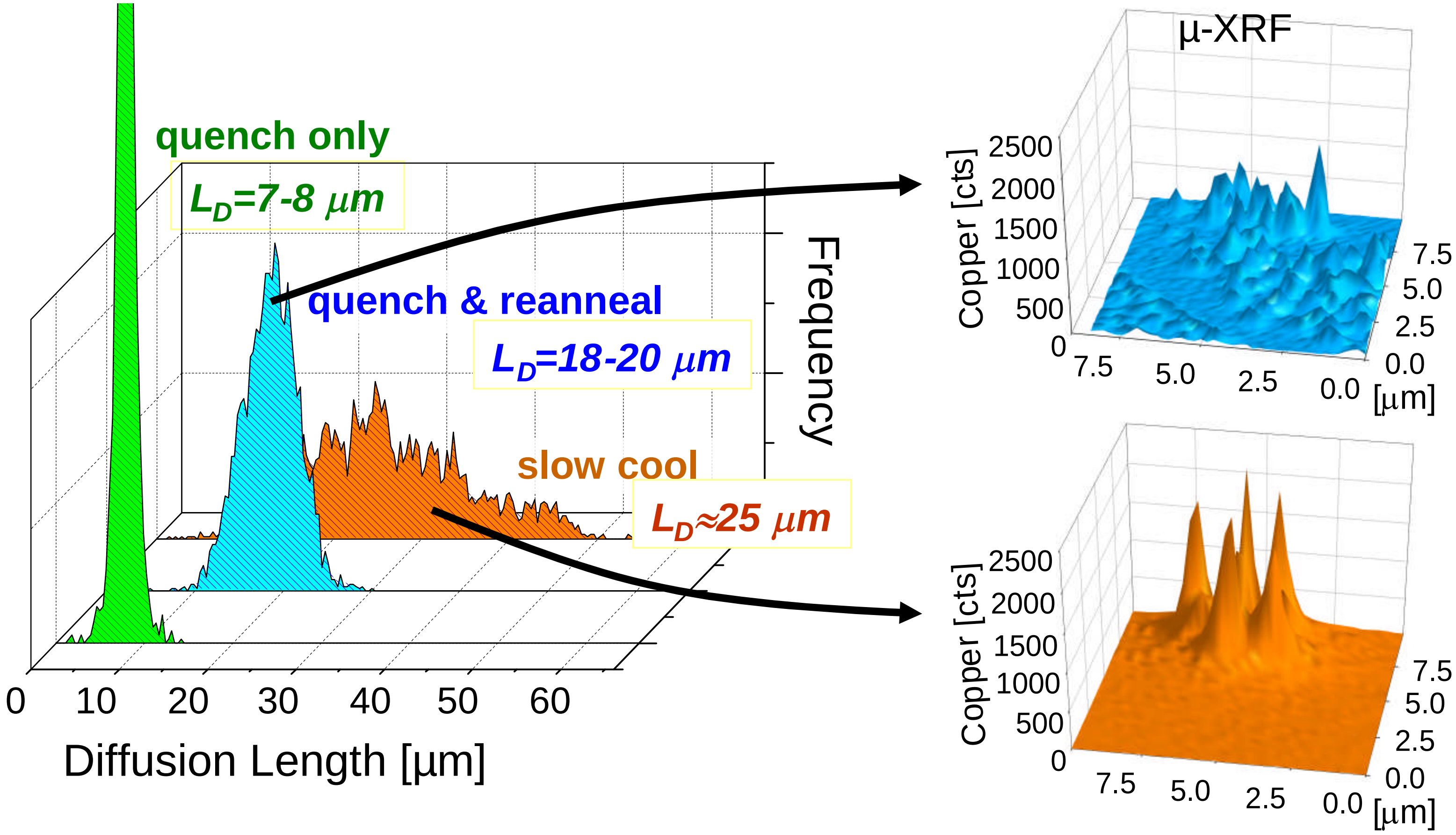
Three types of metal clusters in mc-Si



Defect engineering: design process to reduce density of defect

Properly chosen annealing sequence decreases spatial density of metal clusters and improves the minority carrier diffusion length L_D

*T.Buonassisi, et al., Nature Materials **4**, 676-679 (2005)*



Mc-Si intentionally contaminated at 1200°C, either quenched in silicone oil, or slowly cooled in the furnace, or quenched and then reannealed again at 655°C. The processing was not yet optimized.

SUMMARY

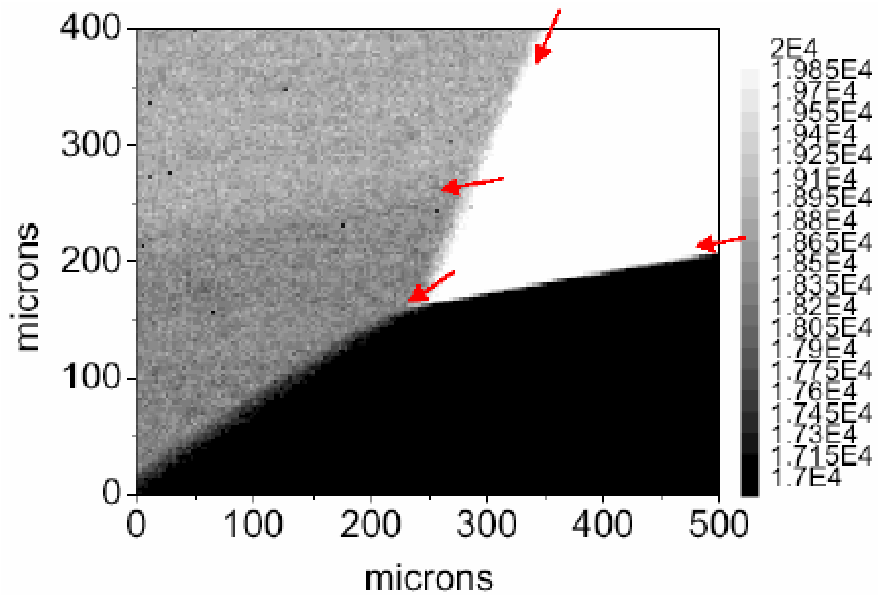
- Transition metals are major culprits of efficiency losses in solar cells; one has either use cleaner materials, or learn how to tame them and control their behavior

- Defect engineering of transition metals is suggested as a new concept to reduce recombination activity of metals. This concept opens opportunities not only for the improvement of existing solar cells, but also for the utilization of less pure and less expensive “solar-grade” silicon feedstock material

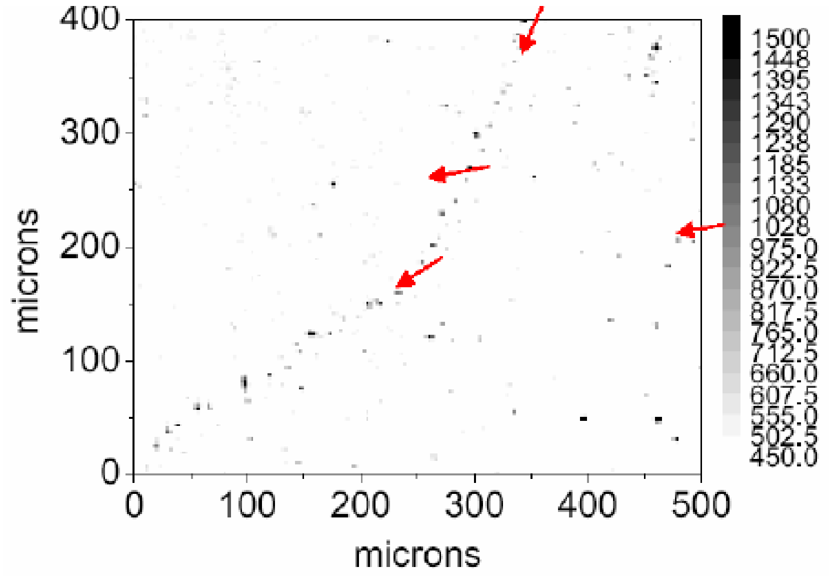
- The goal of defect engineering of metals can be achieved through the detection of the main sources of metal contamination and understanding the preferred defect reactions of metals during crystal growth and processing $\Rightarrow$ μ-probes

Metals selectively precipitate at certain grain boundaries?

Scattered X-ray beam intensity (grain structure)



Iron distribution (μ-XRF)



EBSD (electron backscattering diffraction) measurements in the future to correlate the grain boundary index / boundary plane with density of metal clusters.