Polycrystalline CdS/CdTe solar cells

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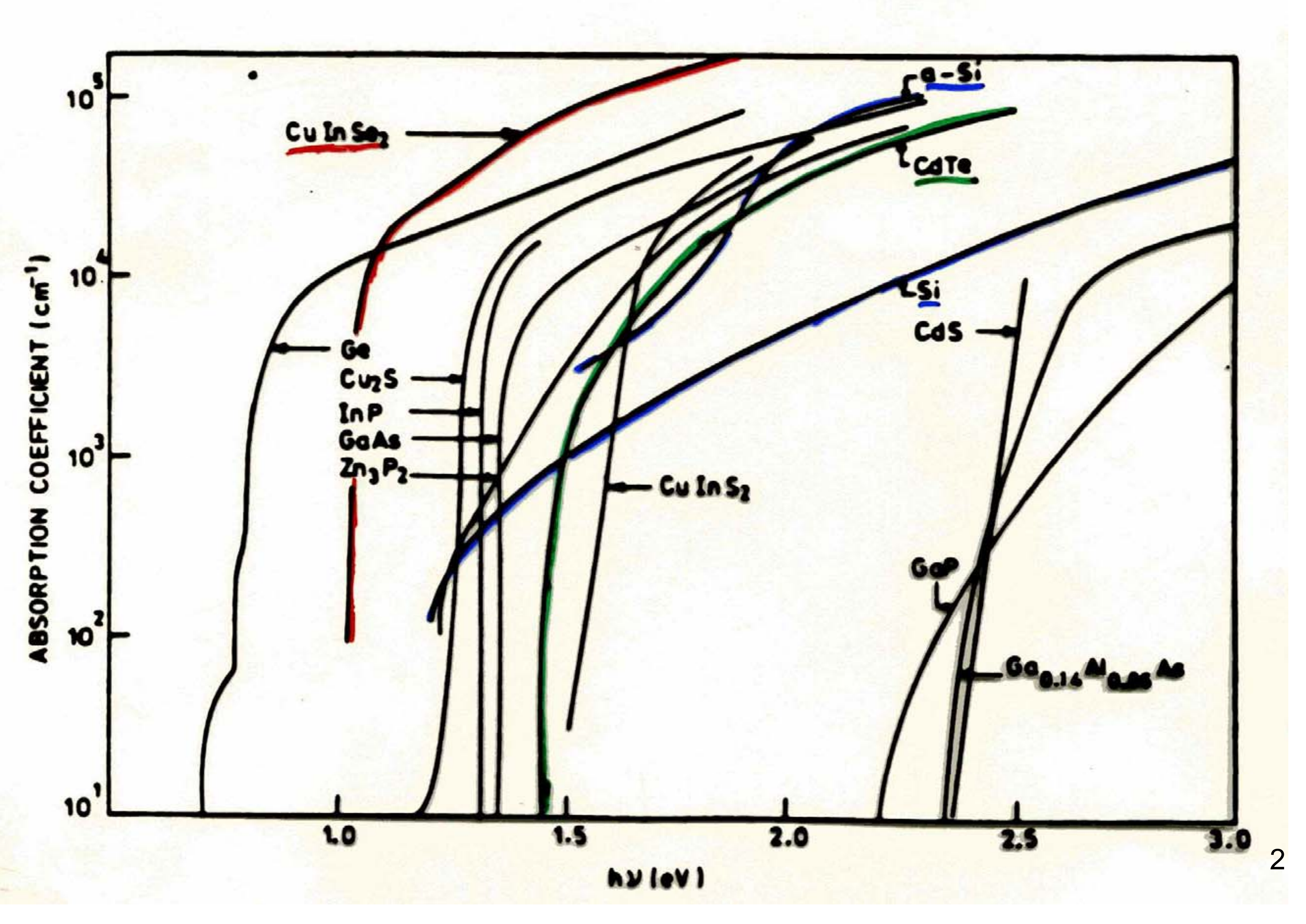
Distinguished University Professor of Physics, Emeritus

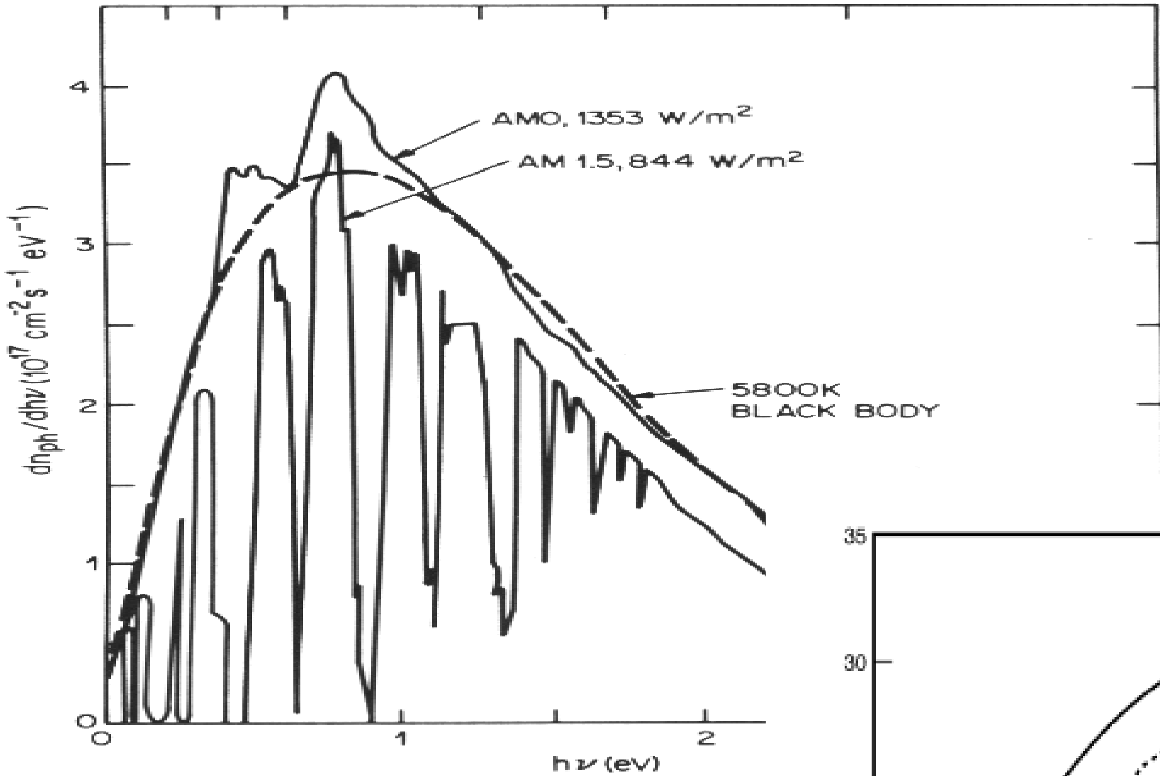
(Lecture for Heben/Ellingson solar cells class)

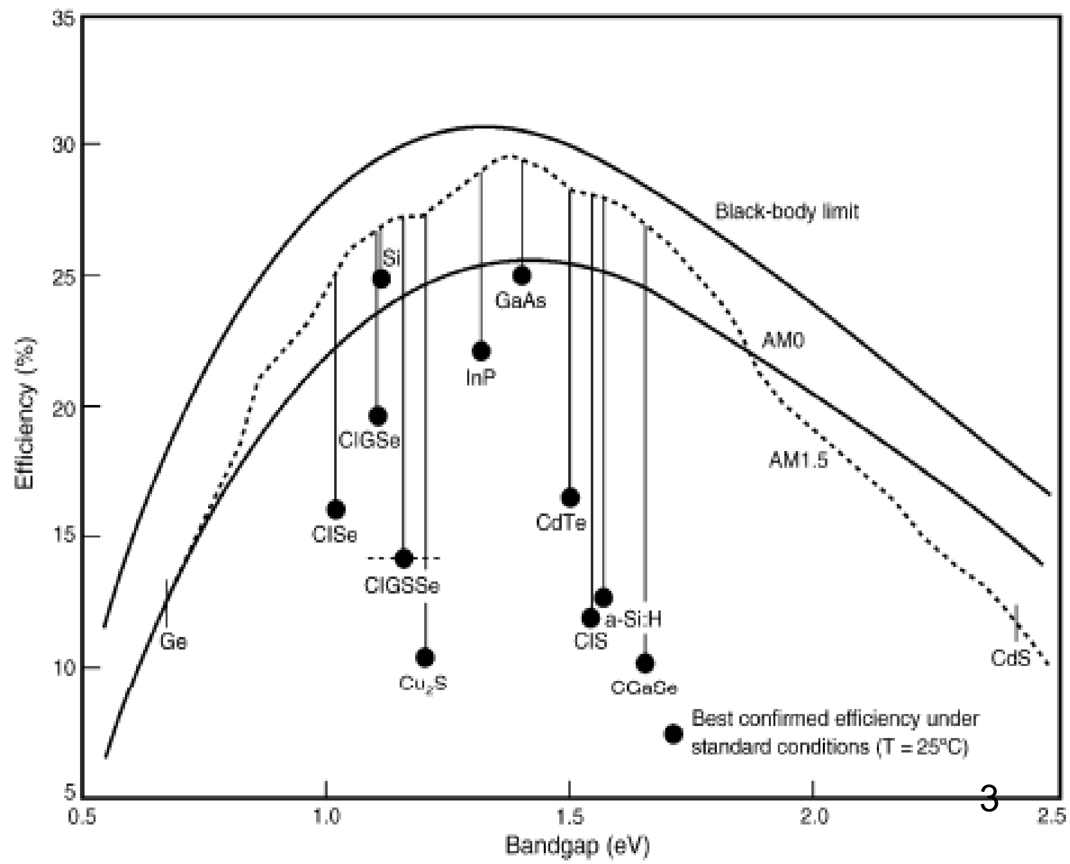
March 15, 2012

Absorption spectra of various semiconductors



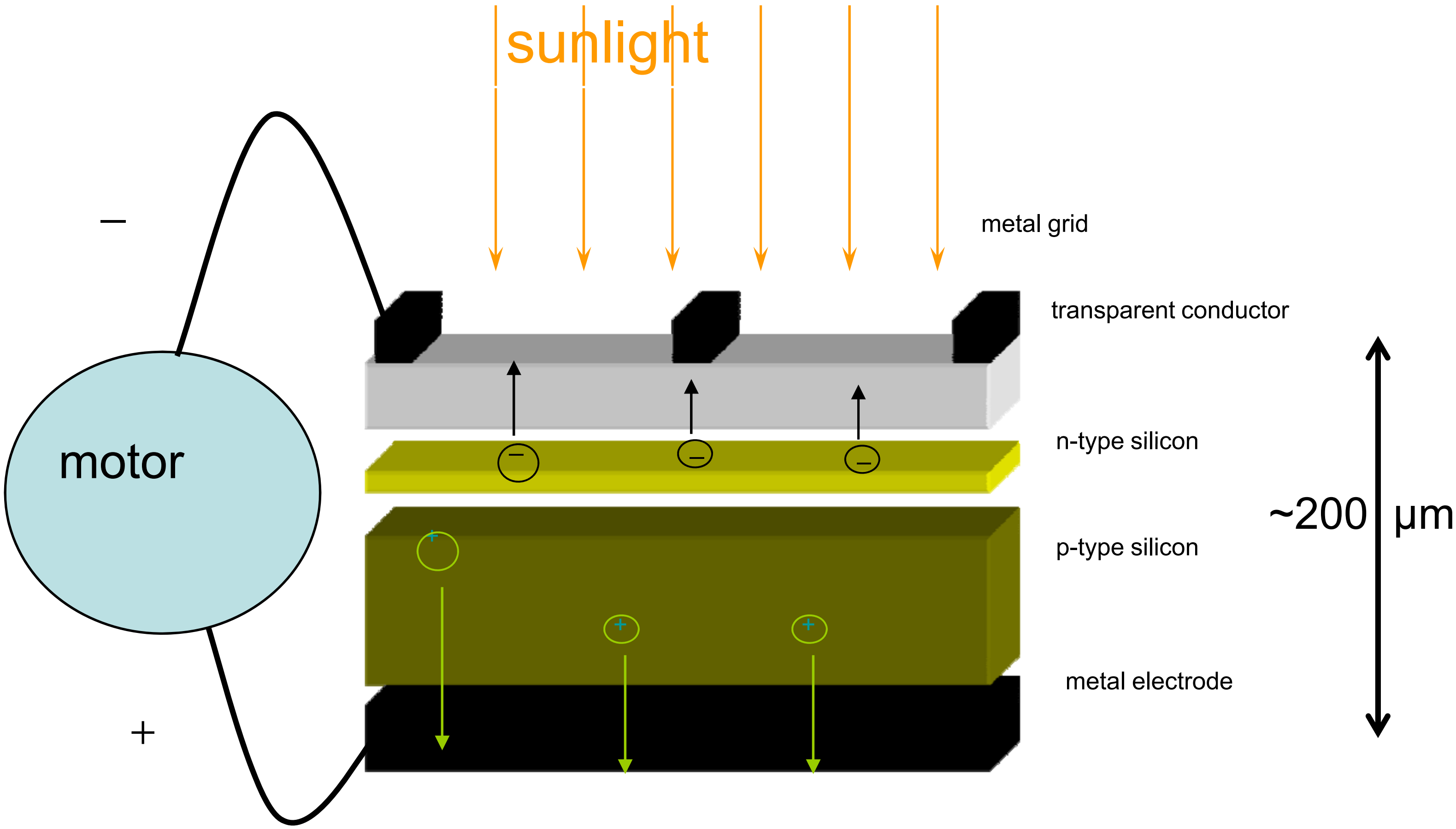
actual and attainable single junction cell efficiencies (inorganic materials)





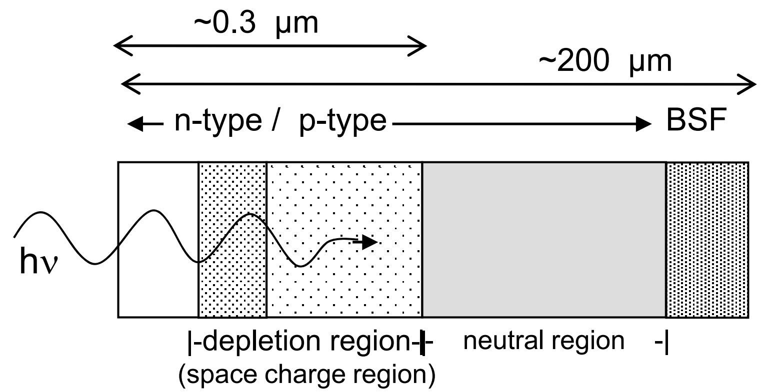
Attainable cell efficiencies for AM0 (solid lin and AM1.5 spectra (dashed line) and best efficiencies achieved for several materials a single junctions. (Kazmerski 2006)

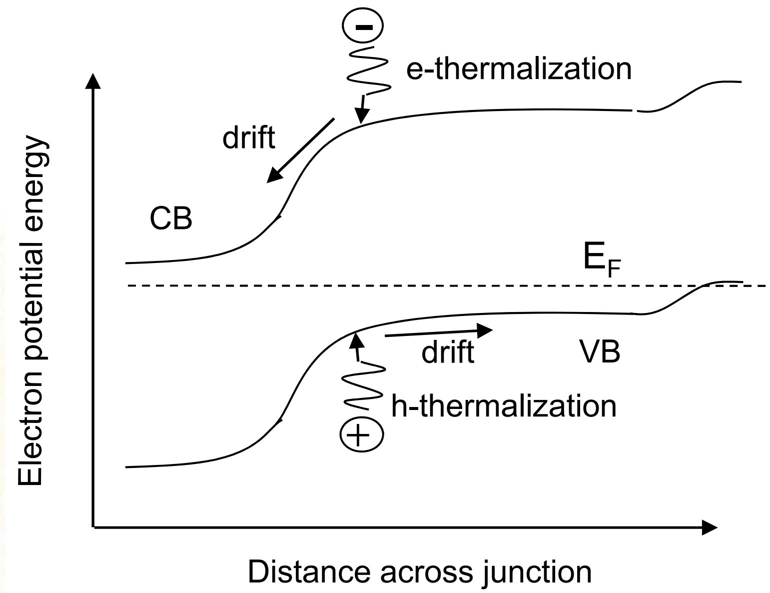
the traditional silicon solar cell

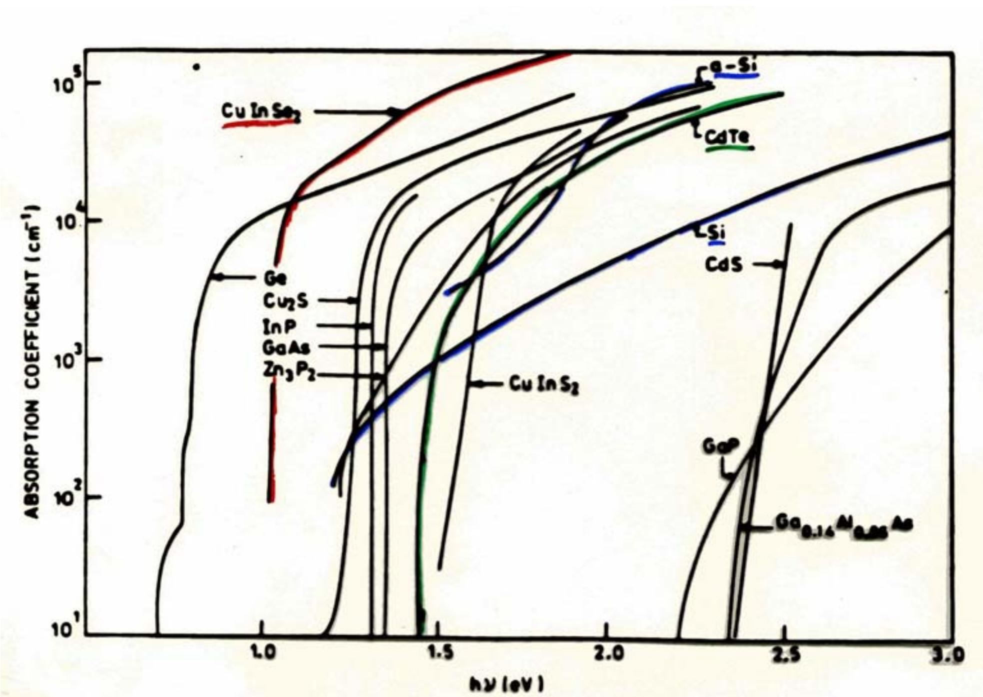


band diagram for a homojunction (n on p)

- Si (indirect band gap) will have typically a thick neutral region--carrier collection by diffusion
- most thin-film (direct band gap materials) will have mostly field-assisted collection



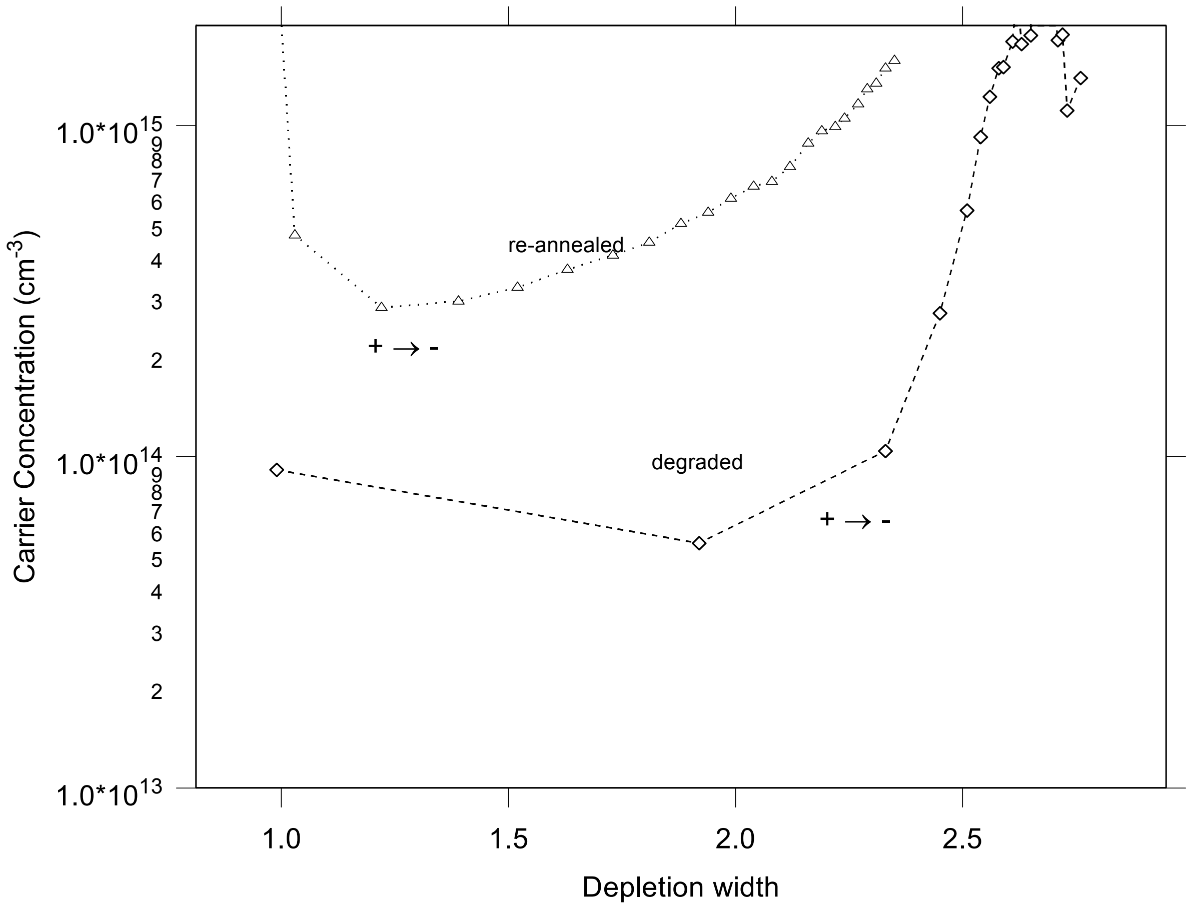




Solar cell structure and energy band diagram showing valence (VB) and conduction bands (CB), Fermi level (E_F), photoabsorption, electron-hole pair generation, thermalization, and drift.
(from Compaan, APS News April, 2005)

C-V measurements of depletion width in CdS/CdTe cells

CdTe is difficult to dope p-type extrinsically



Depletion width in a single-sided step junction:

$W = \{(2K\varepsilon_o V_{bi}) / qN_a\}^{1/2}$

(for Si with Na = 1×10^{16} cm^{-3}, W ≈ 0.35 µm)

Construct a band diagram of the CdS/CdTe solar cell….
What information do we need?

J. Appl. Phys., Vol. 87, No. 3, 1 February 2000

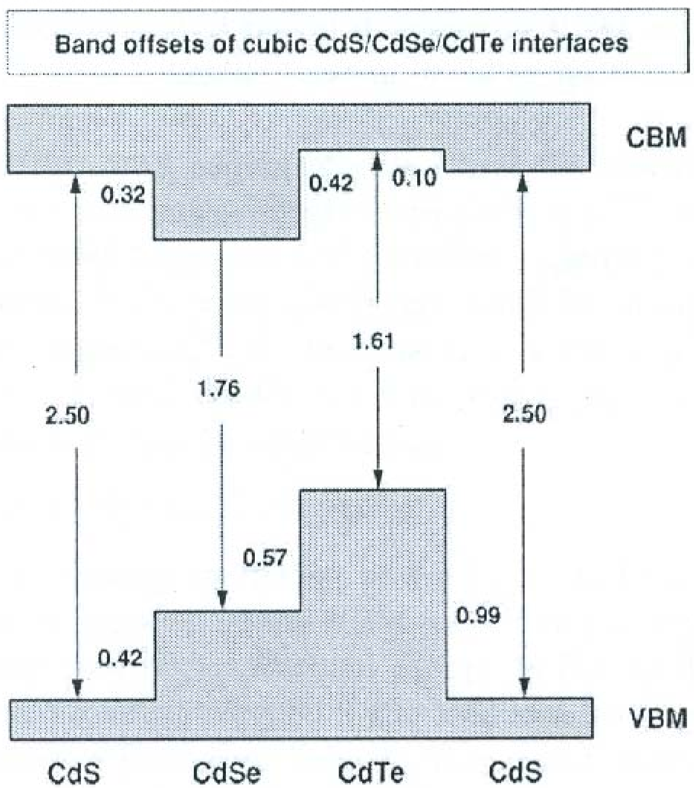


FIG. 2. Calculated natural valence band and conduction band offsets for interfaces between Cd-based compounds.

S-H Wei, S.B. Zhang, A. Zunger (T = 0 K band gaps)

Electron affinity of CdTe
E_a = 4.4 eV

Work functions of common metals

Metal	(Work Function)
Ag (silver)	4.26
Al (aluminum)	4.28 see notes
Au (gold)	5.1
Cs (cesium)	2.14
Cu (copper)	4.65
Li (lithium)	2.9
Pb (lead)	4.25
Sn (tin)	4.42
Chromium	4.6
Molybdenum	4.37
Stainless Steel	4.4
Gold	4.8
Tungsten	4.5
Copper	4.5
Nickel	4.6

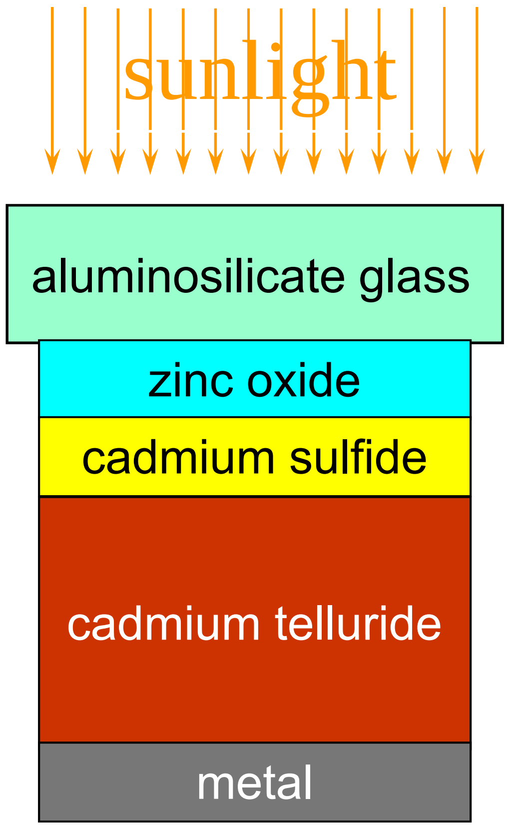
Band structure?

(Construct on board with class discussion)

- Cliff or spike at the CdS/CdTe interface?
- Doping densities in CdTe, in CdS?
- Back barrier for hole transport?

UT CdTe sputtered cell on aluminosilicate glass

14.0% efficiency at one-sun illumination

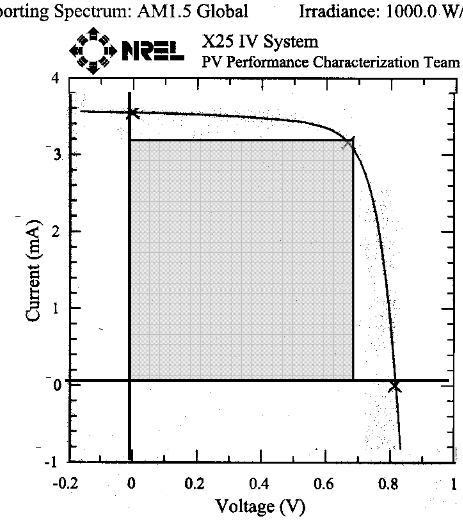


University of Toledo

CdS/CdTe Cell

Device ID: SSC011-2.36
Jun 24, 2002 10:56
Reporting Spectrum: AM1.5 Global

Device Temperature: 25.0 ± 1.0 °C
Device Area: 0.150 cm^2
Irradiance: 1000.0 W/m^2



V_{oc} = 0.8140 V
I_{sc} = 3.5429 mA
J_{sc} = 23.563 mA/cm^2
Fill Factor = 73.25 %

I_{max} = 3.1571 mA
V_{max} = 0.6691 V
P_{max} = 2.1123 mW
Efficiency = 14.0 %

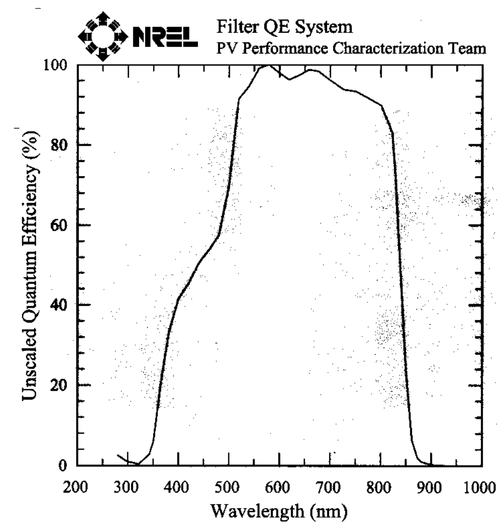
Kelvin probe , series resistance 19.8 ohms.

University of Toledo

CdS/CdTe Cell

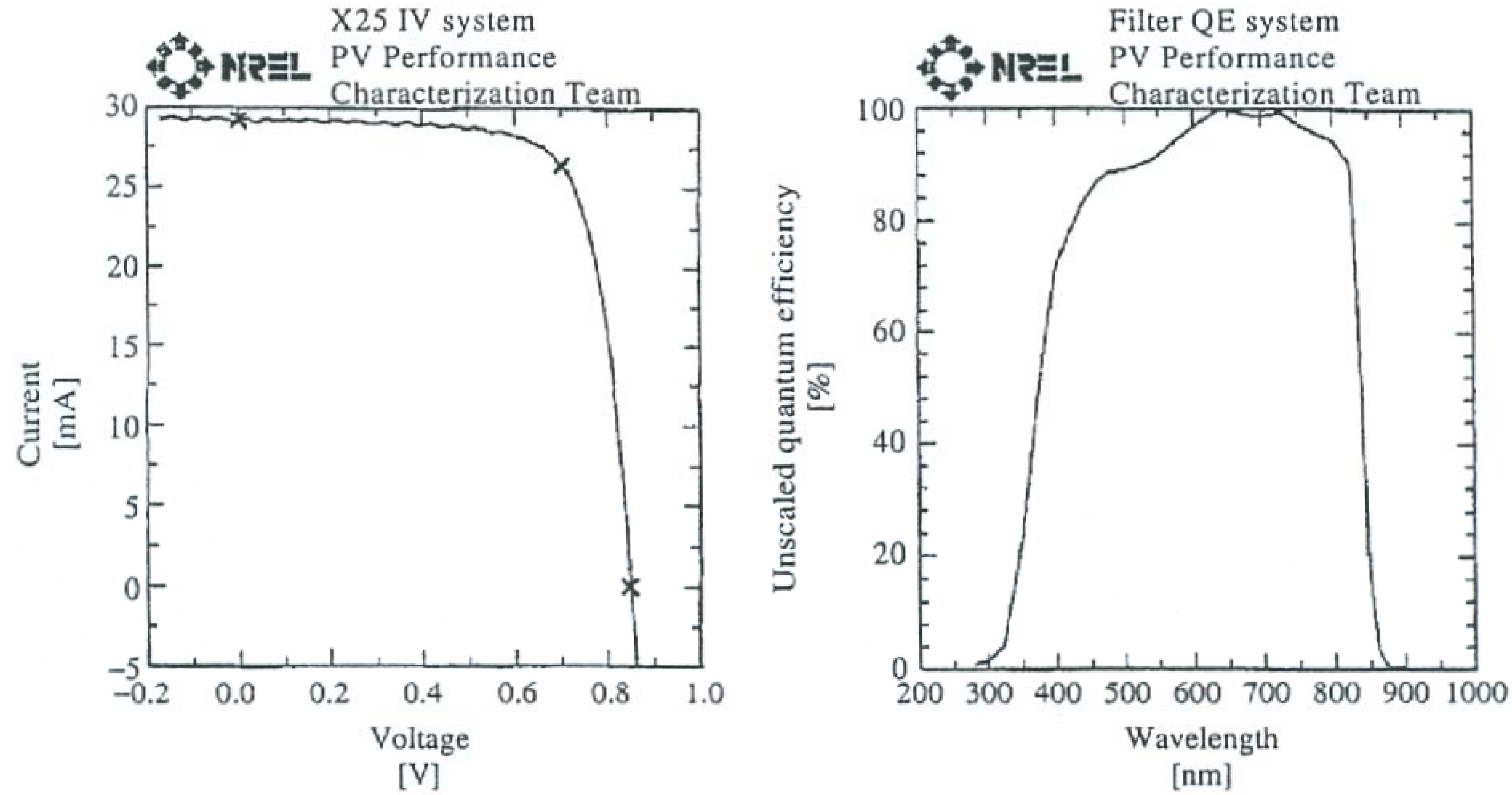
Device ID: SSC011-2.36
Jun 24, 2002 1:27 PM

Device Temperature: 25.0 ± 1 °C
Device Area: 0.1504 cm^2



Voltage Bias: 0.0 V
Light bias for 1.23 mA
Light Bias region area: 0.1504 cm^2
Light Bias Density: 8.206 mA/cm^2

J_{sc} Estimate:
J_{sc} (Global) = 24.9 mA/cm^2

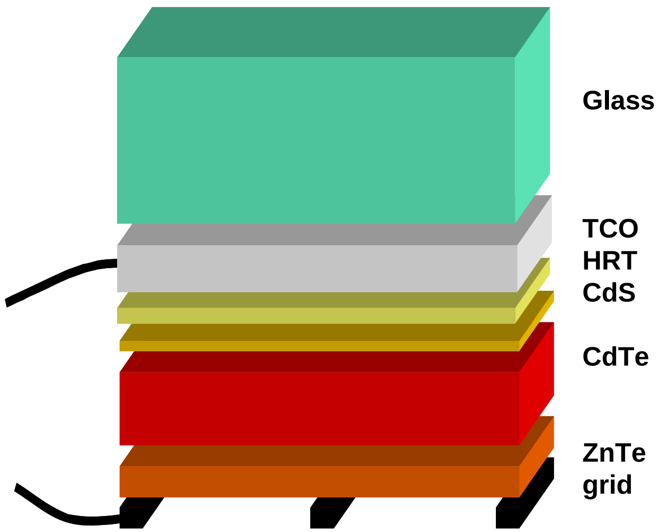


ure 14.2 Current–voltage and relative quantum efficiency curves for 16.4%-efficient CdTe/CdS ı-film solar cell [37]

From B.E. McCandless and J.R. Sites, PV Handbook, 2002

New record CdTe cell: First Solar, 2011 efficiency = 17.3%
(done “on production equipment”)

From S.H. Demtsu and J.R. Sites, IEEE PVSC-2005



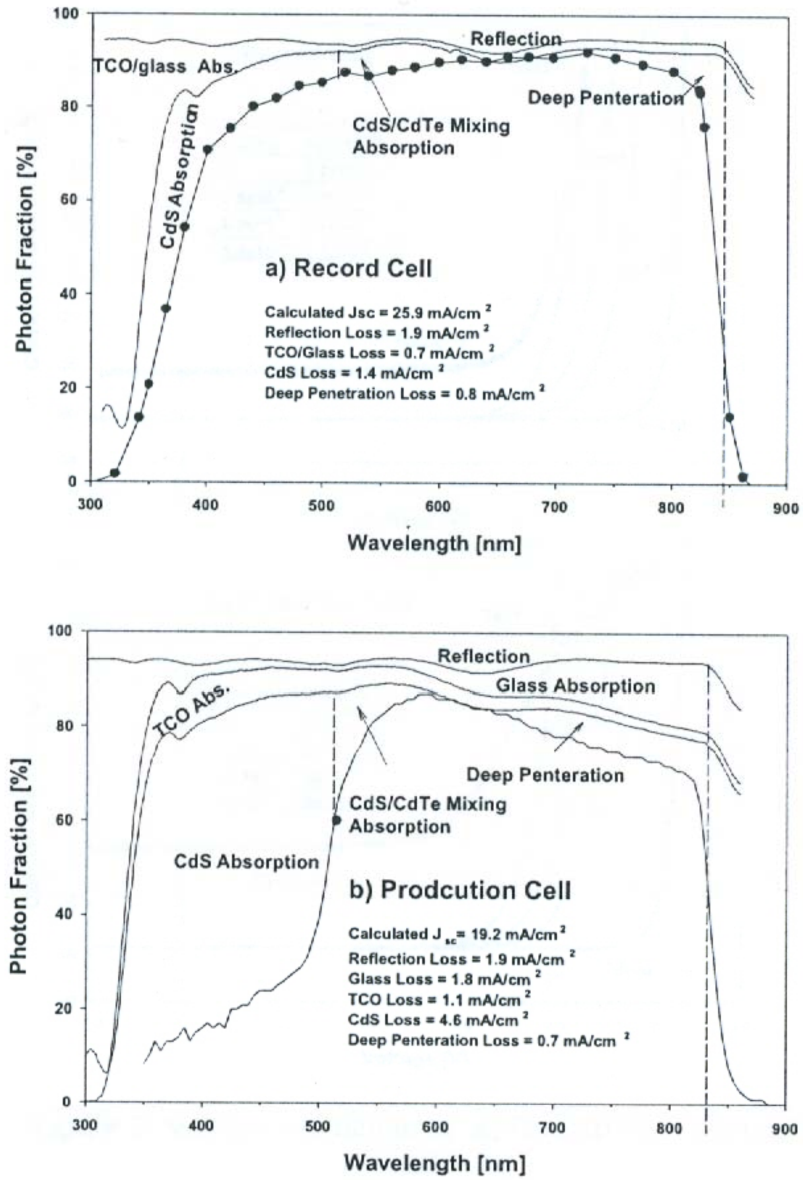


Figure 2. Photon accounting for a) Record cell b) Production cell.

Typically the back contact is a metal or carbon paste rather than the transparent ZnTe shown here.

Note particularly the following:

- Loss due to CdS absorption edge at 2.4 eV or 517 nm
- Loss due to intermixing
- Increased red response due to intermixing

(1.5 eV ~ 830 nm; 1.4 eV ~880 nm)

PL in CdS/CdTe junctions (from D-H Kwon)

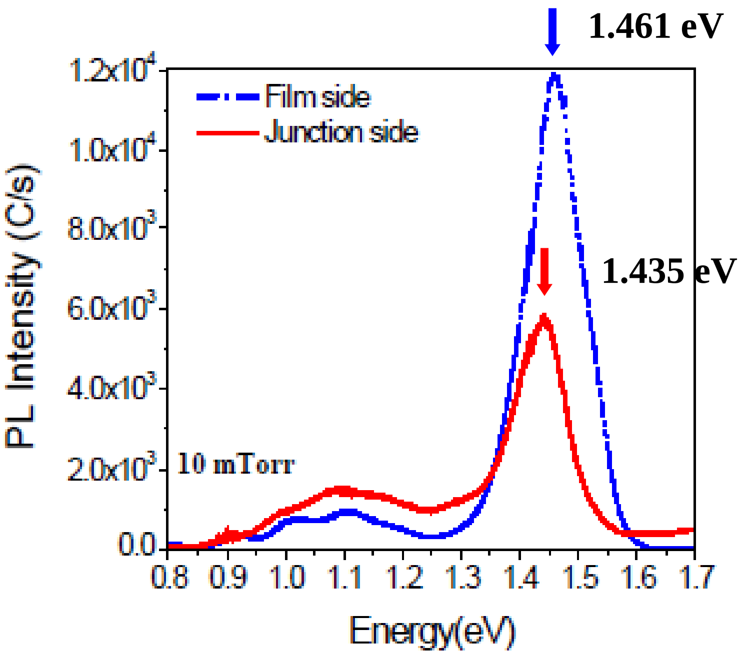


Fig10. Film and Junction side PLs of the same film

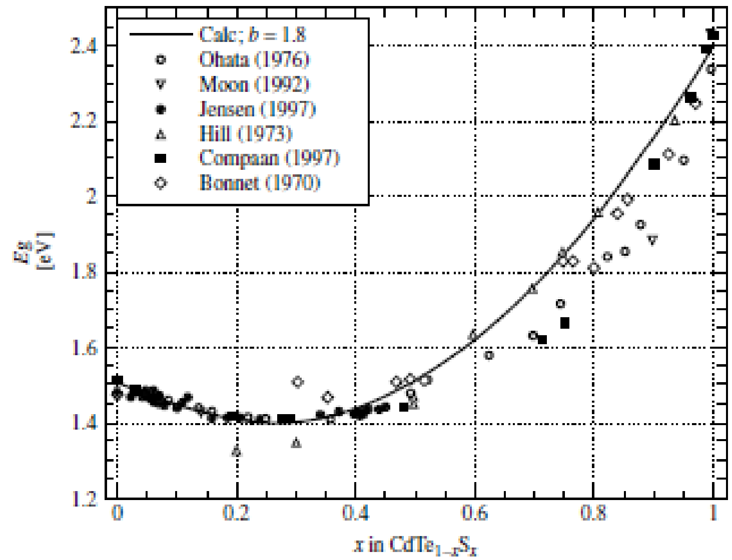


Fig 11. Optical bandgap of $CdTe_{1-x}S_x$ alloy thin films versus composition.

- Film side and junction side PL at 10 K from as-deposited cells
- Intermixing of S at the junction changes the bandgap of the material and ratio of S can be indirectly estimated

Fig. 10 from: DoHyoung Kwon, X. Liu, N. R. Paudel, K. A. Wieland, and A. D. Compaan, “INFRARED PL STUDIES OF SPUTTERED CdTe FILMS AND CELLS”, 35th IEEE PVSC conference proceedings, June 2010

Fig. 11 from: Antonio Luque and Steven Hegedus, “Handbook of Photovoltaic Science and Engineering”, p638, Wiley, West Sussex England, 2003

From B.E. McCandless and J.R. Sites, PV Handbook, Chap 14, 2002

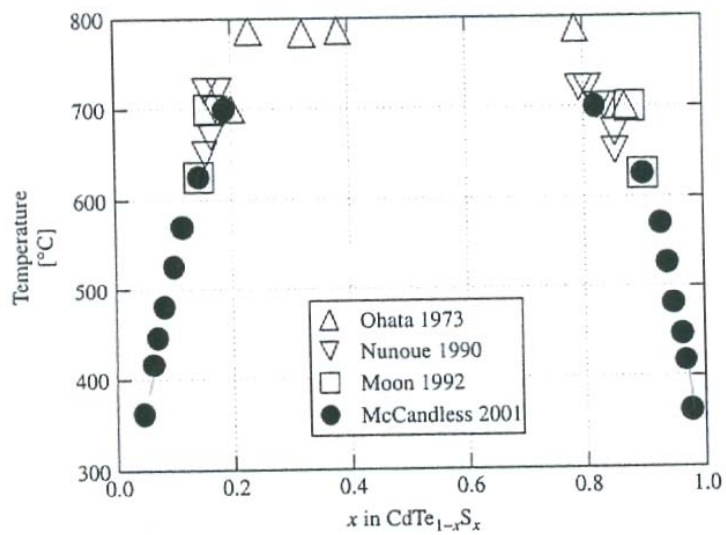


Figure 14.14 CdTe–CdS pseudobinary phase diagram. (Data listed in order from References [72, 139, 144, 147])

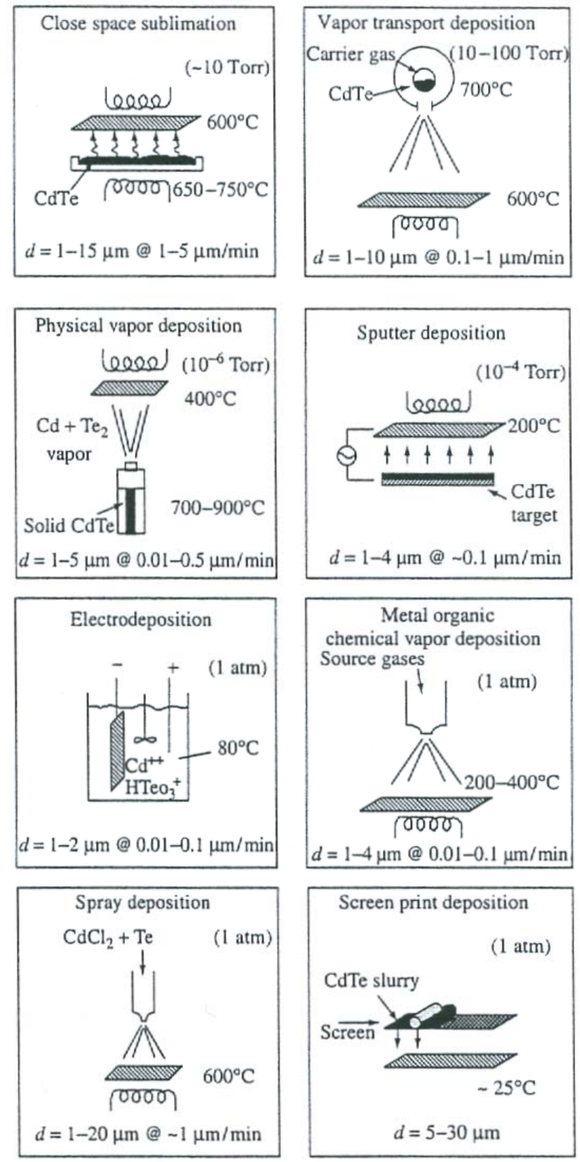


Figure 14.6 Schematic representations of eight CdTe thin-film deposition techniques. The substrate in each view is the cross-lined rectangle. Film thickness, d, and growth rate are shown at the bottom of each panel

Calculated impurity levels in CdTe

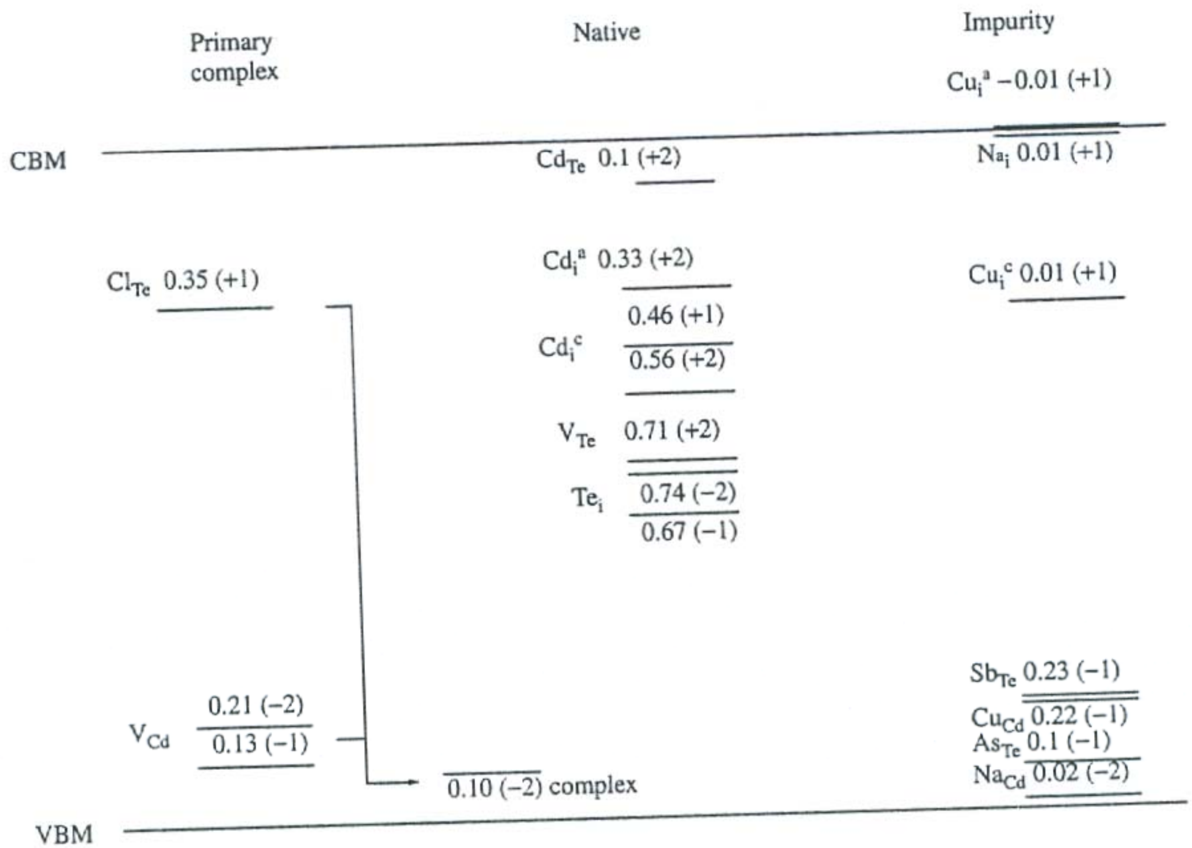


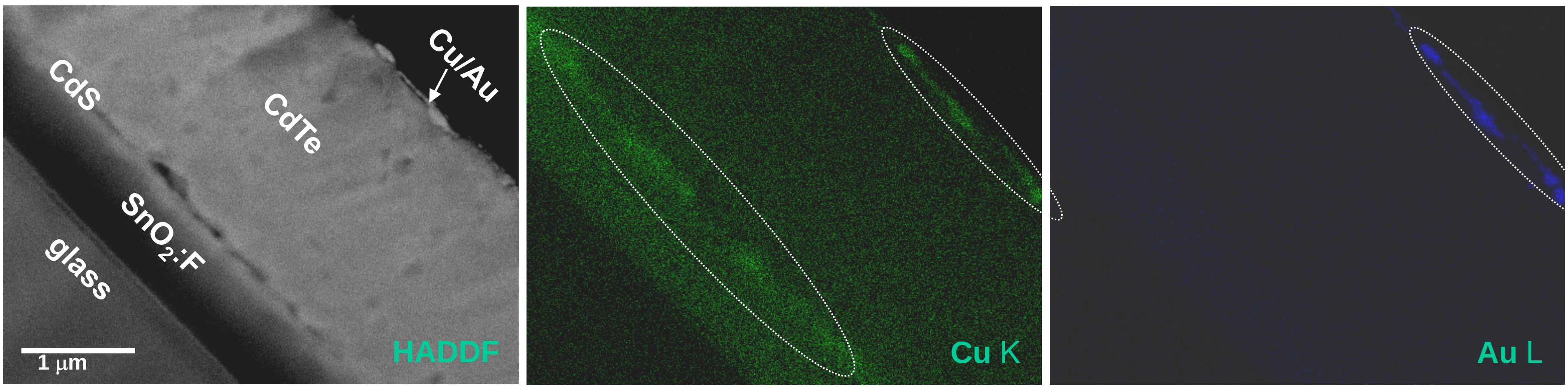
Figure 14.5 CdTe band structure with doping and defect levels. Charge states are in parentheses; energy is in electron volts measured from the conduction band for donor (positive) states and valence band for acceptor (negative) states. The superscripts a and c represent alternative interstitial sites. (Adapted from Wei S, Mtg. Record, National CdTe R&D Team Meeting (2001) Appendix 9 [59])

Discuss Cu distributions

- Secondary Ion Mass Spectroscopy
  (usually done in conjunction with ion beam etching for depth profiling)
- Cu is used in the back contact
- $CdCl_2$ “activation” anneal is used just prior to the back contact deposition
- $CdCl_2$ activation is done in the presence of O_2 at 387 C

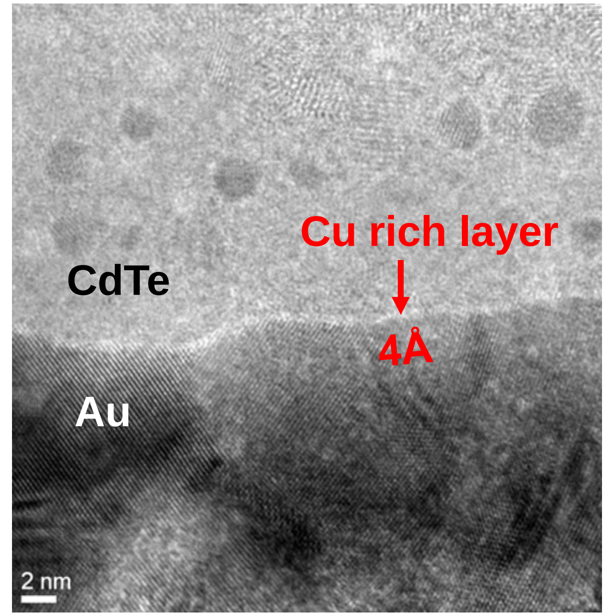
• *small spot XRF data from Umich's EMAL*

EDS mapping and High Angle Annular Dark Field (HAADF)

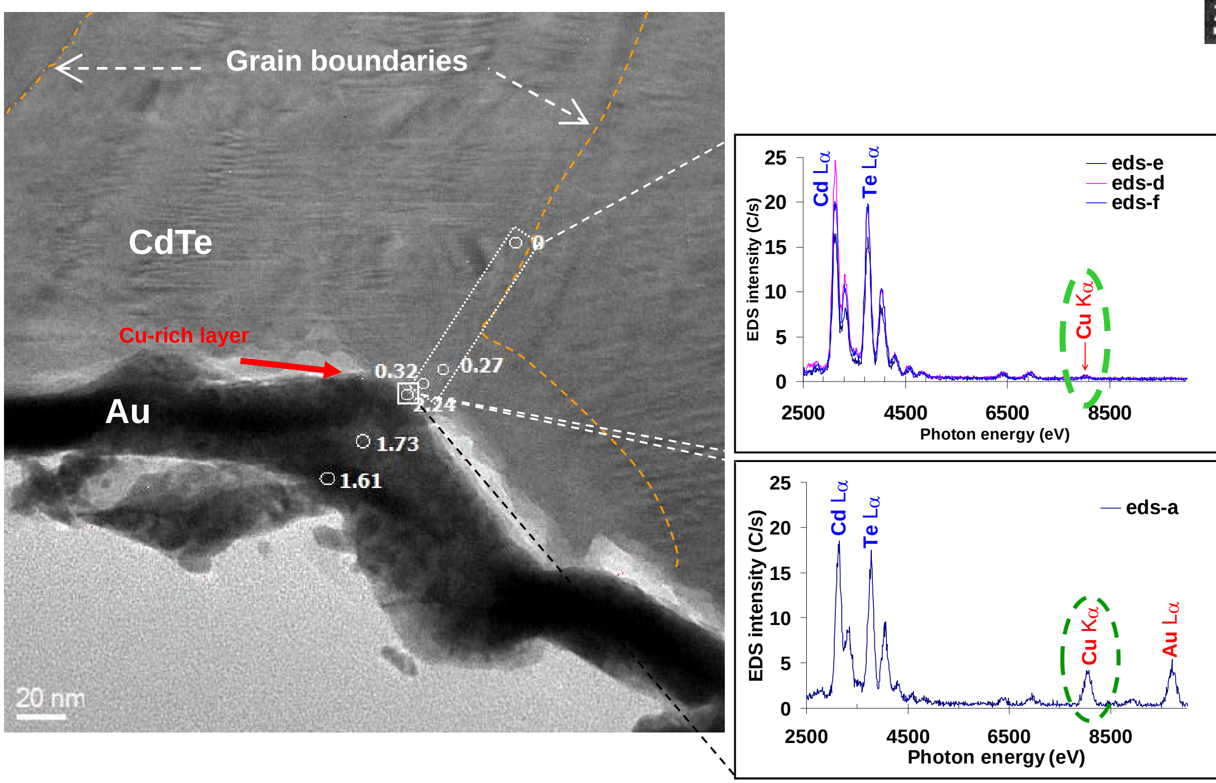


1. A high concentration of Cu at back contact
2. Au layer has high Cu content, Cu-Au alloy phases
3. Relatively high concentration in the CdS layer and some in SnO_2:F accounts for most of the ~10% Cu diffused from the back contact.

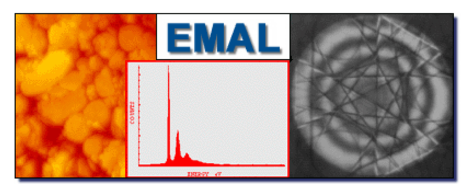
Little evidence for Cu concentrated at grain boundaries: XTEM with small spot EDS



- **evidence of some voids near the CdS/CdTe interface**
- **high Cu concentration at interface and in the Au layer**
- **little evidence of Cu along grain boundaries**

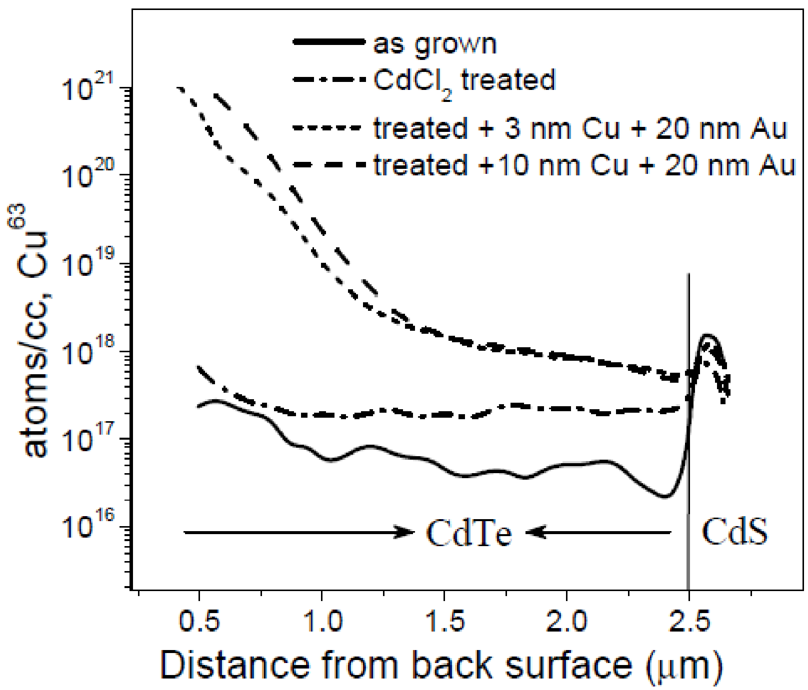


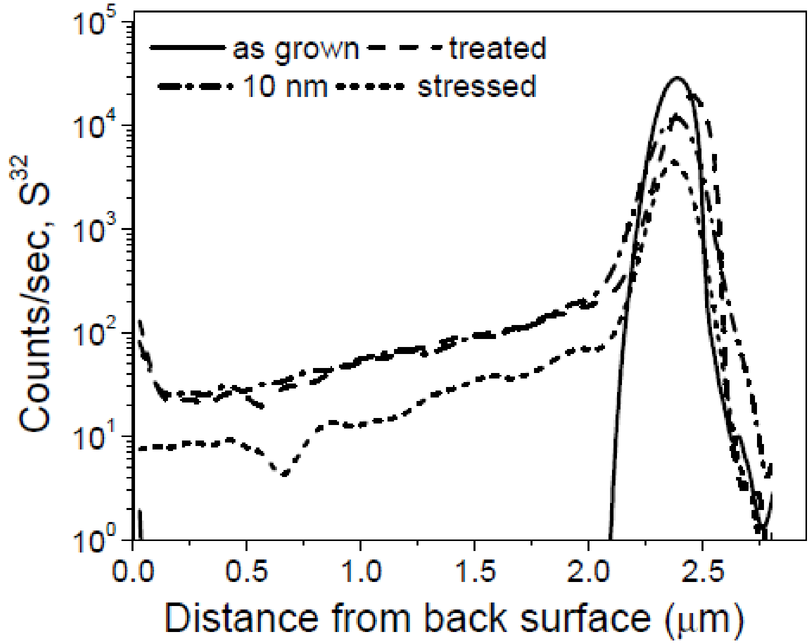
Data obtained in collaboration with Kai Sun UMich EMAL.



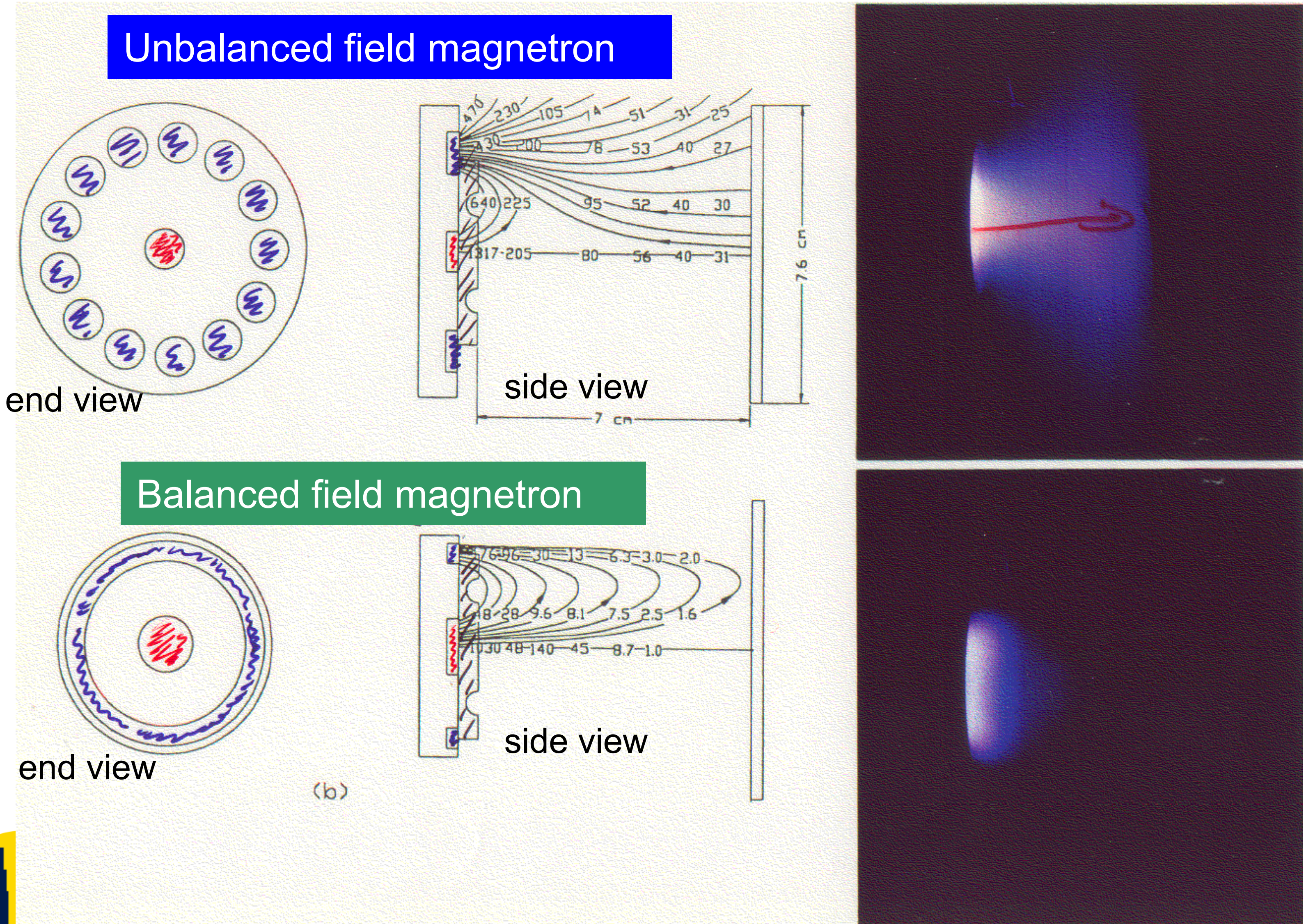
SIMS profiles of Cu and S in CdTe/CdS

(data from Matt Young and Sally Asher (NREL))

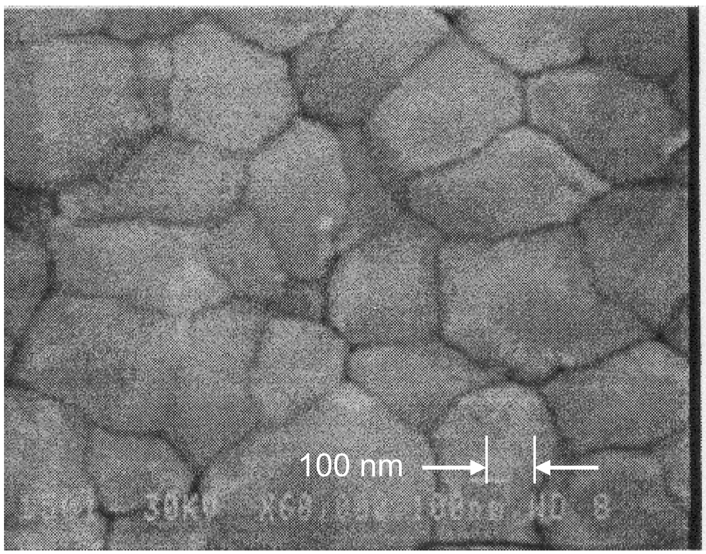




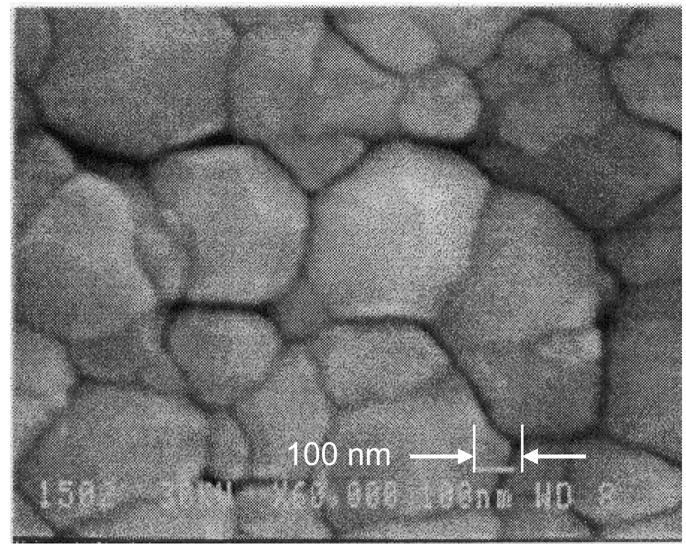
Plasma dependence on magnetic field



Grain morphology vs magnetron B-field



Strongly **unbalanced** gun (39,1),
CdTe: 25 W RF, 300 C,18 mT



Nearly **balanced** gun (13,12),
CdTe: 25 W RF, 300 C,18 mT

UT SEM data from magnetron-sputtered samples grown at UT

Grain boundaries:

the challenge of polycrystalline thin-film cells

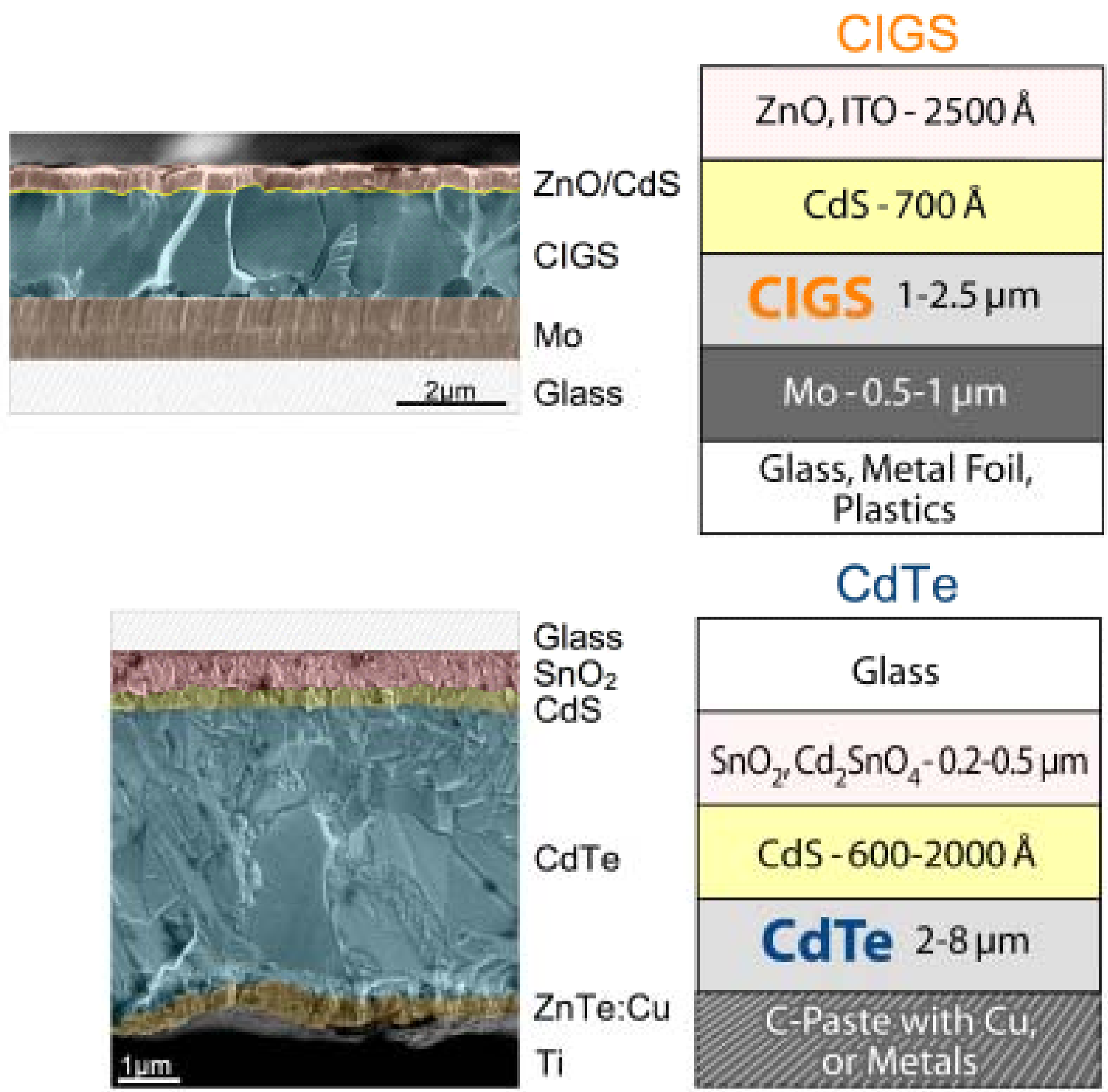


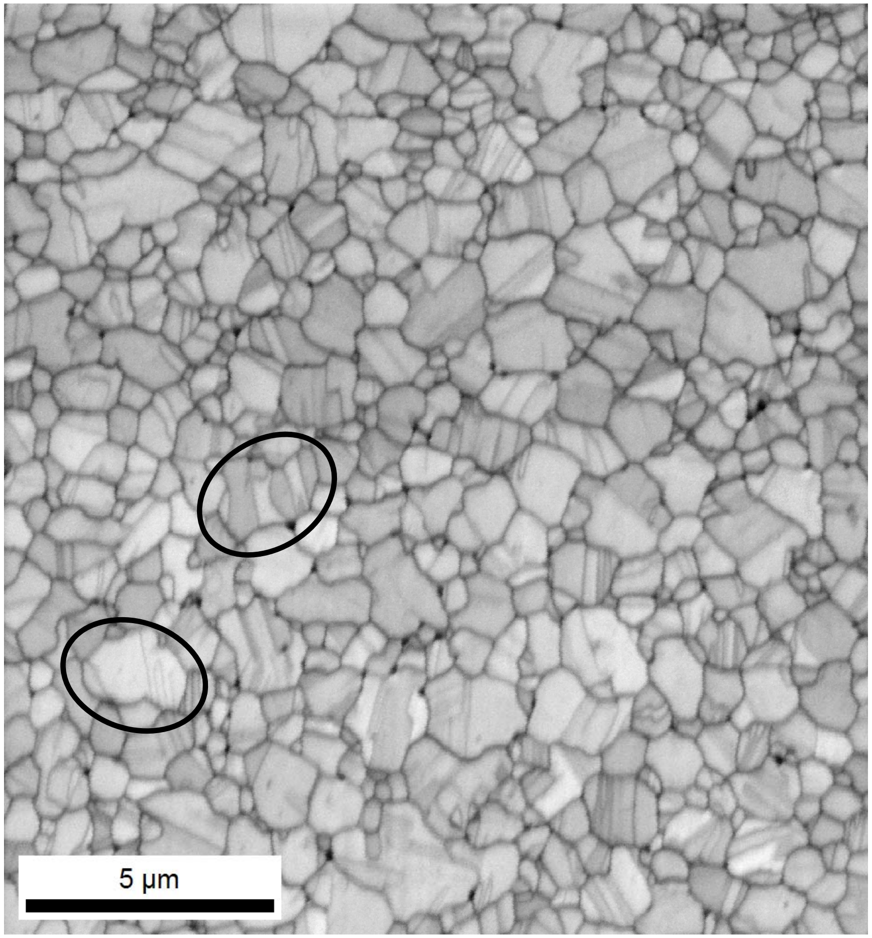
Fig. 4.2 Structure of the polycrystalline CIGS and CdTe cells. From Noufi 2006.

EBSD data of grain size and low-angle grain boundaries

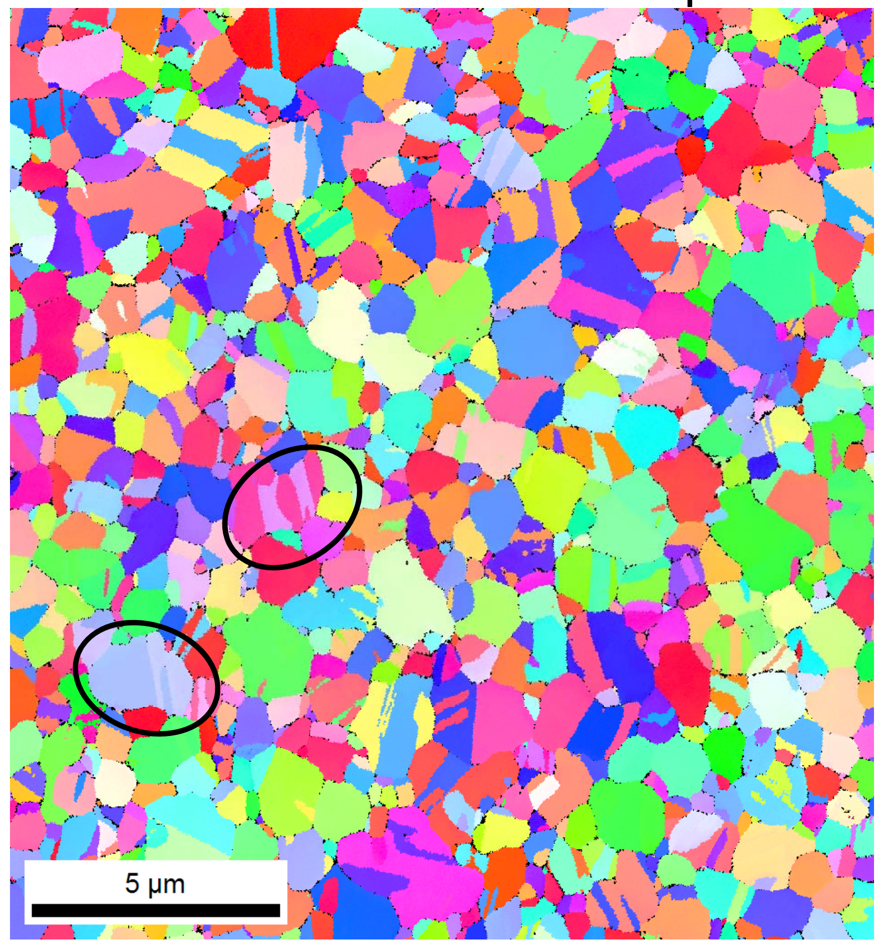
(Data taken on UT cell SSC548 by Matt Nowell of EDAX-TSL / U. Utah)

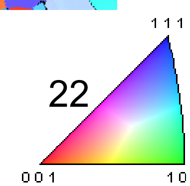
(sputtered CdTe-center region $CdCl_2$ treated)

secondary electron Image



EBSD orientation map





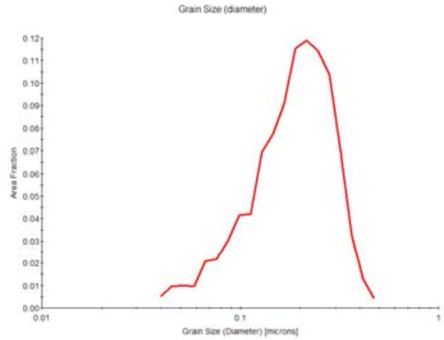
Grain size increases with $CdCl_2$ activation: EBSD

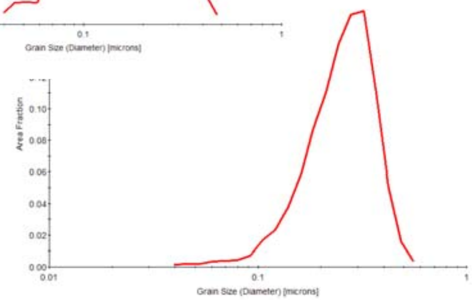
Data from Matt Nowell of EDAX-TSL / U. Utah obtained on UT films

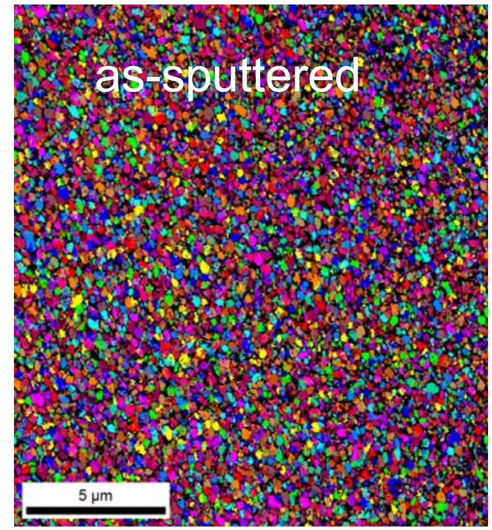
SSC548 Center As-Grown

- Grain map and size distribution **including** twins (ave. grain size = 115 nm)

- Grain map and size distribution **excluding** twins ($\Delta\theta < 5^o$) (ave. grain size = 176nm)



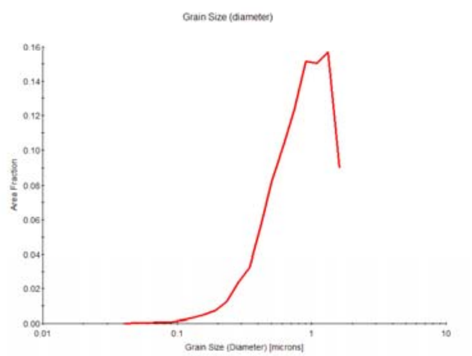


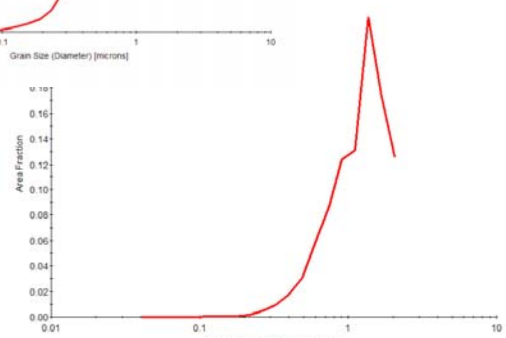


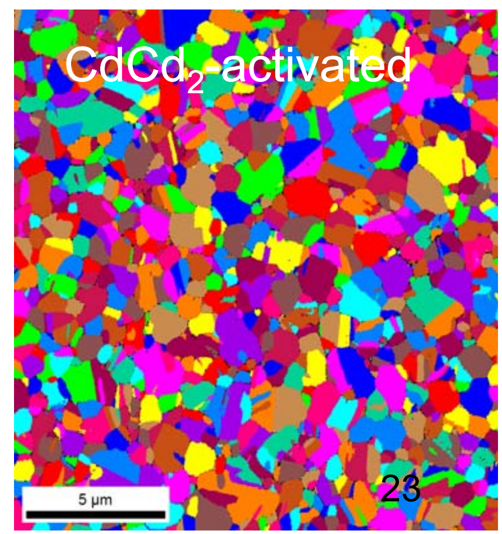
SSC548 Center $CdCl_2$ treated

- Grain map and size distribution **including** twins (ave. grain size = 400 nm)

- Grain map and size distribution **excluding** twins (ave. grain size = 710 nm)



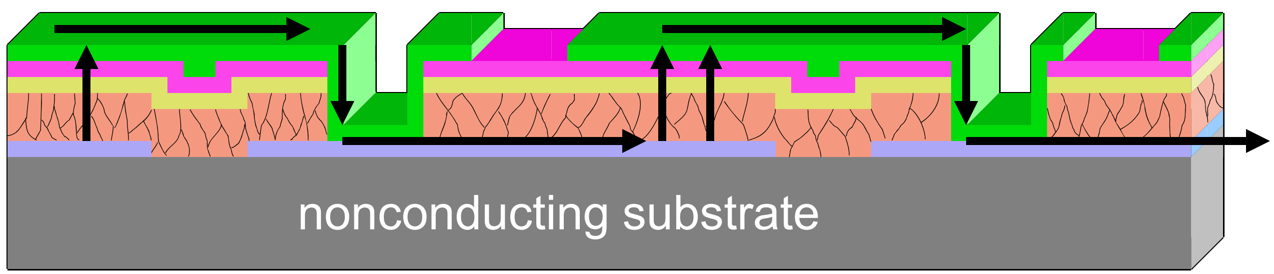




from cell to module--
series integration

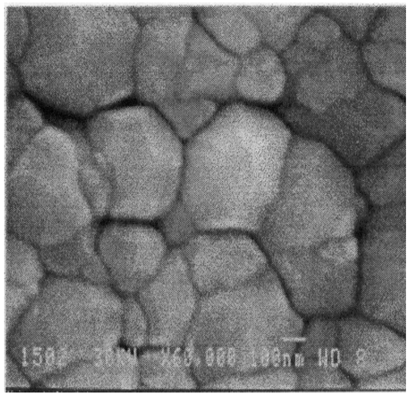
assembly from smaller cells

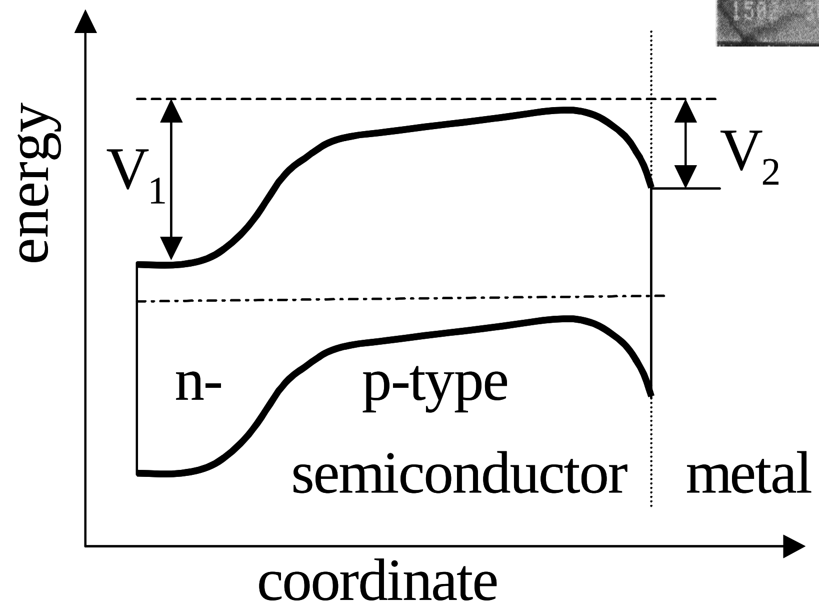
monolithic integration



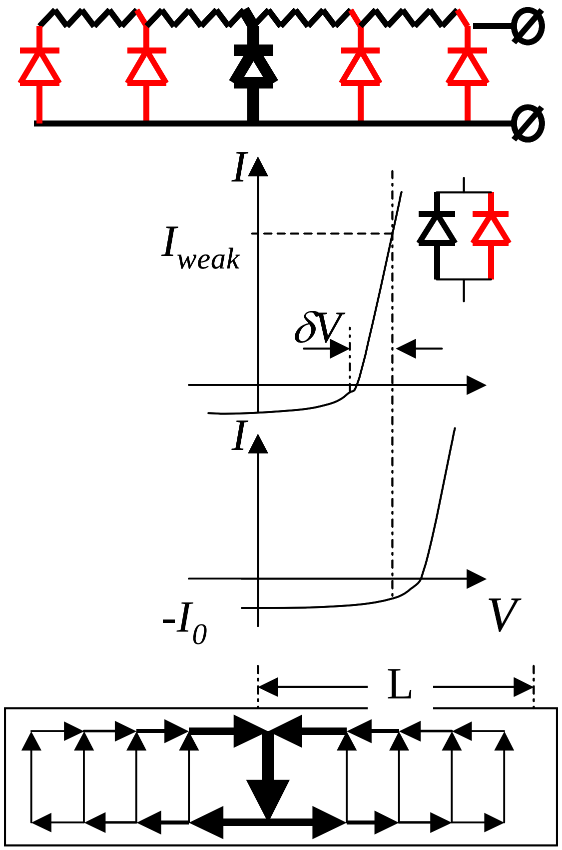
Diodes in parallel with variable performance

(model and analysis by Victor Karpov, Diana Shvydka of U. Toledo)





Schematic band diagram of the CdS/CdTe cell emphasizing the presence of a hole barrier, V_2, at the back contact typically ~300 meV.



Elements of a random diode model which can result from variations in the back barrier leading to weak diodes which can shunt large amounts of current if the diodes are strongly linked with low resistance paths.