IEEE Hamilton:
The Future of Photovoltaics
Ongoing Research at McMaster University

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Department of Engineering Physics
McMaster University

May 9, 2012

This presentation...

- Is presented from a materials perspective, because I'm a materials guy
- Can be interrupted any time by your questions
- Is hopefully a gentle introduction into the challenges of the physics of solar cells

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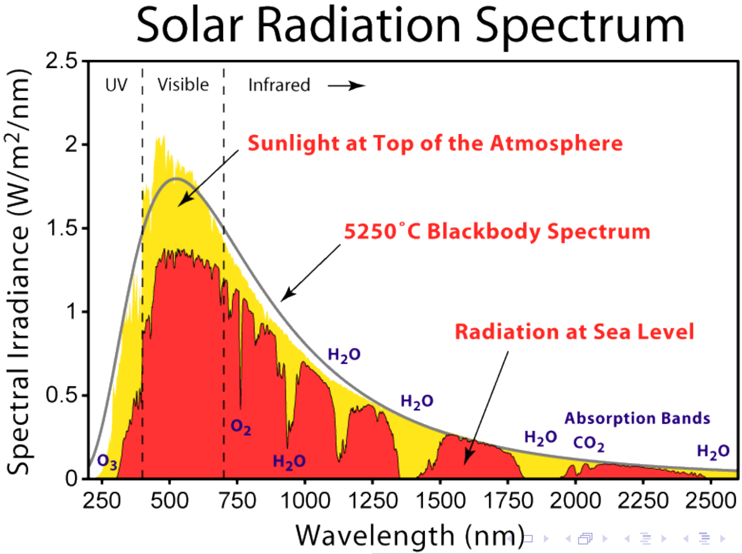
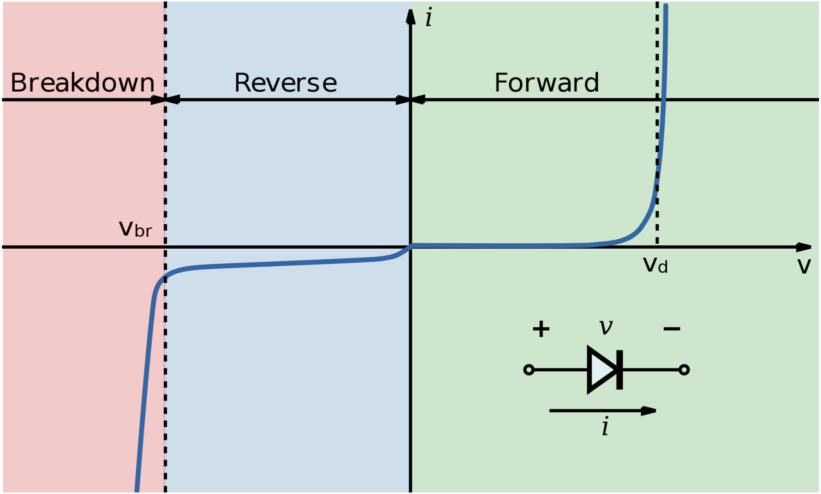
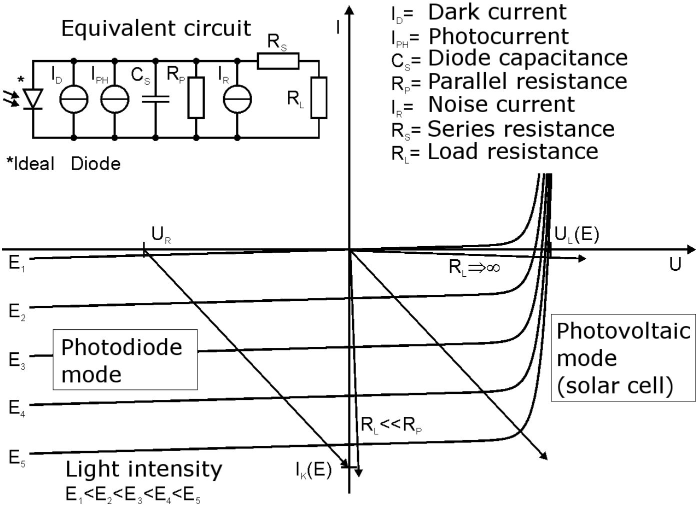

Solar Radiation Spectrum
Spectral Irradiance (W/m²/nm)
Wavelength (nm)
UV
Visible
Infrared
Sunlight at Top of the Atmosphere
5250°C Blackbody Spectrum
Radiation at Sea Level
Absorption Bands
O3
O2
H2O
H2O
H2O
H2O
H2O
CO2
H2O
2.5
2
1.5
1
0.5
0
250
500
750
1000
1250
1500
1750
2000
2250
2500


i
Breakdown
Reverse
Forward
Vbr
Vd
V
+
v
−
i


Equivalent circuit
R_S
I_D
I_{PH}
C_S
R_P
I_R
R_L
*
*Ideal Diode
I
I_D= Dark current
I_{PH}= Photocurrent
C_S= Diode capacitance
R_P= Parallel resistance
I_R= Noise current
R_S= Series resistance
R_L= Load resistance
U_R
U_L(E)
U
$R_L \Rightarrow \infty$
E_1
E_2
E_3
E_4
E_5
Photodiode mode
Photovoltaic mode (solar cell)
R_L<<R_P
Light intensity
$E_1<E_2<E_3<E_4<E_5$
I_K(E)

How does photovoltaic behaviour arise?

- Absorption in semiconductors
- Production of electron-hole pairs
- Electrons and holes are current carriers in semiconductors
- How can these carriers spontaneously separate

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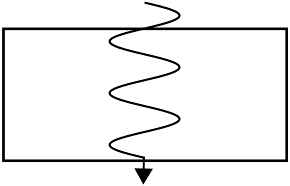

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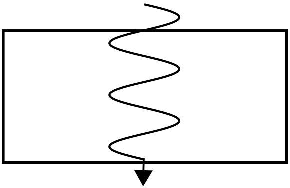

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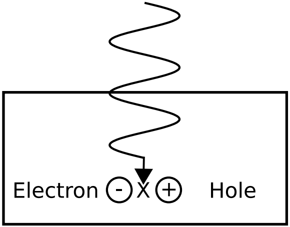

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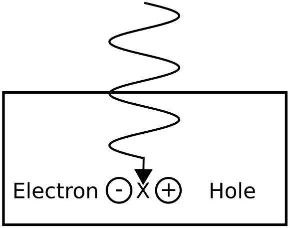

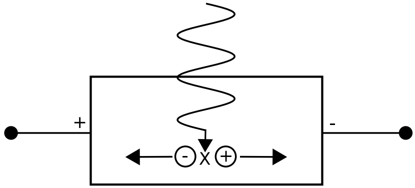

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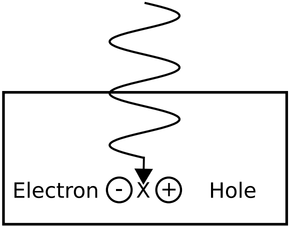

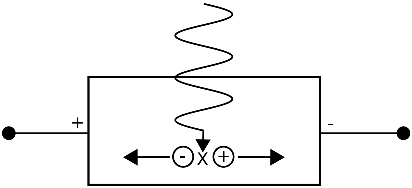

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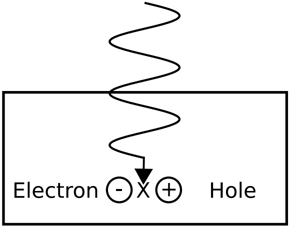

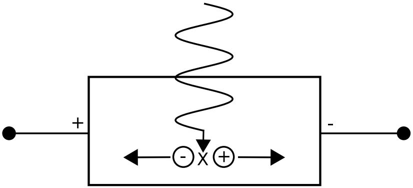

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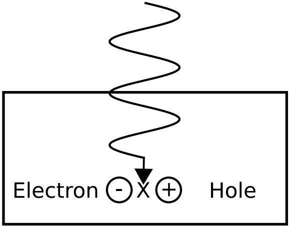

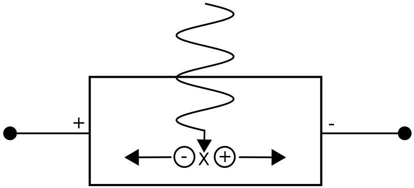

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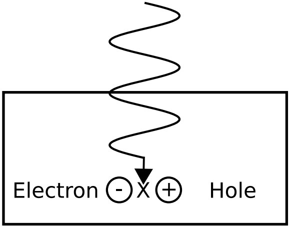

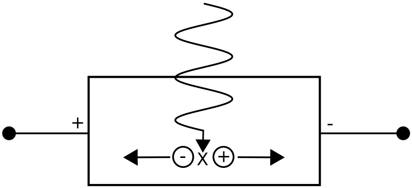

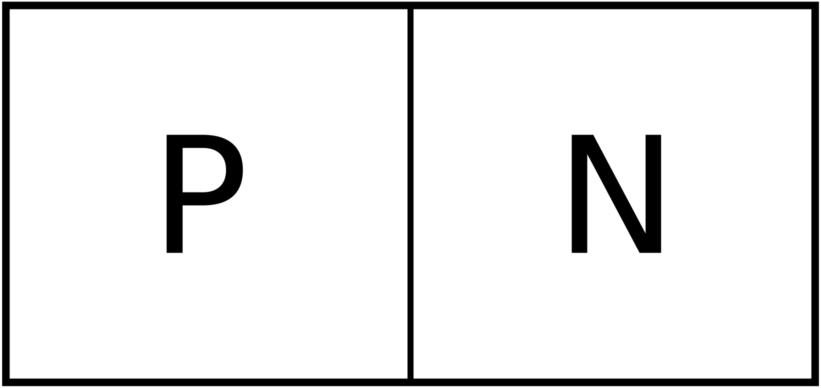
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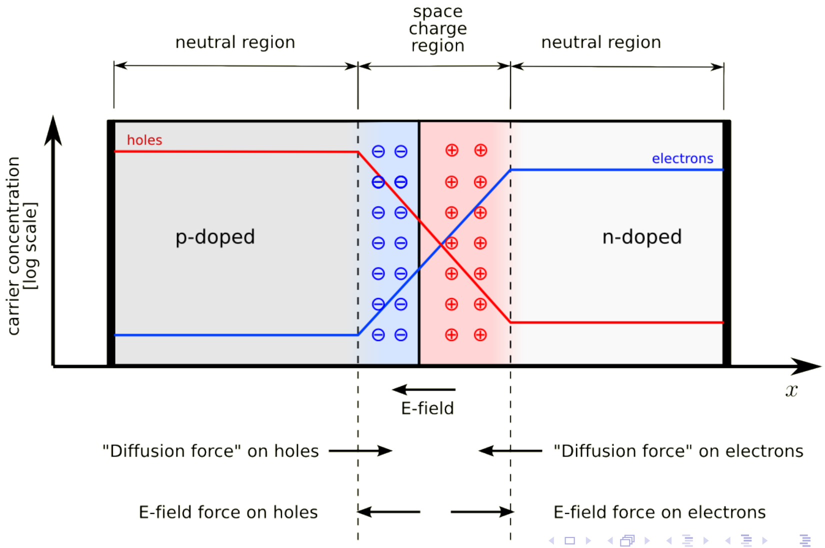
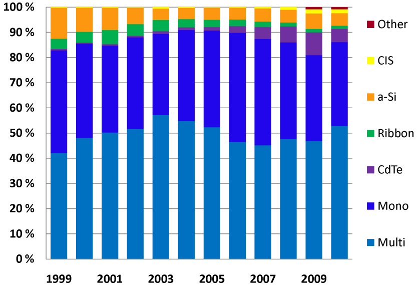

space charge region
neutral region
neutral region
carrier concentration [log scale]
holes
electrons
p-doped
n-doped
x
E-field
"Diffusion force" on holes
"Diffusion force" on electrons
E-field force on holes
E-field force on electrons

Silicon Cells

- Silicon solar cells dominate market
- Leverage microelectronics industry
- 85% of Market is Silicon
- Half multicrystalline, half monocrystalline



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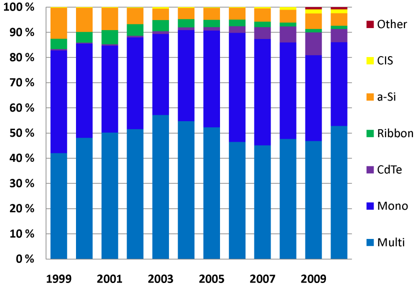

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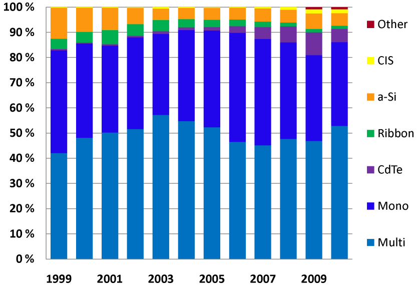

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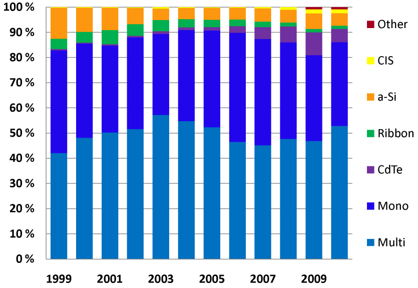
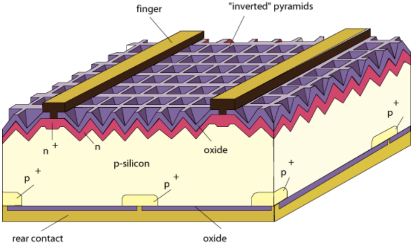


State-of-the-art

- PERL Cell made by Martin Green
- Ph.D. from McMaster
- Professor University New South Wales
- 25% Efficient
- Not in production



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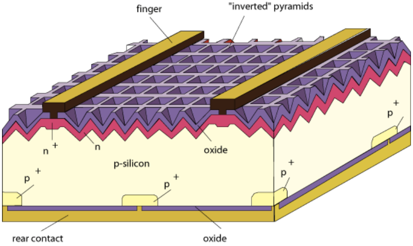

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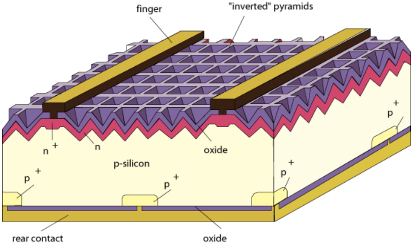

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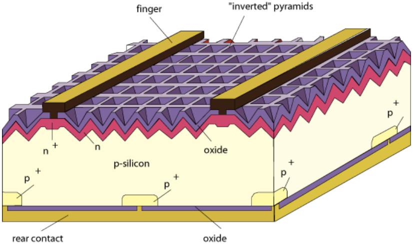

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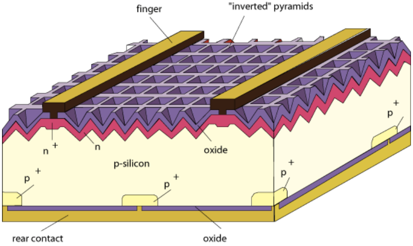

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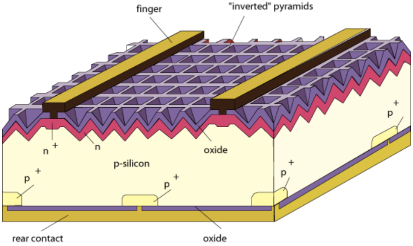

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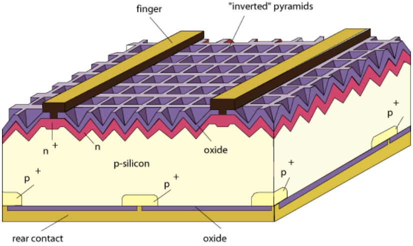

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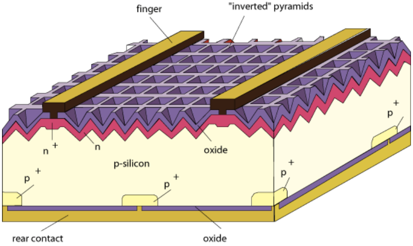

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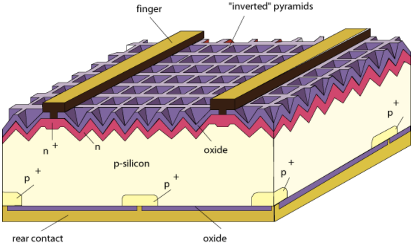

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- Why is it non-ideal?
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- Non-ideal bandgap
- High energy input for refinement

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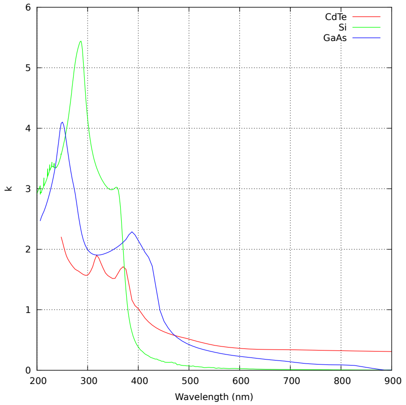

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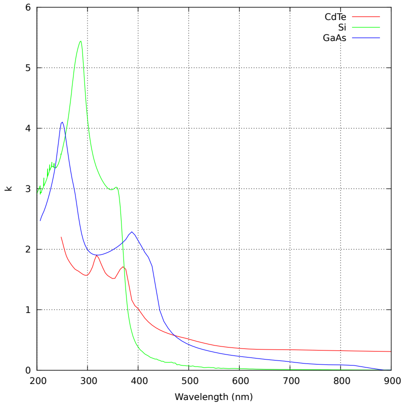

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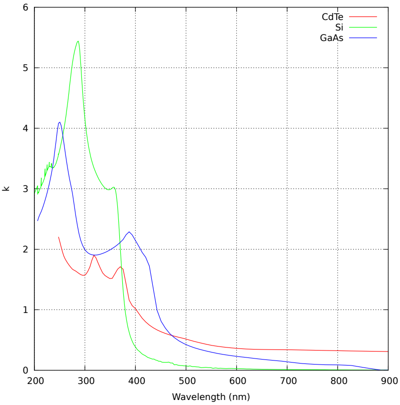

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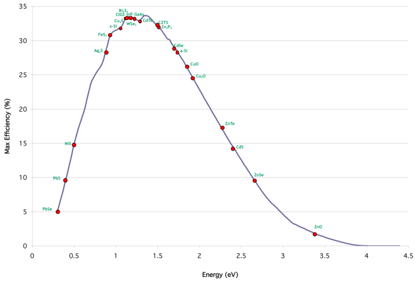

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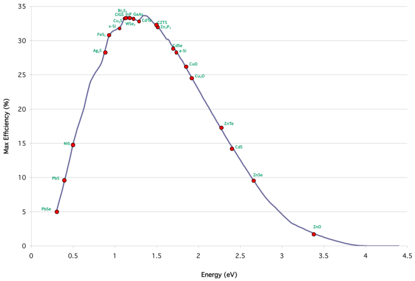

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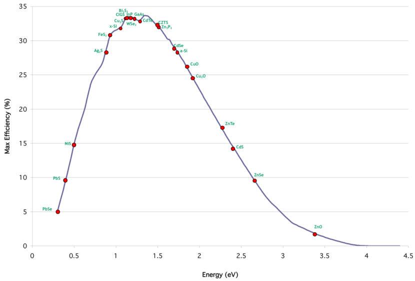

Effciency

- Traditional Silicon relies on economies of scale
- We haven't met cost parity with Silicon
- Do we need higher efficiency?

- Cost per Watt is King
- Cheap low efficiency cells are fine
- Expensive high efficiency cells are fine
- Research is ongoing in both areas

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Better Materials

- Improving material quality
- Reducing material waste
- Finding new and interesting materials

Better Physics

- Tandem cell structures
- New physics structures
- Enhancement of light absorption

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- Improving photovoltage via HIT cells (amorphous Silicon Hybrid cells)

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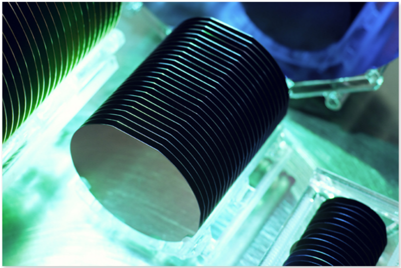

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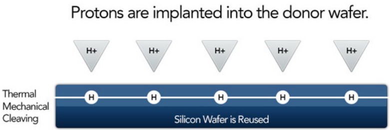

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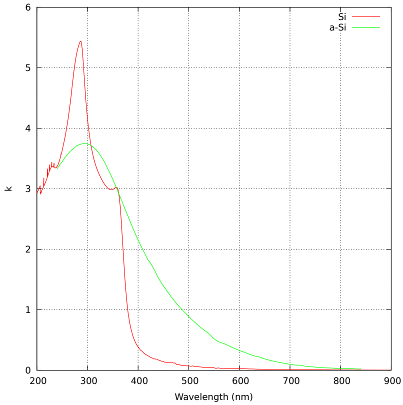

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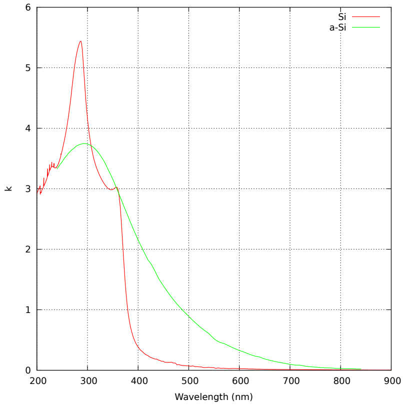

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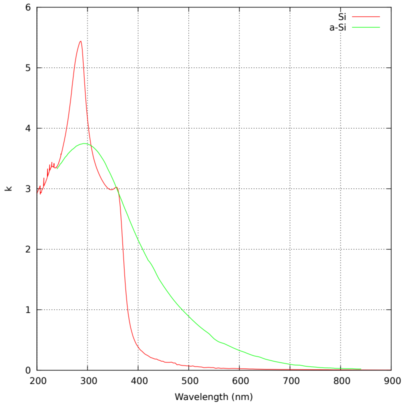

CdTe Solar Cells

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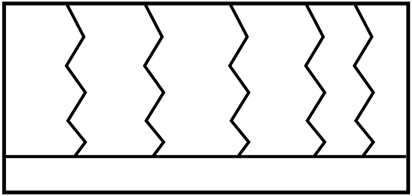
- All cells made are polycrystalline
- Shunt pathways
- Dopant segregation
- Carrier trapping
- Limit maximum efficiency



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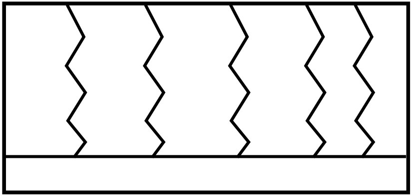

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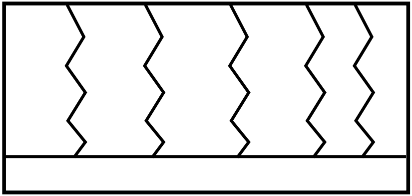

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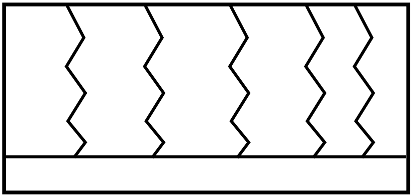

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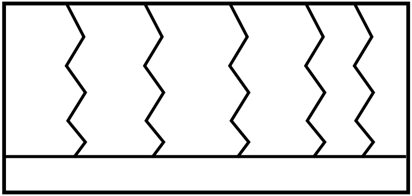

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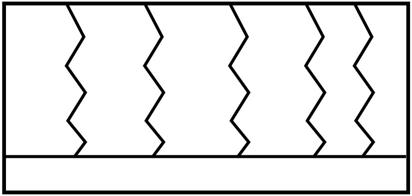

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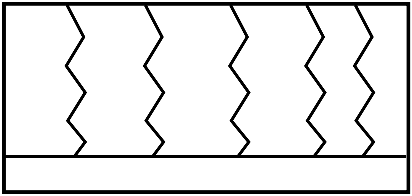

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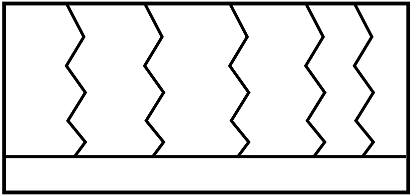

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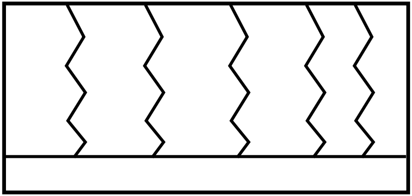

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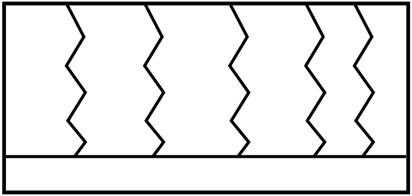

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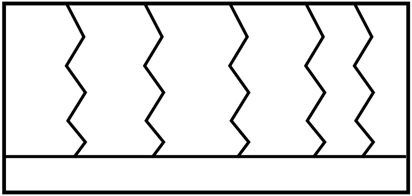

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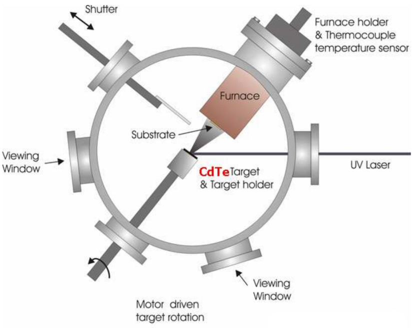

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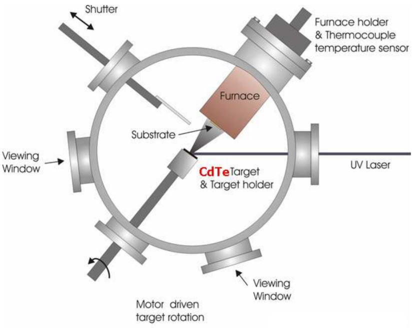

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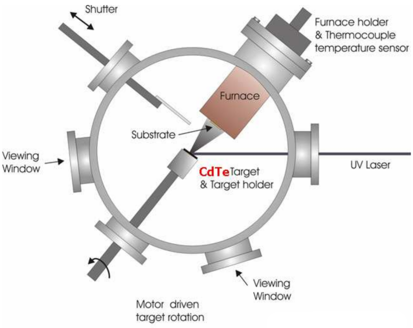

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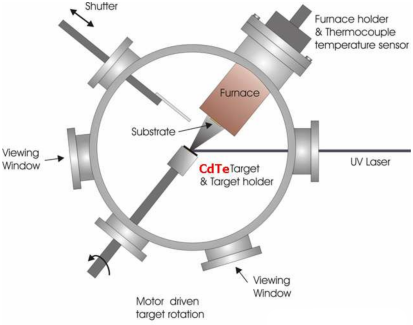

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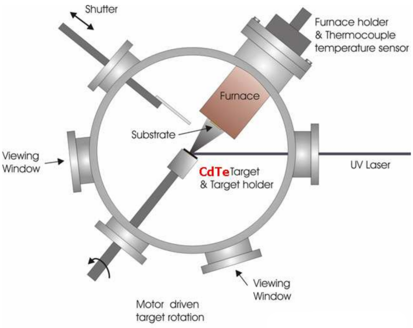

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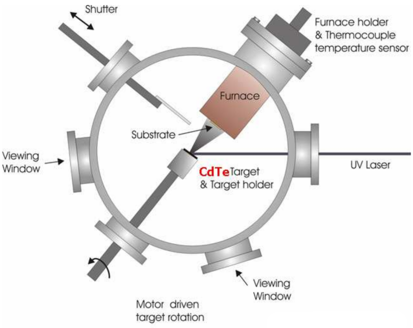

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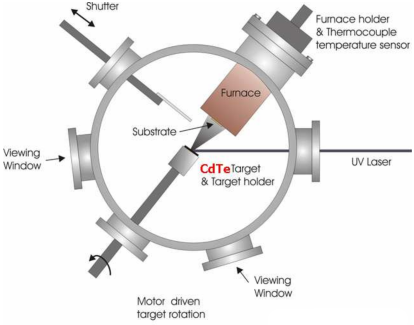

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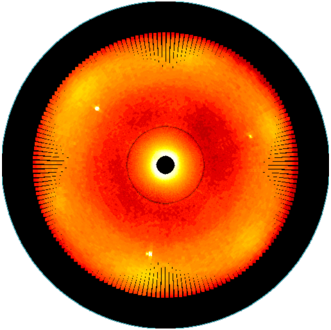

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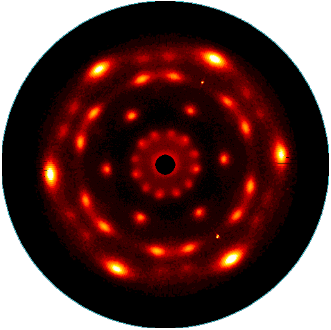

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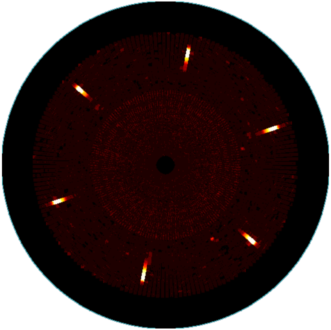

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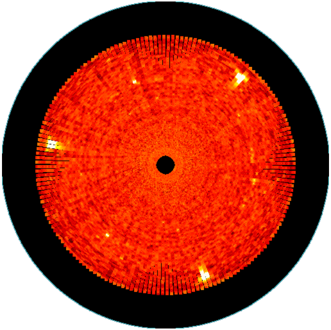

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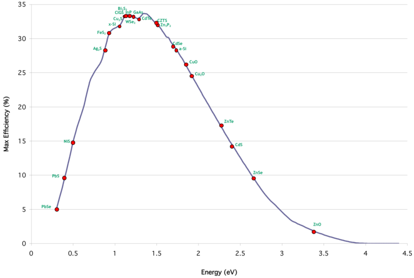

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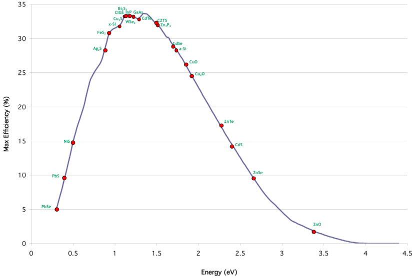

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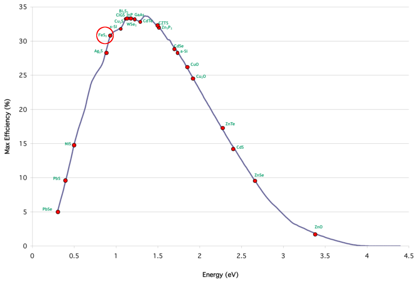

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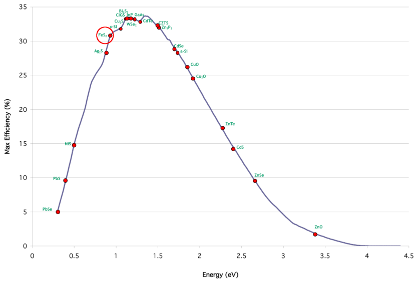

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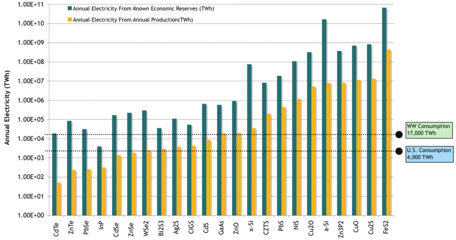

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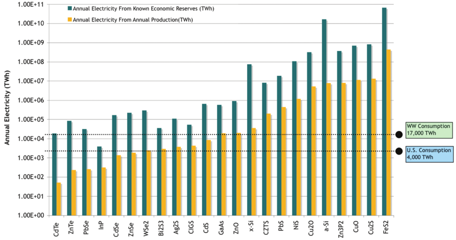

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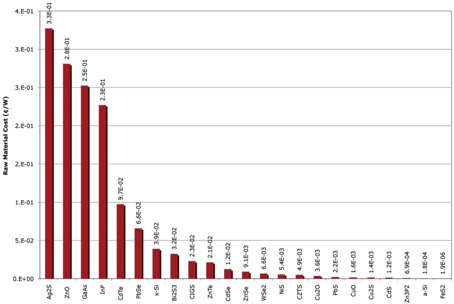

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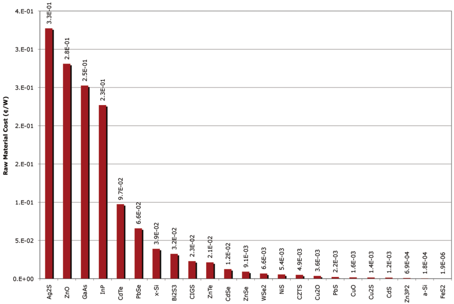

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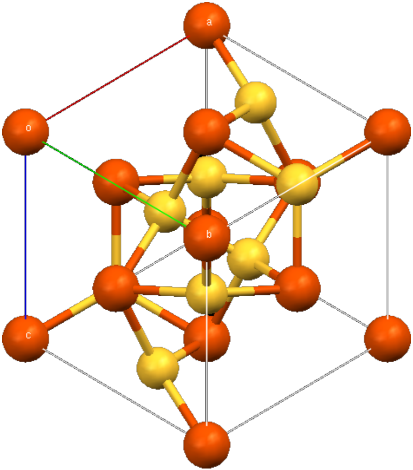

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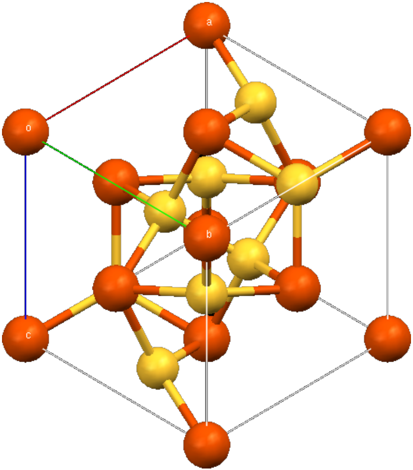

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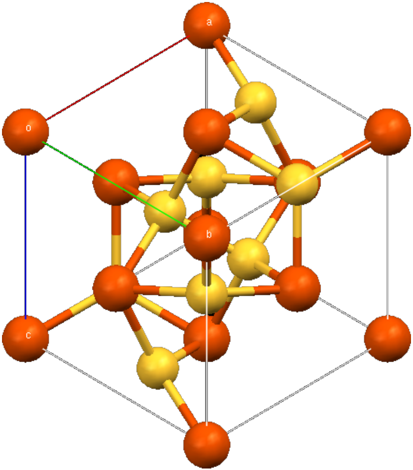

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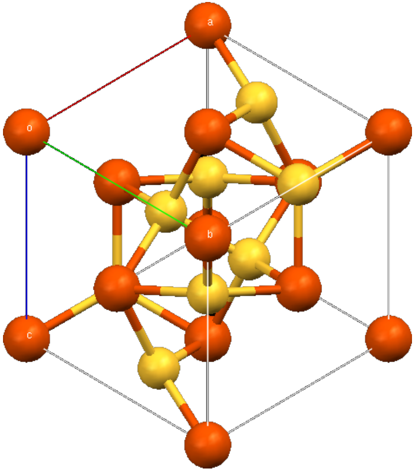

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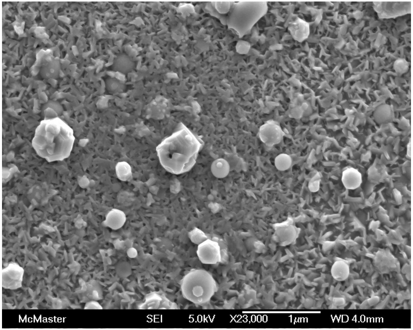

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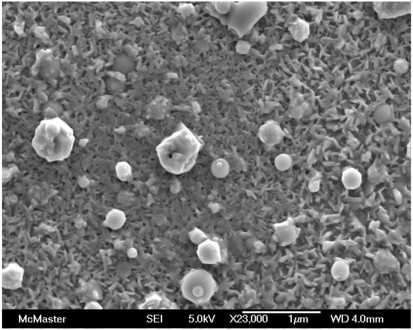

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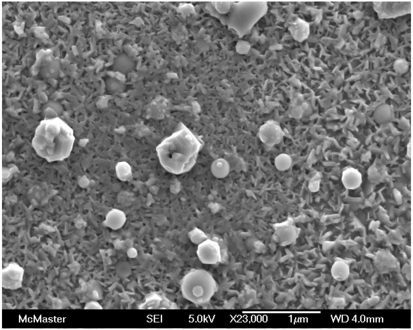

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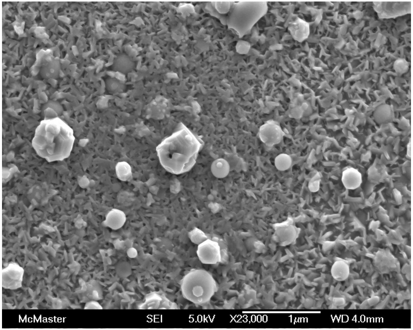

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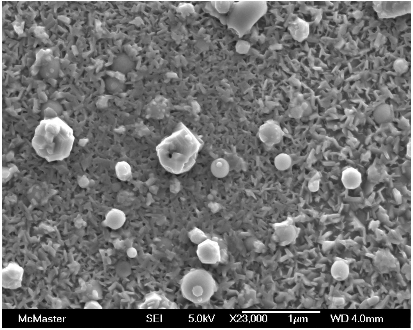

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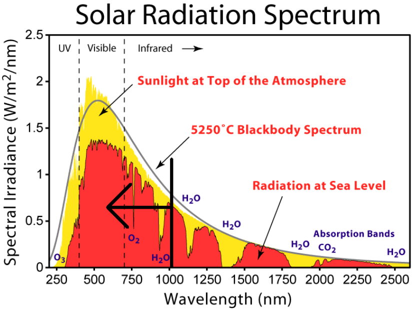

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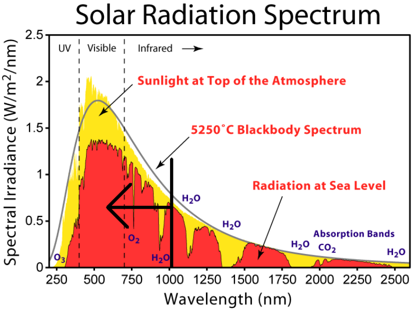

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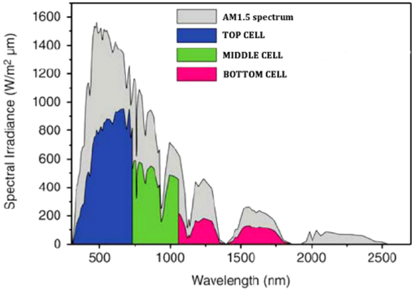

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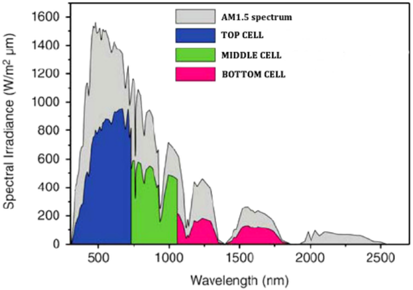

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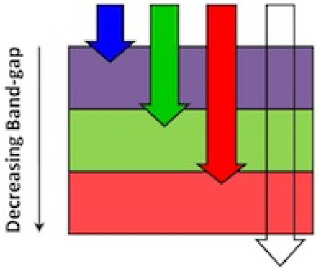

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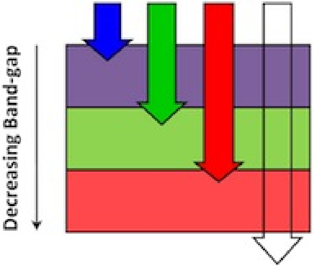

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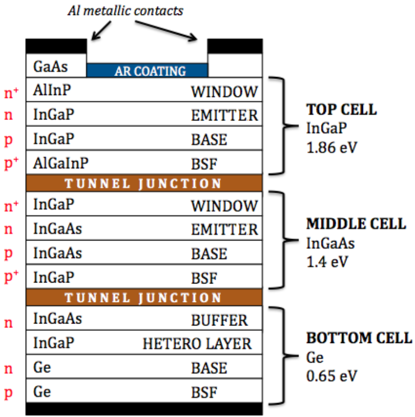
- The easy multi-junction designs are very expensive
- Cheaper multi-junction choices have problems with crystal quality



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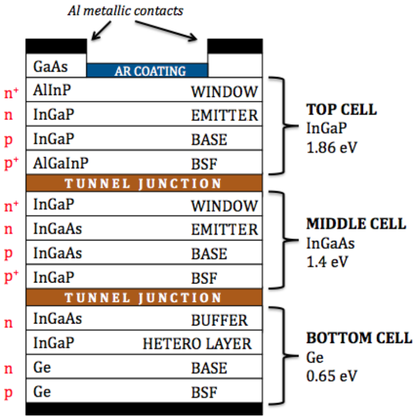

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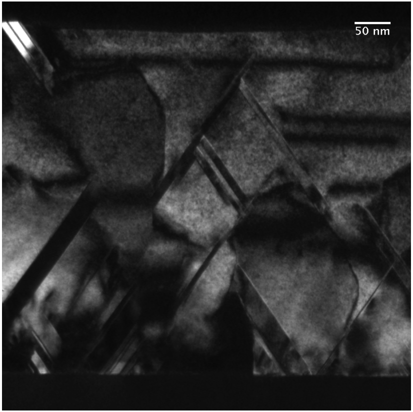

Improving lattice-mismatched multi-junction cells at McMaser

- Leverage existing Silicon technology
- Improve performance via tandem thin films
- Many material problems
- Problems with lattice mismatch
- Problems with anti-phase-boundaries
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- Nothing matches silicon
- Why not ignore the match?
- GaSb on silicon forms a low energy defect network to handle mismatch

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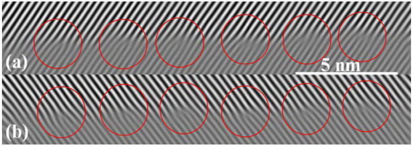

Anti-Phase Boundaries

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- Boundaries between opposite polar sections results in electrical defects
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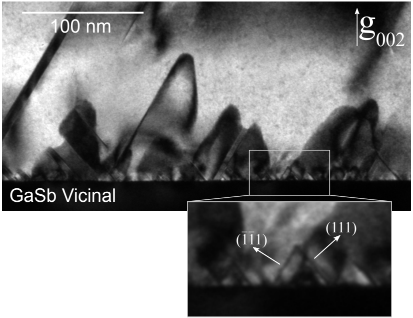
- Twins are a low energy defect that occurs spontaneously during growth
- Colliding twin fronts result in high energy defects
- Offcut substrates, in addition to solving APDs, appear to strongly reduce twinning



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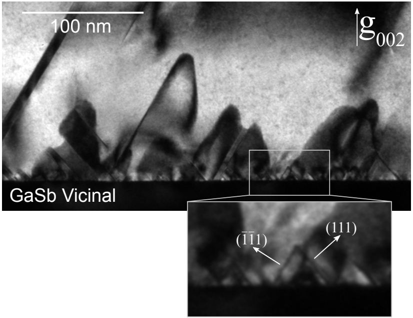

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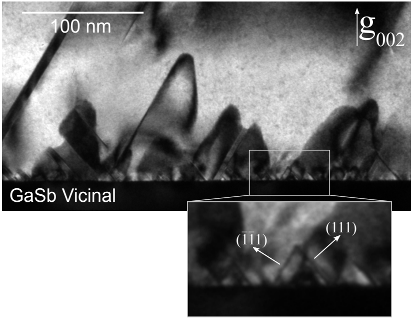

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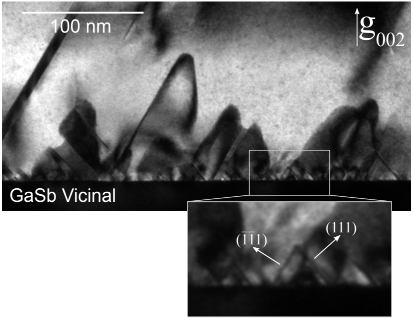

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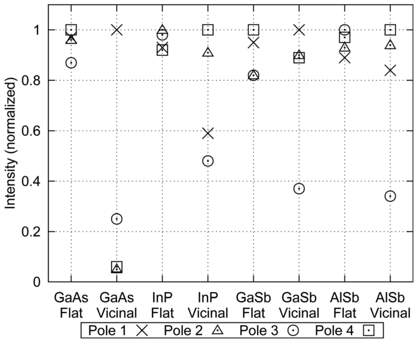

(211) Substrates

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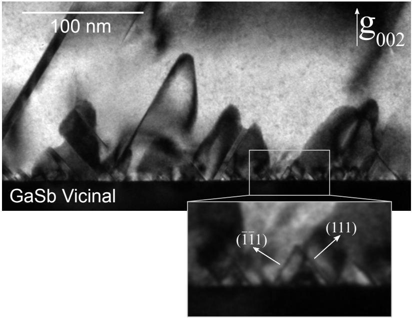

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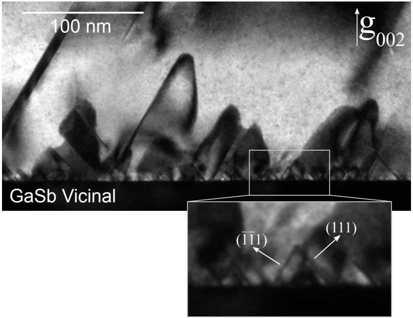

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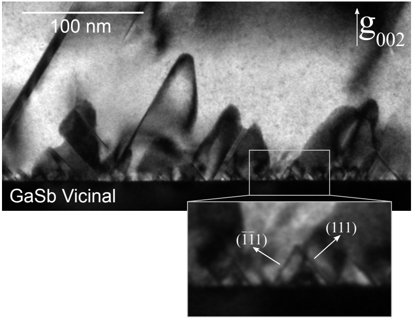

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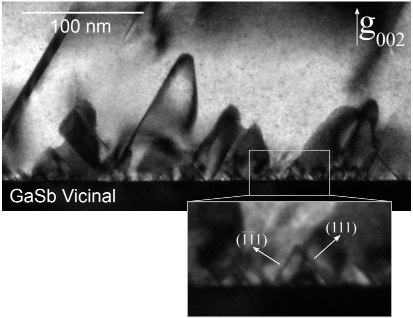

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- Hot carrier cells attempt to avoid thermalization losses by extracting carriers before they thermalize
- Intermediate band cells attempt to have a tandem cell in one device
- Up/downconversion cells attempt to combine/split photons prior to absorption by the cell
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- Tradeoff is optics size versus cell size
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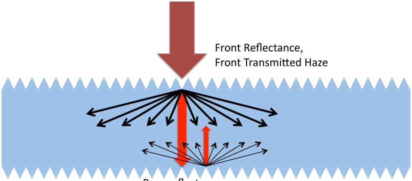
- Reduces material requirements
- Careful control of re-emission angles have been shown to improve voltage



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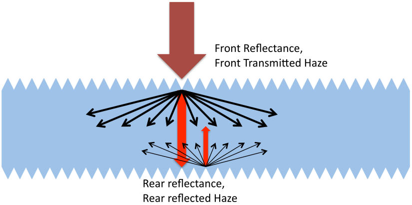

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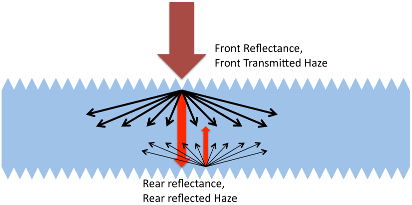

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- Process is analogous to antennas and radio waves
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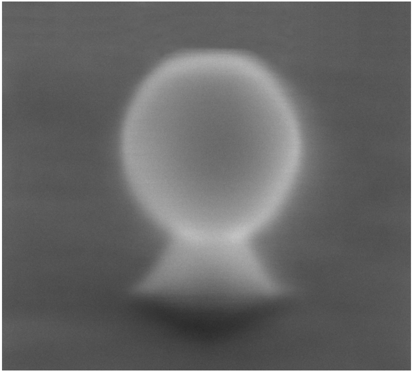

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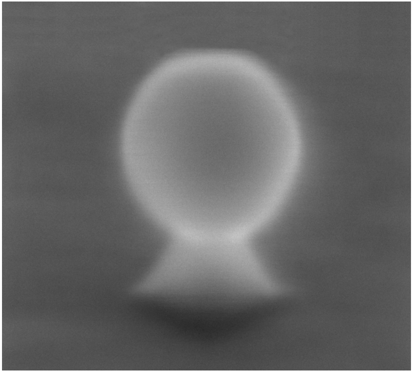

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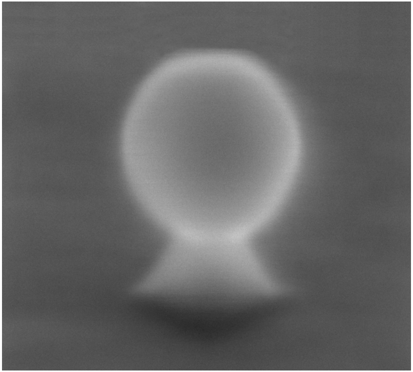

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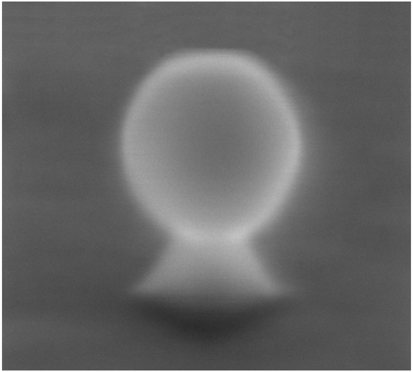

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ccem Canadian Centre for Electron Microscopy

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