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

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Department of Engineering Physics 
McMaster University

May 9, 2012
Introduction

1. Background
   - The Diode
   - Semiconductors and Absorption
   - Industry
   - Silicon Market Domination
   - State of the Art
   - Limitations
   - Why find new solar cells?

2. Future
   - Better Materials

3. New Devices
   - Tandem Cells
   - Tandem Cells on Silicon

4. New Physics
   - Light Capture
   - Plasmonics

5. Conclusions

6. Acknowledgements

Gabriel A. Devenyi
Future of Solar
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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Introduction

Background

Future

New Devices

New Physics

Conclusions

Acknowledgements

The Diode

Semiconductors and Absorption

Silicon Market Domination

State of the Art

Limitations

Why find new solar cells?
The Diode
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Why find new solar cells?

*Ideal Diode

Equivalent circuit

$I_D$ = 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

Photovoltaic mode (solar cell)

Gabriel A. Devenyi

Future of Solar
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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Silicon Cells

- **Silicon solar cells dominate market**
- Leverage microelectronics industry
- 85% of Market is Silicon
- Half multicrystalline, half monocrystalline
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  - Professor, University New South Wales
  - 25% Efficient
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- Why is it non-ideal?
  - Poor absorption
  - Non-ideal bandgap
  - High energy input for refinement
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**Wavelength (nm)**

![Graph](image_url)
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Efficiency

- 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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Economies of scale are important for traditional Silicon, but we haven’t met cost parity with it. Do we need higher efficiency?
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- Reducing material waste
- Finding new and interesting materials

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Future of Solar
Silicon Improvements

- Reducing Silicon material losses
- Amorphous Silicon provides stronger absorption
- Improving photovoltage via HIT cells (amorphous Silicon Hybrid cells)
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Protons are implanted into the donor wafer.

Thermal Mechanical Cleaving

Silicon Wafer is Reused
**Silicon Improvements**

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CdTe Solar Cells

- Biggest single solar cell company in the world makes CdTe cells (First Solar)
  - All cells made are polycrystalline
  - Shunt pathways
  - Dopant segregation
  - Carrier trapping
  - Limit maximum efficiency
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Fool's Gold
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These issues limit the maximum efficiency of CdTe solar cells.


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PLD Grown CdTe at McMaster

- Experimental thin film growth technique
  - Laser used to deliver energy to target
  - Plume created in vacuum chamber
  - Plume collected on appropriate heated substrate
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2DXRD Results

- X-ray technique that maps all reflections from the sample
  - A poor crystal
  - Better
  - Almost there
  - Single Crystal
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Optical Results

- Room temperature photoluminescence
  - Best PL defect bands published
  - Best PR results yet achieved at Mac
  - Boule and MBE grown CdTe are not this good

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What’s next for CdTe?

- 500nm CdTe thin films absorb most useful light
- Need to produce a PN junction
- Electrical measurements of undoped films
- Doping of films by several methods
- Electrical measurements of doped films
- Device creation by combined doping
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What about new materials?

- Recent Environmental Science publication examines the availability of PV materials
  - One material stood out for us
  - FeS₂, Pyrite, Fool’s Gold
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Pyrite, wonder solar cell?

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- Absorption is very strong
- Base components are inexpensive
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- Vastly different vapour pressures pose problems
- Iron crystallite formation

McMaster SEI 5.0kV ×23,000 1μm WD 4.0mm
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Thermalization Loss

- Single junction solar cells have fundamental thermalization losses
  - Photon energy larger than the bandgap is lost to heat
  - What happens if we use more than one junction?
  - Output of the solar cell is now boosted by better matching energy capture
  - Stacked, or "multi junction" solar cells results
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**Solar Radiation Spectrum**

- Sunlight at Top of the Atmosphere
- 5250°C Blackbody Spectrum
- Radiation at Sea Level
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- Stacked, or "multi junction" solar cells results

Gabriel A. Devenyi
Future of Solar
**Thermalization Loss**

- Single junction solar cells have fundamental thermalization losses
- Photon energy larger than the bandgap is lost to heat
- What happens if we use more than one junction?
- Output of the solar cell is now boosted by better matching energy capture
- Stacked, or "multi junction" solar cells results
Why don’t we make these?

- Multi-junction designs are very complicated
- The easy multi-junction designs are very expensive
- Cheaper multi-junction choices have problems with crystal quality
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**Tandem Cells**

**Tandem Cells on Silicon**
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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
  - Problems with twins creating defect planes
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Solving mismatch

- Traditional methods try to grow lattice matched materials
  - Nothing matches silicon
  - Why not ignore the match?
  - GaSb on silicon forms a low-energy defect network to handle mismatch
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(a) [Image of GaSb on silicon]
(b) [Image of 5 nm layer]
Anti-Phase Boundaries

- Growing polar on non-polar semiconductors causes problems
  - Boundaries between opposite polar sections result in electrical defects
  - Substrates offcut from (100) can enforce surface reconstruction
  - Double stepped reconstruction eliminates APDs

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- Colliding twin fronts result in high energy defects.
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(211) Substrates

- Traditional Silicon work uses (100) Silicon substrates
- (211) orientation provides some distinct advantages
- Naturally eliminates APDs
- Natural asymmetry reduces twinning
- Appears to allow tilt of thin film to reduce strain

GaSb Vicinal

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New Physics

- Many new designs attempt to utilize complicated physical phenomenon
  - 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
  - Nanowire solar cells attempt to separate the light collection and carrier extraction steps via geometry
- All of these methods are still theoretical
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Getting more light into solar cells

- Traditional concentrators collect light via lenses
  - Concentration improves efficiency
  - Tradeoff is optics size versus cell size
  - Concentrators require mechanical tracking
  - Photonic engineering offers an alternative way to capture light
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- Reduces material requirements
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- Process is analogous to antennas and radio waves.
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Conclusions

- Photovoltaics has many places left to improve
- McMaster is actively working on several aspects of improved cells
- There doesn’t have to be a single winner, climate and economy will determine what’s best in a given area
- Sustainable energy has a bright and sunny future
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