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

Gabriel A. Devenyi

Department of Engineering Physics McMaster University

May 9, 2012

< ロ > (四 > (四 > (三 > (三 >))) (三 >) (=

Introduction

- 2 Background
 - The Diode
 - Semiconductors and Absorption
 - Industry
 - Silicon Market Domination
 - State of the Art
 - Limitations
 - Why find new solar cells?
- 3 Future
 - Better Materials

- Better Silicon
- Material Quality
- Single Crystal CdTe
- New Materials
- Fool's Gold
- 4 New Devices
 - Tandem Cells
 - Tandem Cells on Silicon

- 5 New Physics
 - Light Capture
 - Plasmonics
- Conclusions
 - Acknowledgements

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

イロト イポト イヨト イヨト

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

イロト イポト イヨト イヨト

Introduction	
Background	
Future	
New Devices	
New Physics	
Conclusions	
Acknowledgements	

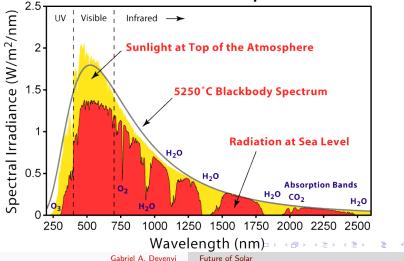
This presentation...

- 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

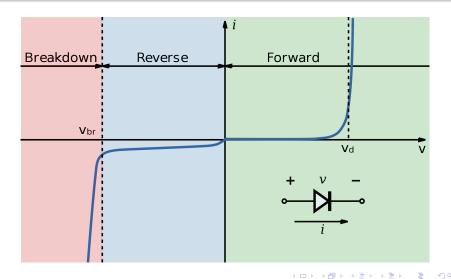
▲ 同 ▶ ▲ 国 ▶ ▲

1 B 1 B 1

Solar Radiation Spectrum



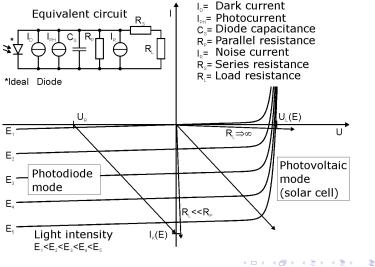
The Diode Semiconductors and Absorption Silicon Market Domination State of the Art Limitations Why find new solar cells?



Gabriel A. Devenyi

Future of Solar





Gabriel A. Devenyi

The Diode Semiconductors and Absorption Silicon Market Domination State of the Art Limitations Why find new solar cells?

イロト イポト イヨト イヨト

э

How does photovoltaic behaviour arise?

• Absorption in semiconductors

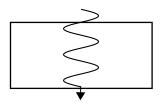
The Diode Semiconductors and Absorption Silicon Market Domination State of the Art Limitations Why find new solar cells?

・ロト ・ 日 ・ ・ ヨ ・ ・ ヨ ・ ・

э

How does photovoltaic behaviour arise?

• Absorption in semiconductors

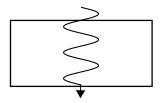


The Diode Semiconductors and Absorption Silicon Market Domination State of the Art Limitations Why find new solar cells?

イロト イポト イヨト イヨト

э

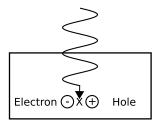
- Absorption in semiconductors
- Production of electron-hole pairs



The Diode Semiconductors and Absorption Silicon Market Domination State of the Art Limitations Why find new solar cells?

How does photovoltaic behaviour arise?

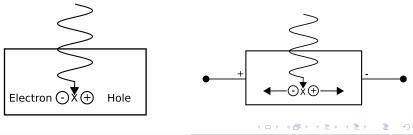
- Absorption in semiconductors
- Production of electron-hole pairs



The Diode Semiconductors and Absorption Silicon Market Domination State of the Art Limitations Why find new solar cells?

How does photovoltaic behaviour arise?

- Absorption in semiconductors
- Production of electron-hole pairs
- Electrons and holes are current carriers in semiconductors

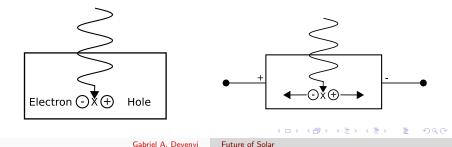


Gabriel A. Devenyi

Future of Solar

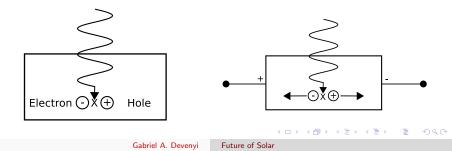
The Diode Semiconductors and Absorption Silicon Market Domination State of the Art Limitations Why find new solar cells?

- Absorption in semiconductors
- Production of electron-hole pairs
- Electrons and holes are current carriers in semiconductors



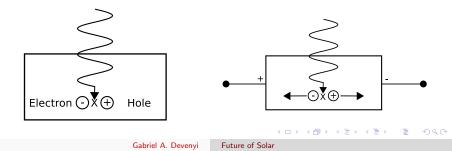
The Diode Semiconductors and Absorption Silicon Market Domination State of the Art Limitations Why find new solar cells?

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



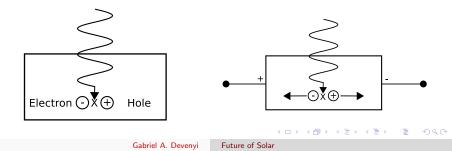
The Diode Semiconductors and Absorption Silicon Market Domination State of the Art Limitations Why find new solar cells?

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



The Diode Semiconductors and Absorption Silicon Market Domination State of the Art Limitations Why find new solar cells?

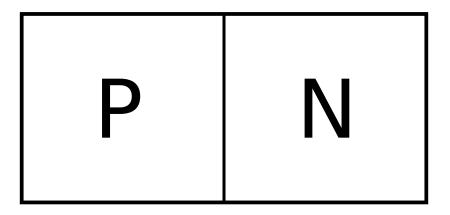
- Absorption in semiconductors
- Production of electron-hole pairs
- Electrons and holes are current carriers in semiconductors
- How can these carriers spontaneously separate



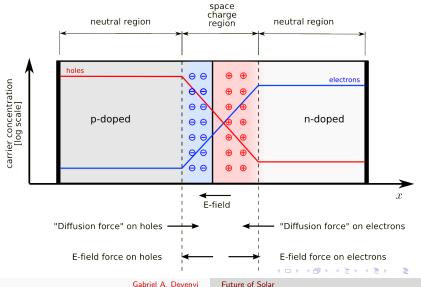
The Diode Semiconductors and Absorption Silicon Market Domination State of the Art Limitations Why find new solar cells?

イロト イヨト イヨト イヨト

æ





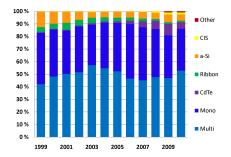


Gabriel A. Devenvi

The Diode Semiconductors and Absorption Silicon Market Domination State of the Art Why find new solar cells?

Silicon Cells

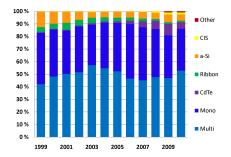
- Silicon solar cells dominate market



The Diode Semiconductors and Absorption Silicon Market Domination State of the Art Why find new solar cells?

Silicon Cells

- Silicon solar cells dominate market
- Leverage microelectronics industry

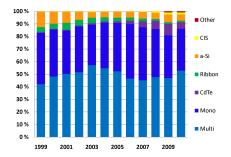


イロト イポト イヨト イヨト

The Diode Semiconductors and Absorption Silicon Market Domination State of the Art Why find new solar cells?

Silicon Cells

- Silicon solar cells dominate market
- Leverage microelectronics industry
- 85% of Market is Silicon

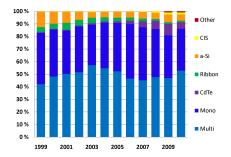


イロト イポト イヨト イヨト

The Diode Semiconductors and Absorption Silicon Market Domination State of the Art Limitations Why find new solar cells?

Silicon Cells

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



イロト イポト イヨト イヨト

The Diode Semiconductors and Absorption Silicon Market Domination State of the Art Limitations Why find new solar cells?

State-of-the-art

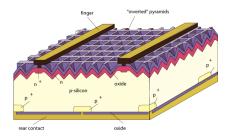
- PERL Cell made by Martin Green
- finger "merted" pyramids

・ロト ・ 日 ・ ・ ヨ ・ ・ ヨ ・

The Diode Semiconductors and Absorption Silicon Market Domination State of the Art Limitations Why find new solar cells?

State-of-the-art

• PERL Cell made by Martin Green

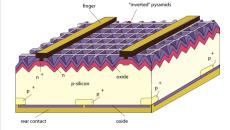


・ロト ・ 日 ・ ・ ヨ ・ ・ ヨ ・

The Diode Semiconductors and Absorption Silicon Market Domination State of the Art Limitations Why find new solar cells?

State-of-the-art

- PERL Cell made by Martin Green
- Ph.D. from McMaster

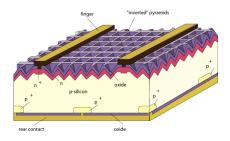


・ロト ・ 日 ・ ・ ヨ ・ ・ ヨ ・

The Diode Semiconductors and Absorption Silicon Market Domination State of the Art Limitations Why find new solar cells?

State-of-the-art

- PERL Cell made by Martin Green
- Ph.D. from McMaster

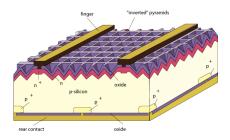


・ロト ・ 日 ・ ・ ヨ ・ ・ ヨ ・

The Diode Semiconductors and Absorption Silicon Market Domination State of the Art Limitations Why find new solar cells?

State-of-the-art

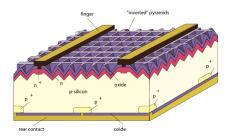
- PERL Cell made by Martin Green
- Ph.D. from McMaster
- Professor University New South Wales



The Diode Semiconductors and Absorption Silicon Market Domination State of the Art Limitations Why find new solar cells?

State-of-the-art

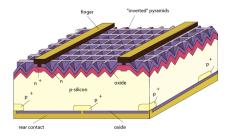
- PERL Cell made by Martin Green
- Ph.D. from McMaster
- Professor University New South Wales



The Diode Semiconductors and Absorption Silicon Market Domination State of the Art Limitations Why find new solar cells?

State-of-the-art

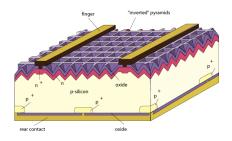
- PERL Cell made by Martin Green
- Ph.D. from McMaster
- Professor University New South Wales
- 25% Efficient



The Diode Semiconductors and Absorption State of the Art Why find new solar cells?

State-of-the-art

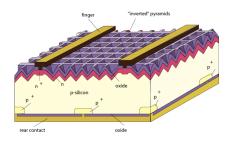
- PERL Cell made by Martin Green
- Ph.D. from McMaster
- Professor University New South Wales
- 25% Efficient



The Diode Semiconductors and Absorption Silicon Market Domination State of the Art Limitations Why find new solar cells?

State-of-the-art

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



・ロト ・ 一 ・ ・ ヨ ・ ・

The Diode Semiconductors and Absorption Silicon Market Domination State of the Art Limitations Why find new solar cells?

イロト イポト イヨト イヨト

э

Limitations of Silicon

• Why is it non-ideal?

Poor absorption

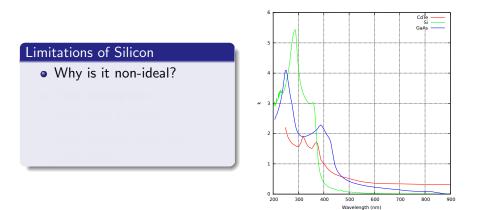
Non-ideal bandgap

High energy input for

Gabriel A. Devenyi Future of Solar

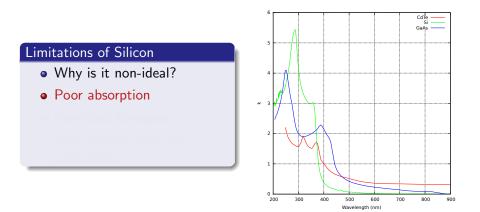


The Diode Semiconductors and Absorption Silicon Market Domination State of the Art Limitations Why find new solar cells?



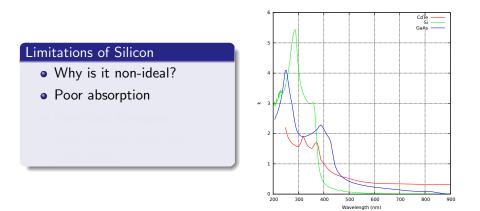
イロト イロト イヨト イヨト

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?



・ロト ・ 日 ・ ・ ヨ ・ ・ ヨ ・

Introduction Background Future New Devices Conclusions Acknowledgements The Diode Semiconductors and Absorption State of the Art Limitations

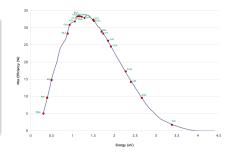


・ロト ・ 日 ・ ・ ヨ ・ ・ ヨ ・

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?

Limitations of Silicon

- Why is it non-ideal?
- Poor absorption
- Non-ideal bandgap

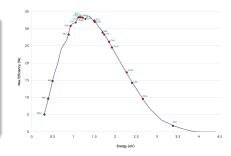


・ロト ・ 一下・ ・ ヨト ・

Introduction Background Future New Devices Conclusions Acknowledgements The Diode Semiconductors and Absorption Silicon Market Domination State of the Art Limitations Why find new solar cells?

Limitations of Silicon

- Why is it non-ideal?
- Poor absorption
- Non-ideal bandgap



・ロト ・ 一下・ ・ ヨト ・

 Introduction
 The Diode

 Background
 Semiconductors and Absorption

 Future
 Silicon Market Domination

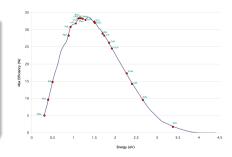
 New Devices
 State of the Art

 Conclusions
 Limitations

 Acknowledgements
 Why find new solar cells?

Limitations of Silicon

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



イロト イヨト イヨト イ

The Diode Semiconductors and Absorption Silicon Market Domination State of the Art Limitations Why find new solar cells?

・ロト ・ 日 ・ ・ ヨ ・ ・ ヨ ・ ・

æ



The Diode Semiconductors and Absorption Silicon Market Domination State of the Art Limitations Why find new solar cells?

・ロト ・ 日 ・ ・ ヨ ・ ・ ヨ ・ ・

э

Effciency

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

- Cost per Watt is King.
- Cheap low efficiency cells are fine
- Expensive high efficiency cells are finee

Research is ongoing in both areas

The Diode Semiconductors and Absorption Silicon Market Domination State of the Art Limitations Why find new solar cells?

・ロト ・ 日 ・ ・ ヨ ・ ・ ヨ ・ ・

æ

Effciency

• Traditional Silicon relies on economies of scale

Cost per Watt is King

Cheap low efficiency cells are fine.

Expensive high efficiency cells are fine

The Diode Semiconductors and Absorption Silicon Market Domination State of the Art Limitations Why find new solar cells?

イロト イポト イヨト イヨト

э

- Traditional Silicon relies on economies of scale
- We haven't met cost parity with Silicon

The Diode Semiconductors and Absorption Silicon Market Domination State of the Art Limitations Why find new solar cells?

イロト イポト イヨト イヨト

э

- Traditional Silicon relies on economies of scale
- We haven't met cost parity with Silicon

The Diode Semiconductors and Absorption Silicon Market Domination State of the Art Limitations Why find new solar cells?

イロト イポト イヨト イヨト

э

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

The Diode Semiconductors and Absorption Silicon Market Domination State of the Art Limitations Why find new solar cells?

イロト イポト イヨト イヨト

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

The Diode Semiconductors and Absorption Silicon Market Domination State of the Art Limitations Why find new solar cells?

イロト イポト イヨト イヨト

э

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

The Diode Semiconductors and Absorption Silicon Market Domination State of the Art Limitations Why find new solar cells?

イロト イポト イヨト イヨト

э

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

The Diode Semiconductors and Absorption Silicon Market Domination State of the Art Limitations Why find new solar cells?

イロト イポト イヨト イヨト

э

- Traditional Silicon relies on economies of scale
- We haven't met cost parity with Silicon
- Do we need higher efficiency?
 - Yes
 - No

The Diode Semiconductors and Absorption Silicon Market Domination State of the Art Limitations Why find new solar cells?

イロト イポト イヨト イヨト

э

- Traditional Silicon relies on economies of scale
- We haven't met cost parity with Silicon
- Do we need higher efficiency?
 - Yes
 - No

The Diode Semiconductors and Absorption Silicon Market Domination State of the Art Limitations Why find new solar cells?

< ロ > (同 > (回 > (回 >)))

- Traditional Silicon relies on economies of scale
- We haven't met cost parity with Silicon
- Do we need higher efficiency?
 - Yes
 - No
- Cost per Watt is King

The Diode Semiconductors and Absorption Silicon Market Domination State of the Art Limitations Why find new solar cells?

< ロ > (同 > (回 > (回 >)))

- Traditional Silicon relies on economies of scale
- We haven't met cost parity with Silicon
- Do we need higher efficiency?
 - Yes
 - No
- Cost per Watt is King

The Diode Semiconductors and Absorption Silicon Market Domination State of the Art Limitations Why find new solar cells?

イロト イポト イヨト イヨト

- Traditional Silicon relies on economies of scale
- We haven't met cost parity with Silicon
- Do we need higher efficiency?
 - Yes
 - No
- Cost per Watt is King
- Cheap low efficiency cells are fine
- Expensive high efficiency cells are fine

The Diode Semiconductors and Absorption Silicon Market Domination State of the Art Limitations Why find new solar cells?

イロト イポト イヨト イヨト

- Traditional Silicon relies on economies of scale
- We haven't met cost parity with Silicon
- Do we need higher efficiency?
 - Yes
 - No
- Cost per Watt is King
- Cheap low efficiency cells are fine

The Diode Semiconductors and Absorption Silicon Market Domination State of the Art Limitations Why find new solar cells?

イロト イポト イヨト イヨト

- Traditional Silicon relies on economies of scale
- We haven't met cost parity with Silicon
- Do we need higher efficiency?
 - Yes
 - No
- Cost per Watt is King
- Cheap low efficiency cells are fine
- Expensive high efficiency cells are fine

The Diode Semiconductors and Absorption Silicon Market Domination State of the Art Limitations Why find new solar cells?

イロト イポト イヨト イヨト

- Traditional Silicon relies on economies of scale
- We haven't met cost parity with Silicon
- Do we need higher efficiency?
 - Yes
 - No
- Cost per Watt is King
- Cheap low efficiency cells are fine
- Expensive high efficiency cells are fine

The Diode Semiconductors and Absorption Silicon Market Domination State of the Art Limitations Why find new solar cells?

イロト イポト イヨト イヨト

- Traditional Silicon relies on economies of scale
- We haven't met cost parity with Silicon
- Do we need higher efficiency?
 - Yes
 - No
- Cost per Watt is King
- Cheap low efficiency cells are fine
- Expensive high efficiency cells are fine
- Research is ongoing in both areas

Introduction Background Future Better Materials New Physics Fool's Gold Conclusions Acknowledgements

Better Materials

0	Improving material quality
	materials

Better Physics

 Tandem cell structures
 New physics structures
 Enhancement of light absorption

・ロト ・ 日 ・ ・ 日 ・ ・ 日 ・ ・

æ

Introduction Background Future Better Materials New Devices Fool's Gold New Physics Conclusions Acknowledgements

Better Materials

• Improving material quality

Better Physics

Tandem cell structures

New physics structures

・ロト ・ 日 ・ ・ ヨ ・ ・ ヨ ・

æ

Enhancement of light.

absorption

Better Materials

• Improving material quality

Better Physics • Tandem cell structures • New physics structures • Enhancement of light absorption

・ロト ・ 日 ・ ・ ヨ ・ ・ ヨ ・

æ

Gabriel A. Devenyi Futu

Better Materials

- Improving material quality
- Reducing material waste

イロト イヨト イヨト イヨト

Better Materials

- Improving material quality
- Reducing material waste



イロト イヨト イヨト イヨト

Better Materials Fool's Gold

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

< ロ > (同 > (回 > (回 >)))

Better Materials Fool's Gold

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

< ロ > (同 > (回 > (回 >)))

Better Materials Fool's Gold

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

< ロ > (同 > (回 > (回 >)))

Better Materials Fool's Gold

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

< ロ > (同 > (回 > (回 >)))

Better Materials Fool's Gold

Silicon Improvements

Gabriel A. Devenyi Future of Solar

・ロト ・ 日 ・ ・ ヨ ・ ・ ヨ ・ ・

æ

Better Materials Fool's Gold

Silicon Improvements

 Reducing Silicon material losses



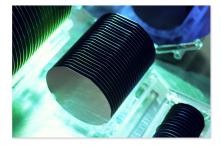
<ロ> (日) (日) (日) (日) (日)

æ

Better Materials Fool's Gold

Silicon Improvements

• Reducing Silicon material losses



<ロ> (日) (日) (日) (日) (日)

Better Materials Fool's Gold

Silicon Improvements

• Reducing Silicon material losses

Protons are implanted into the donor wafer.

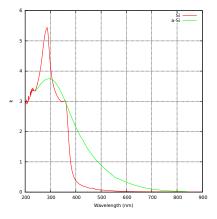


<ロ> (日) (日) (日) (日) (日)

Better Materials Fool's Gold

Silicon Improvements

- Reducing Silicon material losses
- Amorphous Silicon provides stronger absorption

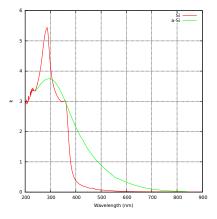


イロト イヨト イヨト イヨト

Better Materials Fool's Gold

Silicon Improvements

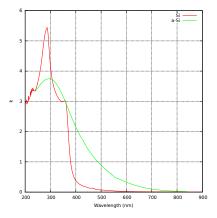
- Reducing Silicon material losses
- Amorphous Silicon provides stronger absorption



Better Materials Fool's Gold

Silicon Improvements

- Reducing Silicon material losses
- Amorphous Silicon provides stronger absorption
- Improving photovoltage via HIT cells (amorphous Silicon Hybrid cells)

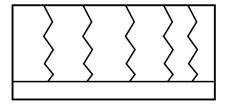


・ロト ・ 日 ・ ・ ヨ ・ ・ ヨ ・

Better Materials Fool's Gold

CdTe Solar Cells

 Biggest single solar cell company in the world makes CdTe cells (First Solar)



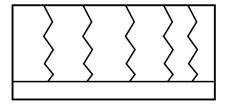
・ロト ・ 一下・ ・ ヨト ・

.⊒ →

Better Materials Fool's Gold

CdTe Solar Cells

 Biggest single solar cell company in the world makes CdTe cells (First Solar)



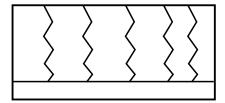
• • • • • • • • • • • •

.⊒ →

Better Materials Fool's Gold

CdTe Solar Cells

- Biggest single solar cell company in the world makes CdTe cells (First Solar)
- All cells made are polycrystalline

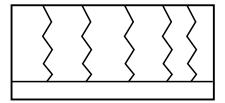


(日)、

Better Materials Fool's Gold

CdTe Solar Cells

- Biggest single solar cell company in the world makes CdTe cells (First Solar)
- All cells made are polycrystalline

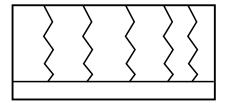


(日)、

Better Materials Fool's Gold

CdTe Solar Cells

- Biggest single solar cell company in the world makes CdTe cells (First Solar)
- All cells made are polycrystalline
- Shunt pathways

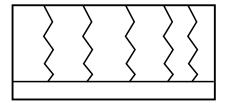


(日)、

Better Materials Fool's Gold

CdTe Solar Cells

- Biggest single solar cell company in the world makes CdTe cells (First Solar)
- All cells made are polycrystalline
- Shunt pathways

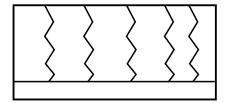


(日)、

Better Materials Fool's Gold

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

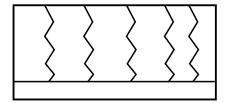


ヘロト ヘヨト ヘヨト

Better Materials Fool's Gold

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

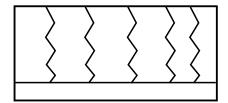


ヘロト ヘヨト ヘヨト

Better Materials Fool's Gold

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

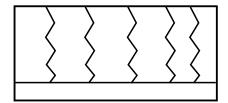


(日)、

Better Materials Fool's Gold

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

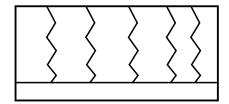


(日)、

Better Materials Fool's Gold

CdTe Solar Cells

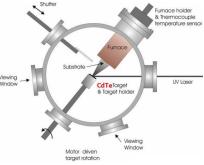
- Biggest single solar cell company in the world makes CdTe cells (First Solar)
- All cells made are polycrystalline
- Shunt pathways
- Dopant segregation
- Carrier trapping
- Limit maximum efficiency



ヘロト ヘヨト ヘヨト

Better Materials Fool's Gold

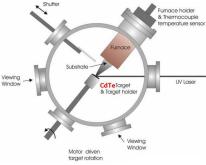




イロト イヨト イヨト イヨト

Better Materials Fool's Gold

PLD Grown CdTe at McMaster • Experimental thin film growth technique

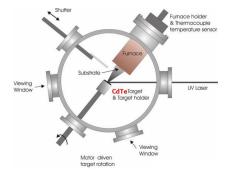


イロト イヨト イヨト イヨト

Better Materials Fool's Gold

PLD Grown CdTe at McMaster

- Experimental thin film growth technique
- Laser used to deliver energy to target

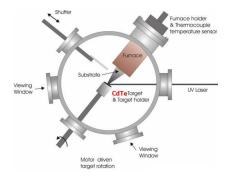


イロト イポト イヨト イヨト

Better Materials Fool's Gold

PLD Grown CdTe at McMaster

- Experimental thin film growth technique
- Laser used to deliver energy to target

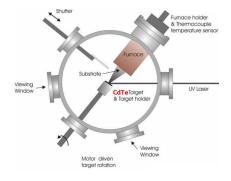


イロト イポト イヨト イヨト

Better Materials Fool's Gold

PLD Grown CdTe at McMaster

- Experimental thin film growth technique
- Laser used to deliver energy to target
- Plume created in vacuum chamber

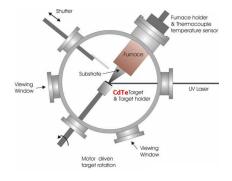


< ロ > (同 > (回 > (回 >)))

Better Materials Fool's Gold

PLD Grown CdTe at McMaster

- Experimental thin film growth technique
- Laser used to deliver energy to target
- Plume created in vacuum chamber

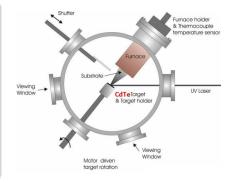


< ロ > (同 > (回 > (回 >)))

Better Materials Fool's Gold

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



< ロ > (同 > (回 > (回 >)))

Better Materials Fool's Gold

2DXRD Results

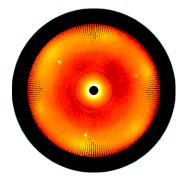
- X-ray technique that maps all reflections from the sample
- A poor crystal
- Better
- Almost there
- Single Crystal

< ロ > (同 > (回 > (回 >)))

Better Materials Fool's Gold

2DXRD Results

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

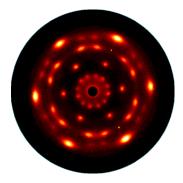


(日)

Better Materials Fool's Gold

2DXRD Results

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



・ロト ・ 一下・ ・ ヨト ・

.⊒ →

Better Materials Fool's Gold

2DXRD Results

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



・ロト ・ 一下・ ・ ヨト ・

.⊒ →

Better Materials Fool's Gold

2DXRD Results

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



・ロト ・ 一下・ ・ ヨト ・

Better Materials Fool's Gold

Optical Results

• Room temperature photoluminesesnce

Unpublished figures removed.

イロト イポト イヨト イヨト

э

Gabriel A. Devenyi Future of Solar

Better Materials Fool's Gold

Optical Results

• Room temperature photoluminesesnce

Unpublished figures removed.

・ロト ・ 一 ・ ・ ヨ ・ ・

3 x 3

Gabriel A. Devenyi Future of Solar

Better Materials Fool's Gold

Optical Results

- Room temperature photoluminesesnce
- Best PL defect bands published

Unpublished figures removed.

• • • • • • • • • • • • •

3 x 3

Better Materials Fool's Gold

Optical Results

- Room temperature photoluminesesnce
- Best PL defect bands published

Unpublished figures removed.

(日)、<(同)、<(日)、</p>

3 x 3

Better Materials Fool's Gold

Optical Results

- Room temperature photoluminesesnce
- Best PL defect bands published
- Best PR results yet achieved at Mac

Unpublished figures removed.

< ロ > (同 > (回 > (回 >)))

Better Materials Fool's Gold

Optical Results

- Room temperature photoluminesesnce
- Best PL defect bands published
- Best PR results yet achieved at Mac

Unpublished figures removed.

.⊒ →

Better Materials Fool's Gold

Optical Results

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

Unpublished figures removed.

イロト イヨト イヨト イ

.⊒ →

Better Materials Fool's Gold

What's next for CdTe?

S00nm 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

Gabriel A. Devenyi Future of Solar

・ロト ・四ト ・ヨト ・ヨト

æ

Better Materials Fool's Gold

What's next for CdTe?

• 500nm CdTe thin films absorb most useful light

Gabriel A. Devenyi Future of Solar

・ロト ・ 日 ・ ・ ヨ ・ ・ ヨ ・

Better Materials Fool's Gold

What's next for CdTe?

• 500nm CdTe thin films absorb most useful light

Gabriel A. Devenyi Future of Solar

・ロト ・ 日 ・ ・ ヨ ・ ・ ヨ ・

Better Materials Fool's Gold

What's next for CdTe?

- 500nm CdTe thin films absorb most useful light
- Need to produce a PN junction

イロト イポト イヨト イヨト

Better Materials Fool's Gold

What's next for CdTe?

- 500nm CdTe thin films absorb most useful light
- Need to produce a PN junction

イロト イポト イヨト イヨト

Better Materials Fool's Gold

What's next for CdTe?

- 500nm CdTe thin films absorb most useful light
- Need to produce a PN junction
- Electrical measurements of undoped films

イロト イポト イヨト イヨト

Better Materials Fool's Gold

What's next for CdTe?

- 500nm CdTe thin films absorb most useful light
- Need to produce a PN junction
- Electrical measurements of undoped films

イロト イポト イヨト イヨト

Better Materials Fool's Gold

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

イロト イヨト イヨト イ

Better Materials Fool's Gold

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

イロト イヨト イヨト イ

Better Materials Fool's Gold

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

(日)、

Better Materials Fool's Gold

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

(日)、

Better Materials Fool's Gold

What's next for CdTe?

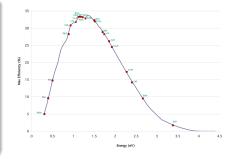
- 500nm CdTe thin films absorb most useful light
- Need to produce a PN junction
- Electrical measurements of undoped films
- Doping of films by several methods
- Electrical measurements of doped films
- Device creation by combined doping

イロト イヨト イヨト イ

Better Materials Fool's Gold

What about new materials?

 Recent Environmental Science publication examines the availability of PV materials

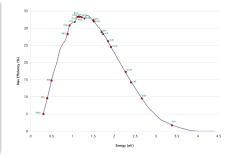


・ロト ・ 一日 ・ ・ 日 ・

Better Materials Fool's Gold

What about new materials?

 Recent Environmental Science publication examines the availability of PV materials

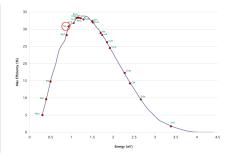


・ロト ・ 一日 ・ ・ 日 ・

Better Materials Fool's Gold

What about new materials?

- Recent Environmental Science publication examines the availability of PV materials
- One material stood out for us

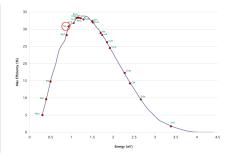


(日)、

Better Materials Fool's Gold

What about new materials?

- Recent Environmental Science publication examines the availability of PV materials
- One material stood out for us

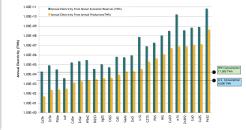


(日)、

Better Materials Fool's Gold

What about new materials?

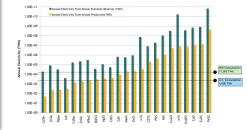
- Recent Environmental Science publication examines the availability of PV materials
- One material stood out for us
- FeS₂, Pyrite, Fool's Gold



Better Materials Fool's Gold

What about new materials?

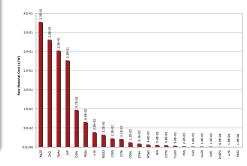
- Recent Environmental Science publication examines the availability of PV materials
- One material stood out for us
- FeS₂, Pyrite, Fool's Gold



Better Materials Fool's Gold

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

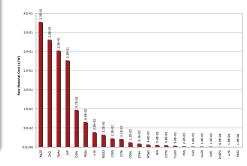


(日)、

Better Materials Fool's Gold

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

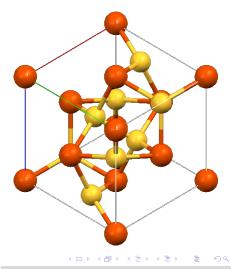


(日)、

Better Materials Fool's Gold

Pyrite, wonder solar cell?

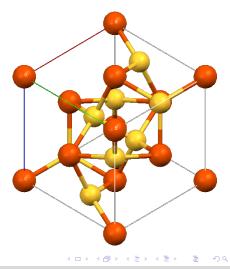
• Cubic crystal is easy to understand



Better Materials Fool's Gold

Pyrite, wonder solar cell?

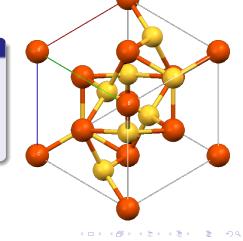
• Cubic crystal is easy to understand



Better Materials Fool's Gold

Pyrite, wonder solar cell?

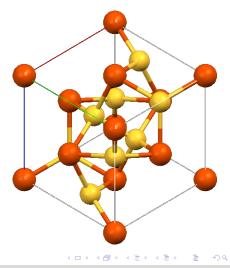
- Cubic crystal is easy to understand
- Absorption is very strong



Better Materials Fool's Gold

Pyrite, wonder solar cell?

- Cubic crystal is easy to understand
- Absorption is very strong



Better Materials Fool's Gold

Pyrite, wonder solar cell?

- Cubic crystal is easy to understand
- Absorption is very strong
- Base components are inexpensive



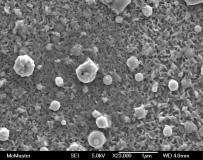
(日) (同) (三)

Better Materials Fool's Gold

PLD Grown FeS₂ at McMaster

• Grown with PLD from natural Pyrite crystal

rstal

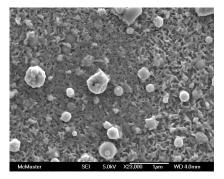


<ロト < 同ト < ヨト < ヨト

Better Materials Fool's Gold

PLD Grown FeS₂ at McMaster

• Grown with PLD from natural Pyrite crystal

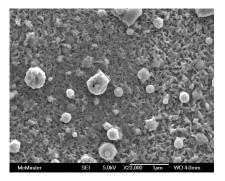


・ロト ・ 一 ・ ・ ヨ ・ ・

Better Materials Fool's Gold

PLD Grown FeS₂ at McMaster

- Grown with PLD from natural Pyrite crystal
- Vastly different vapour pressures pose problems

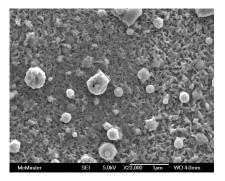


(日)、<(同)、<(日)、</p>

Better Materials Fool's Gold

PLD Grown FeS₂ at McMaster

- Grown with PLD from natural Pyrite crystal
- Vastly different vapour pressures pose problems

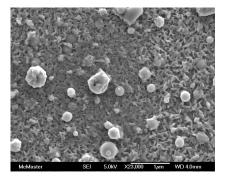


(日)、<(同)、<(日)、</p>

Better Materials Fool's Gold

PLD Grown FeS₂ at McMaster

- Grown with PLD from natural Pyrite crystal
- Vastly different vapour pressures pose problems
- Iron crystallite formation



(日)、<(同)、<(日)、</p>

Tandem Cells Tandem Cells on Silicon

Better Materials

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

Better Physics

イロト イポト イヨト イヨト

Tandem Cells Tandem Cells on Silicon

Better Materials

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

Better PhysicsTandem cell structures

イロト イポト イヨト イヨト

Tandem Cells Tandem Cells on Silicon

Better Materials

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

Better Physics

• Tandem cell structures

イロト イポト イヨト イヨト

Tandem Cells Tandem Cells on Silicon

Better Materials

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

Better Physics

- Tandem cell structures
- New physics structures

< ロ > (同 > (回 > (回 >)))

Tandem Cells Tandem Cells on Silicon

Better Materials

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

Better Physics

- Tandem cell structures
- New physics structures

< ロ > (同 > (回 > (回 >)))

Tandem Cells Tandem Cells on Silicon

Better Materials

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

Better Physics

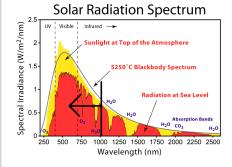
- Tandem cell structures
- New physics structures
- Enhancement of light absorption

< ロ > (同 > (回 > (回 >)))

Tandem Cells Tandem Cells on Silicon

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



(日)、

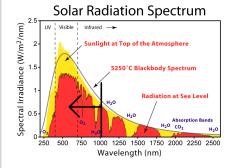
э

Gabriel A. Devenyi

Tandem Cells Tandem Cells on Silicon

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



ヘロト ヘヨト ヘヨト

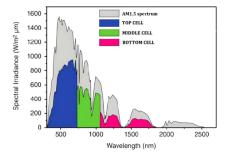
э

Gabriel A. Devenyi

Tandem Cells Tandem Cells on Silicon

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



(日)、

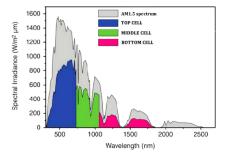
э

Gabriel A. Devenyi

Tandem Cells Tandem Cells on Silicon

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



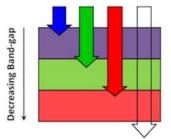
(日)、



Tandem Cells Tandem Cells on Silicon

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



(日)、

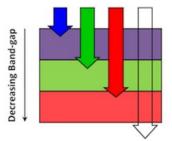
-



Tandem Cells Tandem Cells on Silicon

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



(日)、

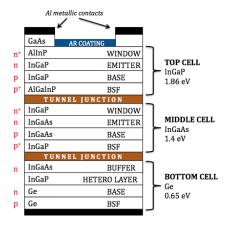
-



Tandem Cells Tandem Cells on Silicon

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

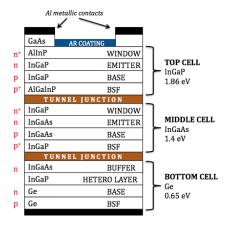


< ロ > < 同 > < 回 > < 回 >

Tandem Cells Tandem Cells on Silicon

Why don't we make these?

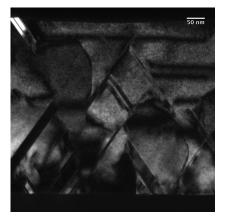
- Multi-junction designs are very complicated
- The easy multi-junction designs are very expensive
- Cheaper multi-junction choices have problems with crystal quality



Tandem Cells Tandem Cells on Silicon

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



(日)

э

Tandem Cells Tandem Cells on Silicon

< ロ > (同 > (回 > (回 >)))

- Leverage existing Silicon technology
- Many material problems
- Problems with lattice mismatch.
- Problems with anti-phase-boundaries
- Problems with twins creating defect planes
- Grow films on Silicon in McMaster MBE.

Tandem Cells Tandem Cells on Silicon

< ロ > (同 > (回 > (回 >)))

Improving lattice-mismatched multi-junction cells at McMaser

• Leverage existing Silicon technology

- Problems with anti-phase-boundaries
- · Problems with twins creating defect planes
- Grow films on Silicon in McMaster MBE.

Tandem Cells Tandem Cells on Silicon

Improving lattice-mismatched multi-junction cells at McMaser

- Leverage existing Silicon technology
- Improve performance via tandem thin films

< ロ > (同 > (回 > (回 >)))

Tandem Cells Tandem Cells on Silicon

Improving lattice-mismatched multi-junction cells at McMaser

- Leverage existing Silicon technology
- Improve performance via tandem thin films

< ロ > (同 > (回 > (回 >)))

Tandem Cells Tandem Cells on Silicon

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
- o Grow films on Silicon in McMaster MBE.

イロト イポト イヨト イヨト

Tandem Cells Tandem Cells on Silicon

Improving lattice-mismatched multi-junction cells at McMaser

- Leverage existing Silicon technology
- Improve performance via tandem thin films
- Many material problems

イロト イポト イヨト イヨト

Tandem Cells Tandem Cells on Silicon

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
- Grow films on Silicon in McMaster MBE.

(日) (同) (三) (

Tandem Cells Tandem Cells on Silicon

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
- Grow films on Silicon in McMaster MBE.

A B A B A
 A
 B
 A
 A
 B
 A
 A
 B
 A
 A
 B
 A
 A
 B
 A
 A
 B
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A

Tandem Cells Tandem Cells on Silicon

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

A B A A B A A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A

3 A.

Tandem Cells Tandem Cells on Silicon

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

3 A.

Tandem Cells Tandem Cells on Silicon

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

< A > <

Tandem Cells Tandem Cells on Silicon

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

A A A

3 A.

Tandem Cells Tandem Cells on Silicon

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
- Grow films on Silicon in McMaster MBE

< A >

Tandem Cells Tandem Cells on Silicon

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
- Grow films on Silicon in McMaster MBE

< A >

Tandem Cells Tandem Cells on Silicon

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
- Grow films on Silicon in McMaster MBE
 - Control the Silicon orientation

< A > <

Tandem Cells Tandem Cells on Silicon

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
- Grow films on Silicon in McMaster MBE
 - Control the Silicon orientation

< A > <

31.5

Tandem Cells Tandem Cells on Silicon

イロト イポト イラト イラト

- 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
- Grow films on Silicon in McMaster MBE
 - Control the Silicon orientation
 - Control temperature

Tandem Cells Tandem Cells on Silicon

- 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
- Grow films on Silicon in McMaster MBE
 - Control the Silicon orientation
 - Control temperature

Tandem Cells Tandem Cells on Silicon

• □ ▶ • • □ ▶ • • □ ▶

3

- 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
- Grow films on Silicon in McMaster MBE
 - Control the Silicon orientation
 - Control temperature
 - Control composition

Tandem Cells Tandem Cells on Silicon

<ロ> (日) (日) (日) (日) (日)

э

Solving mismatch

• Traditional methods try to grow lattice matched materials

Gabriel A. Devenyi Future of Solar

Tandem Cells Tandem Cells on Silicon

<ロ> (日) (日) (日) (日) (日)

э

Solving mismatch

 Traditional methods try to grow lattice matched materials

Tandem Cells Tandem Cells on Silicon

イロト イポト イヨト イヨト

э

- Traditional methods try to grow lattice matched materials
- Nothing matches silicon

Tandem Cells Tandem Cells on Silicon

イロト イポト イヨト イヨト

э

- Traditional methods try to grow lattice matched materials
- Nothing matches silicon

Tandem Cells Tandem Cells on Silicon

ヘロト ヘヨト ヘヨト

- Traditional methods try to grow lattice matched materials
- Nothing matches silicon
- Why not ignore the match?

Tandem Cells Tandem Cells on Silicon

ヘロト ヘヨト ヘヨト

- Traditional methods try to grow lattice matched materials
- Nothing matches silicon
- Why not ignore the match?

Tandem Cells Tandem Cells on Silicon

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



A B A A B A A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A

Tandem Cells Tandem Cells on Silicon

Anti-Phase Boundaries

 Growing polar on non-polar semiconductors causes problems

opposite polar sections results in electrical defects Substrates offcut from (100 can enforce surface reconstruction Double stepped Unpublished figures removed.

イロト イポト イヨト イヨト

э

Tandem Cells Tandem Cells on Silicon

Anti-Phase Boundaries

 Growing polar on non-polar semiconductors causes problems

opposite polar sections results in electrical defects Substrates offcut from (100 can enforce surface reconstruction Double stepped reconstruction eliminates Unpublished figures removed.

э

Tandem Cells Tandem Cells on Silicon

Anti-Phase Boundaries

- Growing polar on non-polar semiconductors causes problems
- Boundaries between opposite polar sections results in electrical defects

Unpublished figures removed.

(日)、

Tandem Cells Tandem Cells on Silicon

Anti-Phase Boundaries

- Growing polar on non-polar semiconductors causes problems
- Boundaries between opposite polar sections results in electrical defects

Unpublished figures removed.

(日)

Tandem Cells Tandem Cells on Silicon

Anti-Phase Boundaries

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

Unpublished figures removed.

• □ ▶ • • □ ▶ • • □ ▶

Tandem Cells Tandem Cells on Silicon

Anti-Phase Boundaries

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

Unpublished figures removed.

• □ ▶ • • □ ▶ • • □ ▶

Tandem Cells Tandem Cells on Silicon

Anti-Phase Boundaries

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

Unpublished figures removed.

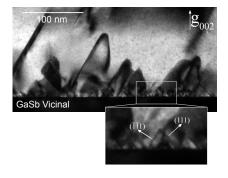
(日)、

Tandem Cells Tandem Cells on Silicon

Twins

• 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

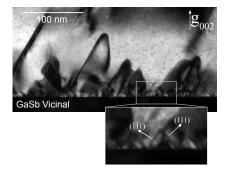


<ロト < 同ト < ヨト < ヨト

Tandem Cells Tandem Cells on Silicon

Twins

- 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

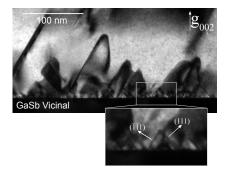


イロト イポト イヨト イヨト

Tandem Cells Tandem Cells on Silicon

Twins

- 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

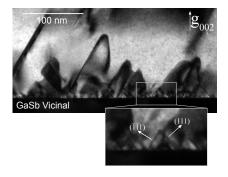


・ロト ・ 日 ・ ・ ヨ ・ ・ ヨ ・

Tandem Cells Tandem Cells on Silicon

Twins

- 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

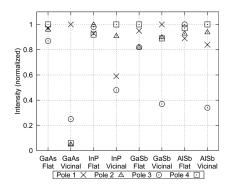


・ロト ・ 日 ・ ・ ヨ ・ ・ ヨ ・

Tandem Cells Tandem Cells on Silicon

Twins

- 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



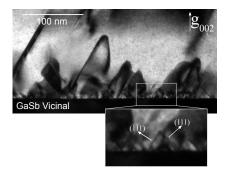
< 🗇 > <

Background New Devices New Physics Acknowledgements

Tandem Cells on Silicon

(211) Substrates

- Traditional Silicon work uses (100) Silicon substrates

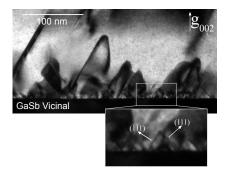


(日)

Tandem Cells Tandem Cells on Silicon

(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

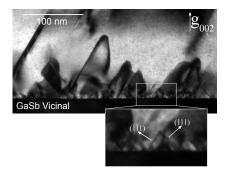


(日)

Tandem Cells Tandem Cells on Silicon

(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

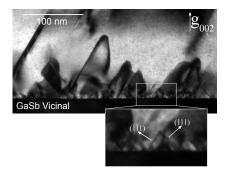


(日)

Tandem Cells Tandem Cells on Silicon

(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



イロト イヨト イヨト イ

Tandem Cells Tandem Cells on Silicon

(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

Unpublished figures removed.

(日)、

Light Capture Plasmonics

New Physics

- Many new designs attempt to utilize complicated physical phenomon
- 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

Light Capture Plasmonics

New Physics

- Many new designs attempt to utilize complicated physical phenomon
- 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

Light Capture Plasmonics

New Physics

- Many new designs attempt to utilize complicated physical phenomon
- 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

Light Capture Plasmonics

New Physics

- Many new designs attempt to utilize complicated physical phenomon
- 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

Light Capture Plasmonics

New Physics

- Many new designs attempt to utilize complicated physical phenomon
- 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

Light Capture Plasmonics

New Physics

- Many new designs attempt to utilize complicated physical phenomon
- 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

Light Capture Plasmonics

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

(日)、

Light Capture Plasmonics

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

< D > < A > < B >

Light Capture Plasmonics

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

< D > < A > < B >

Light Capture Plasmonics

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

• □ ▶ • • □ ▶ • • □ ▶

ヨート

Light Capture Plasmonics

Getting more light into solar cells

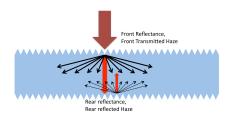
- Traditional concentrators collect light via lenses
- Concentration improves efficiency
- Tradeoff is optics size versus cell size
- Concentrators require mechanical tracking
- Photonic engineering offers an alternative way to capture light

(日) (同) (三) (

Light Capture Plasmonics

Light Scattering

- Light trapping increases the effective thickness of cells
- Reduces material requirements
- Careful control of re-emission angles have been shown to improve voltage

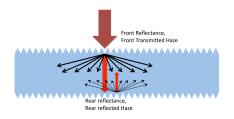


(日)、

Light Capture Plasmonics

Light Scattering

- Light trapping increases the effective thickness of cells
- Reduces material requirements
- Careful control of re-emission angles have been shown to improve voltage

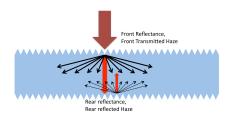


(日)、

Light Capture Plasmonics

Light Scattering

- Light trapping increases the effective thickness of cells
- Reduces material requirements
- Careful control of re-emission angles have been shown to improve voltage

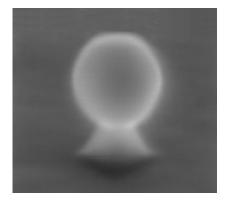


< D > < A > < B >

Light Capture Plasmonics

Plasmonic Scattering

- Metal nanoparticles have been shown to have strong interactions with light
- Process is analogous to antennas and radio waves
- Resonant scattering can be tuned by size/shape/composition
- Self assembly of particles is one route to production

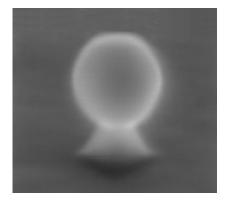


(日)、

Light Capture Plasmonics

Plasmonic Scattering

- Metal nanoparticles have been shown to have strong interactions with light
- Process is analogous to antennas and radio waves
- Resonant scattering can be tuned by size/shape/composition
- Self assembly of particles is one route to production

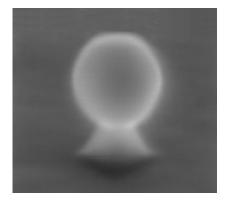


(日)、

Light Capture Plasmonics

Plasmonic Scattering

- Metal nanoparticles have been shown to have strong interactions with light
- Process is analogous to antennas and radio waves
- Resonant scattering can be tuned by size/shape/composition
- Self assembly of particles is one route to production

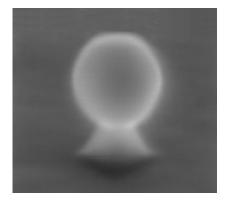


< ロ > < 同 > < 回 > < 回 >

Light Capture Plasmonics

Plasmonic Scattering

- Metal nanoparticles have been shown to have strong interactions with light
- Process is analogous to antennas and radio waves
- Resonant scattering can be tuned by size/shape/composition
- Self assembly of particles is one route to production



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

ヘロト ヘヨト ヘヨト

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

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

< ロ > < 同 > < 回 > < 回 > < 回 > <

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

< 日 > < 同 > < 回 > < 回 > < 回 > < 回 > < 回 > < 回 > < 回 > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ >

Acknowledgements

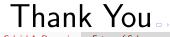






Brockhouse Institute for Materials Research





Gabriel A. Devenyi

Future of Solar