Raising the Efficiency Ceiling in Multijunction Solar Cells

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Outline

- Global climate change and the solar resource
- Solar cell theoretical efficiency limits
  - Opportunities to change ground rules for higher terrestrial efficiency
  - Cell architectures capable of >70% in theory, >50% in practice
- Metamorphic semiconductor materials
  - Control of band gap to tune to solar spectrum
  - Dislocations in metamorphic III-Vs imaged by CL and EBIC
- High-efficiency **Multijunction** terrestrial concentrator cells
  - **Metamorphic (MM) and lattice-matched (LM)** 3-junction solar cells with >40% efficiency
  - **4-junction** MM and LM concentrator cells
    - Inverted metamorphic structure, semiconductor bonded technology (SBT) for MJ terrestrial concentrator cells
- Concentrator photovoltaic (CPV) systems and economics
Global Climate Change
Climate and CO₂ Over the Last 400,000 Years

Vostok Ice Core Data

- Antarctic ice core data allows for mapping of temperature and CO₂ profiles

(J.R. Petit, J. Jouzel, Nature 399:429-436)
Climate and CO$_2$ Over the Last 400,000 Years

Vostok Ice Core Data

- Clear correlation between temperature and CO$_2$ levels

(J.R. Petit, J. Jouzel, Nature 399:429-436)
• CO₂ has reached levels never before seen in measured history
• If we do nothing, we allow this rising trend to continue at our own peril
Temperature Anomaly by Year

1000 years of Earth temperature history… and 100 years of projection

Rosina Bierbaum, Univ. of Michigan, IPCC
The Solar Resource
• Entire US electricity demand can be provided by concentrator PV arrays using 37%-efficient cells on:

  150 km x 150 km area of land  or  ten 50 km x 50 km areas
  or  similar division across US

Ref.: http://rredc.nrel.gov/solar/old_data/nsrdb/redbook/atlas/
Higher multijunction cell efficiency has a huge impact on the economics of CPV, and on the way we will generate electricity.
Solar Cell Theoretical Efficiency
Energy Transitions in Semiconductors

- Insufficient energy to reach $E_c$
- Thermalization of carriers

$h \nu < E_g$

$h \nu > E_g$
LM and MM 3-Junction Cell Cross-Section

Lattice-Matched (LM)

Lattice-Mismatched or Metamorphic (MM)
Photon Utilization Efficiency
3-Junction Solar Cells

Energy Transitions in Semiconductors

V = voltage of solar cell

$V = q \left| \phi_p - \phi_n \right|$ = quasi-Fermi level splitting

- Not all of bandgap energy is available to be collected at terminals, even though electron in conduction band has energy $E_g$

- Only $qV = q \left| \phi_p - \phi_n \right|$ is available at solar cell terminals

- Due to difference in entropy $S$ of carriers at low concentration in conduction band, and at high concentration in contact layers: $G = H - TS$
V = voltage of solar cell

q\phi_n = quasi-Fermi level splitting

= |\phi_p - \phi_n|
Detailed Balance Limit of Solar Cell Efficiency

- **30%** efficient single-gap solar cell at one sun, for 1 e-/photon
- **44%** ultimate efficiency for device with single cutoff energy
Assumptions → Opportunities

- Assumptions for theoretical efficiency in Shockley and Quiesser (1961)
- Viewed from a different angle, these assumptions represent new opportunities, for devices that overcome these barriers

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Theoretical Multijunction Cell Efficiency

- Detailed balance limit efficiency
- Radiative recombination only
- Series res. and shadowing, optimized grid spacing
- Normalized to experimental efficiency

Efficiency (%) vs. Incident Intensity (suns)

3J & 4J MM solar cells

(1 sun = 0.100 W/cm²)
Maximum Solar Cell Efficiencies

Measured  Theoretical

95%  Carnot eff. = 1 – T/T_{sun}  \quad T = 300 \text{ K}, T_{sun} \approx 5800 \text{ K}
93%  Max. eff. of solar energy conversion  
= 1 − TS/E = 1 − (4/3)T/T_{sun}  \quad (Henry)
72%  Ideal 36-gap solar cell at 1000 suns  \quad (Henry)
56%  Ideal 3-gap solar cell at 1000 suns  \quad (Henry)
50%  Ideal 2-gap solar cell at 1000 suns  \quad (Henry)
44%  Ultimate eff. of device with cutoff E_g:  \quad (Shockley, Queisser)
43%  1-gap cell at 1 sun with carrier multiplication  
(>1 e-h pair per photon)  \quad (Werner, Kolodinski, Queisser)
37%  Ideal 1-gap solar cell at 1000 suns  \quad (Henry)
31%  Ideal 1-gap solar cell at 1 sun  \quad (Henry)
30%  Detailed balance limit of 1 gap solar cell at 1 sun  
(Shockley, Queisser)

3-gap GaInP/GaInAs/Ge LM cell, 364 suns  \quad (Spectrolab) 41.6%
3-gap GaInP/GaInAs/Ge MM cell, 240 suns  \quad (Spectrolab) 40.7%

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Tandem Solar Cells,” Proc. 21st IEEE Photovoltaic Specialists Conf., Kissimmee, 
J. Zhao, A. Wang, M. A. Green, F. Ferrazza, “Novel 19.8%-efficient ‘honeycomb’ 
textured multicrystalline and 24.4% monocrystalline silicon solar cells,” Appl. 
Growth on Ge or GaAs substrate, followed by substrate removal from sunward surface.

Metamorphic (MM) 3-Junction Cells — Inverted 1.0-eV GaInAs Subcell
Solar Spectrum Partition for 3-Junction Cell

Current Density per Unit Wavelength (mA/(cm² μm))

Wavelength (nm)

External Quantum Efficiency (%)

AM1.5D, low-AOD
AM1.5G, ASTM G173-03
AM0, ASTM E490-00a

5- and 6-Junction Cells

- Divides available current density above GaAs $E_g$ among 3-4 subcells
- Allows low-current GaInNAs cell to be matched to other subcells
- Lower series resistance

Ref.: U.S. Pat. No. 6,316,715, Spectrolab, Inc., filed 3/15/00, issued 11/13/01.

Photon Utilization Efficiency
3-Junction Solar Cells

- AM1.5D, ASTM G173-03, 1000 W/m²

Utilization efficiency of photon energy
- 1-junction cell
- 3-junction cell
Photon Utilization Efficiency
6-Junction Solar Cells

AM1.5D, ASTM G173-03, 1000 W/m²
Utilization efficiency of photon energy

1-junction cell
3-junction cell
6-junction cell

3-Junction Cell Efficiency
Losses from 100%

Metamorphic Semiconductor Materials
• Metamorphic = "changed form"

• Thick, relaxed epitaxial layers grown with different lattice constant than growth substrate

• Allows access to subcell band gaps desired for more efficient division of the solar spectrum in multijunction solar cells

• Also called lattice-mismatched

• Misfit dislocations are allowed to form in metamorphic buffer, which typically has graded composition and lattice constant

• Threading dislocations which can propagate up into active device layers grown on buffer are minimized as much as possible
Bandgap vs. Lattice Constant

Courtesy J. Geisz – NREL

Bandgap vs. Lattice Constant

- Ge (indirect)
- GaAs
- 1%-In
- 8%-In GaInAs
- 12%-In GaInAs
- 23%-In GaInAs
- 35%-In GaInAs
- ordered GaInP
- disordered GaInP

Internal QE of Metamorphic GaInAs Cells on Ge

GaInAs single-junction solar cells

1.6% lattice mismatch

2.4% lattice mismatch

Wavelength (nm)

Internal Quantum Efficiency (%)

• Low dislocation density in active cell layers in top portion of epilayer stack:
  \[ \sim 2 \times 10^5 \text{ cm}^{-2} \] from EBIC and CL meas.

• Dislocations confined to graded buffer layers in bottom portion of epilayer stack
• GaInP/ 8%-In GaInAs/ Ge metamorphic (MM) cell structure

• Nearly 100% relaxed step-graded buffer → removes driving force for dislocations to propagate into active cell layers

• 56%-In GaInP top cell pseudomorphomorphic with respect to GaInAs middle cell
Inverted Lattice-Matched (LM) 1.39-eV GaInAs Subcell

Growth on Ge or GaAs substrate, followed by substrate removal from sunward surface
Metamorphic (MM) 3-Junction Cells — Inverted 1.10-eV GaInAs Subcell

Growth on Ge or GaAs substrate, followed by substrate removal from sunward surface.
Metamorphic (MM) 3-Junction Cells — Inverted 0.97-eV GaInAs Subcell

Growth on Ge or GaAs substrate, followed by substrate removal from sunward surface
Metamorphic (MM) 3-Junction Cells — Inverted 0.84-eV GaInAs Subcell

Growth on Ge or GaAs substrate, followed by substrate removal from sunward surface
Dislocations in Inverted Metamorphic Cells – EBIC

EBIC images and dislocation density of inverted metamorphic cell test structures

Dislocations in Inverted Metamorphic Cells

**Inverted metamorphic (MM)**

Ga$_x$In$_{1-x}$As solar cells

- Band gap $E_g$, Open-Circuit Voltage $V_{oc}$, and Band Gap-Voltage Offset ($V$)
- Lattice Mismatch Relative to Ge (%)
- Dislocation Density from EBIC ($10^6$ cm$^{-2}$)

Dislocations in Inverted Metamorphic Cells

Lattice Mismatch Relative to Ge (%)

Dislocation density from EBIC (10^6 cm^-2)
Overall % photon intensity from CL (10^3 cps)
% carrier loss at each dislocation from CL

Inverted metamorphic (MM)
Ga_xIn_{1-x}As solar cells

Dislocation density from EBIC
Overall % photon intensity from CL
% carrier loss at each dislocation from CL

In Composition for Ga_xIn_{1-x}As (%)
Voltage depends on non-equilibrium concentrations of electrons and holes

\[ pn = n_i^2 e^{qV/kT} \]

\[ n_i^2 = N_C N_V e^{-E_g/kT} \]

\[ V = \frac{kT}{q} \ln \left( \frac{pn}{n_i^2} \right) \]

\[ W \equiv \left( \frac{E_g}{q} \right) - V = \frac{kT}{q} \ln \left( \frac{N_C N_V}{pn} \right) \]

- Bandgap-voltage offset \( W \equiv \left( \frac{E_g}{q} \right) - V \) is a useful parameter for gauging solar cell quality, especially when dealing with semiconductors of many different bandgaps.

- Basically a measure of how close electron and hole quasi-Fermi levels are to conduction and valence band edges.
V_{oc} of solar cells with wide range of bandgaps and comparison to radiative limit

- Green line: Voc
- Blue line: Eg from EQE
- Red line: (Eg/q) - Voc
- Dashed line: radiative limit

Band gap - Voltage Offset (E_g/q) - V_{oc} for Single-Junction Solar Cells

Band gap - Voltage Offset (Eg/q) - Voc for Single-Junction Solar Cells

Voc of solar cells with wide range of bandgaps and comparison to radiative limit

Eg/q, Voc, and (Eg/q) - Voc (V)

Intensity per Unit Photon Energy (W/(m²·eV))

Bandgap Eg (eV)

Growth alloy systems include:
- 0.97-eV GainAs
- 1.0-eV GainAs
- 1.3-eV GainAs
- 1.4-eV GainAs
- 1.24-eV GainAs
- 1.30-eV GainAs
- AlGainAs
- o-GainP
- d-GainP
- d-AlGainP
- d-AGainP
- Ge (indirect gap)

High-Efficiency Multijunction Cells
LM and MM 3-Junction Cell Cross-Section

Lattice-Matched (LM)

Lattice-Mismatched or Metamorphic (MM)
Lattice-Mismatched or Metamorphic (MM)

- Metamorphic growth of upper two subcells, GaInAs and GaInP
External QE of LM and MM 3-Junction Cells
Metamorphic (MM) 3-Junction Solar Cell

- Metamorphic GaInAs and GaInP subcells bring band gap combination closer to theoretical optimum

3-junction $E_{g1}/E_{g2}/0.67$ eV cell efficiency
240 suns (24.0 W/cm$^2$), AM1.5D (ASTM G173-03), 25°C
Ideal efficiency -- radiative recombination limit

$E_{g1} = \text{Subcell 1 (Top) Bandgap (eV)}$

$E_{g2} = \text{Subcell 2 Bandgap (eV)}$

- Disordered GaInP top subcell
- Ordered GaInP top subcell

Record 40.7%-Efficient Concentrator Solar Cell

- First solar cell of any type to reach over 40% efficiency

New World Record
41.6% Multijunction Solar Cell

- 41.6% efficiency demonstrated for 3J lattice-matched Spectrolab cell, a new world record
- Highest efficiency for any type of solar cell measured to date
- Independently verified by National Renewable Energy Laboratory (NREL)
- Standard measurement conditions (25°C, AM1.5D, ASTM G173 spectrum) at 364 suns (36.4 W/cm²)
- Lattice-matched cell structure similar to C3MJ cell, with reduced grid shadowing as planned for C4MJ cell
- Incorporating high-efficiency 3J metamorphic cell structure + further improvements in grid design → strong potential to reach 42-43% champion cell efficiency


Concentrator cell light I-V and efficiency independently verified by C. Osterwald, K. Emery – NREL
• At peak 41.6% efficiency → 364 suns, Voc = 3.192 V, FF = 0.887
• Efficiency still >40% at 820 suns, at 940 suns efficiency is 39.8%
• Diode ideality factor of 1.0 for all 3 junctions fits Voc well from 100 to 1000 suns
At peak 41.6% efficiency → 364 suns, Voc = 3.192 V, FF = 0.887
Series resistance causes drop in V_mp above 400 suns, V oc continues to increase
Efficiency still >40% at 820 suns, at 940 suns efficiency is 39.8%
Best Research Cell Efficiencies

Chart courtesy of Larry Kazmerski, NREL

Growth on Ge or GaAs substrate, followed by substrate removal from sunward surface.

- Bottom ~1-eV GaInAs subcell is inverted and metamorphic (IMM)
- Upper two GaInAs and GaInP subcells are inverted and lattice matched (ILM)
Inverted Metamorphic (IMM) 3-Junction Cell

- Raising band gap of bottom cell from 0.67 for Ge to ~1.0 eV for IMM GaInAs raises theoretical 3J cell efficiency

5-Junction Inverted Metamorphic (IMM) Cells

- 0.75-eV GaInAs cell 5
- 1.1-eV GaInAs cell 4
- 1.4-eV GaInAs cell 3
- 1.7-eV AlGaInAs cell 2
- 2.0-eV AlGaInP cell 1

Ge or GaAs growth substrate
metal gridline

• Current density in spectrum above Ge cell 4 is divided 3 ways among GaInAs, AlGa(In)As, GaInP cells
• Lower current and I²R resistive power loss
4-Junction Upright Metamorphic (MM) Terrestrial Concentrator Cell

- 1.8-eV (Al)GaInP cell 1
- 1.55-eV AlGaInAs cell 2
- 1.2-eV GaInAs cell 3
- 0.67-eV Ge cell 4 and substrate

metal gridline
4-Junction Cell
Optimum Band Gap Combinations

- Lowering band gap of subcells 2 and 3, e.g., with MM materials, gives higher theoretical 4J cell efficiency
Measured 4-Junction Cell Quantum Efficiency

AlGaInP subcell 1 1.95 eV
AlGaInAs subcell 2 1.66 eV
GaInAs subcell 3 1.39 eV
Ge subcell 4 0.72 eV
All subcells

AM1.5D ASTM G173-03
Light I-V curves for 3-junction upright MM (40.7%), 3J lattice-matched (41.6%), 3J lattice-matched at 822 suns (39.1%), and 4J lattice-matched cell (36.9%)
Semiconductor-Bonded Technology (SBT) Terrestrial Concentrator Cell

- **Wafer bonding for multijunction solar cells**
  - Low band gap cells for MJ cells using high-quality, lattice-matched materials
  - Epitaxial exfoliation and substrate removal
  - Formation of lattice-engineered substrate for later MJ cell growth
  - Bonding of high-band-gap and low-band-gap cells after growth
  - Electrical conductance of semiconductor-bonded interface
  - Surface effects for semiconductor-to-semiconductor bonding

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6-Junction Solar Cells

- **(Al)GaInP Cell 1**: 2.0 eV
- **GaInP Cell 2 (low Eg)**: 1.78 eV
- **AlGa(In)As Cell 3**: 1.50 eV
- **Ga(In)As Cell 4**: 1.22 eV
- **GaInNAs Cell 5**: 0.98 eV
- **Ge Cell 6** and substrate: 0.67 eV

Current Density / Incident Intensity (A/W) vs. Voltage (V)

- **Red**: MJ cell
- **Purple**: subcell 1
- **Blue**: subcell 2
- **Cyan**: subcell 3
- **Green**: subcell 4
- **Orange**: subcell 5
- **Black**: subcell 6

Photon Utilization Efficiency
6-Junction Solar Cells

Utilization efficiency of photon energy

- 1-junction cell
- 3-junction cell
- 6-junction cell

AM1.5D, ASTM G173-03, 1000 W/m²

Concentrator Photovoltaic (CPV) Systems and Economics
Combination of high efficiency & 500X concentration boosts output per semiconductor area by a factor of 1000.

MJ cells are replaced by less expensive optics and common materials.

Leads to reduced cost of energy despite paying extra for tracking & cooling.

• 1 football field of ~ 17% solar cells at 1-sun produces ~ 500 kW.

• By using MJ cells (> 35%) at concentration of 500 suns, same power is produced from smaller semiconductor area (or the football field produces 500 MW).
Solar Systems, Australia
Hermannsburg Power Station

- III-V MJ cells give 56% measured improvement in module efficiency relative to Si concentrator cells

Equipped with III-V MJ cell receivers

Courtesy of Solar Systems Pty. Ltd., Australia
Balance of System Costs

Optics

Cooling

Tracking

Structure

Operation and Maintenance

Courtesy of Solar Systems Pty. Ltd., Australia
Continuity equation:

\[ \frac{\partial \rho}{\partial t} = qG - qR - \nabla \cdot J \]

...in $$\$\$$ rather than charge carriers:

\[ \frac{\partial \$\$}{\partial t} = \$\$_{\text{gen}} - \$\$_{\text{exp}} - \nabla \cdot F\$\$

change in value of PV system (profit or loss)
value of kWhr generated by PV system - operating expenses for PV system - funds paid out to bank for interest and principal on loan to buy PV system

\[
\text{PV system cost per kWh generated in 5 year payback period} = \frac{\text{module cost/m}^2 + \text{tracking cost/m}^2 + \text{BOS, area cost/m}^2 + \text{BOS, power cost/W} + \text{peak power output, W/m}^2 + \text{cell cost/m}^2}{\text{energy produced, kWh/(m}^2\cdot\text{year})/\text{5 year payback period}}
\]
Terrestrial PV System Cost vs. Cell Cost

Cell cost ranges

PV System Cost / kWh Generated in 5 Year Period ($/kWh)

PV System Cost / Power Output ($/W)

Cell Cost ($/cm²)

Fixed Flat-Plate

500X Point-Focus Conc.

5-Year Payback Threshold, at $0.15/kWh

Decreasing cell cost main priority for flat-plate

Increasing cell efficiency main priority for concentrators

R. R. King et al., 3rd Int'l. Conf. on Solar Concentrators (ICSC-3), Scottsdale, AZ, May 2005

Worldwide PV Production
1990-2007

- Rest of the World
- Europe
- Japan
- United States

Total MW Production

Year
- 90: 46.5
- 91: 55.4
- 92: 57.9
- 93: 60.1
- 94: 69.6
- 95: 77.6
- 96: 88.6
- 97: 125.8
- 98: 194.9
- 99: 203
- 00: 376.2
- 01: 386.0
- 02: 547.0
- 03: 748.1
- 04: 1193.5
- 05: 1782.3
- 06: 2473.7
- 07: 3733.4

Larry Kazmerski, NREL
Cell production hits 7.9 GW
Global survey shows 85 percent growth in 2008
• Urgent global need to address carbon emission, climate change, and energy security concerns → renewable electric power can help

• Theoretical solar conversion efficiency
  – Examining built-in assumptions points out opportunities for higher PV efficiency
  – Multijunction architectures, up/down conversion, quantum structures, intermediate bands, hot-carrier effects, solar concentration → higher $\eta$
  – Theo. solar cell $\eta > 70\%$, practical $\eta > 50\%$ achievable

• Metamorphic multijunction cells have begun to realize their promise
  – Metamorphic semiconductors offer vastly expanded palette of band gaps
  – 40.7% metamorphic GaInP/ GaInAs/ Ge 3J cells demonstrated
  – First solar cells of any type to reach over 40% efficiency

• New world record efficiency of 41.6% demonstrated
  – Highest efficiency yet measured for any type of solar cell
  – 41.6% efficiency independently verified at NREL (364 suns, 25°C, AM1.5D)

• Solar cells with efficiencies in this range can transform the way we generate most of our electricity, and make the PV market explode