The Physics and Applications of High-Efficiency, Ultra-Thin Solar Cells

Jessica Adams

2014-04-11
University of Oklahoma Physics Department Seminar
The Physics and Applications of High-Efficiency, Ultra-Thin Solar Cells

1. Physics of high-efficiency solar cells
2. Manufacturing high-efficiency solar cells
3. Applications for high-efficiency, ultra-thin solar cells
MicroLink Company Background

- Established in 2000 to manufacture heterojunction bipolar transistors
- 30,000 sq ft facility located in Niles, IL
- 2014 ~40 employees
- ~15 employees involved in developing high efficiency solar cells
- Pilot-scale production line manufacturing epitaxial lift-off solar cells
My Background

2007-2011:
PhD Experimental Solid State Physics
(Quantum Photovoltaics Group)
Imperial College London

2011-Present:
Sr. R&D Engineer
(Engineering Group)
MicroLink Devices, Niles IL
1. Physics of High-Efficiency Solar Cells

Worldwide power consumption: 16 TW
Incoming solar power: 86,000 TW
Solar cells with efficiency >30% are required to enable low $/W and high W/kg applications.
Solar Cell Physics 101

1. Sunlight hits the solar cell and photons are absorbed
2. The energy from the sunlight is given to charge carriers inside the material
3. The carriers are separated by the electric field in the device and travel to metal contacts on the surfaces of the solar cell
4. From the metal contacts, the carriers are extracted to an external circuit
5. The carriers then give up their energy to an external load
Physics: Power Generation in a Single-Junction Solar Cell

- High bandgap: low thermalization loss, low recombination rate
- Low bandgap: low below-bandgap photon loss
Optimizing the Solar Cell Bandgap

\[ P = V \times I \]

Efficiency = \frac{\text{Power out}}{\text{Power in}}
Single-Junction Solar Cell Efficiency Limits

Shockley-Queisser Limit

William Shockley

Hans Queisser

Detailed Balance Limit of Efficiency of $p$-$n$ Junction Solar Cells*

William Shockley and Hans J. Queisser

Shockley Transistor, Unit of Cerite Transistor, Palo Alto, California

(Received May 3, 1960; in final form October 31, 1960)
Achieved Single-Junction Cell Efficiencies

- Max theoretical efficiency for a single-junction solar cell ~33%
- GaAs cell efficiency record: 28.8%
- Si cell efficiency record: 25% (indirect bandgap)
Dividing the Spectrum with Multi-Junction Solar Cells

- Cell voltage is sum of subcell voltages
- Cell current is that of limiting subcell
- Theoretical optimum triple-junction bandgap combination arises from subcell current-matching requirement: 1.7 / 1.2 / 0.7 eV
2. Manufacturing High-Efficiency Solar Cells
Making Epitaxial Solar Cells

Design → Growth → Fabrication → Test

Jessica Adams
Designing a Multi-Junction Solar Cell

Epitaxial materials usually grown by:
- Metal-organic chemical vapor deposition (MOCVD)
- Molecular beam epitaxy (MBE)

Layer-by-layer growth on a substrate
Lattice-matched growth has lowest defect density
**Inverted Metamorphic (IMM) Solar Cell: High Efficiency, Low Weight**

**IMM: 44.4% (302X), Sharp**


Jessica Adams
MicroLink Devices Proprietary
Inverted Metamorphic Solar Cell Structure

- IMM triple-junction structure
- Three subcells series-connected via tunnel junctions
- Transparent metamorphic buffer for growth of lattice-mismatched InGaAs subcell
- Release layer to facilitate removal of epitaxial layers by wet chemical process

Jessica Adams
History of Epitaxial Lift-Off (ELO)

- ELO originally developed in the late 1970s
- Incorporation of sacrificial release layer to remove epitaxial material
- Initially plagued by very slow etch rates, crack formation, difficult to lift off large areas
- More recent work (Schermer, et al.) has improved etch rate (hours instead of days)


Jessica Adams
Epitaxial Lift-Off Solar Cells

- Developed wafer-scale ELO technology
- Compatible with low-cost batch processes
- Substrate intact and reusable

4” wafer ELO (2x20cm² cells)

6” wafer ELO (2x61cm² cells)
ELO for Cost and Weight Reduction

- Reduced cost: Substrate is ~50% of cost of cell bill of materials
- Low weight: Enables airborne and space applications
- Flexibility: Wrap cell around curved objects
- Compatible with high efficiency cell designs (inverted metamorphic)

Jessica Adams
Fabrication Process by ELO

Start

Epitaxial Growth → Back Metal → Epitaxial Liftoff (ELO)

Reuse

Repolish

ARC, GRID

Temporary Carrier Mount

SOLAR CELL
BACK METAL
ELO Solar Cell

SOLAR CELL
BACK METAL
CARRIER

SOLAR CELL
RELEASE LAYER
SUBSTRATE

BACK METAL
SOLAR CELL
RELEASE LAYER
SUBSTRATE

CARRIER

BACK METAL
SOLAR CELL

SUBSTRATE

Jessica Adams
Cell Testing

Illuminated current-voltage measurement

Quantum efficiency measurement

Electroluminescence

Jessica Adams
3. Applications for High-Efficiency Ultra-Thin PV
Unmanned Aerial Vehicles

Jessica Adams
MicroLink Devices Proprietary
Portable Power

12 W portable sheet

Testing at Limited Objective Experiment
Possible Application: Space

Venera 2 & 3 launched 1965: 2 m² GaAs PV
Lunokhod-1 & 2, 1970/72: 4 m² GaAs PV, 11% Efficiency

Venera – 3 (1965)  
Lunokhod – 2 (1972)  
ISS
Possible Application: Concentrator PV

Solar Systems - Australia

Amonix - USA
Industry at the Cutting Edge

Jessica Adams 29

50%, 2016

This is an excerpt from the November 29, 2012 edition of the SunShot newsletter:

ARPA-E Funds Eight Transformational Solar Research Efforts

On November 29, eight solar research efforts were announced among 66 projects receiving funding through the Energy Department Advanced Research Projects Agency – Energy (ARPA-E) OPEN 2012 program. These eight projects are part of a $130 million investment in cutting-edge research encompassing 11 technology areas in 24 states. The OPEN 2012 projects represent transformative technologies that show fundamental technical promise but are too early for private-sector investment.

Led by teams from universities, industry, and national labs, the following projects were selected to receive a total of more than $20 million focused on solar energy breakthroughs:

- **California Institute of Technology** (Pasadena, California): $2,400,000 to develop an optical device that focuses and reflects individual color bands to improve the efficiency of solar electricity generation.
- **Georgia Institute of Technology** (Atlanta, Georgia): $3,600,000 to develop a high-efficiency solar reactor to produce liquid metal. The reactor transports heat away from the sunlight-collection point to a chemical reaction zone, minimizing heat. This system would enable cost-effective solar fuels that can be used for transportation and continuous electricity production.
- **Glint Photonics, Inc.** (Menlo Park, California): $523,172 to develop a solar concentrator that can capture the full amount of sunlight regardless of the sun's position. Unlike today's technology, this concentrator does not require complex moving parts to follow the sun's movements. Glint's innovative design uses an automatic optical system of fluid layers that adjust their position as the sun moves.
- **MicroLink Devices** (Niles, Illinois): $3,918,705 to develop high-efficiency solar cells to capture concentrated sunlight with crystal layers in an innovative design. These cells will improve concentrated photovoltaic products to increase the energy generated from solar power plants. MicroLink will use sophisticated manufacturing techniques to allow for reuse of expensive templates to minimize costs normally associated with high-performance solar cells.
- **National Renewable Energy Laboratory** (Golden, Colorado): $890,000 to develop a thermal electric generator that directly converts concentrated sunlight to electricity using a new generation of thermoelectric materials that can operate at high temperatures. The new materials and advanced engineering designs could convert solar heat to electricity at three times the efficiency of current systems.
- **National Renewable Energy Laboratory** (Golden, Colorado): $890,000 to develop a new approach to enhance the efficiency of plastic solar cells using specially engineered photonic structures to capture a larger part of the solar spectrum. NREL’s approach is to triple the efficiency of plastic photovoltaics, enabling the adoption of this low-cost, clean, and renewable electricity source.
- **Otherlab, Inc.** (San Francisco, California): $1,600,000 to develop an inexpensive method to reflect sunlight onto a solar cell using mirrors. Many of today’s mirrors are 20 to 30 feet tall, making them difficult to stabilize and rotate. Otherlab’s hybrid solar tower with boom and mirror will radialize sunlight and reflect it onto the solar cell.
Summary

- The solar resource is huge: >5000x more power falls on Earth’s surface from sun than we consume
- For terrestrial applications it is critical to reduce the solar cell $/W
- For airborne applications it is necessary to increase the solar cell W/kg
- Both of these are achieved via the epitaxial lift-off and substrate reuse process

Thank You.