LINKING NANOSCALE TO GIGAWATTS

PROF. J. POORTMANS, IMEC
PART-TIME PROFESSOR KUL
OUTLINE

Energy, the Grand Challenge of the century

- The Challenge Illustrated
- The possible solutions / challenges

Linking Nanoscale to GigaWatts (GWh)

- Saving, Switching, Storing Energy solutions from the microelectronics process toolbox

Linking Nanoscale to Solar

- Today’s technology situation
- Getting more out of less
  - OPV
  - Towards higher efficiencies
GRAND CHALLENGES

Humanity’s Top Ten Problems for next 50 years

1. ENERGY
2. WATER
3. FOOD
4. ENVIRONMENT
5. POVERTY
6. TERRORISM & WAR
7. DISEASE
8. EDUCATION
9. DEMOCRACY
10. POPULATION

Source: MIT Forum 2003
ELECTRICITY NEEDS

Source: IEA, World Energy Outlook 2008
BOUNDARY CONDITION: THE GREENHOUSE EFFECT

$\Delta T(2100) < 2^\circ C$

Source: IPCC

Enormous Challenge!
Next 40y add 360 GW CO$_2$ neutr. cap./year
Efficiency gain essential!

Source: DOE US
ENERGY RESOURCES

Source: EREC

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SCENARIOS: PART OF TOTAL ENERGY MIX

EXISTING PV-MARKETS: CUMULATIVE INSTALLED PV-POWER

Global market outlook for photovoltaics until 2014

www.epia.org:
PV CAN CONTRIBUTE UP TO 12% OF EU ELECTRICITY DEMAND BY 2020

Baseline Scenario: 4%

Paradigm Shift Scenario: 12%

Accelerated Scenario: 6%

Baseline Scenario: 4%

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Courtesy of EU PV Technology Platform & EPIA

Share of demand by 2020

Indicative

GW

0 50 100 150 200 250 300 350 400 450 500 550 600 650 700


Courtesy M. Lippert, SAFT
TO A DISTRIBUTED ENERGY SYSTEM?

1GWatt = 70 km²
100 farms 60*60km²

1GWatt = 30 km²
PV

1GWatt = 15 km²
CSP

1GWatt = 1km²
Nuclear

Intermittent, distributed sources lead to "SMART GRID"
peak mgmt & hydro and EV storage

Smart Meters

Peak Mgmt & Storage

Gas

Hydro

EV
FUTURE ENERGY SYSTEM VISION

SmartGrids Technology Platform
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“Solid state lighting, where chips emit light, has the potential to save up to 90% energy (Henk Coppens, CEO LED lamps and systems, Philips Lighting)

Courtesy of Philips Applied Technologies (Marc de Samber)
LUMINOUS EFFICACY TREND

Requirement by 2020:

- Luminous Efficacy: 200 [lm/W]
- Cost per lamp: 3 [$/lamp]

Panasonic, Oct’09
86 lm/W, commercial

Nichia: 150 lm/W
at 20mA, lab scale
SAVING ENERGY: LEDs
EXAMPLE: INGaN LEDs

(In)GaN-alloys are very efficient emitting materials

- Growth by MOCVD
- On expensive substrates
  - SiC
  - Sapphire
- Only available in small sizes

GaN-on-Si for LEDs to:

- Availability of large-area substrates
- Reduce process variability
- Reduce cost of in-process and final product testing
- Long term reliability and performance

Source: S. Nakamura
SWITCHING

Increased interconnectivity of the grid

- Additional transmission lines
- HVDC-connections

Taking into account bidirectionality in the transmission and distribution lines

- Requires highly efficient switches
- Invertors have to supply reactive power to stabilize frequency

Power electronics
  - Reliable
  - Operating at high temperature (no cooling, ....)
### HIGH-LEVEL VIEW
SWITCHING MATERIALS

<table>
<thead>
<tr>
<th></th>
<th>Si</th>
<th>GaAs</th>
<th>GaN</th>
<th>4H-SiC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band Gap [eV]</td>
<td>1.12</td>
<td>1.4</td>
<td>3.49</td>
<td>3.26</td>
</tr>
<tr>
<td>Breakdown Field [MV/cm]</td>
<td>0.3</td>
<td>0.4</td>
<td>3.5</td>
<td>3.0</td>
</tr>
<tr>
<td>Electron mobility [cm²/Vs]</td>
<td>1400</td>
<td>8500</td>
<td>2000</td>
<td>700</td>
</tr>
<tr>
<td>Electron sheet density [/cm²]</td>
<td>2E12</td>
<td>2E13</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal conductivity [W/cmK]</td>
<td>1.5</td>
<td>0.5</td>
<td>&gt;1.7</td>
<td>3.5</td>
</tr>
<tr>
<td>Lattice constant [Å]</td>
<td>5.43</td>
<td>5.65</td>
<td>3.19</td>
<td>3.07</td>
</tr>
</tbody>
</table>

**Large bandgap**

- Wide bandgap -> High temperature operation
- High breakdown field -> high voltage operation
- High mobility -> fast switching speed
- High electron density -> low resistance
APPLICATION AREAS: SiC VS GaN

High-Eg materials can replace Si

IT&consumer
- PFC / power supplies
- Converter / inverter
- Electronic appliances & Computing
- UPS

Automotive
- DC/AC inverter
- Hybrid automotive

Industry
- Power distribution
- Inverter
- Rail transport
- Ships and vessels
- Wind turbines

Competition between SiC and GaN
- SiC only

Extract of Yole report: High Voltage Power Electronic Market and Technology Trends Focus
SWITCHING ENERGY – EXAMPLE: GaN-ON-Si

GaN HEMT

**Mobility**

- HEMT
- High mobility due to lack of ionised impurity scattering

**2DEG Charge Density**

- AlGaAs/GaAs 2DEG is dopant induced
- AlGaN/GaN 2DEG is polarisation induced
  - AlGaN is piezo-electric & tensile strained
- GaN has 5-10x higher charge density than GaAs or Si

“The epi is the device”

Wide-bandgap semiconductor used as “oxide”, since native oxide is poor
STORING ELECTRICITY: TRADE OFF BETWEEN CAPACITY AND POWER

In practice: combination of **supercap** for short bursts of power with **batteries** or fuel cells for long-lasting energy.
SCALING FOR P- AND E- DENSITY

- **Energy** (E) density increases with **scaling up aspect ratio** (AR)
  - More material (cathode/anode volume) for deeper structures
- **Power** (P) density increases with **scaling down layer thickness**
  - Faster ion(electron) transport as shorter distances

![Diagram](Planar TF-LIB | 0.2mWh um⁻¹ cm⁻²
3D TF-LIB | 5mWh um⁻¹ cm⁻²)

**3-D Integrated All-Solid-State Rechargeable Batteries**

By Peter H.L. Notten*, Fred Roozeboom, Rogier A.H. Niessen and Loïc Baggetto

* Courtesy of P. Vereecken
PROJECTIONS

- 3D thin-film microbatteries to macrobatteries
  - Processing on metal foils, cheap nanotechnology
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PV ELECTRICITY GENERATION COST

\[ LCOE(\$/kWh) = \frac{\text{Initial cost}(\$/kW) + \text{Maintenance}(\$/kW)}{\text{Lifetime}(\text{yr}) \times \text{Annual output}(kWh/(kW\cdot yr))} \]

PV electricity generation cost determined by:

**Turn-key system price (€/Wp)**
- Module price + Balance-of-System price (*power-related part & area-related part*)

**Energy output (kWh/Wp·yr)**
- Primarily dependent on annual insolation
- Influenced by system quality and design, partial shading, etc.

**Operation and maintenance cost (€/Wp·yr)**

**Capital cost:**
- Depreciation time (yr)
- Interest rate / Return on Investment required (%)
PV SYSTEM PRICE: THE VALUE OF MODULE EFFICIENCY (EXAMPLE)

module efficiency 20%
- modules (2.0 Euro/Wp)
- area-related BoS (100 Euro/m2)
- power-related BoS (0.5 Euro/W)

turn-key system price 3 €/Wp

module efficiency 10%
- modules (1.5 Euro/Wp)
- area-related BoS (100 Euro/m2)
- power-related BoS (0.5 Euro/W)
# PRESENT PV-TECHNOLOGIES: TERRESTRIAL APPLICATION

<table>
<thead>
<tr>
<th>Cell Technology</th>
<th>Type of junction</th>
<th>Lab [%]</th>
<th>Industrial efficiency [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk crystalline Si solar cells</td>
<td>p-n homojunction</td>
<td>25.0</td>
<td>15 – 18</td>
</tr>
<tr>
<td>a-Si:H</td>
<td>p-i-n homojunction</td>
<td>13.5</td>
<td>6-7 single junction</td>
</tr>
<tr>
<td>(a-Si:H; a-SiGe:H, μc-Si:H)</td>
<td>multijunction</td>
<td></td>
<td>9-10 multijunction</td>
</tr>
<tr>
<td>CuIn(Ga)Se$_2$(S$_2$) =CIS</td>
<td>p-n heterojunction with CdS</td>
<td>20.3</td>
<td>9 - 13</td>
</tr>
<tr>
<td>CdTe</td>
<td>p-n heterojunction with CdS</td>
<td>17.3</td>
<td>7 - 11</td>
</tr>
</tbody>
</table>
TECHNOLOGY CONTRIBUTION 1980 THROUGH 2009

Thin-film technologies
Crystalline Si
Example: Nanobased photovoltaic devices
Organic Photovoltaics:

A layer of Donor and a layer of acceptor between electrodes

Exciton dissociation at Donor/Acceptor interface.

Limited efficiency due to:

Small dissociation sites (only D/A interface).
High recombination possibility when D or/and A layer is thicker than ~10 nm.
Low light absorption since films are thin.
Organic Photovoltaics: Bulk donor-acceptor junction

Bulk heterojunction concept

Higher efficiency due to:
- Better dissociation by larger D/A interface.
- Lower recombination rate for thicker films.
- More light absorption due to thicker films.

Exciton Creation
Exciton diffusion
Exciton dissociation
Charge transport
Charge collection

OPV CELL ADVANCEMENTS

For OPV technologies, in general, two deposition processes are used:

- Evaporation of the material (small molecule)
- Solution (wet) processing

Heliatek and IAPP achieve production-relevant efficiency record for organic photovoltaic cells

While carrying out development work in cooperation with the Institute of Applied Photophysics (IAPP) at Dresden University, Heliatek GmbH of Dresden has again set an efficiency record for organic photovoltaic cells (OPVCs): with an efficiency of 8.3% on an active surface area of 1.1 cm², measured by Heliatek and independently confirmed by the Fraunhofer ISE CalLab (Freiburg), this sets a new world record for organic photovoltaic cells (OPVCs).

February 2011

PV works by integrating p- and n-semiconductors to convert light energy into electricity. The newly developed OPV, however, is produced by adding two coatings of organic compounds to a film substrate—one of benzoporphyrin (BP), which acts as the p-semiconductor, and one of fullerene (FLN), which acts as the n-semiconductor. As this renders glass substrates unnecessary, each layer can be of nanosize thickness, enabling the production of extremely thin, highly flexible and easily bendable photovoltaic cells.
Figure 17. Energy-cost calculations in €cents kWh⁻¹ for the presented model of 1 kWp grid-connected roof-top plant under the following set of assumptions: BOS 70 € m⁻²; BOM: varied from 10–100 € m⁻²; lifetime: varied from 3–10 years, efficiency: varied from 3–10%. The full symbols indicates the value at 5 years of lifetime. The error bars and the guided lines around the symbols show the parameter variation in the case of a 3 year and 10 year product, respectively.
THIRD-GENERATION SOLAR CELLS

http://www.pv.unsw.edu.au
SHOCKLEY-QUEISSER MODEL

Unity absorbance for photons $> E_g$

Zero absorbance for photons $< E_g$

Only radiative recombination $\rightarrow J_o$

Dark I-V characteristic of the Cell is described by ideal diode equation

$$J(V) = J_o \left( \exp \left( \frac{qV}{kT} \right) - 1 \right)$$
Detailed Balance Limit of Efficiency of $p$-$n$ Junction Solar Cells

**William Shockley and Hans J. Queisser**

*Shockley Transistor, Unit of Clevite Transistor, Palo Alto, California*  
(Received May 3, 1960; in final form October 31, 1960)

In order to find an upper theoretical limit for the efficiency of $p$-$n$ junction solar energy converters, a limiting efficiency, called the detailed balance limit of efficiency, has been calculated for an ideal case in which the only recombination mechanism of hole-electron pairs is radiative as required by the principle of detailed balance. The efficiency is also calculated for the case in which radiative recombination is only a fixed fraction $f_0$ of the total recombination, the rest being nonradiative. Efficiencies at the matched loads have been calculated with band gap and $f_0$ as parameters, the sun and cell being assumed to be blackbodies with temperatures of 6000°K and 300°K, respectively. The maximum efficiency is found to be 30% for an energy gap of 1.1 eV and $f_0 = 1$. Actual junctions do not obey the predicted current-voltage relationship, and reasons for the difference and its relevance to efficiency are discussed.

![Diagram of energy levels and recombination processes in a solar cell.](image)
TAILORING THE SEMICONDUCTOR LOSSES OF A SOLAR CELL

$$\eta = \frac{\int_{0}^{\infty} P(\lambda) d\lambda \ E_g \int_{0}^{\lambda_g} N(\lambda) d\lambda}{\int_{0}^{\lambda_g} P(\lambda) d\lambda \int_{0}^{\lambda_g} P(\lambda) d\lambda} \frac{A_f}{A_t} (1 - R^*) \eta_d \eta_{coll} \frac{qV_{oc}}{E_g} \frac{FF}{EF}$$

- Long-wavelength losses
- Excess-energy losses
- Incomplete absorption
- Voltage factor
- Fill factor
- Incomplete collection
- Reflection losses outside fingers
BASIC CLASSIFICATION OF APPROACHES TO GO BEYOND SQ

Development of novel active layers tailoring the active material to the solar spectrum

- Multijunctions
- From 3-D to 0-D materials
- Either aimed at:
  - Combining improved long-wavelength absorption with high voltage of host semiconductor with larger bandgap (quantum wells, MIB)
  - Quantum confinement effects
    ▪ Modifying bandgap
    ▪ Hot carrier effects – multiple exciton generation

Development of peripheral layers and structures tailoring the solar spectrum to the active material

- Upconverting materials
- Downconverting materials
- Inclusion of photonic structures
TAILORING THE SEMICONDUCTOR LOSSES OF A SOLAR CELL

\[ \eta = \frac{\int_{0}^{\lambda_g} P(\lambda) d\lambda}{\int_{0}^{\infty} P(\lambda) d\lambda} \]

\[ \frac{E_g}{E_g} \int_{0}^{\lambda_g} N(\lambda) d\lambda \]

\[ A_f \frac{1 - R^* \eta_d \eta_{coll}}{E_g} \frac{qV_{oc}}{FF} \]

- Long-wavelength losses
- Excess-energy losses
- Reflection losses outside fingers
- Incomplete collection
- Voltage factor
- Fill factor
- Incomplete absorption
- Shadowing
Fundamental efficiency limits

- Incomplete absorption
- Thermalisation

• Single junction limited to 30%

AM1.5 spectrum
Multijunction cells: combination of cells with different $E_g$ to reduce thermalisation losses
MULTI-JUNCTION SOLAR CELLS
STATE-OF-THE-ART

$\text{In}_{0.5}\text{Ga}_{0.5}\text{P/GaAs/Ge monolithic triple-junction}$

- Optimal single-junction: GaAs (25.1%)
- Lattice-matched $\text{In}_{0.5}\text{Ga}_{0.5}\text{P}$ top cell (30.3%)
- Ge bottom cell (32.0%)
BASIC STRUCTURE
MULTIJUNCTION CELLS

Active layers (by MOCVD):

• InGaP
• GaAs
• Ge-substrate

Nano-feature is in the tunnel junctions.

Series connections of the cells require nanometer control!
THIRD-GENERATION SOLAR CELLS

http://www.pv.unsw.edu.au
TAILORING THE SEMICONDUCTOR LOSSES OF A SOLAR CELL

\[
\eta = \frac{\int_0^{\lambda_g} P(\lambda) d\lambda \ E_g \int_0^{\lambda_g} N(\lambda) d\lambda}{\int_0^\infty P(\lambda) d\lambda \ \int_0^\infty P(\lambda) d\lambda} \ \frac{A_f}{A_t} (1 - R^*) \eta_d \eta_{\text{coll}} \frac{qV_{oc}}{E_g} FF
\]

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- Fill factor
2-D: QUANTUM WELL SOLAR CELLS

Quantum well solar cells are a (industrial) reality today

▷ Strain-balanced quantum wells of InGaAs surrounded by strain-compensating GaAsP-barriers
▷ Sandwiched in the i-layer of a pin-structure

QuantaSol unveils 28.3% efficient single-junction solar cell World record made public at UK's Royal Society Summer Science Exhibition, Kingston-upon-Thames, UK, June 30th 2009:

QuantaSol Ltd, a new independent designer and manufacturer of strain-balanced quantum-well solar cells, has developed what it believes to be the most efficient single junction solar cell ever manufactured. Developed in just two years, QuantaSol's single-junction device has been independently tested by Fraunhofer ISE as achieving 28.3% efficiency at greater than 500 suns.

Source: K. Barnham et al.

http://www.quantasol.com
I-D: SI-NANOWIRE CELLS

III/V stacks are expensive to grow

⇒ Idea behind all-Si tandem cell: best band gap in combination with 1.12eV is 1.7-1.8eV

⇒ a-Si ? Poor material quality

Courtesy of R. Kurtsjens
HIGH BANDGAP SI BY 1-D CONFINEMENT

Si nanowires (1.8 eV)
Tunnel junction
Bulk Si (1.1 eV)

Courtesy of R. Kurstjens
IDEAL SI-NANOWIRES BY DUV

- DUV + dry etch
- Oxidation + FGA
- Planarization + CMP
- Contact formation

Courtesy of R. Kurstjens & F. Dross
0-D: SI QUANTUM DOTS

All Silicon-multijunction

Si-QD’s in matrix: SiN- or SiC-matrix will result in higher mobility

If these dots are spaced close together, carriers can tunnel between them to produce conducting quantum dot (QD) superlattices.

M. Green et al., 24th European PV-conference, 2009
0-D: SI QUANTUM DOT SOLAR CELLS

pin-structures by dot doping with P and B
Working PV-devices with open-circuit voltage of about 500 mV were shown
Ge or Sn-dots might also work with process temperature much lower than for Si

Figure 2: Silicon QD solar cell presently being developed as the top or middle cell for 2- or 3-cell tandem stack. Note the device is almost entirely SiO_{2}!

M. Green et al., 24th European PV-conference, 2009
TAILORING THE SEMICONDUCTOR LOSSES OF A SOLAR CELL

$$\eta = \frac{\int_0^{\lambda_g} P(\lambda) d\lambda}{\int_0^{\infty} P(\lambda) d\lambda} \frac{E_g}{E_g} \int_0^{\lambda_g} N(\lambda) d\lambda \frac{A_f}{A_t} (1 - R^* \eta_d \eta_{coll}) \frac{qV_{oc}}{E_g} \eta_{FF}$$

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0-D: MULTIPLE EXCITON GENERATION

Shockley-Queisser:
- 1 e-h pair/photon
- Maximum efficiency $\approx 31\%$

Multiple e-h pair generation
- Impact ionisation
  - Ineffective in most bulk materials
- Multiple exciton generation
  - Observed in QD’s

Limiting efficiencies
- 44% non-concentrated light
- 85.9% under concentration

*M.C. Hanna and A.J. Nozik, JAP, 074510, 2006*
0-D: MULTIPLE EXCITON GENERATION

Efficient multiple exciton generation (MEG) has been observed in quantum dots QDs

- Lead salts: PbSe, PbS and PbTe
- CdSe
- For a PbSe QD with a band gap of 0.636 eV, up to seven excitons are created after absorbing a 5 eV photon (see e.g. Schaller et al., Nano Lett. 6, 424 2006)

J.M. Luther et al., Nano Letters, 7, 1779, 2007
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\]

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- Voltage factor
- Incomplete absorption
- Shadowing

\[ E_c \]

\[ E_v \]
NANOWIRE SOLAR CELLS

Collection hindered by surface recombination

- Radial junctions limits distance over which minority carriers have to diffuse
- Limited efficiencies were obtained

Figure 1. Silicon nanowire solar cell structure. (a) Schematic cell design with the single crystalline n-Si NW core in brown, the polycrystalline p-Si shell in blue, and the back contact in black. (b) Cross-sectional SEM of a completed device demonstrating excellent vertical alignment and dense wire bonding. (c) TEM image showing the single crystalline n-Si core and polycrystalline p-Si shell. The inset is the selected area electron diffraction pattern. (d) TEM image from the edge of the core–shell nanowire showing polycrystalline domains.

Courtesy of U. Berkeley

Courtesy of Caltech

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Development of peripheral layers and structures tailoring the solar spectrum to the active material

▸ Upconverting materials
▸ Downconverting materials
▸ Inclusion of photonic structures
ADAPTING THE INCOMING SPECTRUM

Basic idea: convert or to split the incoming photons as to reduce:

▸ IQE-losses: conversion of blue to red photons
▸ Thermalization losses: down-conversion of high-energy photons
▸ Absorption losses: up-conversion of non-absorbed photons
▸ Diffuse concentration (quantum dot concentration)

This can be realised by incorporating layers above or below the solar cell

No modification of semiconductor needed

Down-convertor

Up-convertor
MATERIALS FOR UPCONVERSION

Rare-earth doped nanocrystals in oxyfluoride glass ceramics

Sol-gel preparation of oxyfluoride glasses

89.5(\text{SiO}_2):10(\text{PbF}_2):0.5(\text{RE})

– RE = Yb$^{3+}$, Er$^{3+}$, Ho$^{3+}$ and Tm$^{3+}$
– blue emission band of Tm$^{3+}$
– green emission bands of Er$^{3+}$ or Ho$^{3+}$
– red emission bands of Er$^{3+}$ or Tm$^{3+}$

J. Del Castillo et al.,

Courtesy of V. K. Tikhomirov and V. V. Moshchalkov, KUL

Challenge: coupling in the light
MATERIALS FOR DOWNCONVERSION

Zn$_2$SiO$_4$:1%Tb$^{3+}$, x%Yb$^{3+}$ x=0, 1, 5, 10, and 15 thin films

Upon excitation of Tb$^{3+}$ with a photons of 350–485 nm,

- two NIR photons could be emitted by Yb$^{3+}$
- with an internal QE as high as 154.1%.

![Graphs showing the dependence of green- and NIR-emission intensity on Yb$^{3+}$ doping concentrations in Zn$_2$SiO$_4$:Tb$^{3+}$, Yb$^{3+}$ thin films and transfer efficiency and decay lifetime as a function of the Yb$^{3+}$ concentrations in Zn$_2$SiO$_4$:Tb$^{3+}$, Yb$^{3+}$ thin films.](image)

X. Y. Huang et al., JAP, 105, 053521, 2009

**Challenge:** coupling in the light
SUMMARY

Building up sustainable energy supply is major challenge

Requires major material, device innovations **and** changes in electrical grid architecture due to intermittent character of renewables

In many of these domains and certainly photovoltaics, nanotechnology is expected to enable more efficient solutions

!Thank you for your attention!