How can Physicists Contribute to the Energy Transformation?

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DPG Symposium 'Physics for the Energy Turn'

Berlin, March 17, 2014

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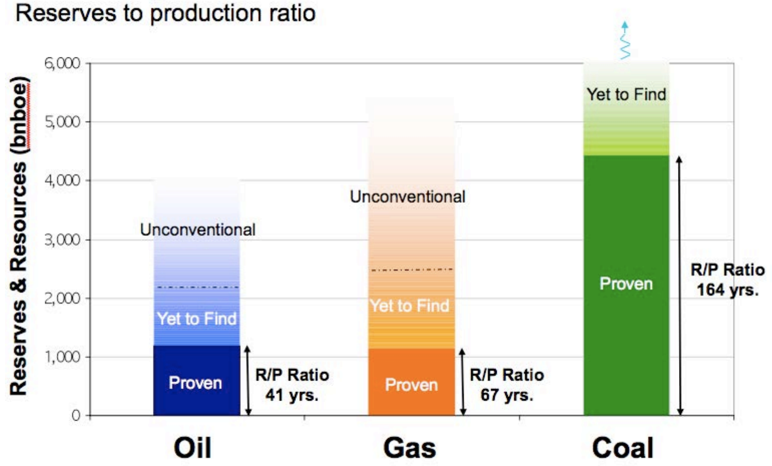
A radical transformation of our energy system is needed –
Jeremy Rifkin: We are starting the 3rd Industrial Revolution!

- The world has to transform to living in a sustainable way!
- Limited availability of fossil fuels
- Danger of catastrophic climate change
- Risk of nuclear disasters
- Growing dependency on imports from politically unstable regions
- **Economic advantages get noticable**

Important aspects to take into account:

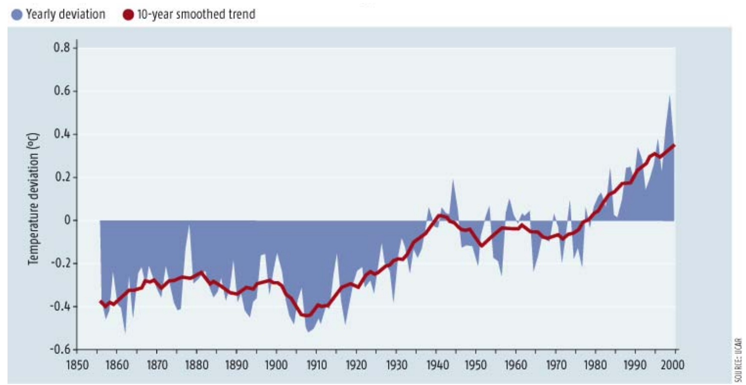
- The transformation needs time and money
  - Technological development
  - Capacity building
  - Investments in infrastructure
- Industrialized countries and countries with high consumption per capita must lead!

Availability of fossil resources
Reserves to production ratio



Source: World Energy Assessment 2001, HIS, WoodMackenzie, BP Stat Review 2005, BP estimates, Graph: Koonin, BP

The world is getting warmer

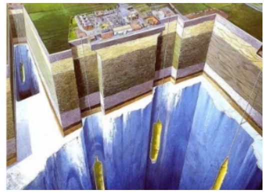


Cornerstones for the transformation of our energy system towards efficient use of ultimately 100% RE (ET)

- **Energy efficiency:**
  Buildings, Production, Transport

- **Massive increase renewable energies**
  Photovoltaics, Solar and geo thermal, wind, hydro, biomass.....

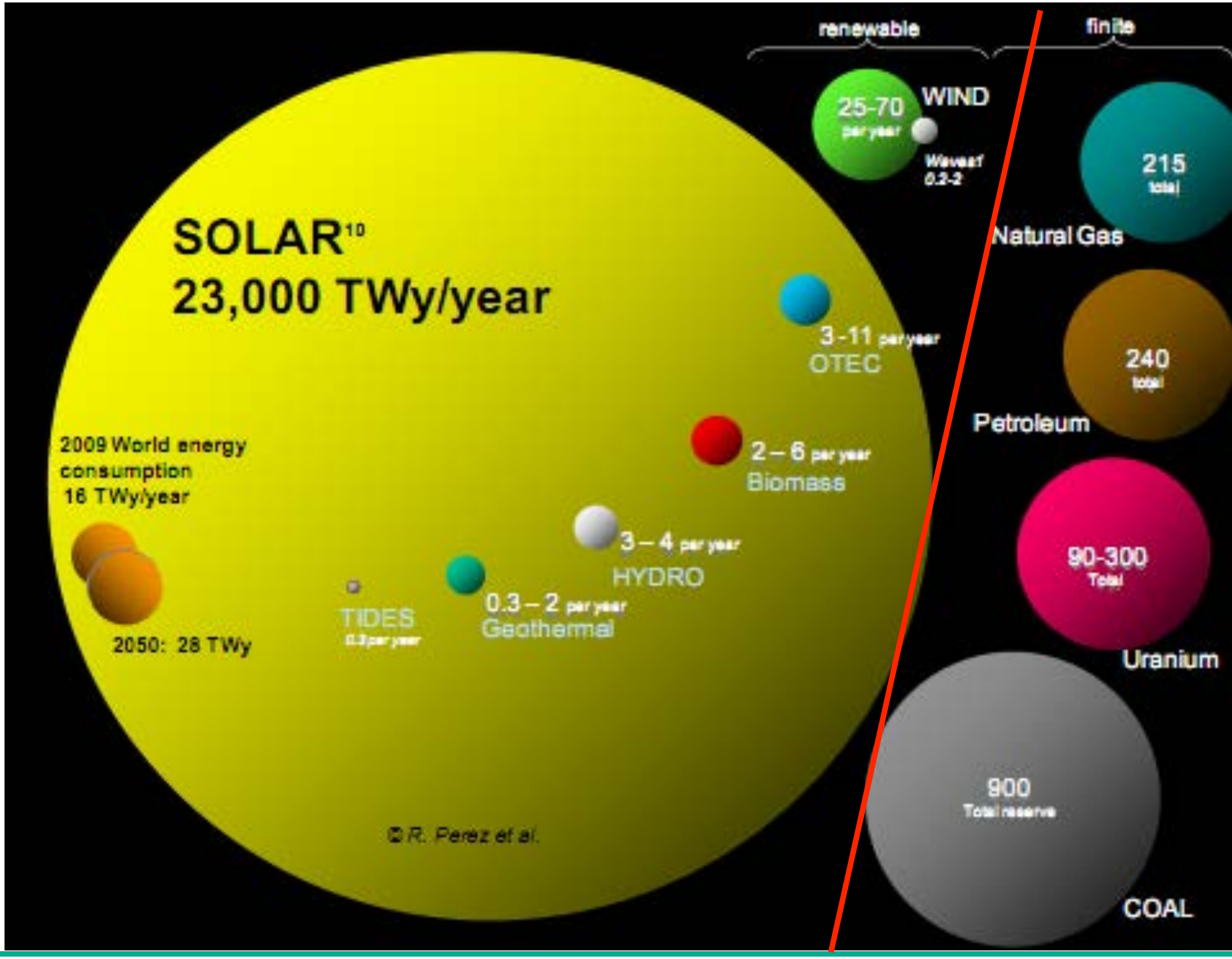
- **Fast development of the electric grid**
  Transmission and distribution grid, bidirectional



- **Small and large scale energy storage systems**
  Electricity, Hydrogen, Methane, Biogas, Solar Heat

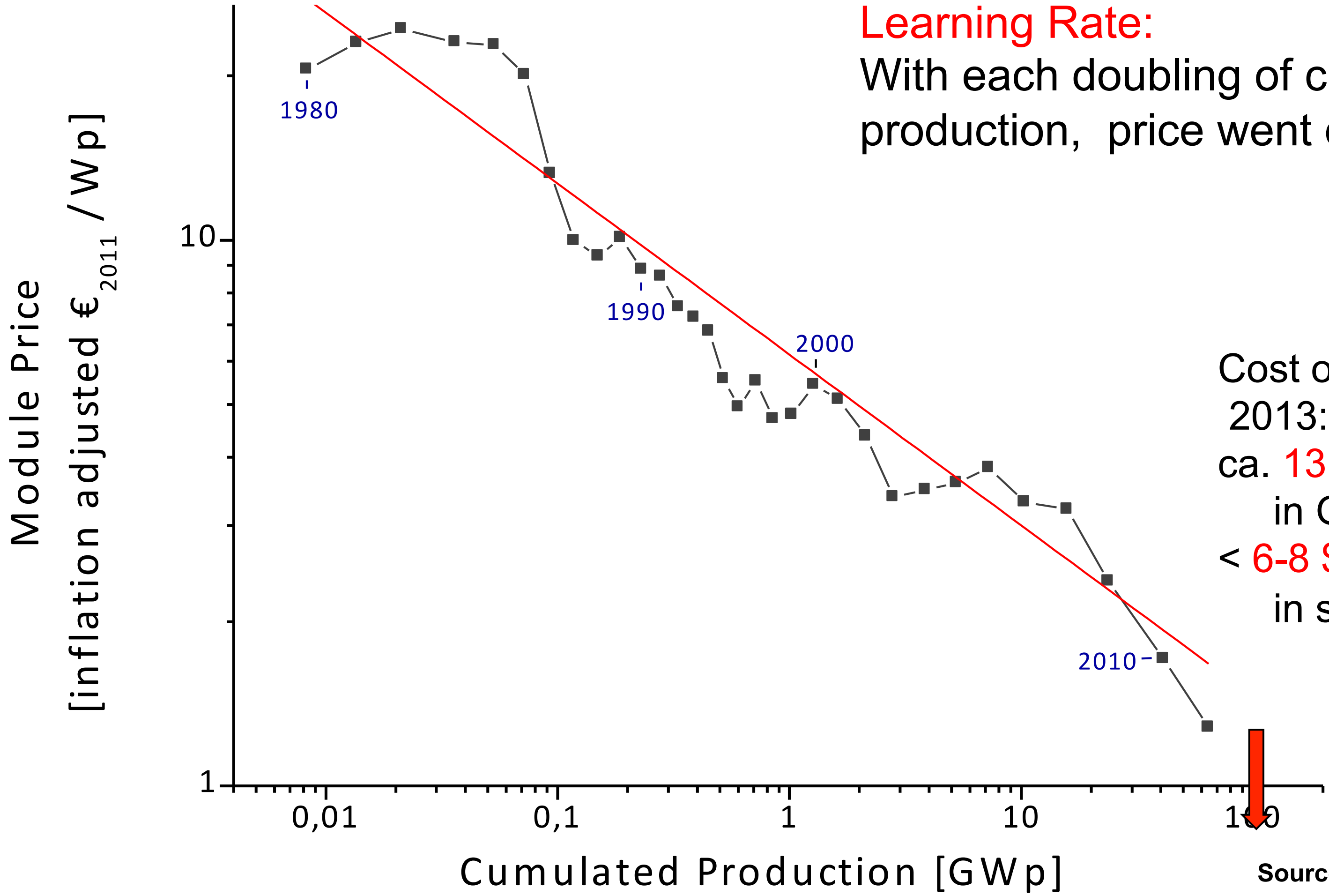
- **Mobility as integral part of the energy system**
  Electric mobility by means of batteries and hydrogen/fuel cells

World Energy Resources *(1Twy = 8760 TWhr)*



Harvesting solar energy will be a key pillar of ET!

Price Learning Curve (all c-Si PV Technologies)



Learning Rate:
With each doubling of cumulative production, price went down by 20%!

Cost of PV electricity 2013:
ca. 13 €ct/kWh in Germany
< 6-8 $ct/kWh in sun-rich countries

Source: Navigant Consulting; EuPD Module price (since 2006)
Design: PSE AG 2012

2013: Ready-installed rooftop system in Germany: **down to € 1.20 /Watt!**

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Crystalline Silicon PV Technology Portfolio

Material quality

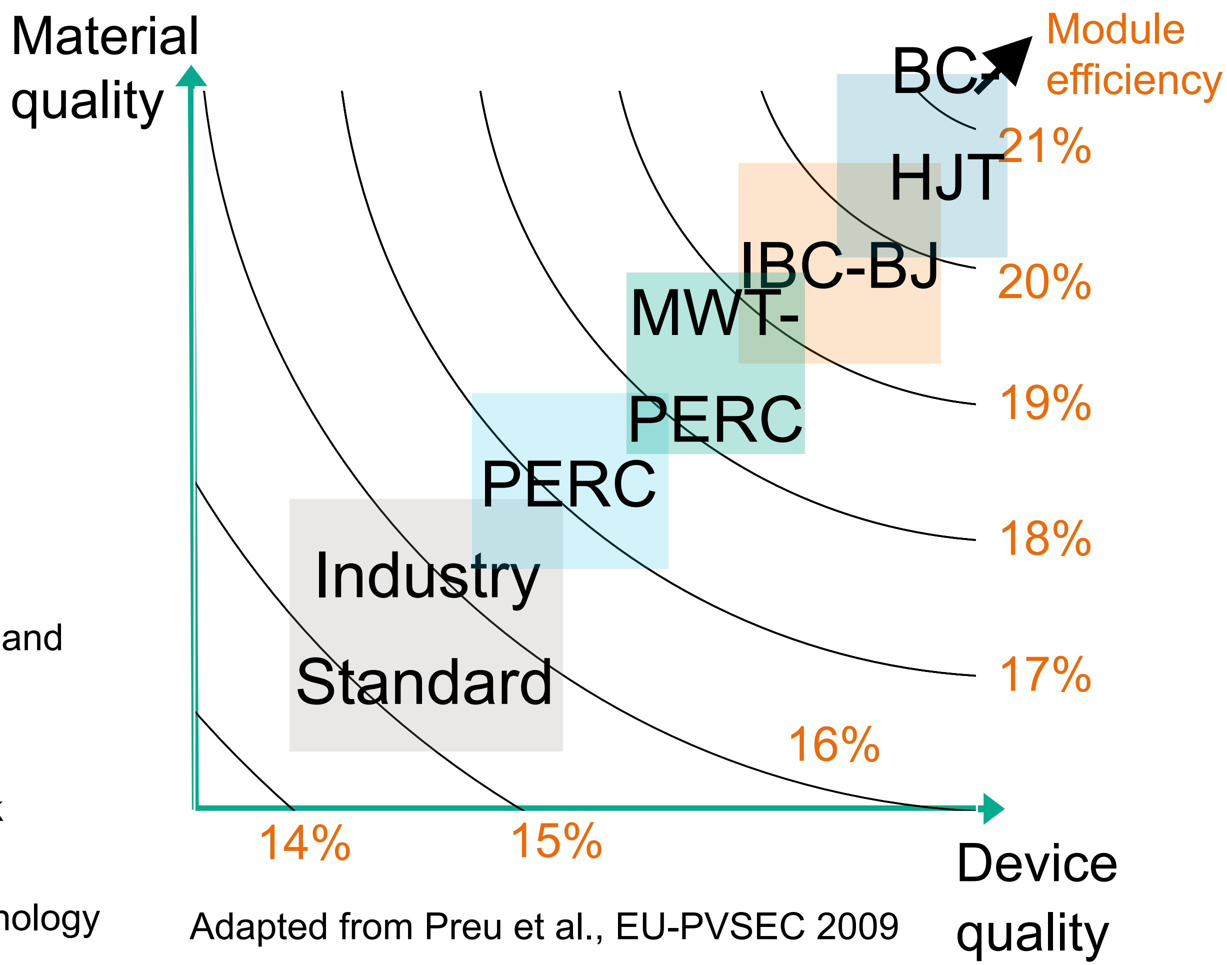
- Impurity content
- Diffusion length
- Base conductivity

Device quality

- Passivation of surfaces
- Low series resistance
- Light confinement

Cell Structures

- PERC: Passivated Emitter and Rear Cell
- MWT: Metal Wrap Through
- IBC-BJ: Interdigitated Back Contact – Back Junction
- HJT: Hetero Junction Technology

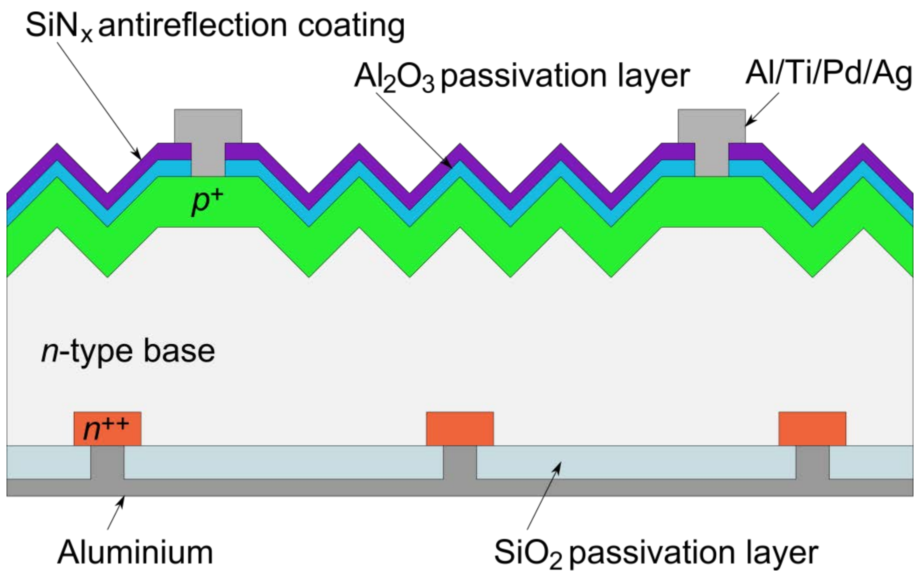


Adapted from Preu et al., EU-PVSEC 2009

High-efficiency n-type PERL Cells
Lab Results

- Excellent performance at cell level
- Only very thin ALD layer necessary

	V_{oc} [mV]	J_{sc} [mA/cm^2]	FF [%]	η [%]
Best cell	**705**	**41.1**	**82.5**	**23.9***



*Confirmed at Fraunhofer ISE CalLab

ap = aperture area
(= bus bar included in illuminated area)

Benick et al., APL 92 (2008)
Glunz et al., IEEE-PVSC (2010)

Topics for Physicists in c-Si PV: examples

- Si material:
  - mechanical properties of thin cells, fracture
  - understanding and controlling crystal defects, such as (B,O), PID, umg-Si…..
  - understanding transport properties: carrier diffusion length, lifetime
- PV device quality
  - surface and interface carrier recombination, passivation
  - metal contact improvements
  - light trapping, confinement
- PV module quality
  - interconnection issues
  - Encapsulation
- To exceed the 29% efficiency limit of c-Si PV
  - Photon management: upconversion, downconversion…….

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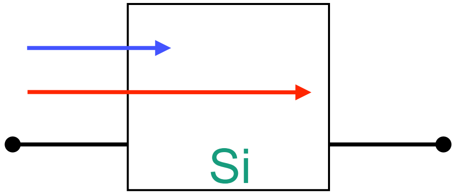
The efficiency limit for a single-material PV Cell

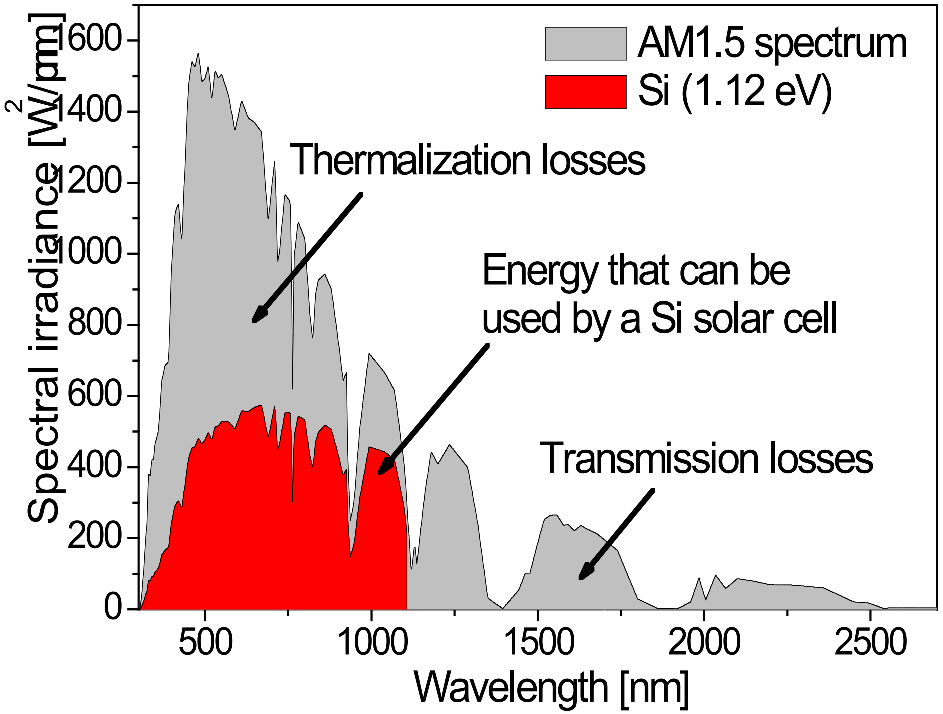
For Silicon:

(AM1.5g, 1000 W/m², 25°C)

$\eta_{max,\ theo}$ = 28 %

Lab cell = 24 %





The benefit of multi-junction solar cells

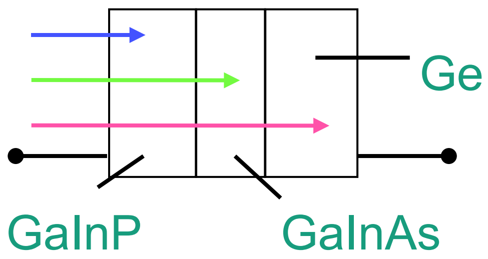
For triple-junction concentrator cells:

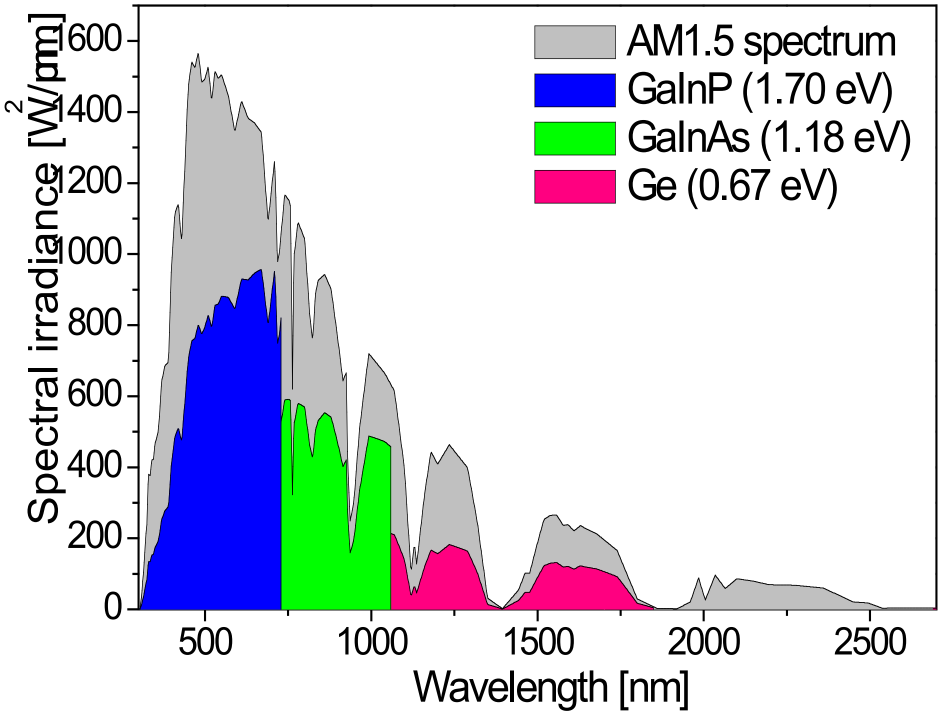
$\eta_{max,\ theo}$ = 61 %

(1000xAM1.5d, 1000 W/m²)

Lab. cell = 40.8 %

230xAM1.5d, 1000 W/m²)

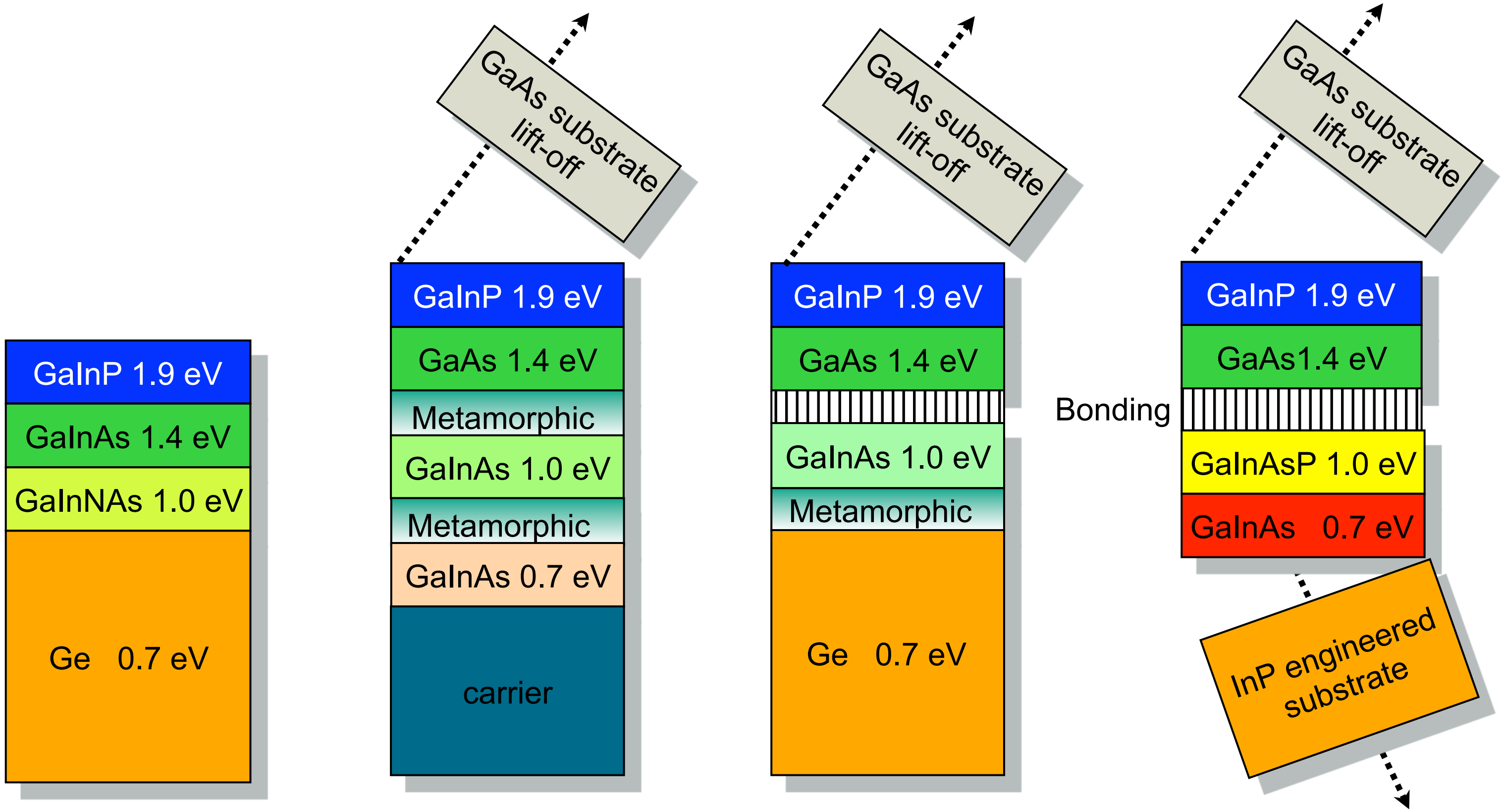




Highest Efficiency 4J Cells

15 % More CPV Energy Harvest

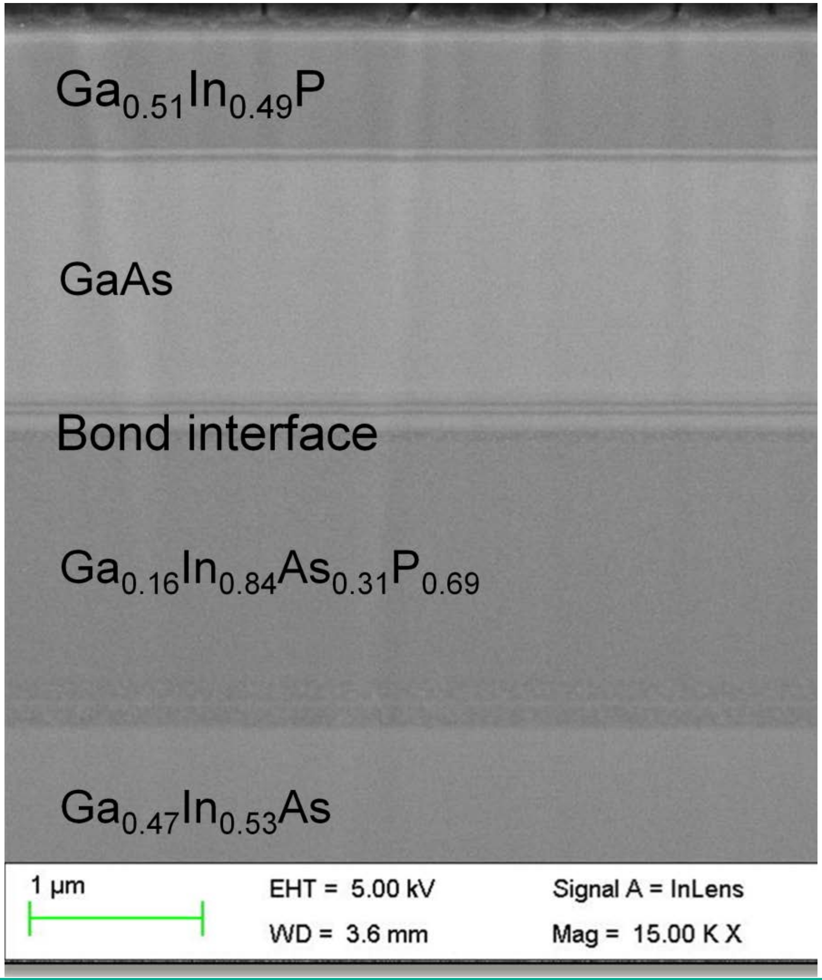
Lattice matched 4-junction on Ge | **Inverted metamorphic** | **4-junction bonded to Ge** | **4-junction bonded to InP**



Wafer bonding

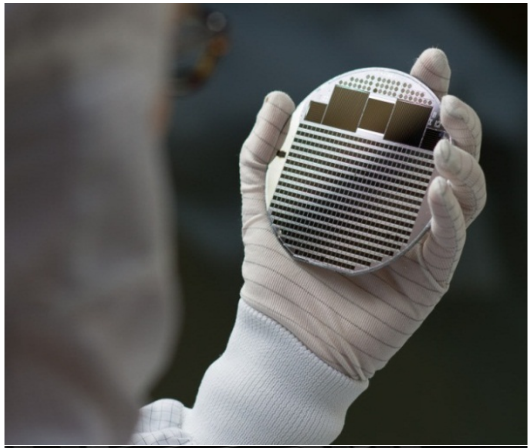
HZB Helmholtz Zentrum Berlin | cea tech | Soitec | Fraunhofer ISE

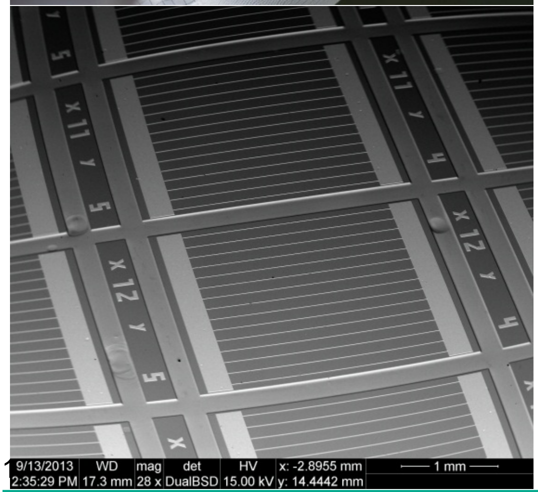
Wafer-Bonded 4-Junction Solar Cell

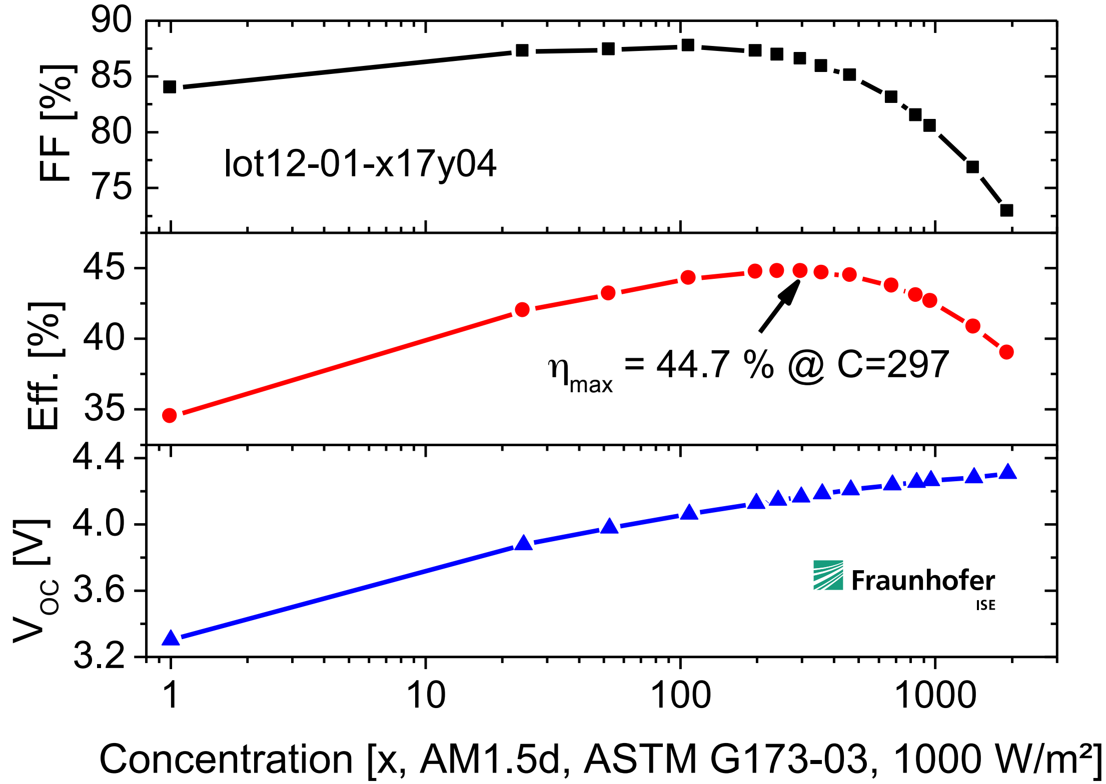


World Record 44.7 % Efficiency Solar Cell Wafer-Bonded, 4-Junction Technology

Fh-ISE with SOITEC, Cea-Leti, HZB







Soitec HZB Helmholtz Zentrum Berlin cea Leti Fraunhofer ISE

Nanowire Array Solar Cells

- may bring to the market single-Xtal III-V solar cells to the cost of Thin Films

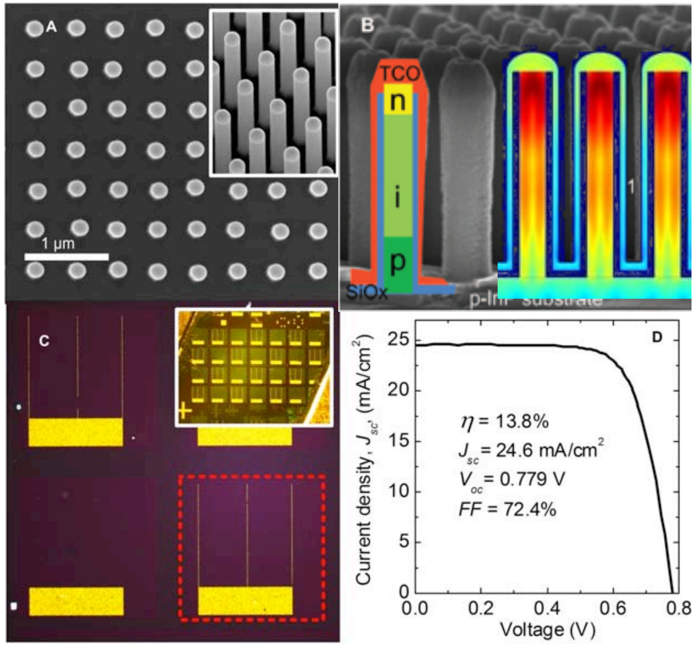
BUT - how will this be achieved?

- Nanowire arrays from EPITAXY
- Nanowire arrays from AEROTAXY

InP Nanowire Array Solar Cells Achieving 13.8% Efficiency by Exceeding the Ray Optics Limit

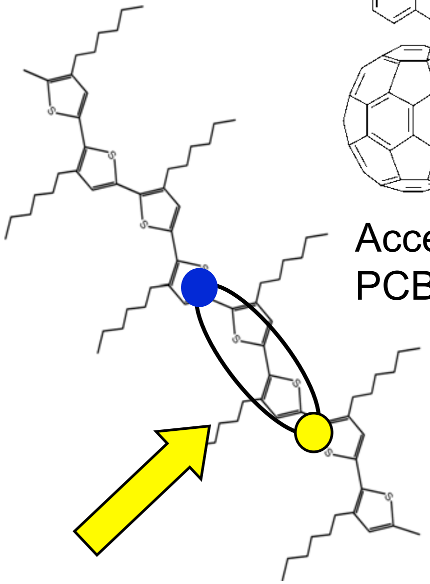
Jesper Wallentin,[1] Nicklas Anttu,[1] Damir Asoli,[2] Maria Huffman,[2] Ingvar Åberg,[2] Martin H. Magnusson,[2] Gerald Siefer,[3] Peter Fuss-Kailuweit,[3] Frank Dimroth,[3] Bernd Witzigmann,[4] H. Q. Xu,[1,5] Lars Samuelson,[1] Knut Deppert,[1] Magnus T. Borgström[1]*

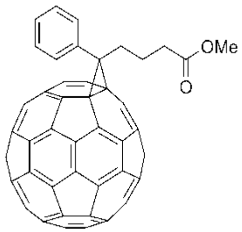
Photovoltaics based on nanowire arrays could reduce cost and materials consumption compared with planar devices but have exhibited low efficiency of light absorption and carrier collection. We fabricated a variety of millimeter-sized arrays of p-type/intrinsic/n-type (p-i-n) doped InP nanowires and found that the nanowire diameter and the length of the top n-segment were critical for cell performance. Efficiencies up to 13.8% (comparable to the record planar InP cell) were achieved by using resonant light trapping in 180-nanometer-diameter nanowires that only covered 12% of the surface. The share of sunlight converted into photocurrent (71%) was six times the limit in a simple ray optics description. Furthermore, the highest open-circuit voltage of 0.906 volt exceeds that of its planar counterpart, despite about 30 times higher surface-to-volume ratio of the nanowire cell.



www.sciencemag.org SCIENCE VOL 339 1 MARCH 2013 1057

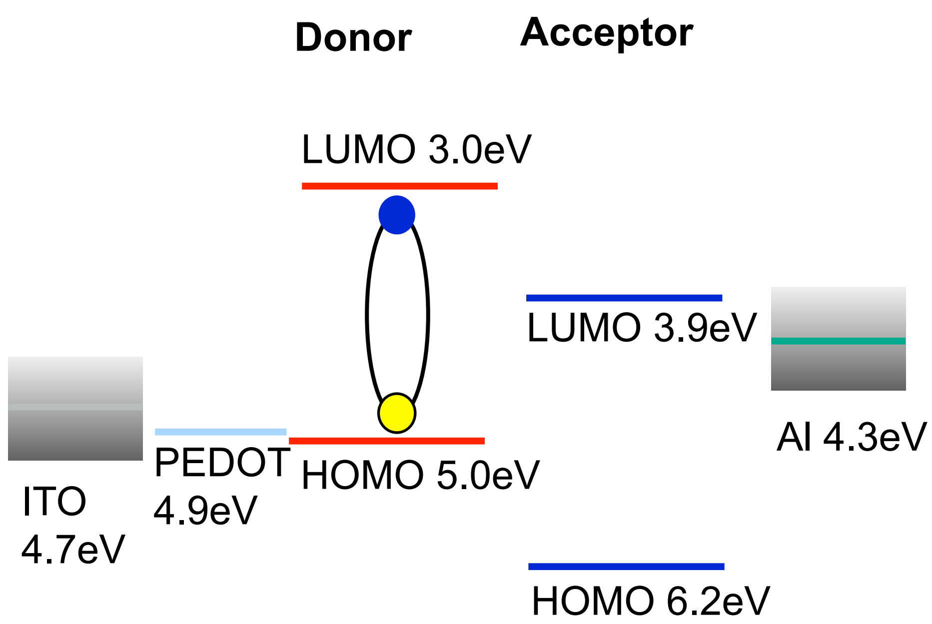
Organic Solar Cells – Creating Carriers from Sunlight





Acceptor:
PCBM

Donor:
Polymers: P3HT…
Small molecules: ZnPc…



P3HT: poly(3-hexylthiophene)
ZnPc: Zincphtalocyanine
PCBM: phenyl-C_{61}-butyric acid methyl ester

How to dissociate electron-hole pairs (excitons) more easily, not loosing 50%?
How to increase the poor carrier mobility in organic structures?

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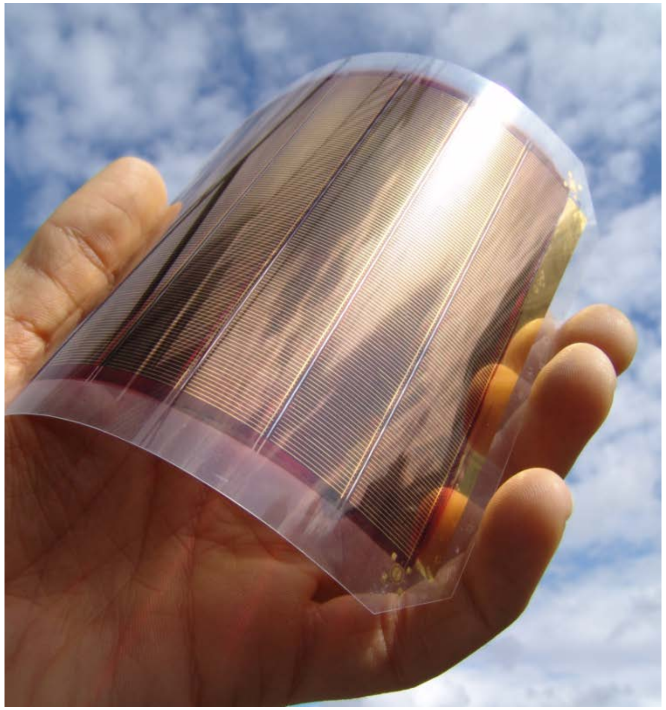
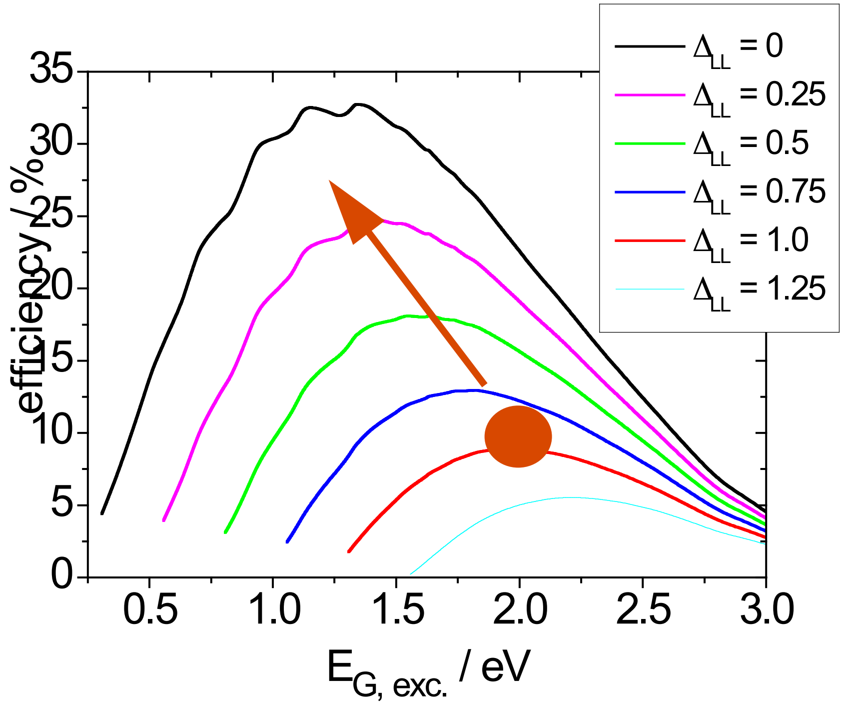
Organic Solar Cells

Our fundamental understanding of light interacting with complex molecules is still lacking; breakthroughs in this field are possible and can open doors to lowest-cost photovoltaic energy conversion





Broad optical absorption should allow high efficiencies

Other Areas of the Energy Transformation that need physicist's research

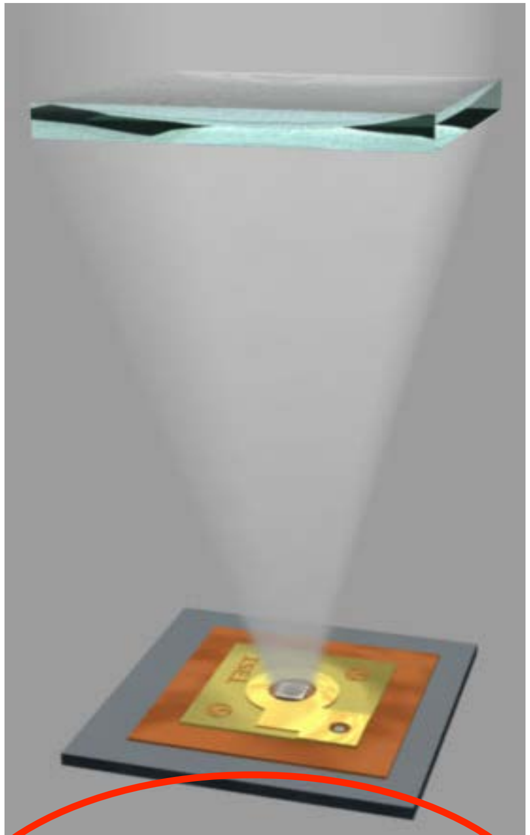
- **Energy efficiency**: new materials, new processes to reduce energy needs
  - Example: GaN-based light emitting diodes
- **Energy storage**: new types of batteries, new electrode materials, new catalysts….
  - Example: reducing Pt need in electrolysis by nanostructured electrodes
- **Energy conversion**: new device materials (SiC, GaN…)
  - Example: world record inverter efficiency (99.03%) with SiC-based devices
- **Mobility:** new & improved batteries, inductive charging, improved fuel cells

How can Physicists Contribute to the Energy Transformation?

- The basic materials and technologies needed for the energy transformation are available; we do not need to wait for specific breakthroughs!
- Our fundamental understanding in many processes relevant for the energy transformation is still lacking; improved understanding allows new approaches
  - Example: organic photovoltaics
- Nuclear fission: complex technology, can never be safely operated, should be phased out asap, will be phased out after the next major nuclear catastrophe.
- Nuclear fusion: exciting plasma research, materials for reactor wall do not exist, will be too expensive compared with PV in 2050
  - Topic for interesting fundamental research, not energy research!
- A good energy research portfolio should contain improvements of existing technologies, such as c-Si PV, and leave space for potential breakthrough research

Reserve slide

III/V Multijunction cells are used in Concentrated PV: CPV



2012: SOITEC SOLAR builds a 300 MW CPV installation, using a new 150 MW_p/yr factory near San Diego, CA!

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