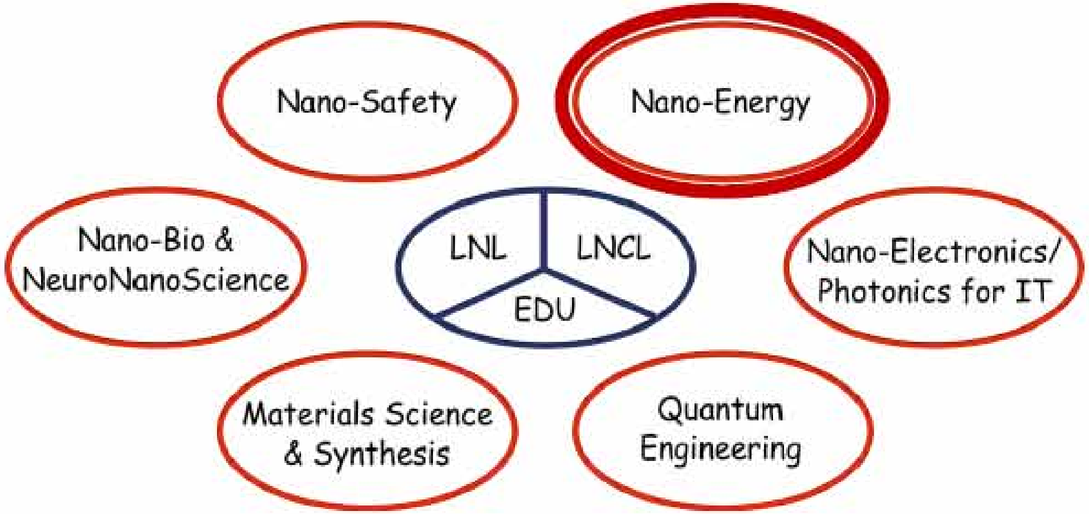
Semiconductor Nanowires for photovoltaics and electronics

M.T. Borgström,
magnus.borgstrom@ftf.lth.se

NW Doping
Total control over axial and radial NW growth
NW pn-junctions

The Nanometer Structure Consortium, nmC@LU

≈ 150 scientists in the technical, science, and medical faculties



- **Materials Science & Synthesis** (coordinator: Reine Wallenberg, Materials Chemistry)
- **Quantum Engineering** (coordinator: Stephanie Reimann, Mathematical Physics)
- **Nano-Electronics/Photonics for IT** (coordinator: Lars-Erik Wernersson, EIT/Physics)
- **Nano-Bio & NeuroNanoScience** (coordinator: Jens Schouenborg, Neurophysiology)
- **Nano-Energy** (coordinator: Villy Sundström, Chemical Physics)
- **Nano-Safety** (coordinator: Sara Linse, Biophysical Chemistry)

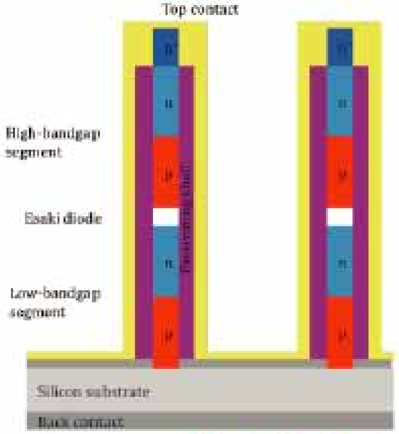
circle around the core facilities providing the resources which all these thrive on:

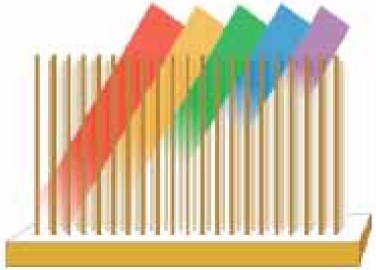
- **Lund Nano Lab** (coordinator: Lars Montelius, Solid State Physics)
- **Lund Nano Characterization Labs** (coordinator: Anders Mikkelsen, Synchr. Rad. Phys.)
- **Nano-Education** (coordinator: Knut Deppert, Solid State Physics)

Coordinator: Lars Samuelson; **Deputy:** Heiner Linke. **Administrative Director**: Anneli Löfgren

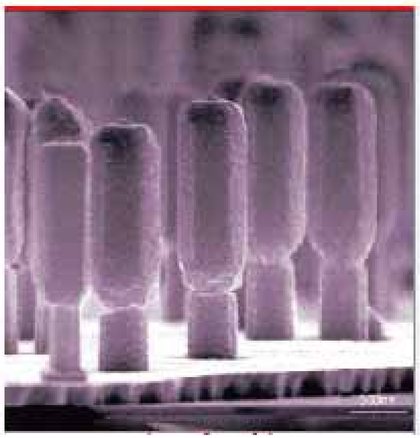
Nanoenergy within nmC@LU

Multi-junction solar cells on Si (K. Deppert)

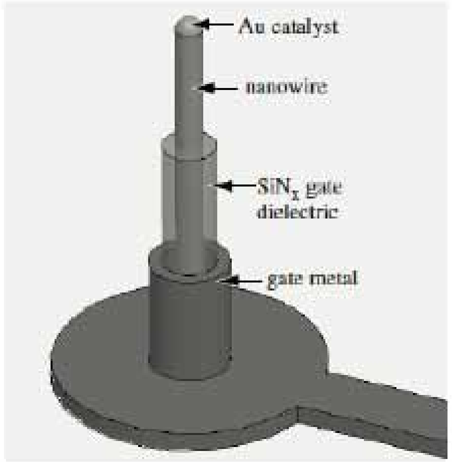




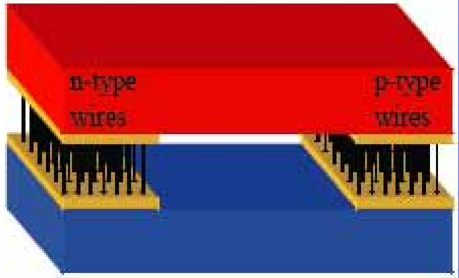
Low-energy lighting (L. Samuelson)

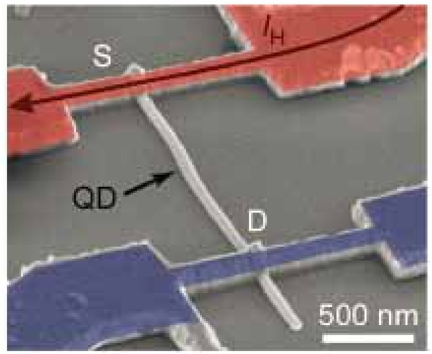


Low-energy electronics (C. Thelander)

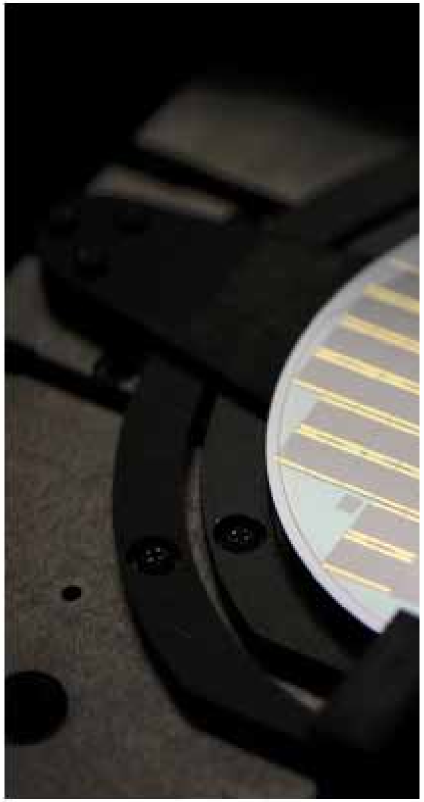


Thermoelectrics (H. Linke)





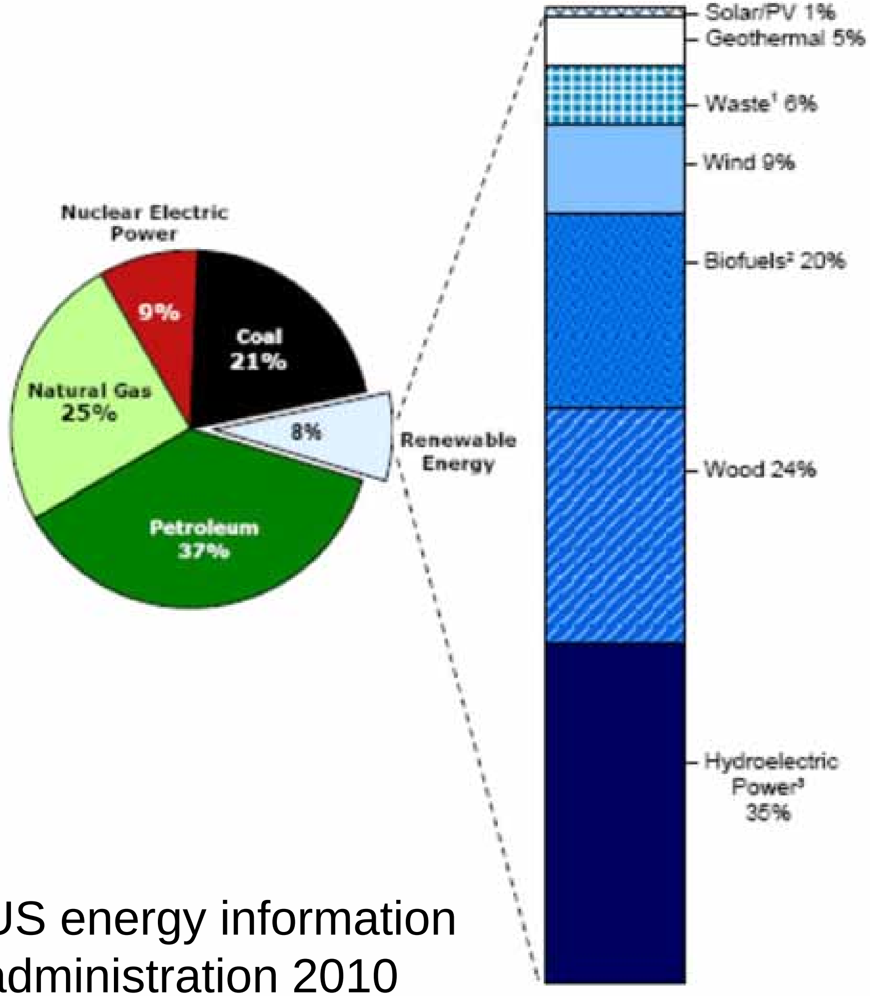
World record efficiency solar cell



A Solar Junction wafer of high-efficiency sol
(Credit: Solar Junction)

Solar Junction, a Silicon Valley solar sta
of 43.5 percent, topping previous record

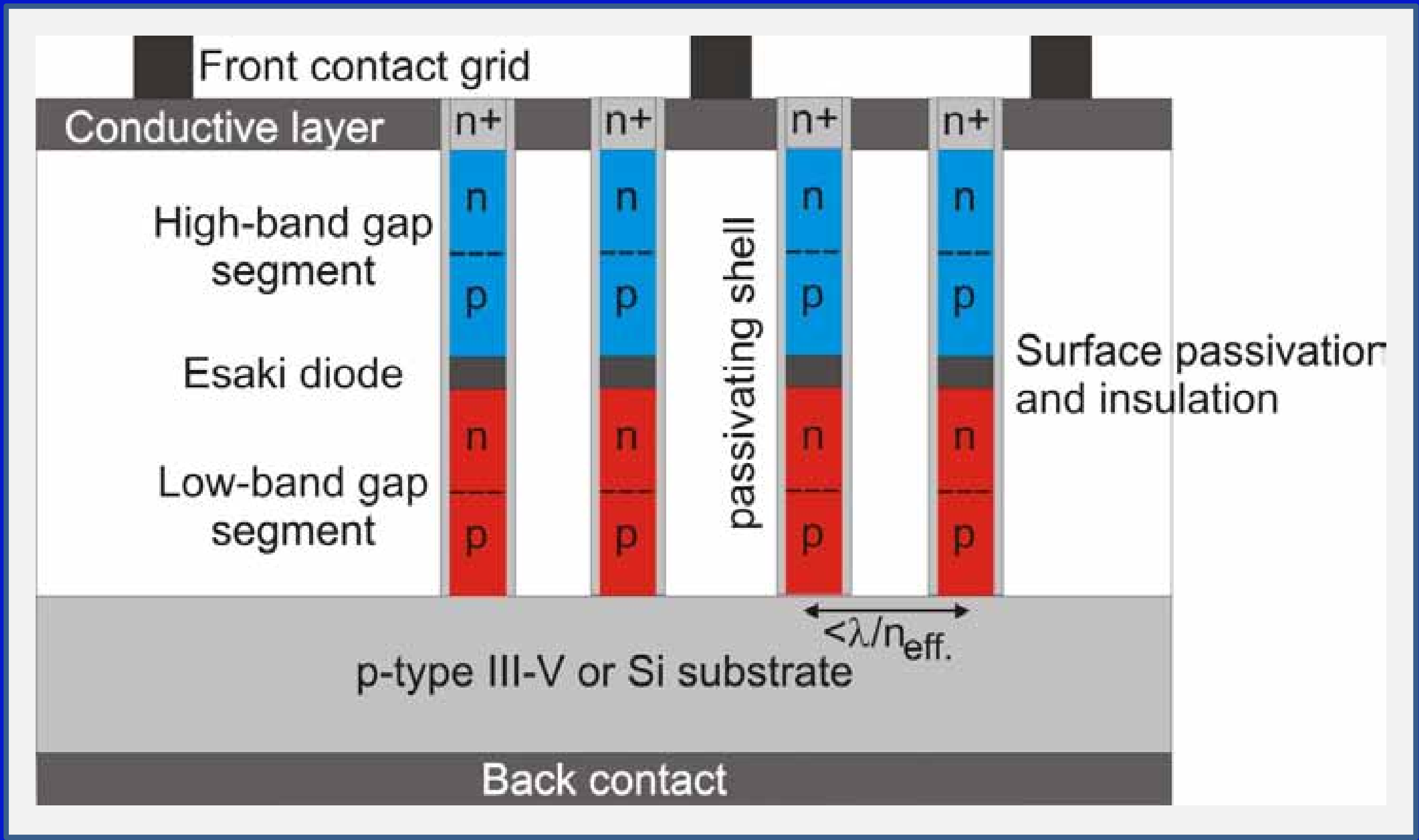
The San Jose, Calif.-based company sa
Laboratory's Measurement and Characti



US energy information administration 2010

- Solar Junction: III-V multi junction solar cell

AMON-RA (FP7 214814)

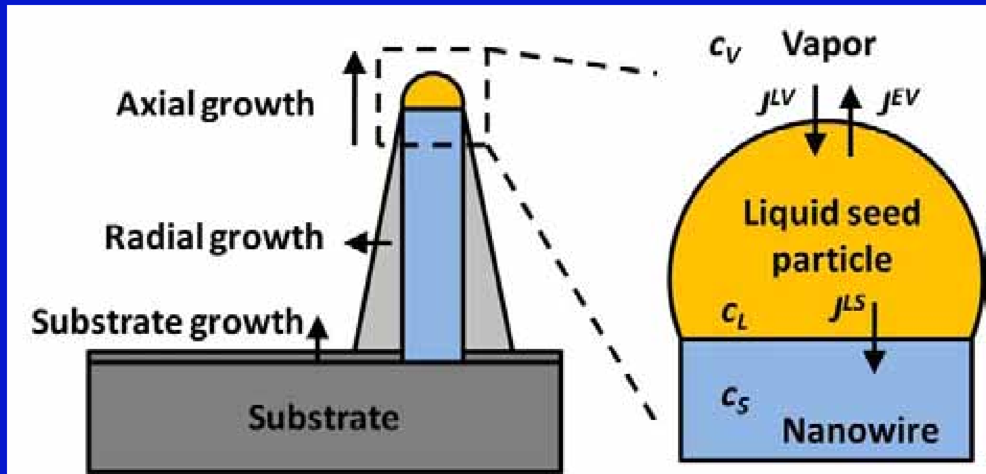


Lund University
Fraunhofer Institute for Solar Energy Systems
University of Kassel
Sol Voltaics AB
Johannes Kepler University Linz
Technical University of Denmark

Impurity doping in nanowires

Particle assisted growth:

- Low temperature (400-500°C)   MOVPE 600-700°C
- Complex growth dynamics
- [111] growth direction
- crystal structure
- Solubility
- Segregation coefficient



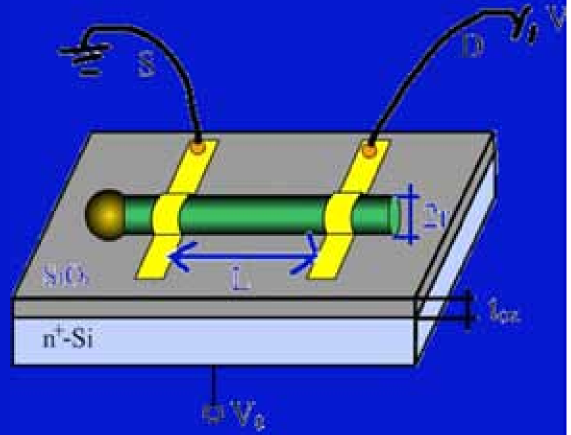
Characterisation:

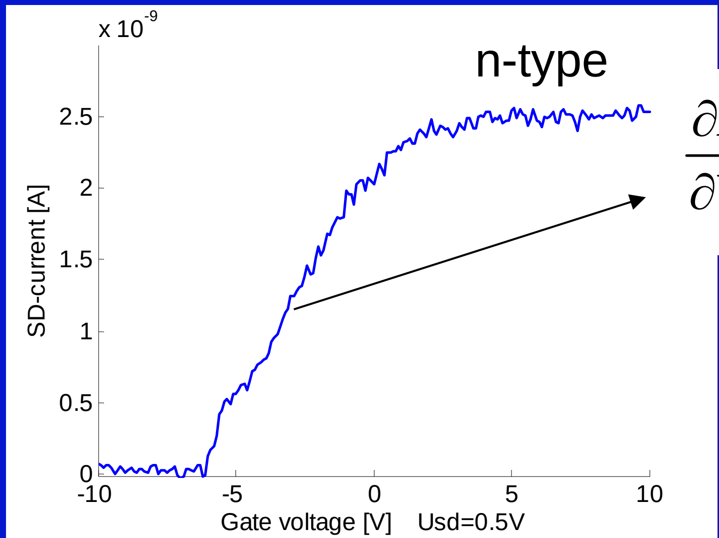
- Chemically (EDX)
- Electrically (Field effect)
- Optically (PL)
- Atom probe

Wallentin, Borgström JMR 2011

Evaluate doping - nw-FET

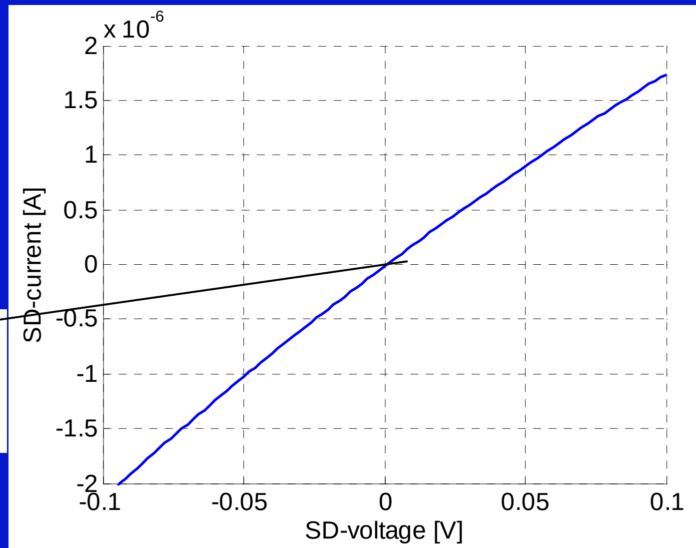
- Drude model, $\sigma = nq\mu$
- Carrier concentration, n = doping concentration
- Mobility (μ) extracted from gate-sweeps
- Conductivity (σ) extracted from I-V





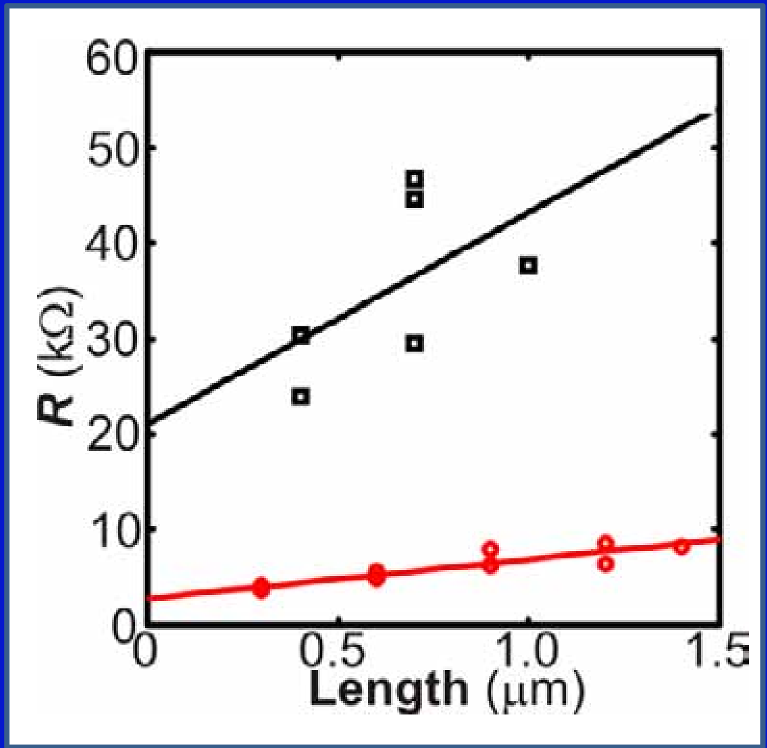
$$\left.\frac{\partial I_D}{\partial V_g}\right|_{V_D=const} = \frac{C_{ox}\mu}{L^2} V_D$$

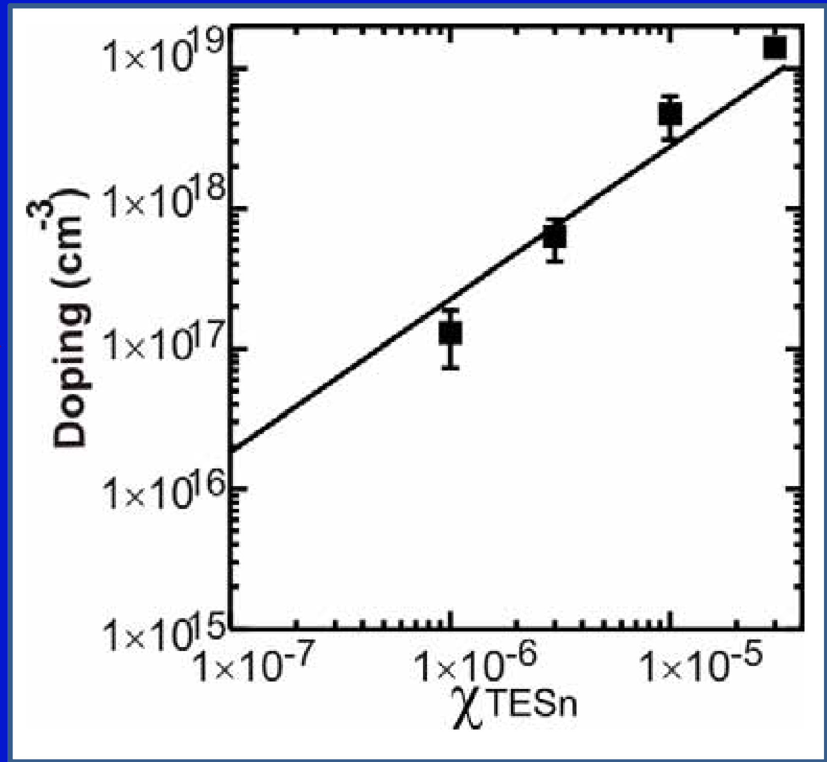
$$V_D = RI_D = \frac{L}{\sigma A} I_D$$



TESn for n-doping

(Sn:InP ionization energy 5.9 meV)



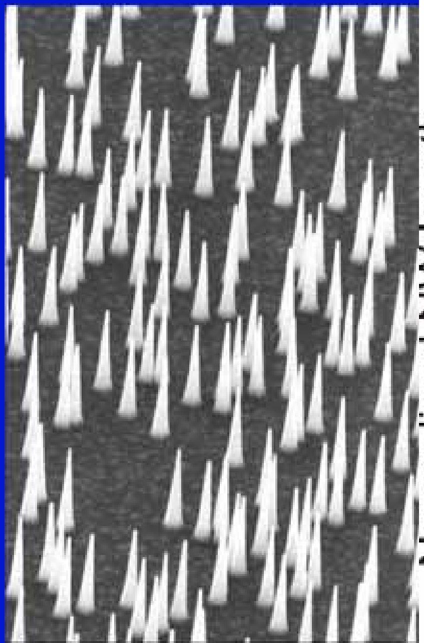


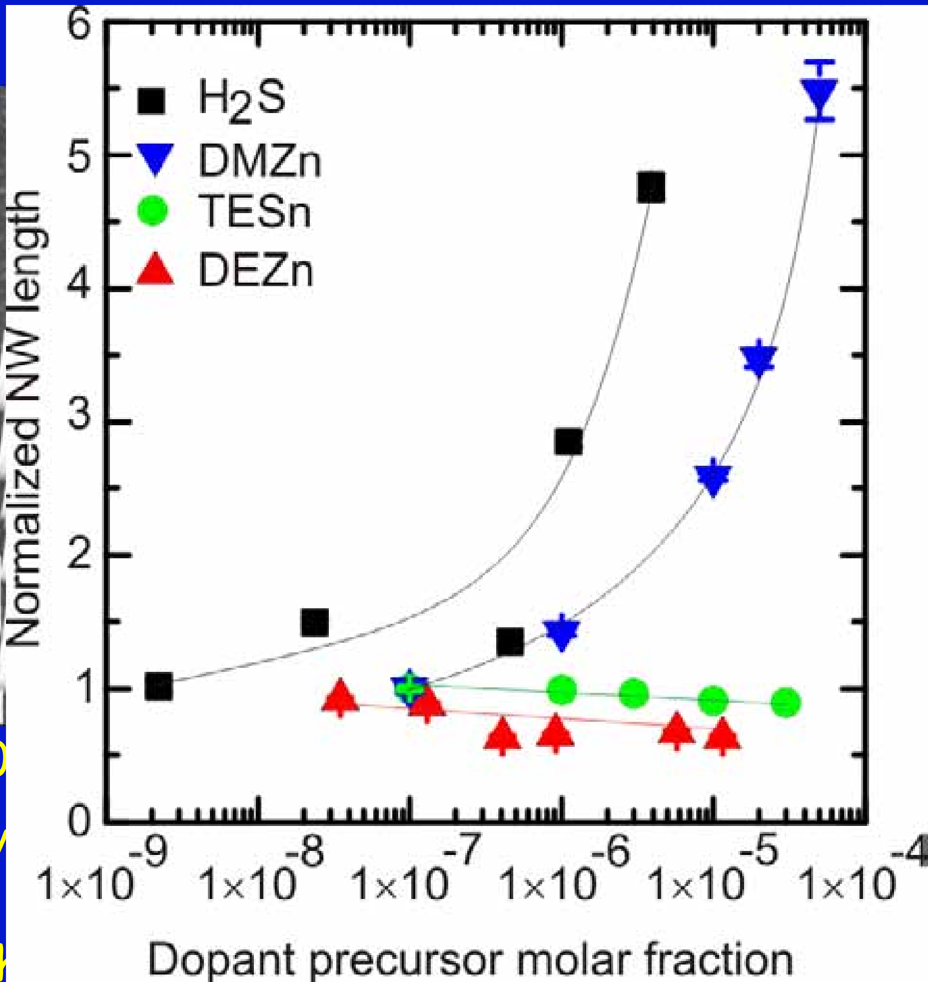
- Gate voltage dependent action - n-type
- transconductance + IV (ohmic contacts)
- threshol $qnV = Q = C_{ox} V_{th}$ contacts)

Borgström et al, Nanotechnology, 2008

Dimethylzinc for p-doping

(Zn:InP ionization energy 35 meV)



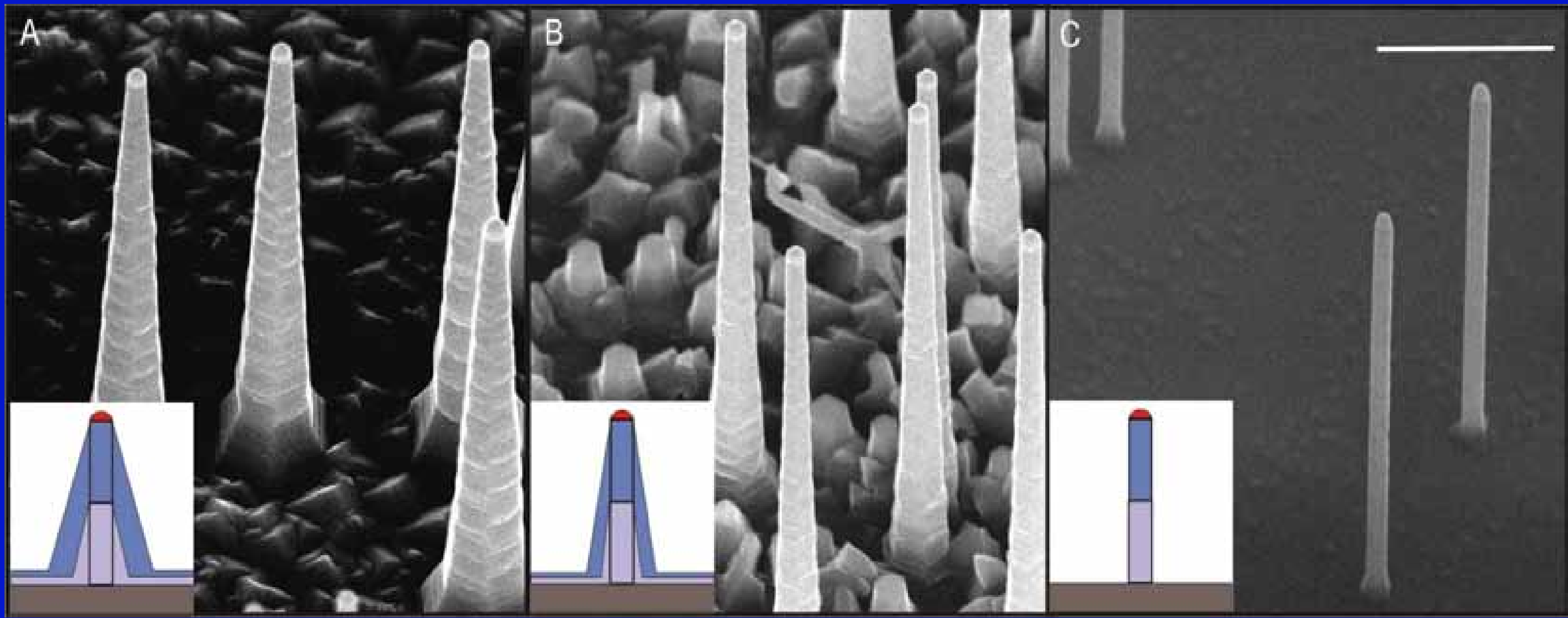


X_{DMZn}=1e-6, 20 … $_{DMZn}$=5e-5, 20min

- Gate v…
- DMZn … uppresses side wall growth…
- Nucleation problems for high dopant precursor molar fraction

Borgström et al, IEEE J Sel Top Quant 2011

Decoupled axial and radial growth

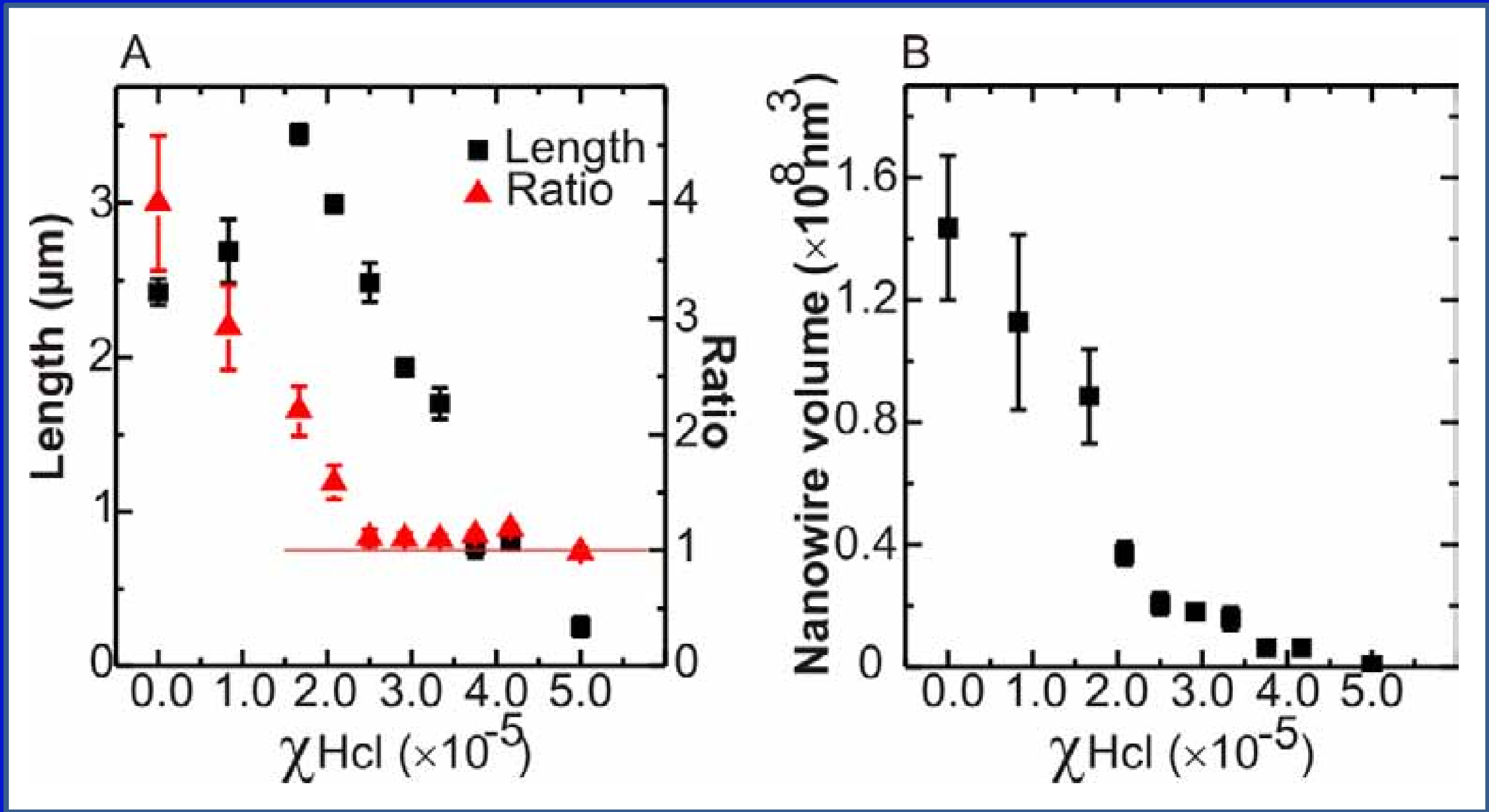


Increasing in-situ HCl molar fraction

- 80 nm aerosol particles
- TMI, PH3, HCl
- Growth temperature 450°C

Borgström et al, Nano Research, 2010

In-situ InP NW etching by HCl

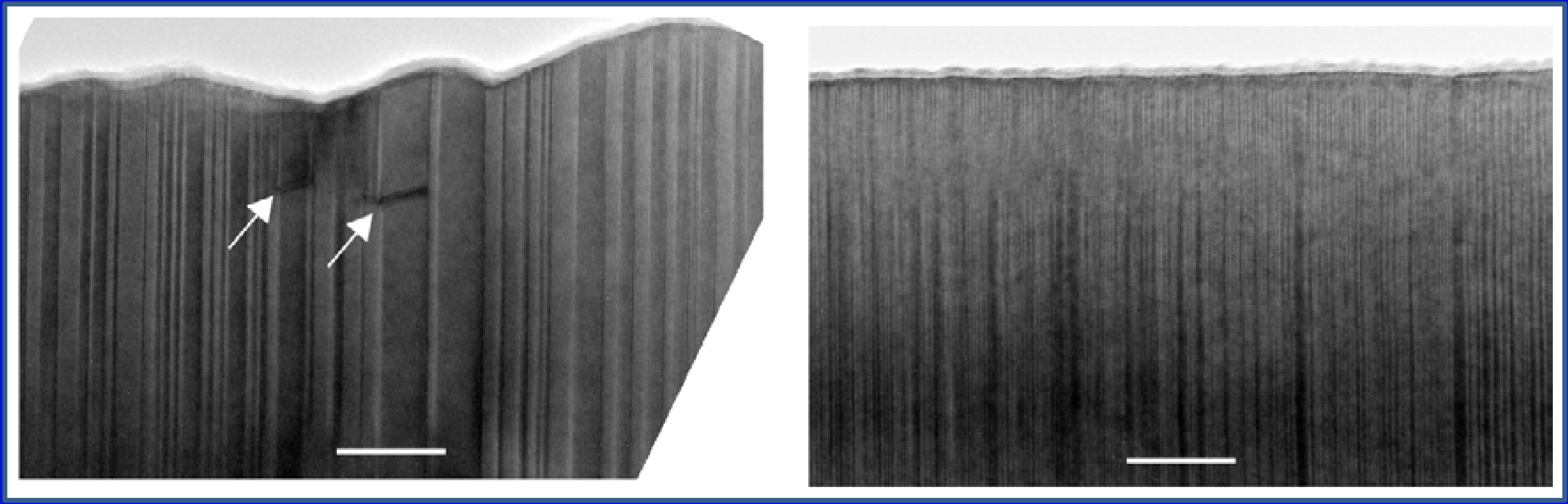


- Radial growth can be fully impeded

Borgström et al, Nano Research, 2010

TEM characterisation

Without HCl | With HCl



Structural defects in radial growth

Rough sidewalls due to faceting

Zinc blende:91%

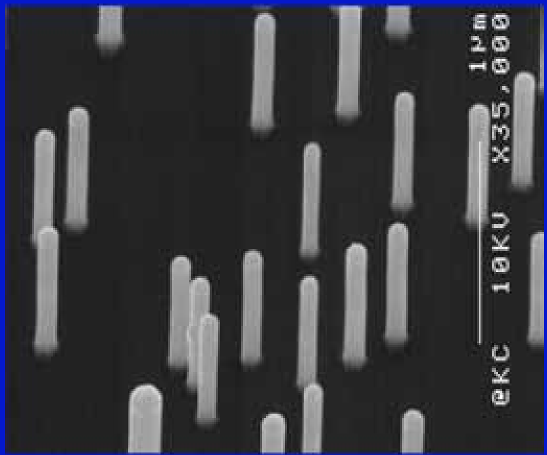
No defects from shell growth

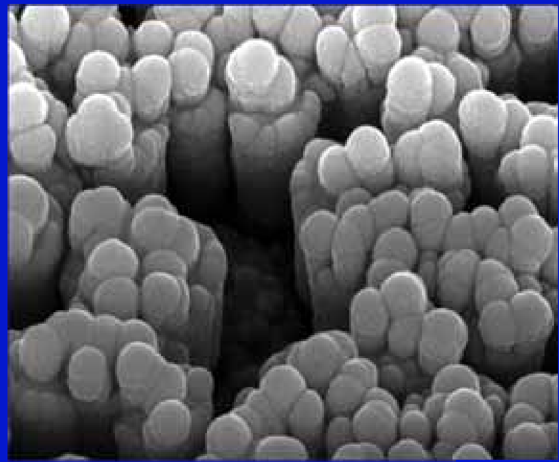
Straight sidewalls

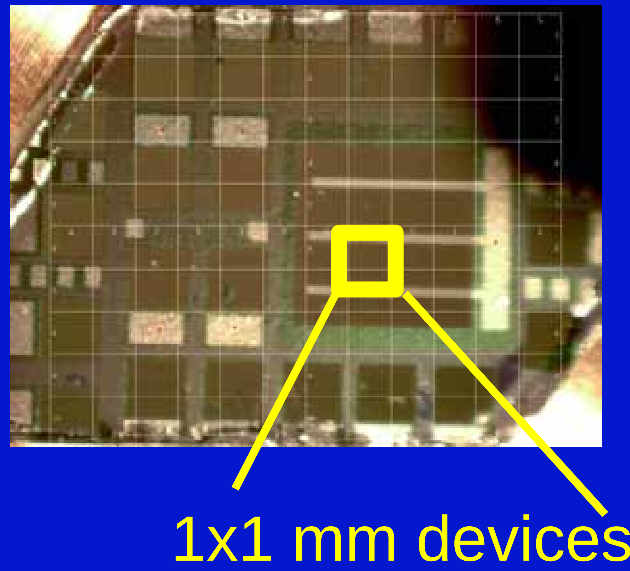
Zinc blende 32%, wurtzite 55%

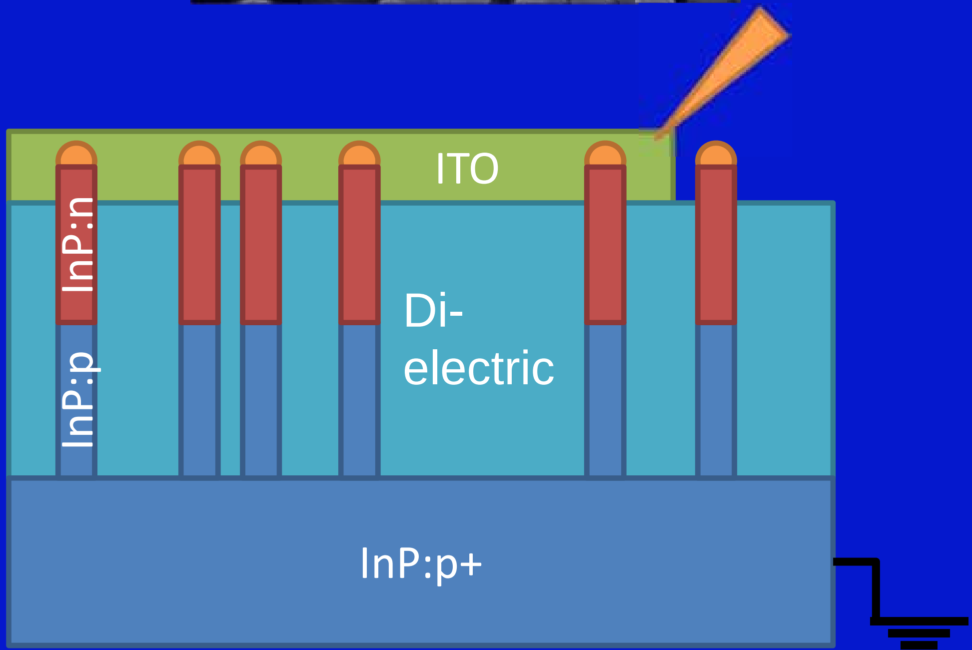
Borgström et al, Chem Pys Lett, 2011
Wallentin et al, J Cryst Growth (InAsP)
Jacobsson et al, submitted to Nanotech (GaInP)

NW solar cell fabrication





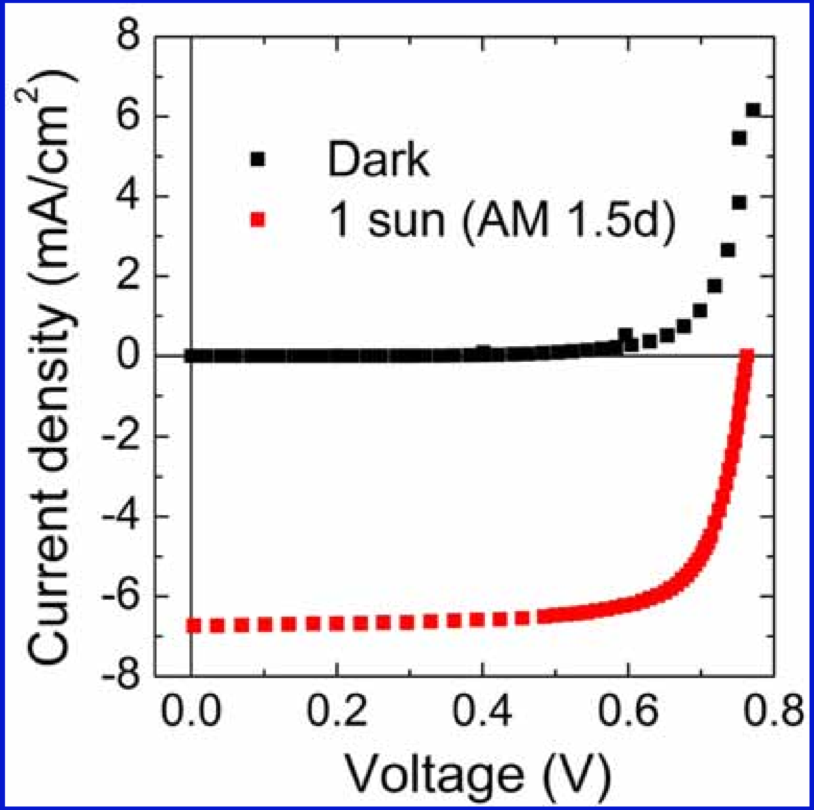




Borgström et al, IEEE J Sel Top Quant 2011

Photocurrent measurements

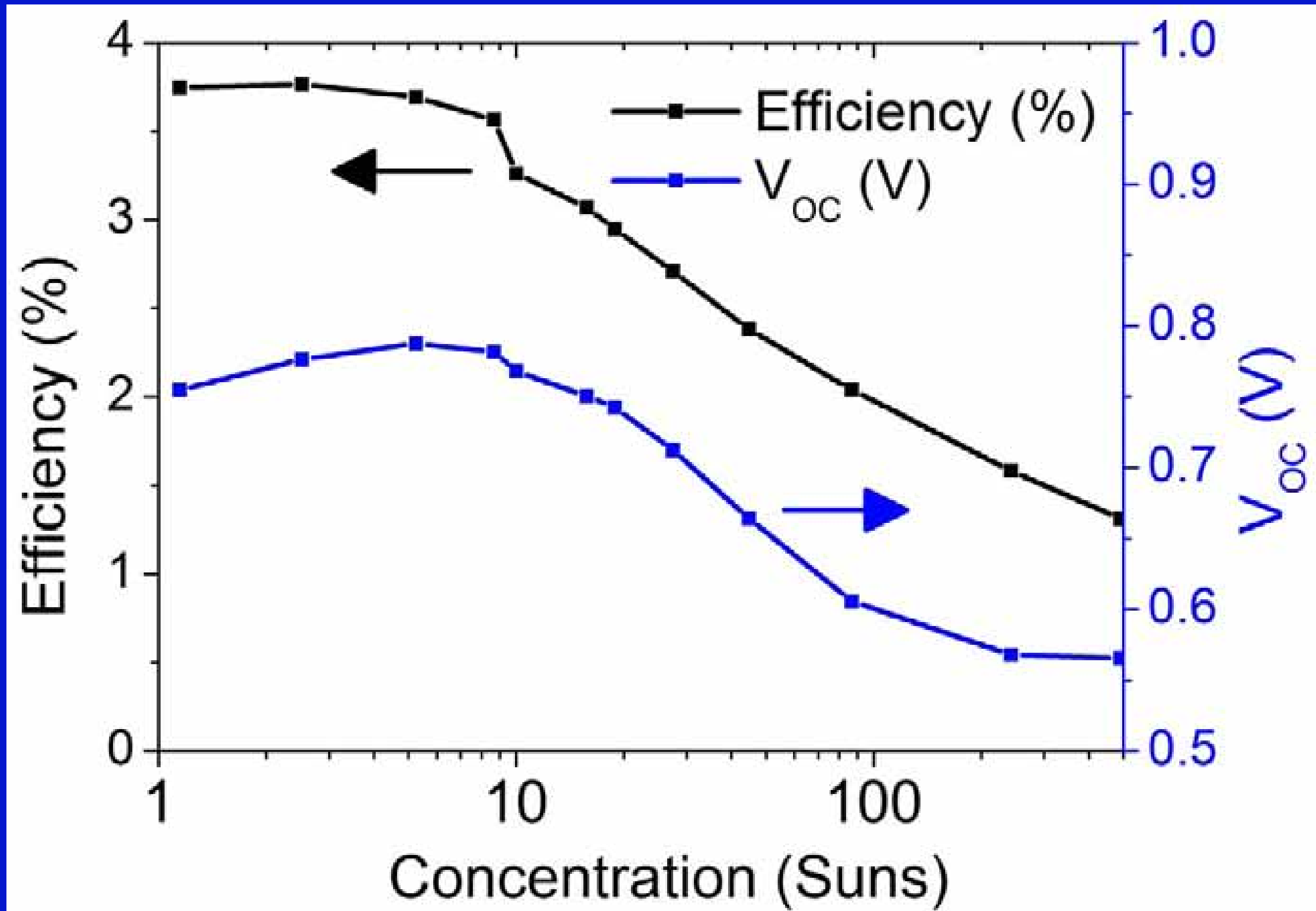
- Efficiency 3.8% (1 sun, AM 1.5)
- Fill factor 74%
- V_{oc} = 0.75 V



- Excellent light capture despite low density (are fill factor 3%)
- 5 times more efficient per surface area than thin film InP cell
- Current density through NW about 3 times higher than in record multi junction solar cells.

In collaboration with Sol Voltaics AB and Fraunhofer ISE

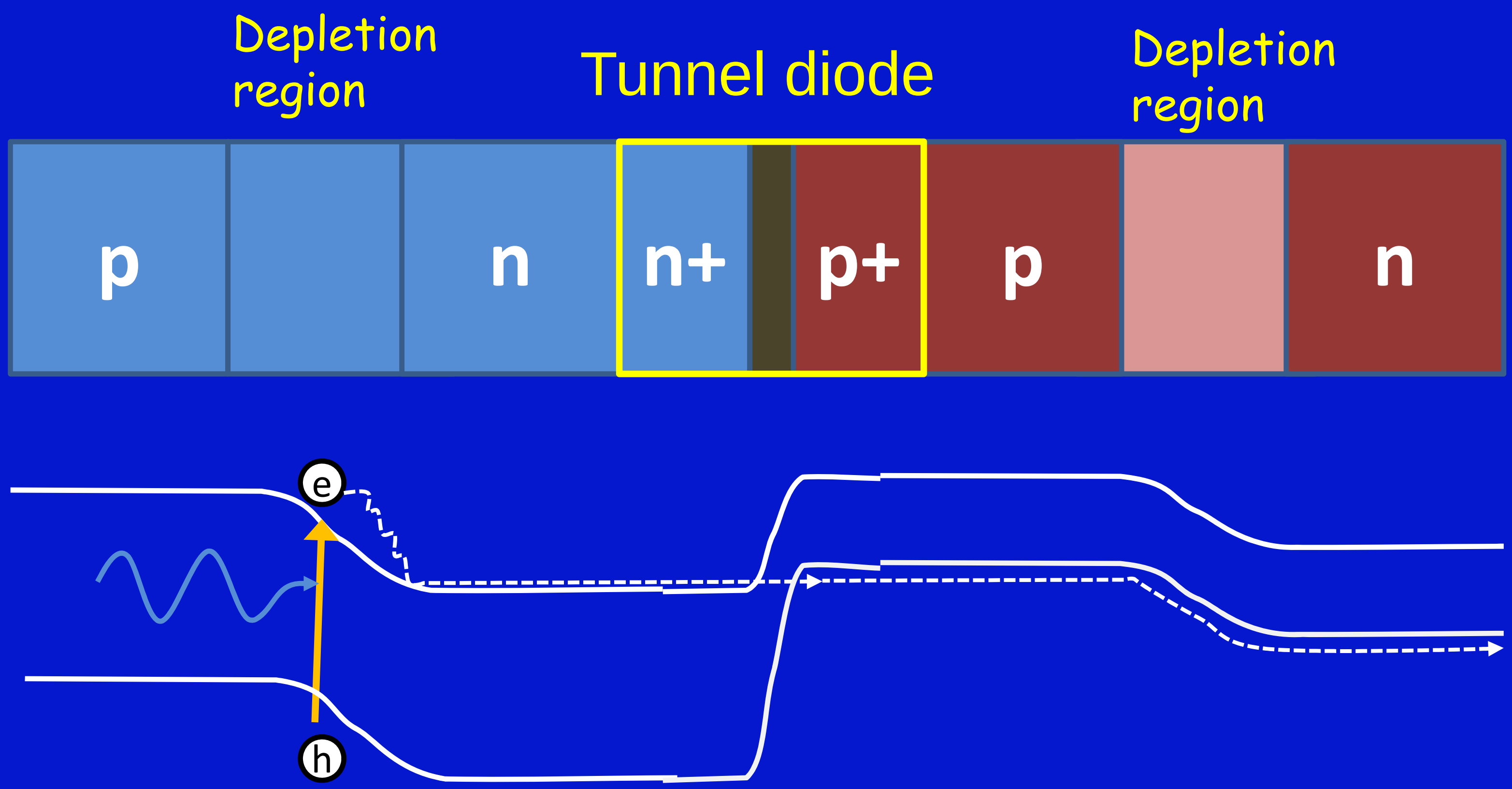
Concentrated light



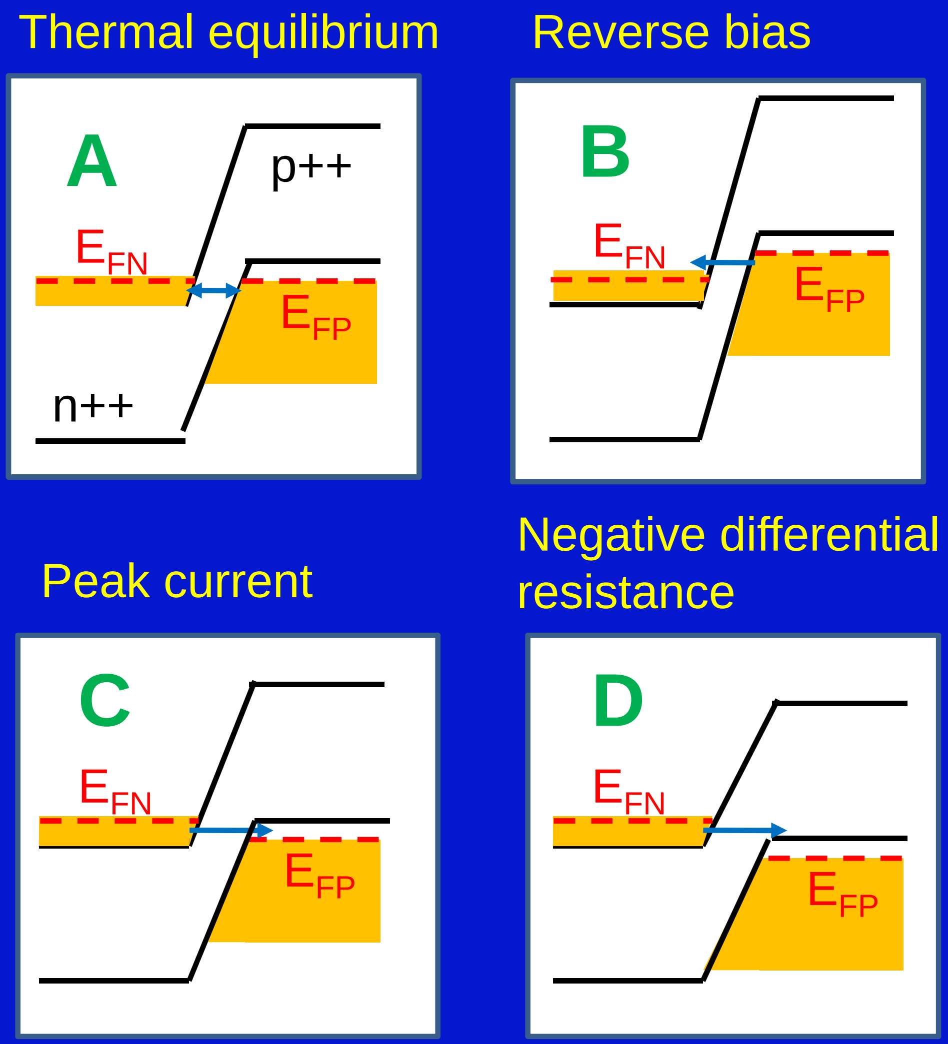
- Efficiency and Voc drops with increasing concentration
  → Reverse diode in series with pn junction?

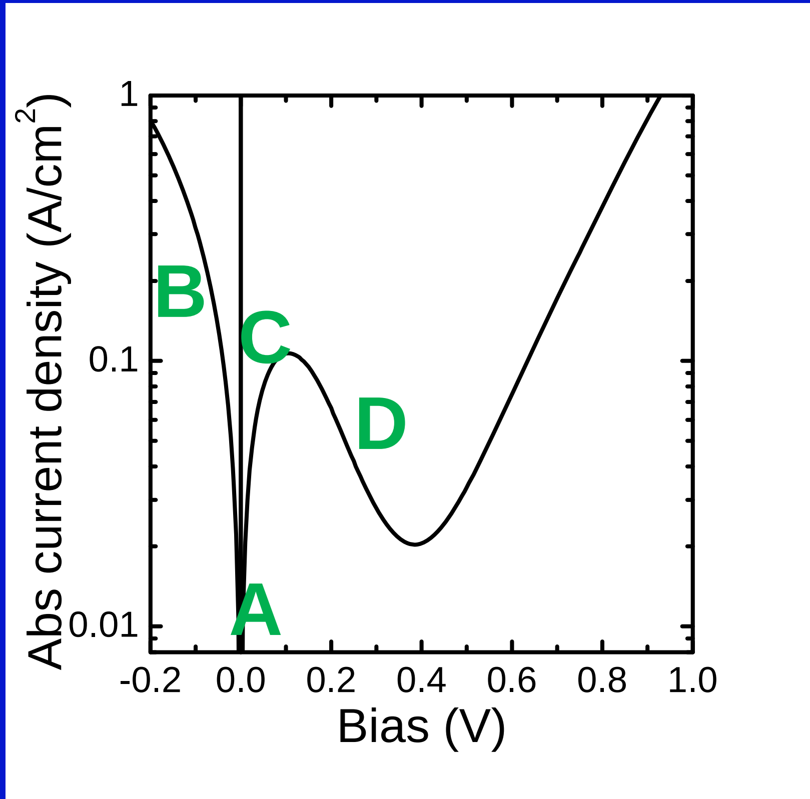
In collaboration with Sol Voltaics AB and Fraunhofer ISE

Tunnel diode in dual junction solar cell



Tunnel diode principles





- InP tunneling junction
- Current density 0.11 A/cm^2
- RT peak to valley current ratios of 5.3

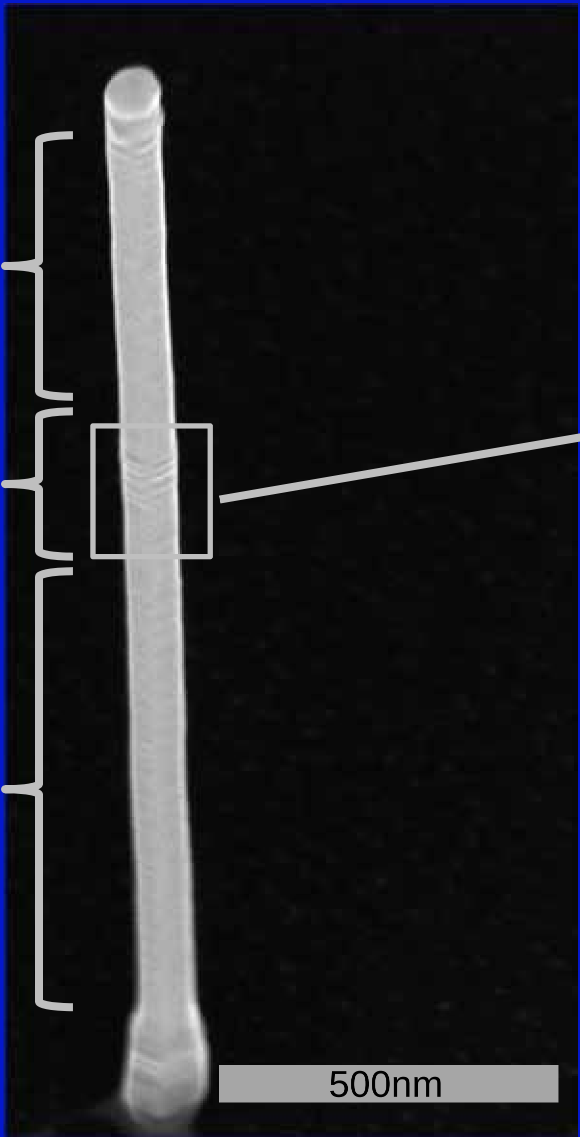
L Esaki, Phys Rev 1958

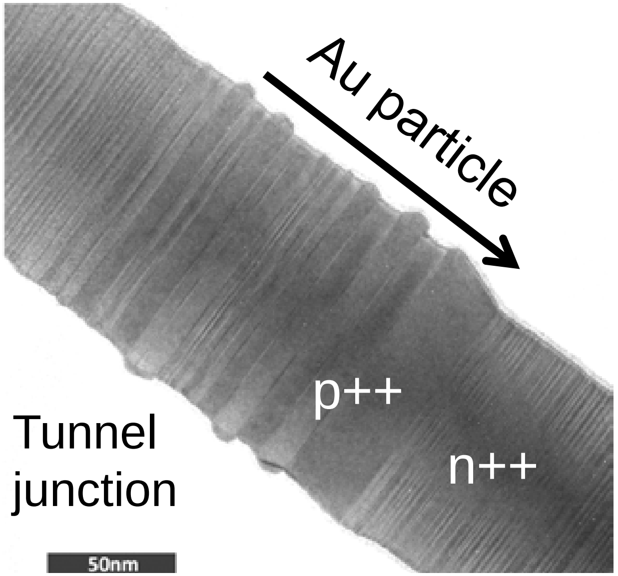
InP tandem homojunction on Si

Junction 2

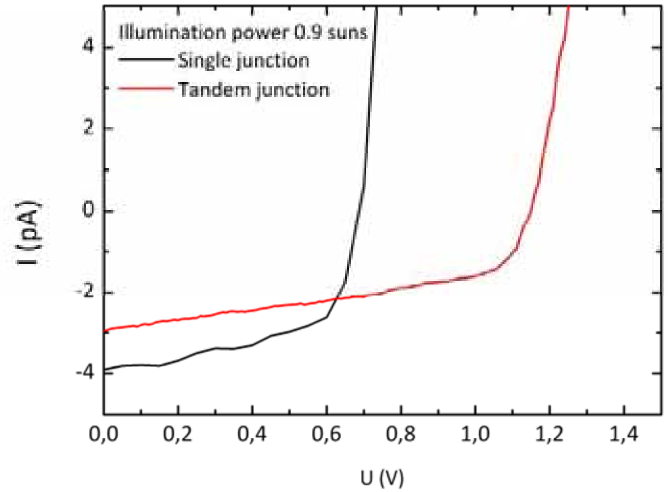
Tunnel junction

Junction 1





Dopant induced change in crystal structure.



V_{oc} = 0.69/1.15 V

→ 67% increase

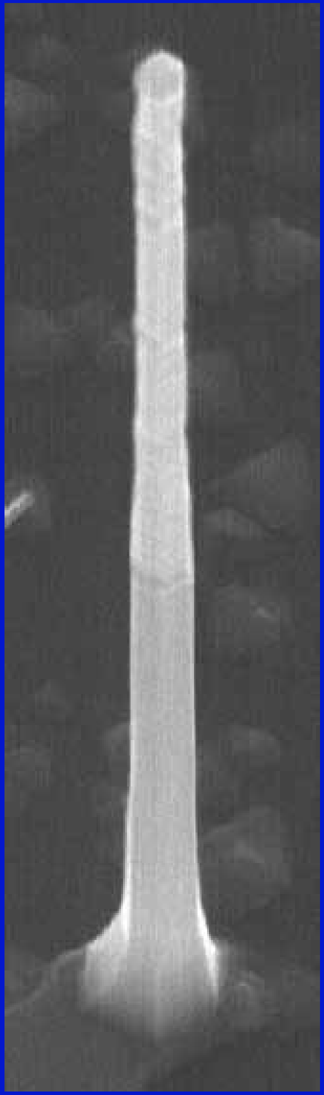
Heurlin et al, Nano Letters 2011

InP (n+) –GaAs (p+) heterostructure

- InP readily n-doped,

  Borgström et al, Nanotech, 2008
- GaAs readily p-doped,

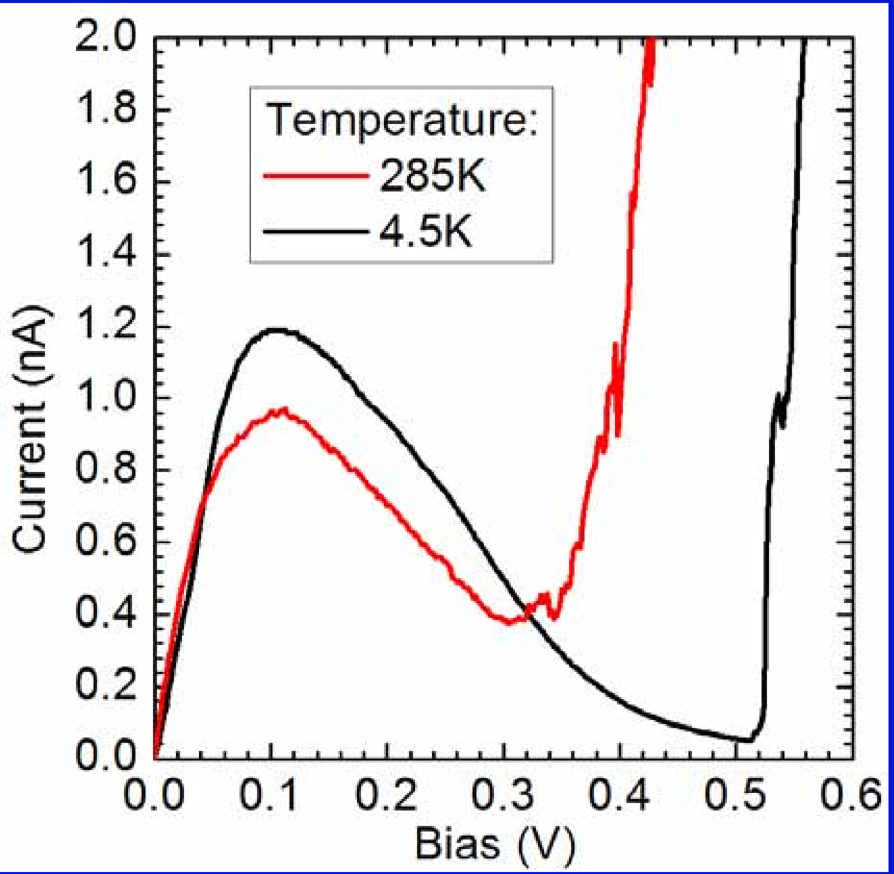
  Gutsche et al, J Appl Phys, 2009
- Favourable type II band alignment
- Lattice mismatch 3.8%



- 80 nm Au particles
- Growth temperature 420 C
- H2S n-doping
- DEZn p-doping

Single InP-GaAs NW tunnel diode

- Peak to Valley Current Ratio (PVCR) up to 8.2 at room temperature
- Peak current density up to 890 A/cm^2, typical 15 A/cm^2
- 41.1% solar cell (FISE): 15-25 A/cm^2 (@1000 suns)



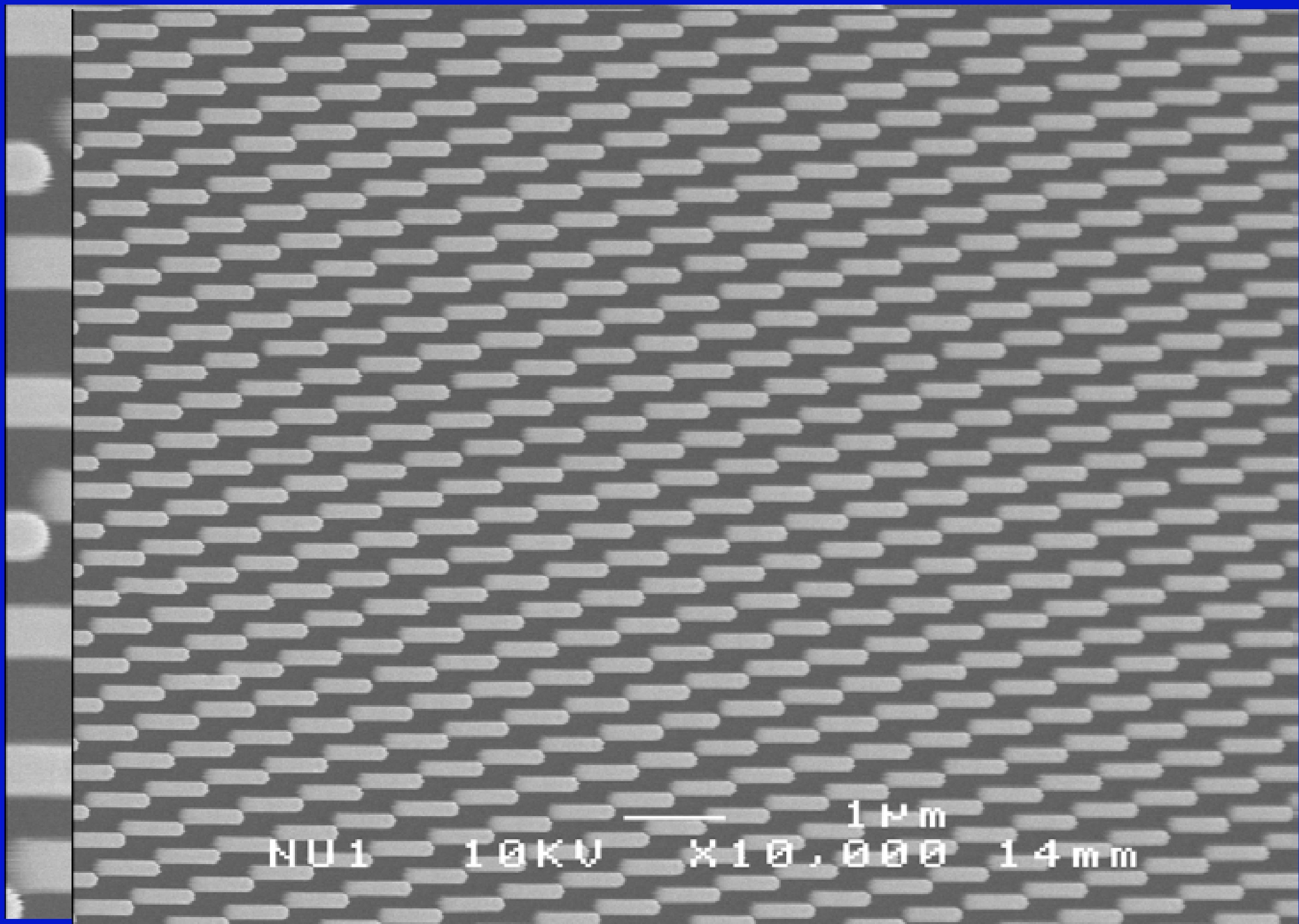
Wallentin et al., Nano Letters **2010**

Summary

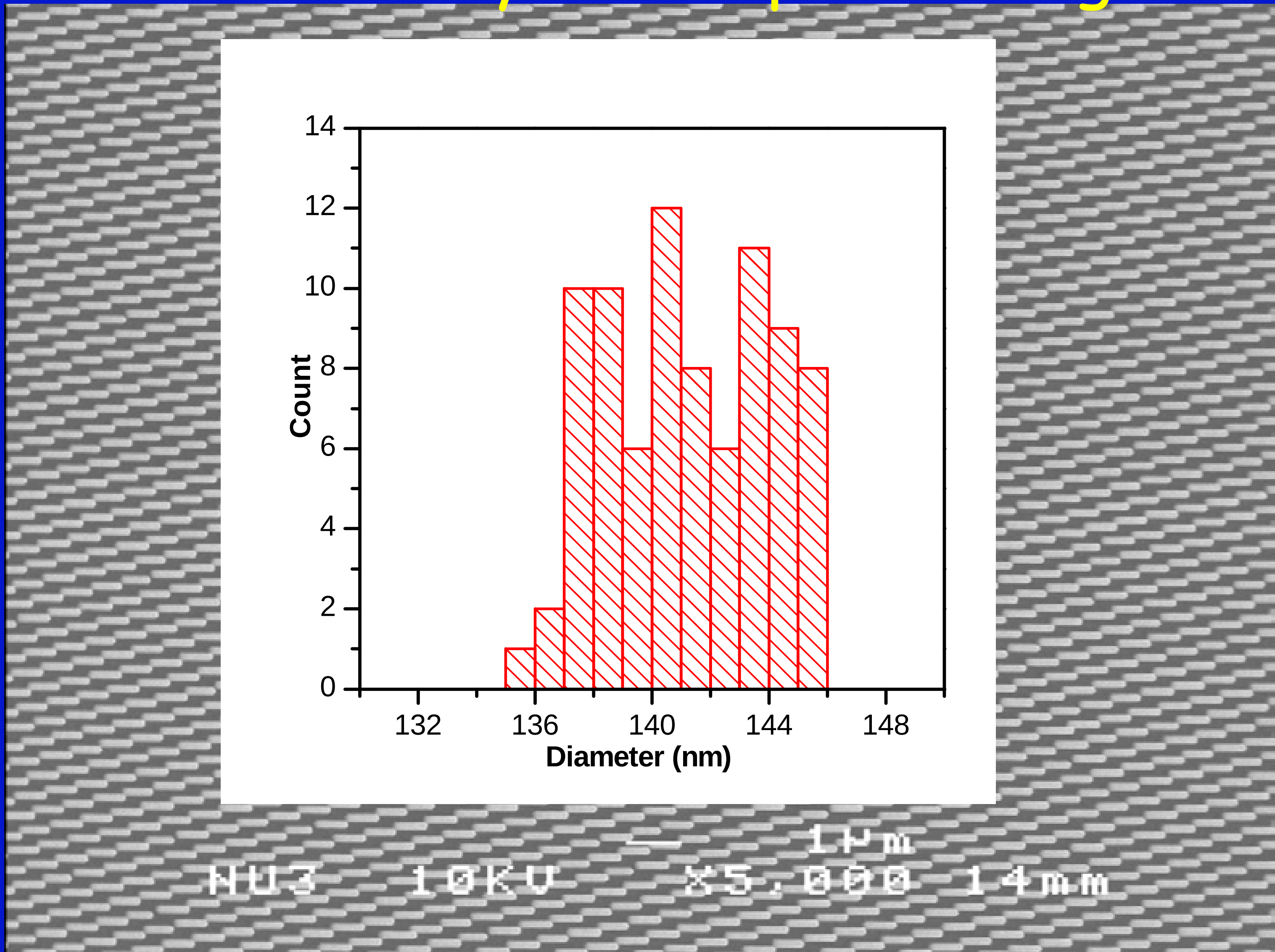
NWs promising for high efficiency solar energy harvesting

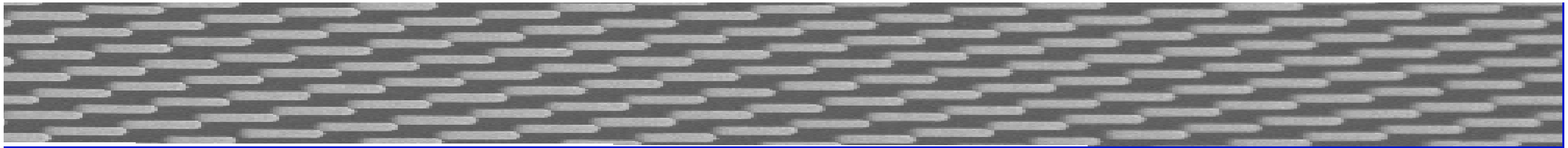
- NW Doping
- Decoupled Axial and radial NW growth by in situ etching
- Nanowire pn-junctions, esaki diodes
  - Nano imprint lithography for large area patterning
  - GaInP for high band gap junction

Nano imprint lithography for large scale economically viable patterning



Nano imprint lithography for large scale economically viable patterning





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