Thermoelectrics (TE) at the Nanometer

Sun-to-Fiber (S2F) at the Micrometer

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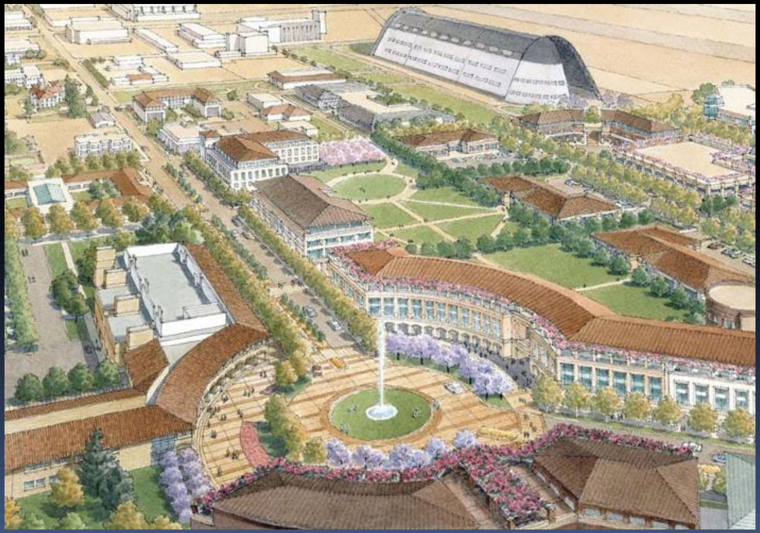
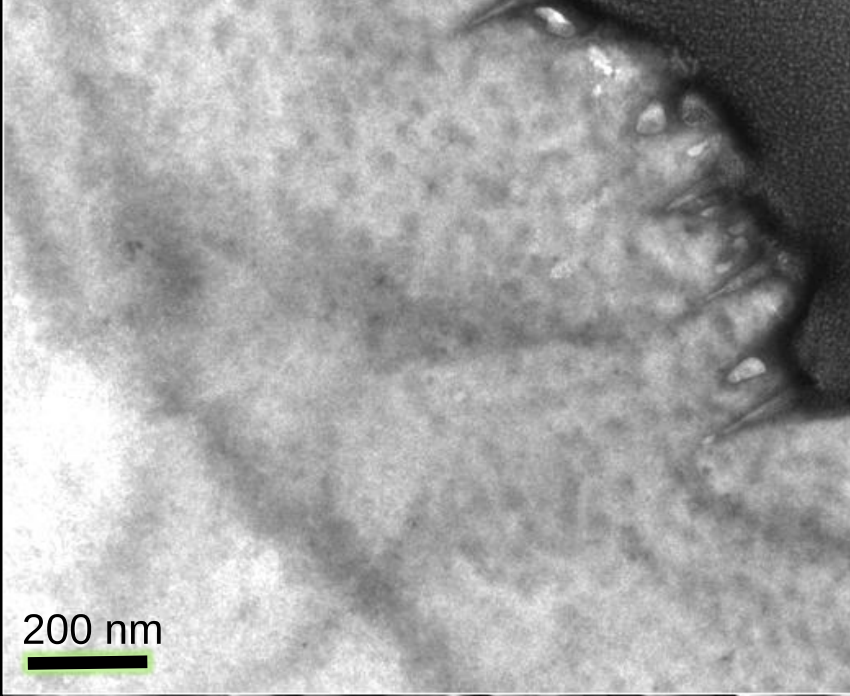
Introduction to Univ. of California Santa Cruz

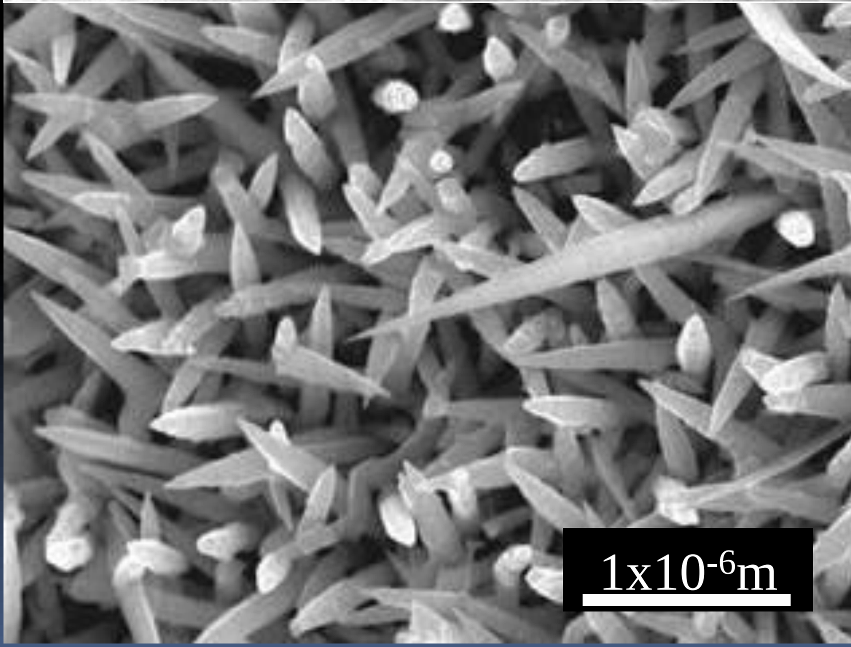
Santa Cruz off-Campus (2300 Delaware Ave. Santa Cruz)

Silicon Valley Campus (Advanced Studies Laboratories at NASA ARC)



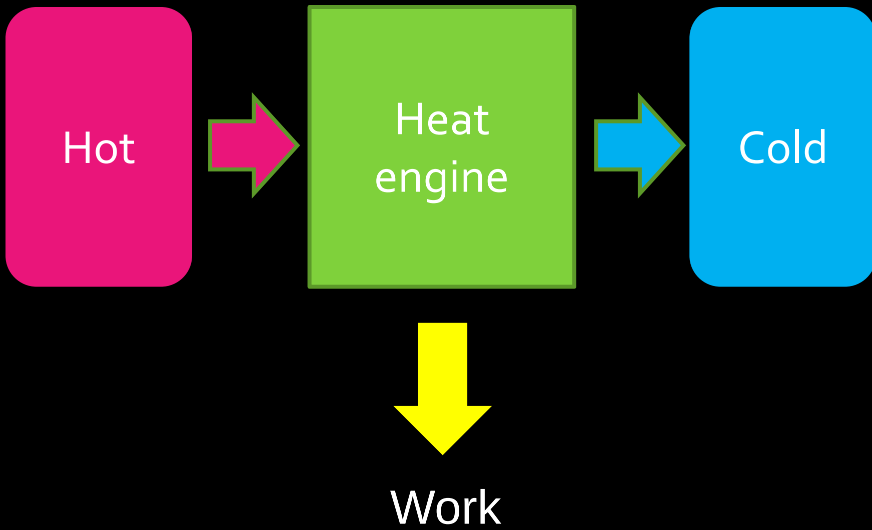
TE
@
the Nanometer





Background and Motivation

Solid state heat engine



- ❑Mechanical heat engines with efficiencies ~40% produce 90% of the required energy.
- ❑Waste heat generated annually is ~18TW .
- ❑Converting even 1% of the waste heat into electricity ($0.11/kWh) could create a $20B annuity.

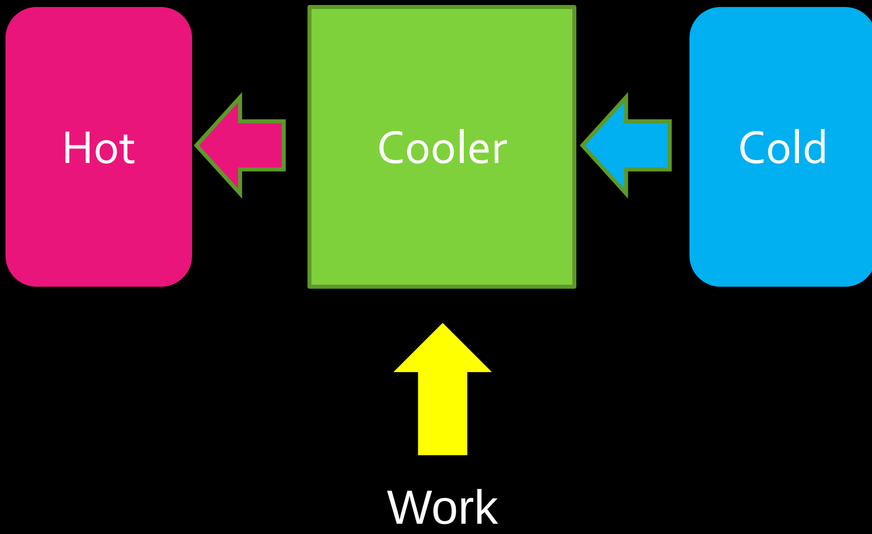
http://www.instantgoldrefining.com/

http://www.thedailygreen.com/

interestingenergyfacts.blogspot.com/

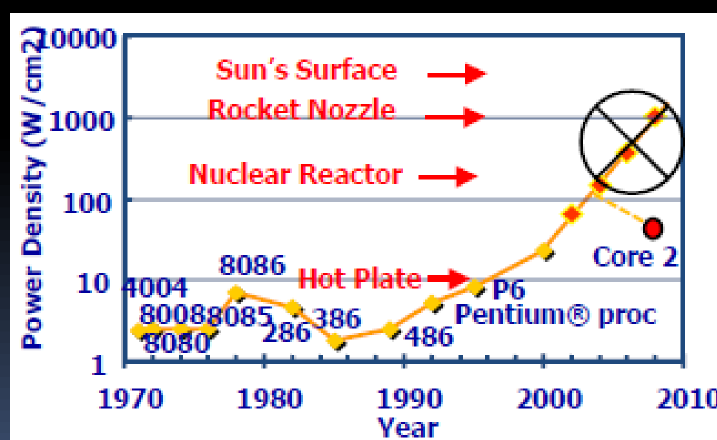
Background and Motivation

Solid state cooler

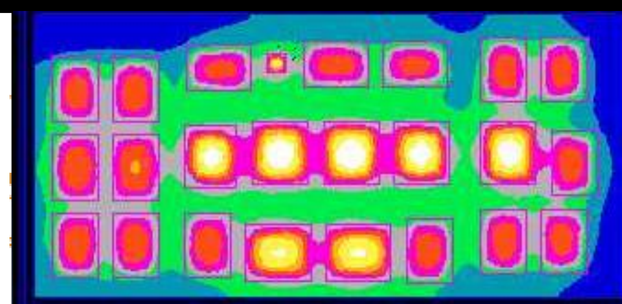


- ❑Annual energy cost of the U.S. data centers was $4.5B. (61BkWh) in 2006 (EPA 2007).
- ❑Cooling consumes ~40%.
- ❑Heat generation is spatially and temporally non-uniform.
- ❑Hot spot can be >650W/cm^2.

www.zalman.com



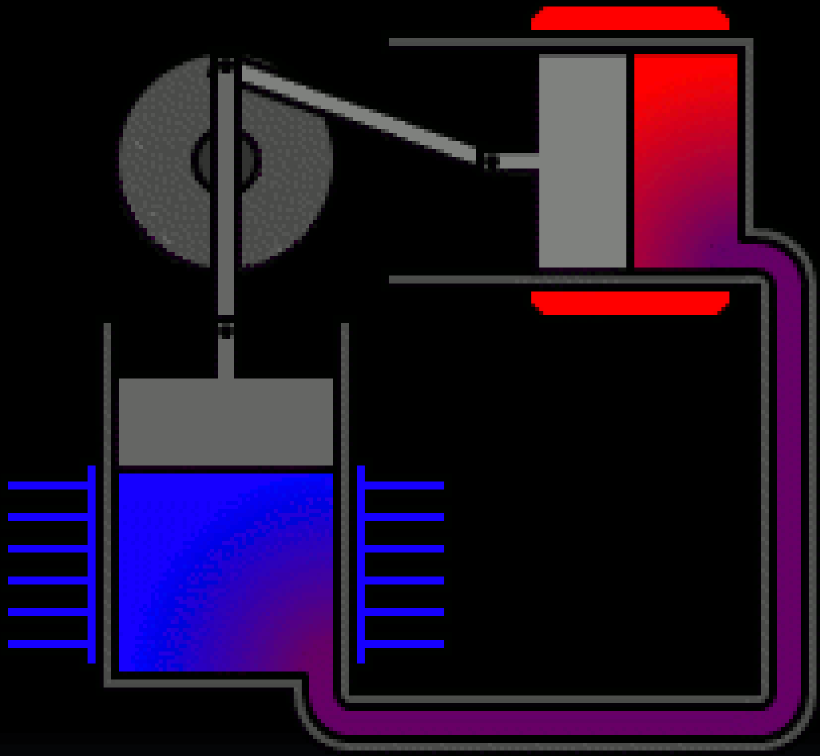
S. Borkar (Intel)



http://www.ecse.rpi.edu/frisc/theses/GargThesis/chapter6.html

Background and Motivation

Competitors



http://en.wikipedia.org/wiki/Stirling_engine

www.sunshinekelly.com

- ❑Stirling engine η ~40%
- ❑TE module η ~10%

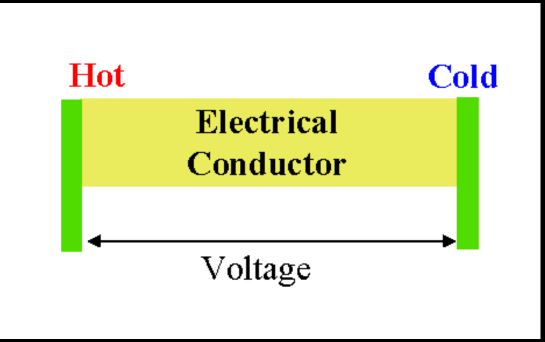
- ❑Refrigerator COP ~5.9
- ❑TE cooler COP ~0.7

Traditional Thermoelectrics

Limitations of bulk materials

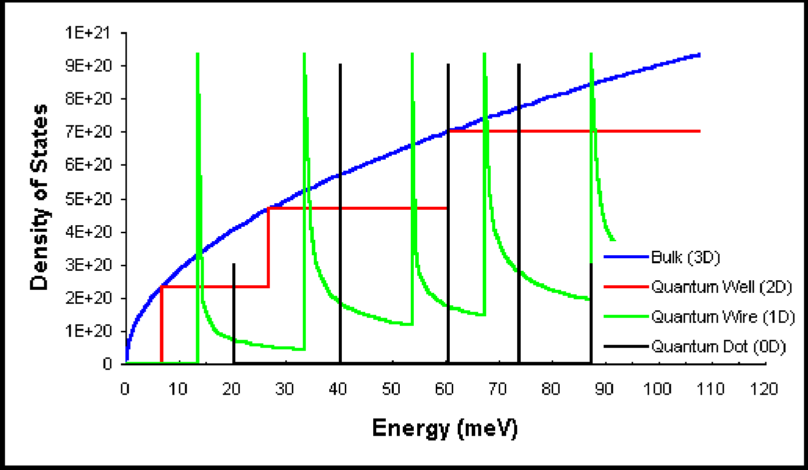
$$ZT = \frac{S^2 \sigma T}{\kappa_l + \kappa_e}$$

S: Seebeck coefficient
σ: Electrical conductivity
κ_l : Lattice thermal conductivity
κ_e: Electronic thermal conductivity
T: Temperature



$$\eta_{max} = \eta_c \frac{(1+ZT)^{0.5}-1}{(1+ZT)^{0.5}+1}$$

- Maximize σ: → metal
- Minimize $\kappa_l + \kappa_e$ → wood



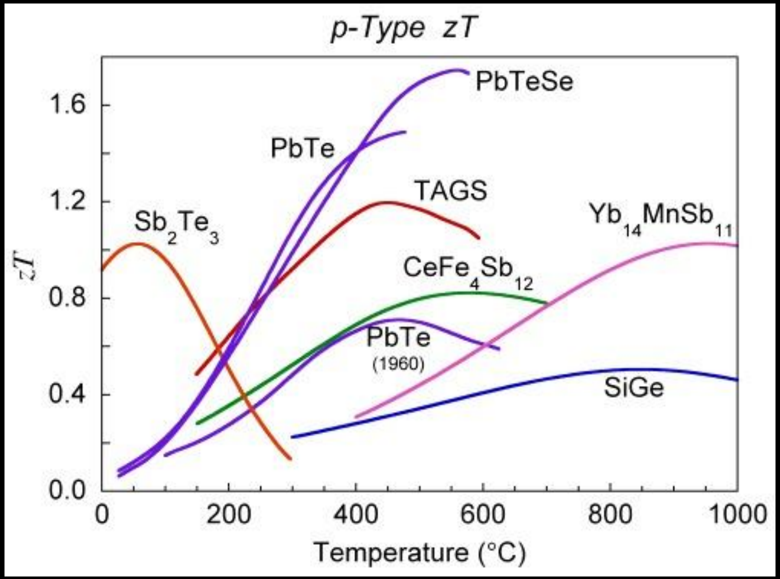
http://britneyspears.ac/physics/dos/dos.htm

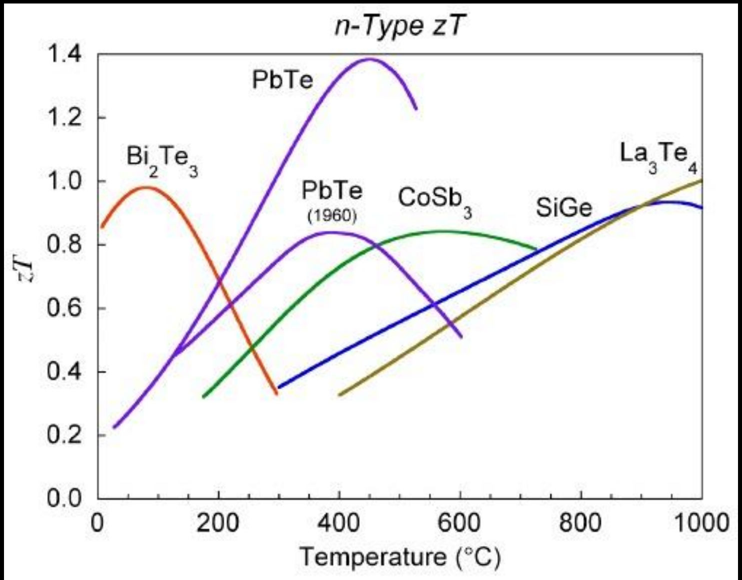
$S \sim d\sigma(E)/dE,\ \sigma(E) = n(E)\mu(E)q$
$S \sim dn(E)/dE\ d\mu(E)/dE$
$S \sim dg(E)/dE\ d\tau(E)/dE$

g: Density of states
τ: Scattering time
E: Energy

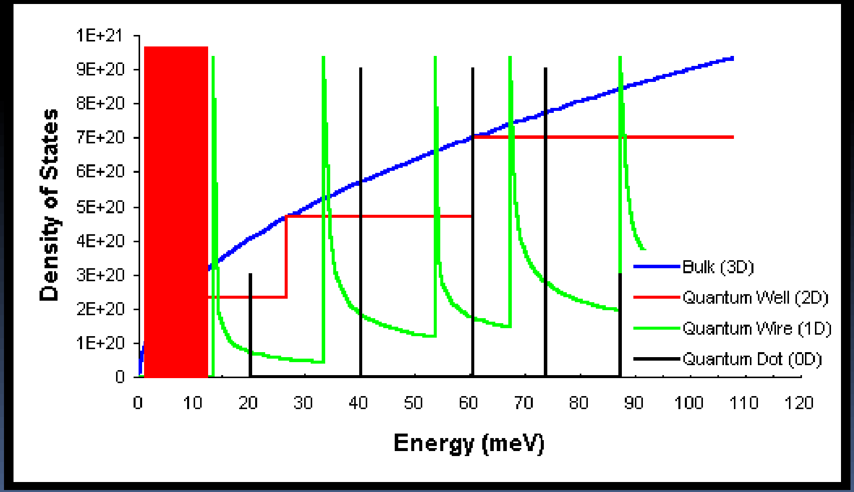
Traditional Thermoelectrics

Limitations of bulk materials





http://www.its.caltech.edu/~jsnyder/thermoelectrics/



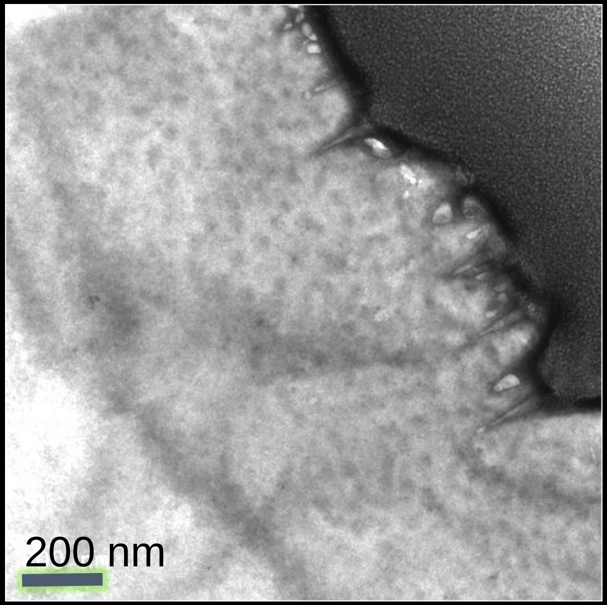
$$S \sim dg(E)/dE \; d\tau(E)/dE$$

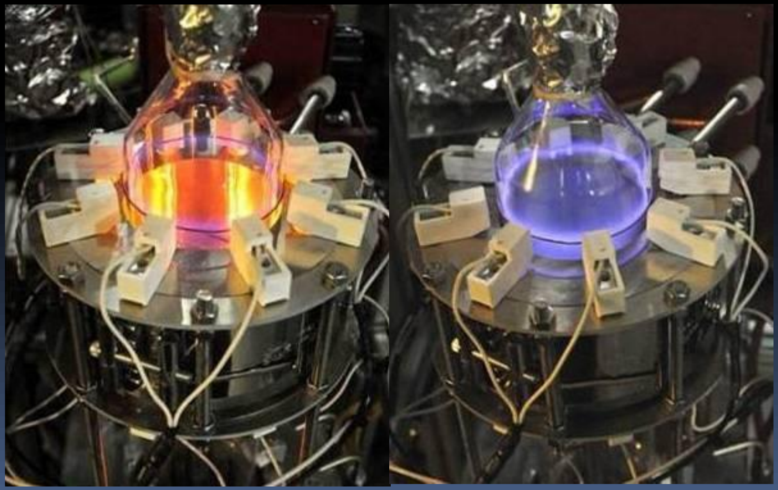
- ❑Low-dimensional semiconductor
- ❑Energy filter

http://britneyspears.ac/physics/dos/dos.htm

Advanced Approaches

Our “Nano” approach 1: Metal-semiconductor nanocomposites





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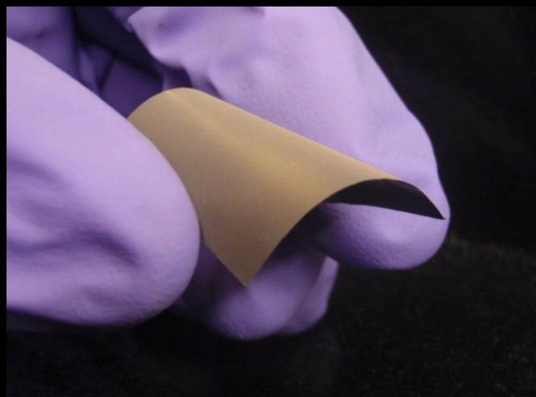
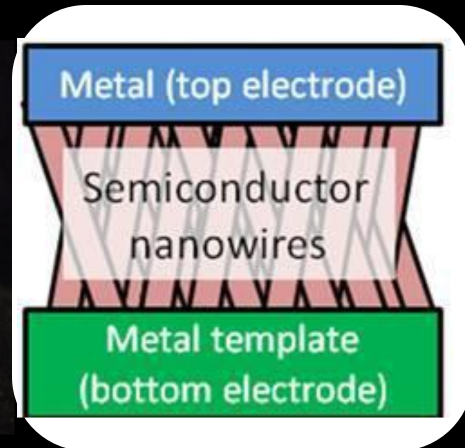
Advanced Approaches

HOT POWER INC.

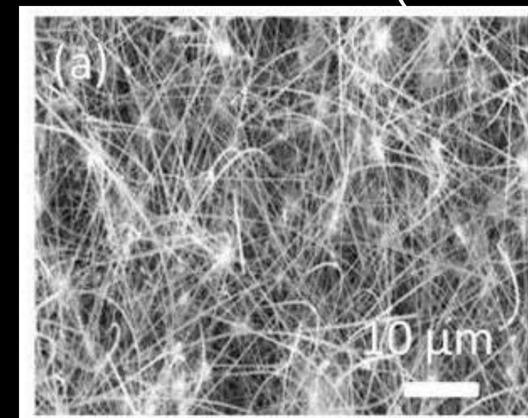
Our "Nano" approach 2: Nanowire network



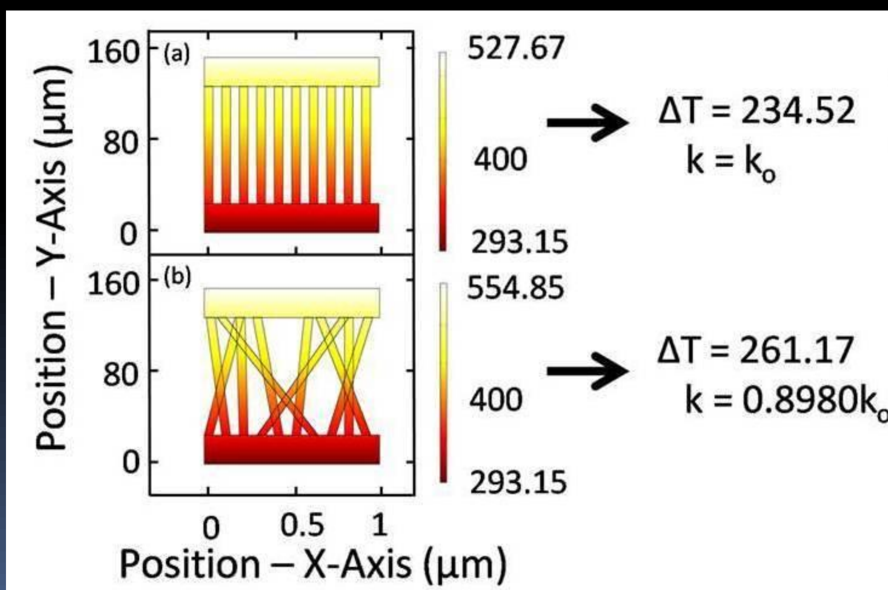
Flexible TE device employing silicon nanowires

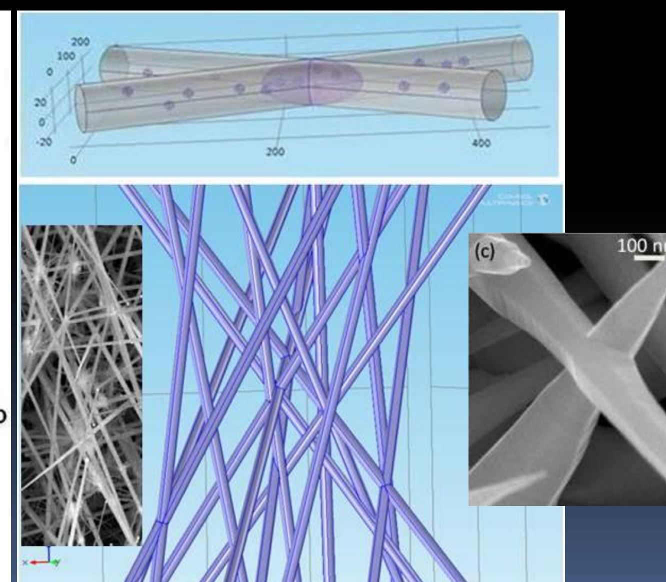


Nanowire network (silicon)



Physica Status Solidi (a) 209, 171 (2012)





S2F
@
the Micrometer

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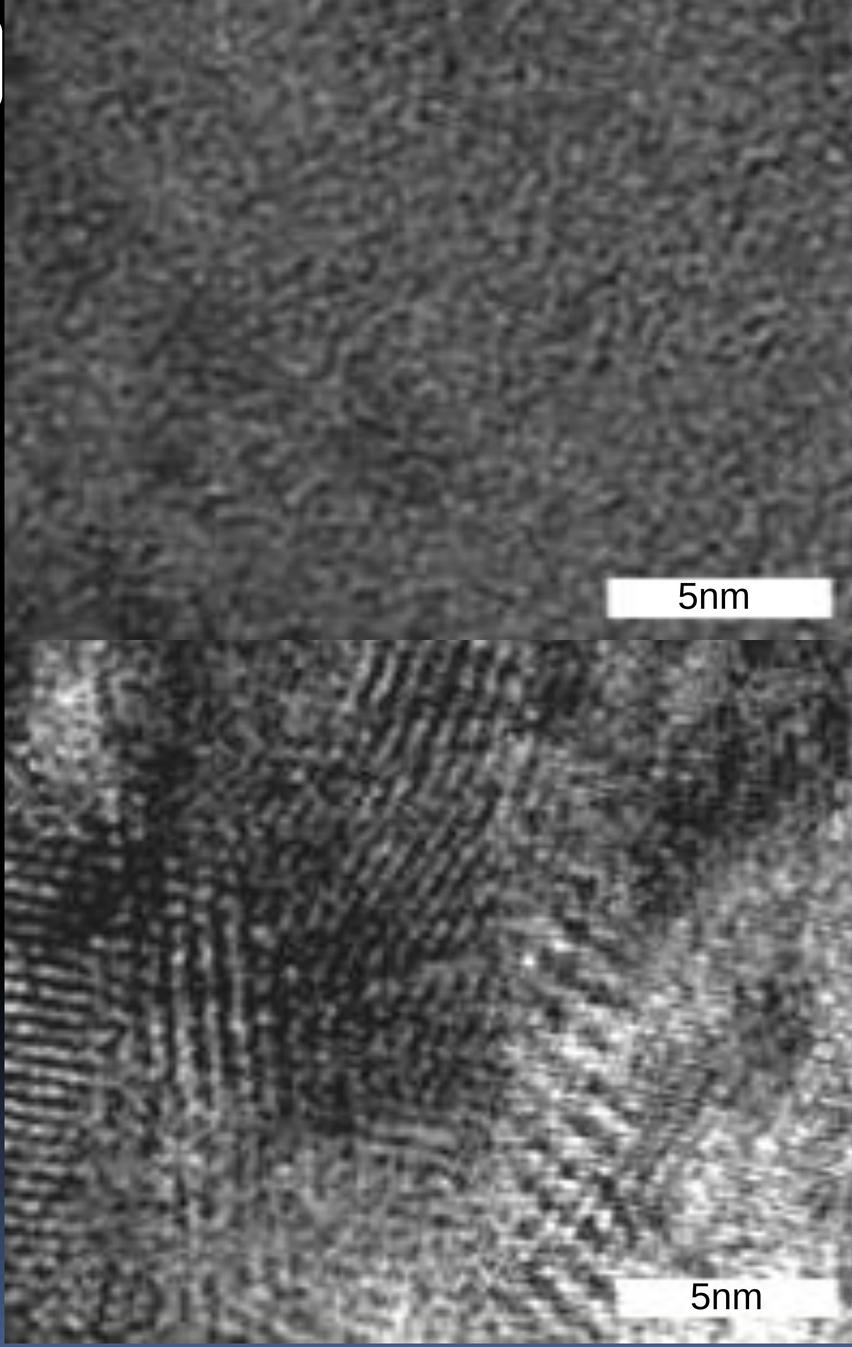


Background and Motivation

A large amount of energy from the sun

In a single hour the sun delivers the same amount of energy as consumed by all of humanity in a year – about 5 × 10^{20}J.

Sun light → Electricity

Transport

Electricity → Light

Electricity → Heat

Sun light → Light

No transportation

Light → Light

Light → Heat

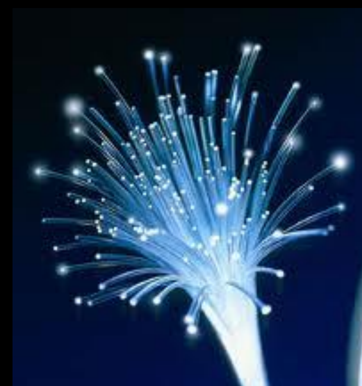
http://www.keepbanderabeautiful.org

Strategy

Concentrated sun light into an optical fiber

Sun light ➔ Concentration Transportation Light ➔ Daylighting

http://kjcoop.com
greenpowerscience.com



http://www.familievink.nl

http://www.syneco.co.uk

Use as heat or storage for later uses

http://en.wikipedia.org/wiki/Thermal_energy_storage

Strategy

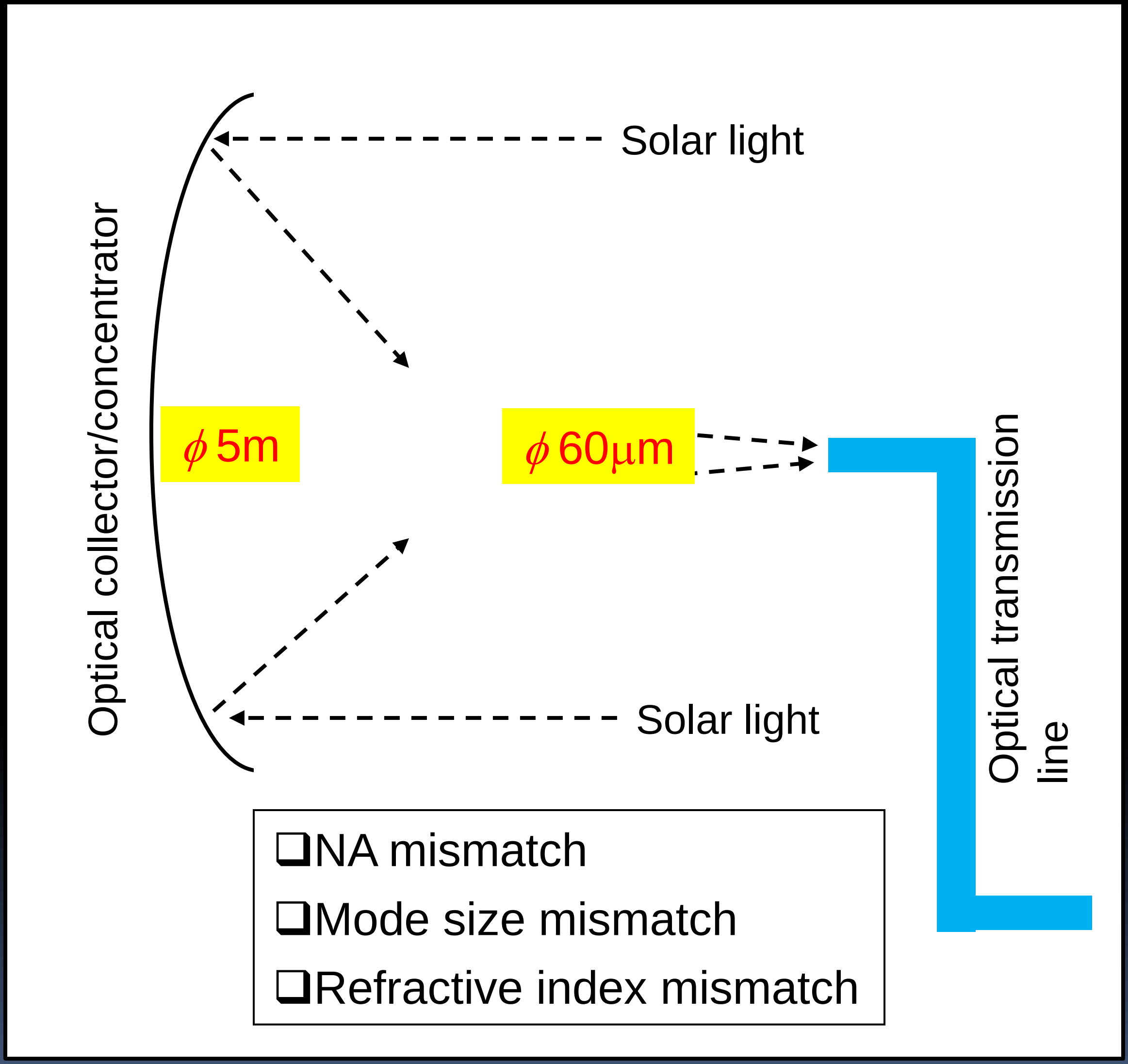
Concentrated sun light into an optical fiber

Himawari System
La Foret Eng (Tokyo, Japan)

Oak Ridge System
Sunlight Direct (Oak Ridge, TN)

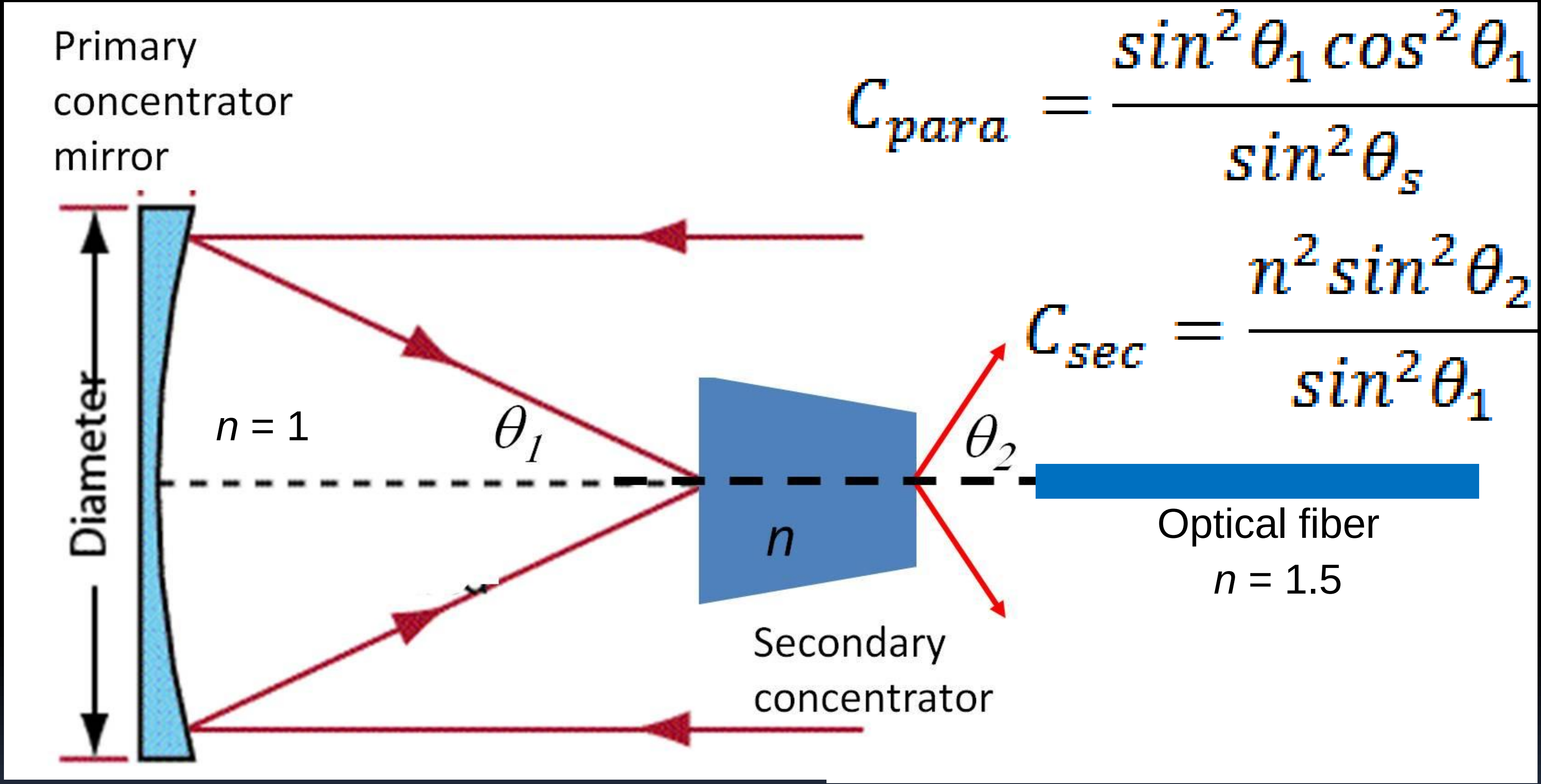
Goal

Concentrated sun light into an optical fiber



Goal

Concentrated sun light into an optical fiber



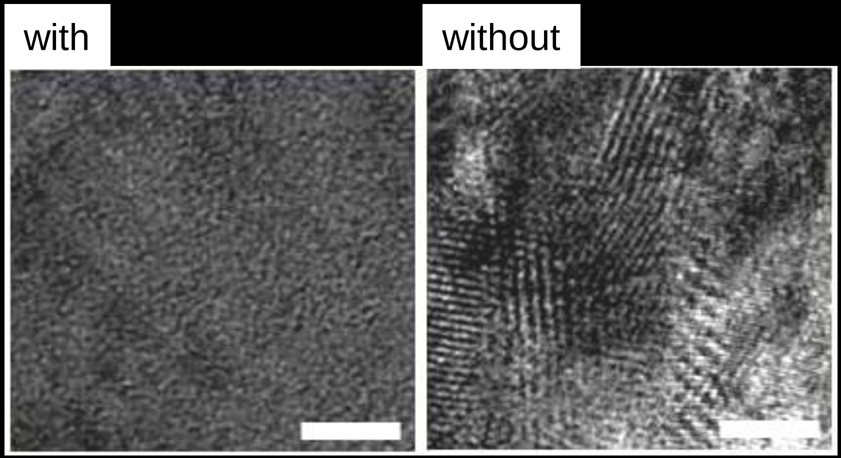
$$C_{para} = \frac{\sin^2\theta_1 \cos^2\theta_1}{\sin^2\theta_s}$$

$$C_{sec} = \frac{n^2 \sin^2\theta_2}{\sin^2\theta_1}$$

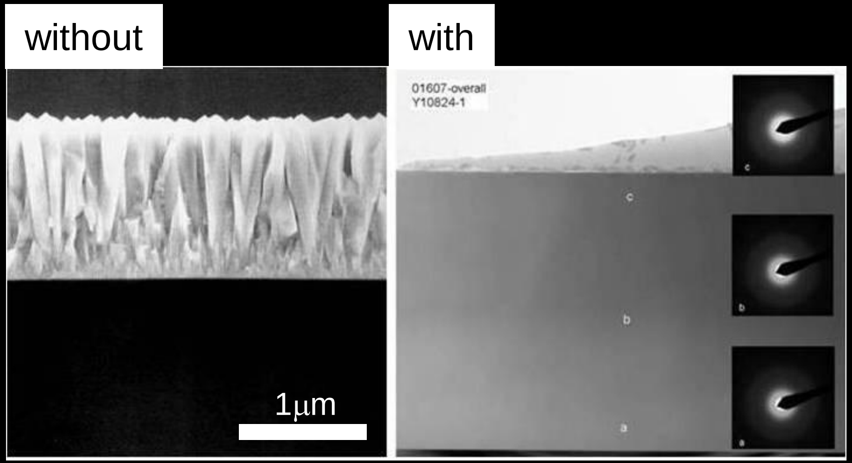
Need thin films with $1.4 < n < 2.8$ for 400-1000nm and k as small as possible

Concentrated Sun Light into an Optical Fiber

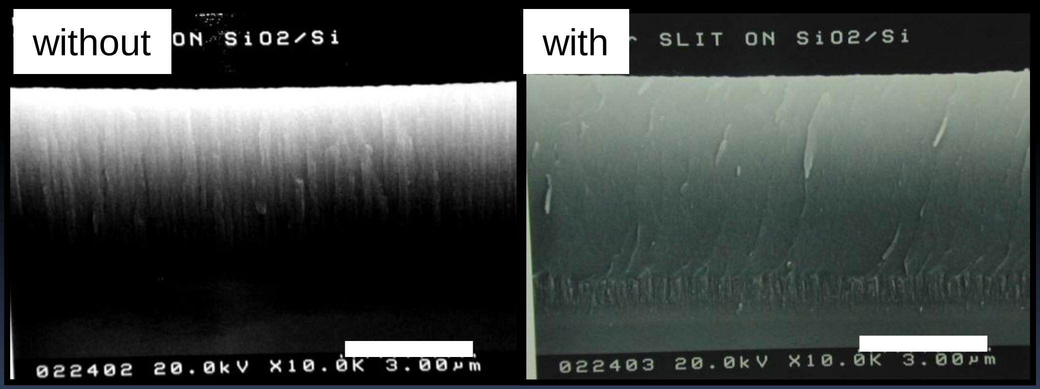
Enabling thin film technology



Niobium oxide (TEM, scale bar 5nm)



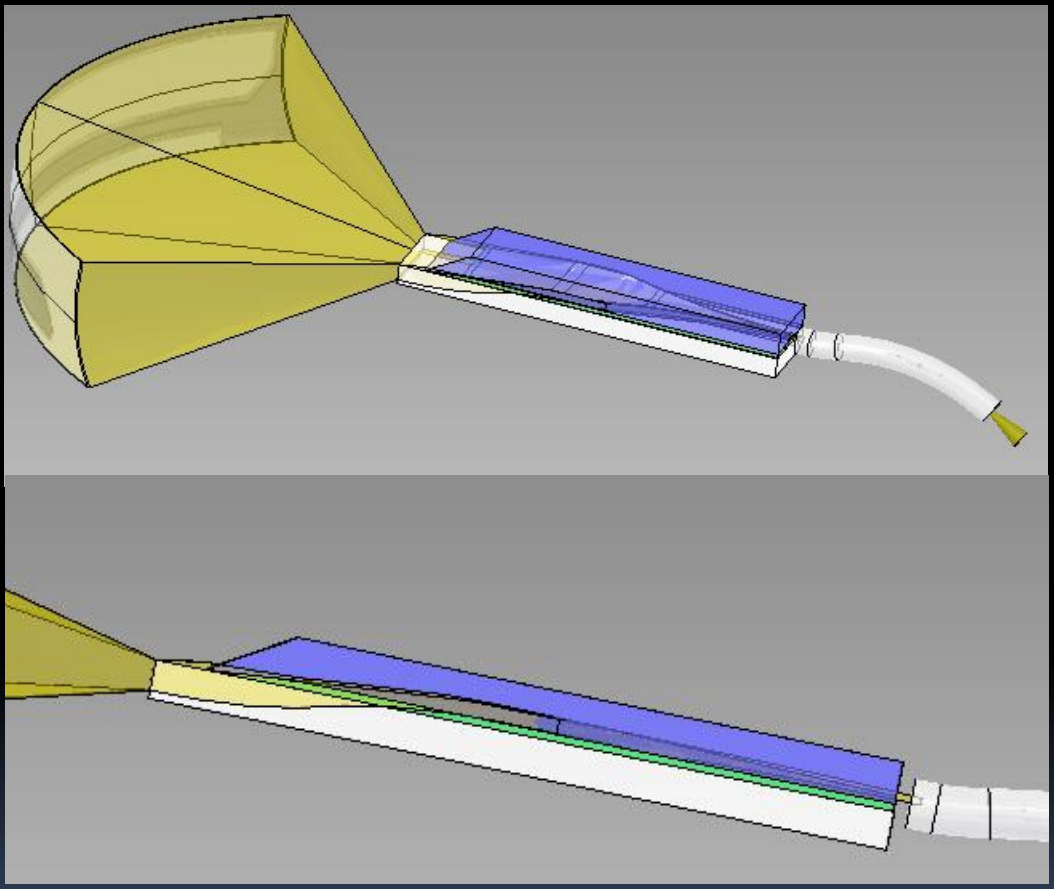
Zirconium oxide (Right TEM x200k)

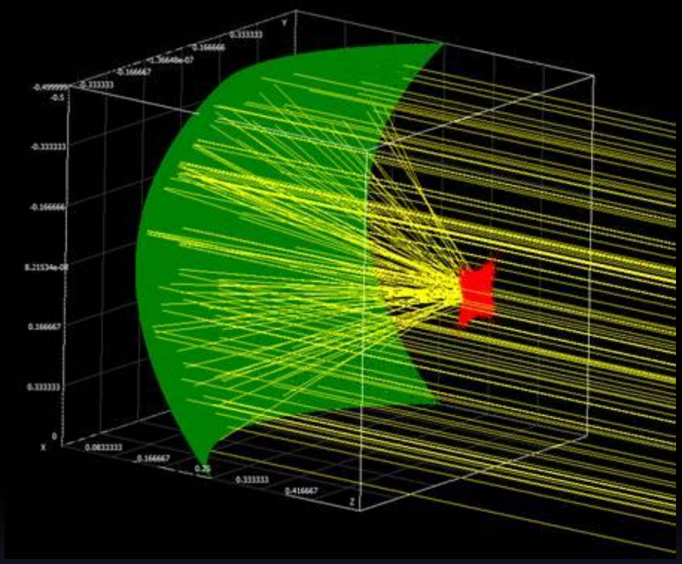


Aluminosilicate (SEM, scale bar 3µm)

Concentrated Sun Light into an Optical Fiber

Devices

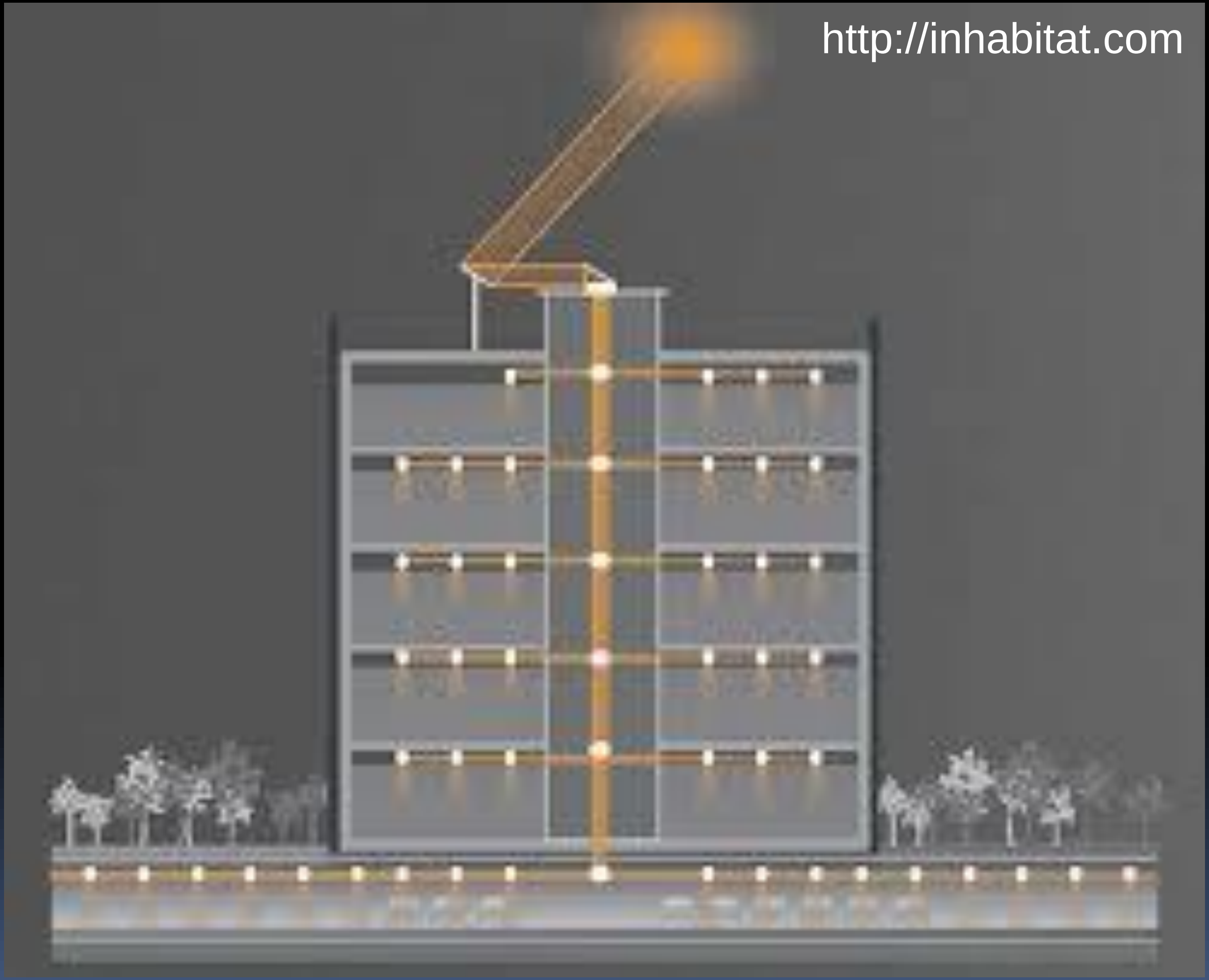




Courtesy: David Berkstresser and Allan Lewandowski

Concentrated Sun Light into an Optical Fiber

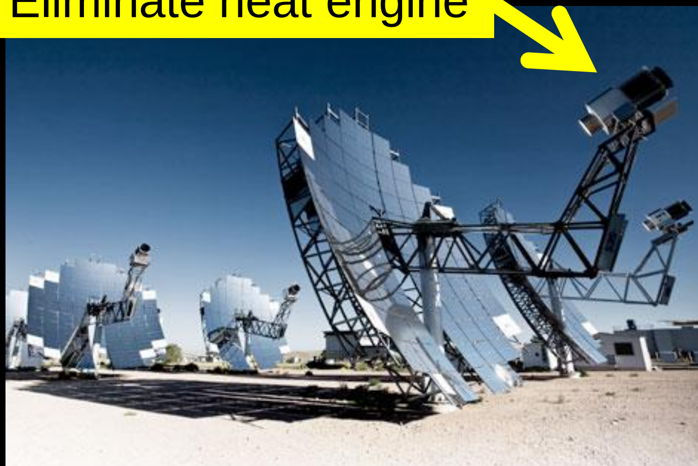
Ultimate application



Concentrated Sun Light into an Optical Fiber

Really ultimate applications

Eliminate heat engine



http://mcensustainableenergy.pbworks.com

Eliminate working fluid

www.getsolar.com

- ❑1m^2 concentrator for solar daylighting
- ❑25m^2 concentrator for solar thermal power generation

Eliminate tower

www.rainbowskill.com

Demaray and Kobayashi at the NREL solar furnace

Acknowledgement

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