Field-Effect Modulation of Seebeck Coefficient in Single PbSe Nanowires

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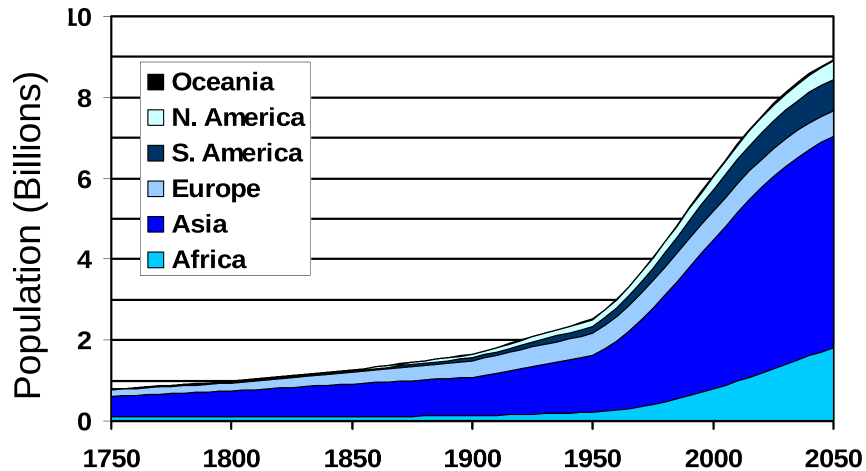
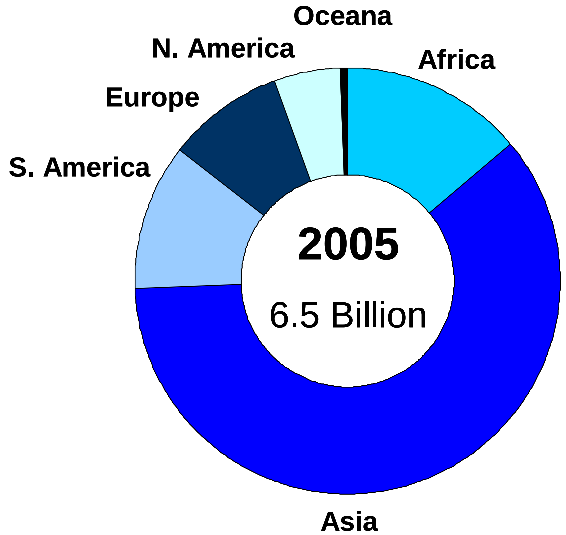
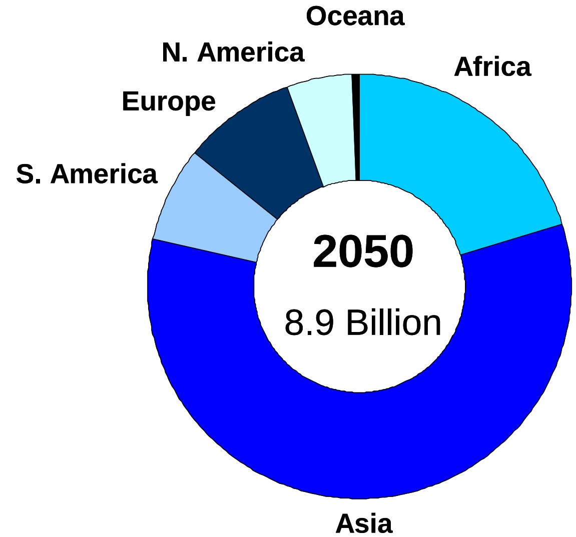
Demographic Expansion







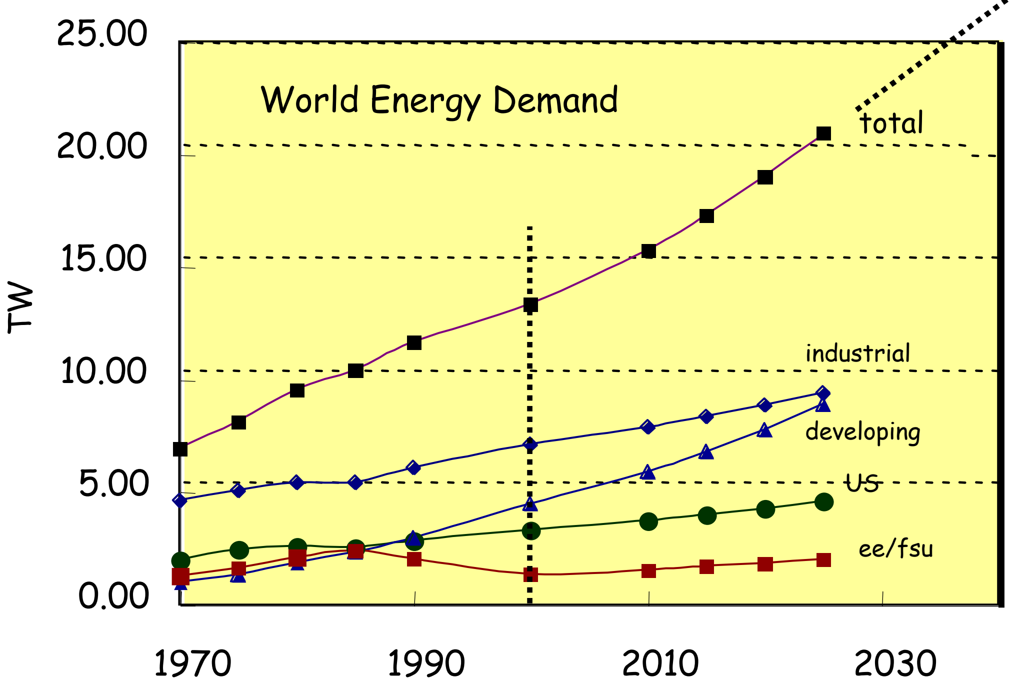
Material Challenges for Clean Energy in the New Millennium

-M.S. Dresselhaus

Massachusetts Institute of Technology

The World Energy Demand Challenge

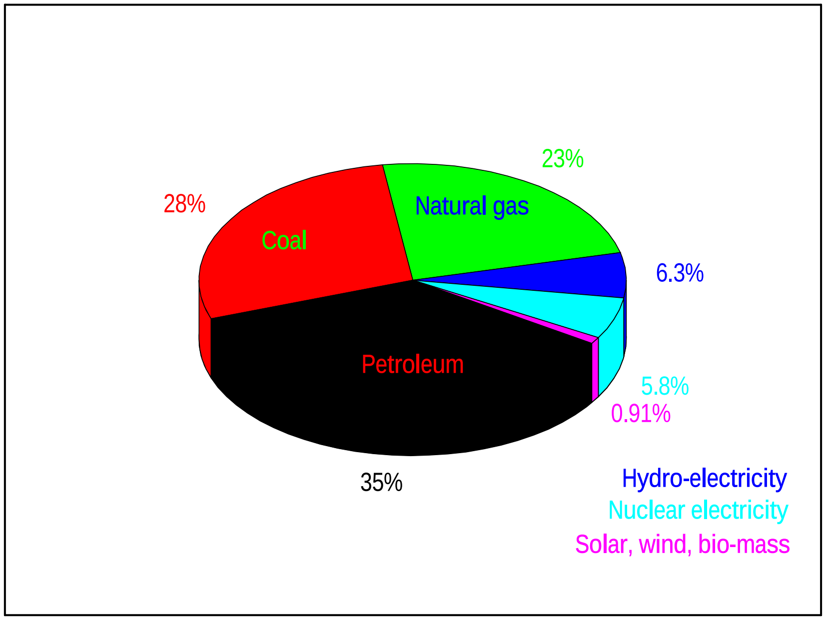
2100: 40-50 TW
2050: 25-30 TW
2000: 13 TW



EIA Intl Energy Outlook 2004
http://www.eia.doe.gov/oiaf/ieo/index.html

Hoffert et al Nature 395, 883,1998

energy gap
~ 14 TW by 2050
~ 33 TW by 2100



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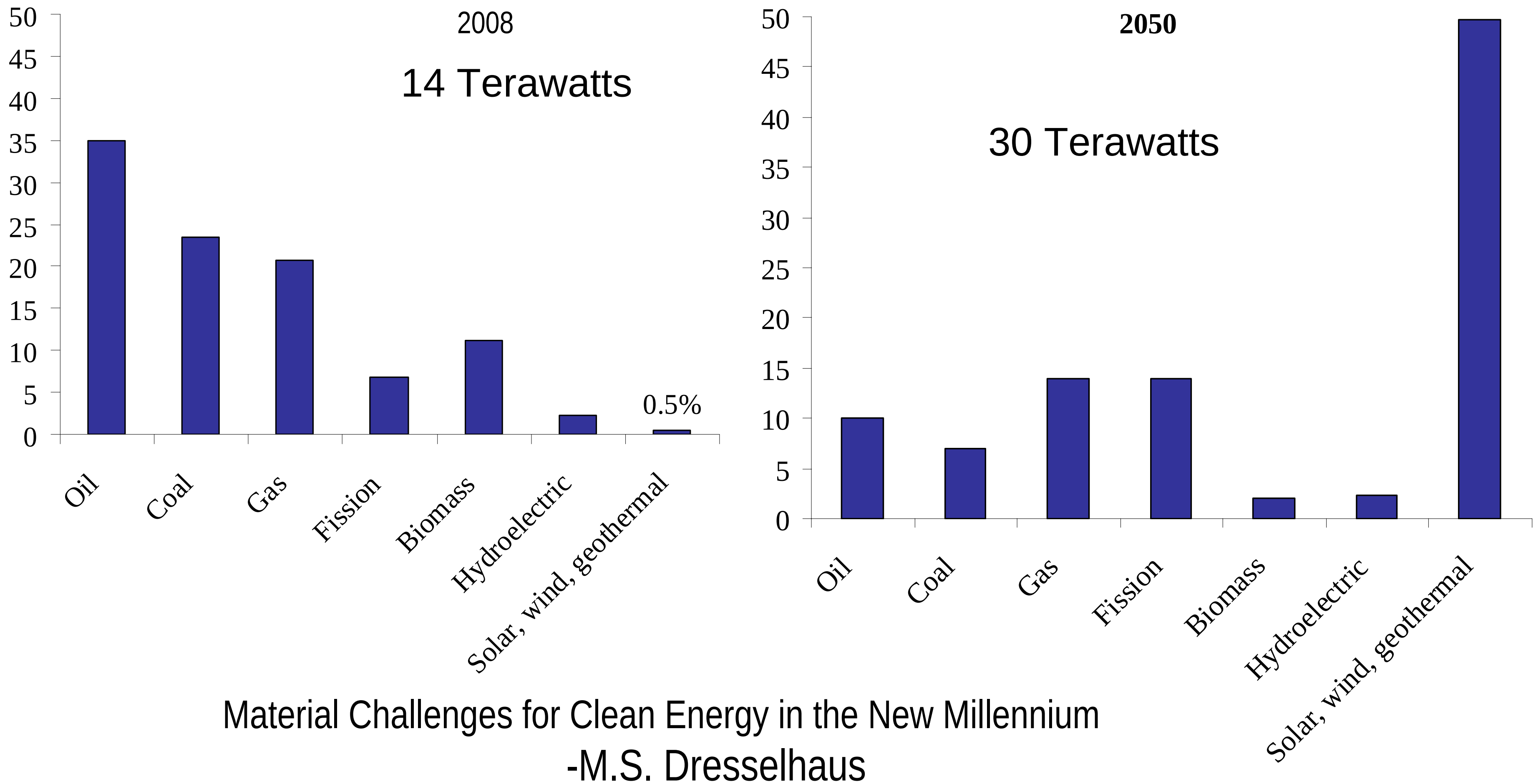
The Energy Revolution



Material Challenges for Clean Energy in the New Millennium

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THERMOELECTRIC DEVICES

for energy conversion and conservation

Seebeck Coefficient, Conductivity, Temperature, Thermal Conductivity

$$ZT = \frac{S^2 \sigma T}{\kappa}$$

$ZT \sim 3$ for desired goal

Difficulties in increasing ZT in bulk materials:

$S \uparrow \Longleftrightarrow \sigma \downarrow$

$\sigma \uparrow \Longleftrightarrow S \downarrow$ *and* $\kappa \uparrow$

$\Rightarrow$ *A limit to Z is rapidly obtained in conventional materials*

$\Rightarrow$ *So far, best bulk material ($Bi_{0.5}Sb_{1.5}Te_3$) has ZT ~ 1 at 300 K*

Low dimensional physics gives additional control:

- *Enhanced density of states due to quantum confinement effects*
  - $\Rightarrow$ *Increase S without reducing σ*
- *Boundary scattering at interfaces can reduce κ more than σ*
- *Possibility of materials engineering to further improve ZT*

In this paper…

- *A novel strategy to control the thermoelectric properties of individual PbSe nanowires using a field-effect gated device.*

- *Able to tune the Seebeck coefficient of single PbSe nanowires from 64 to 193 $\mu V \cdot K^{-1}$.*

- *This direct electrical field control of σ and S suggests a powerful strategy for optimizing ZT in thermoelectric devices.*

Synthetic Details

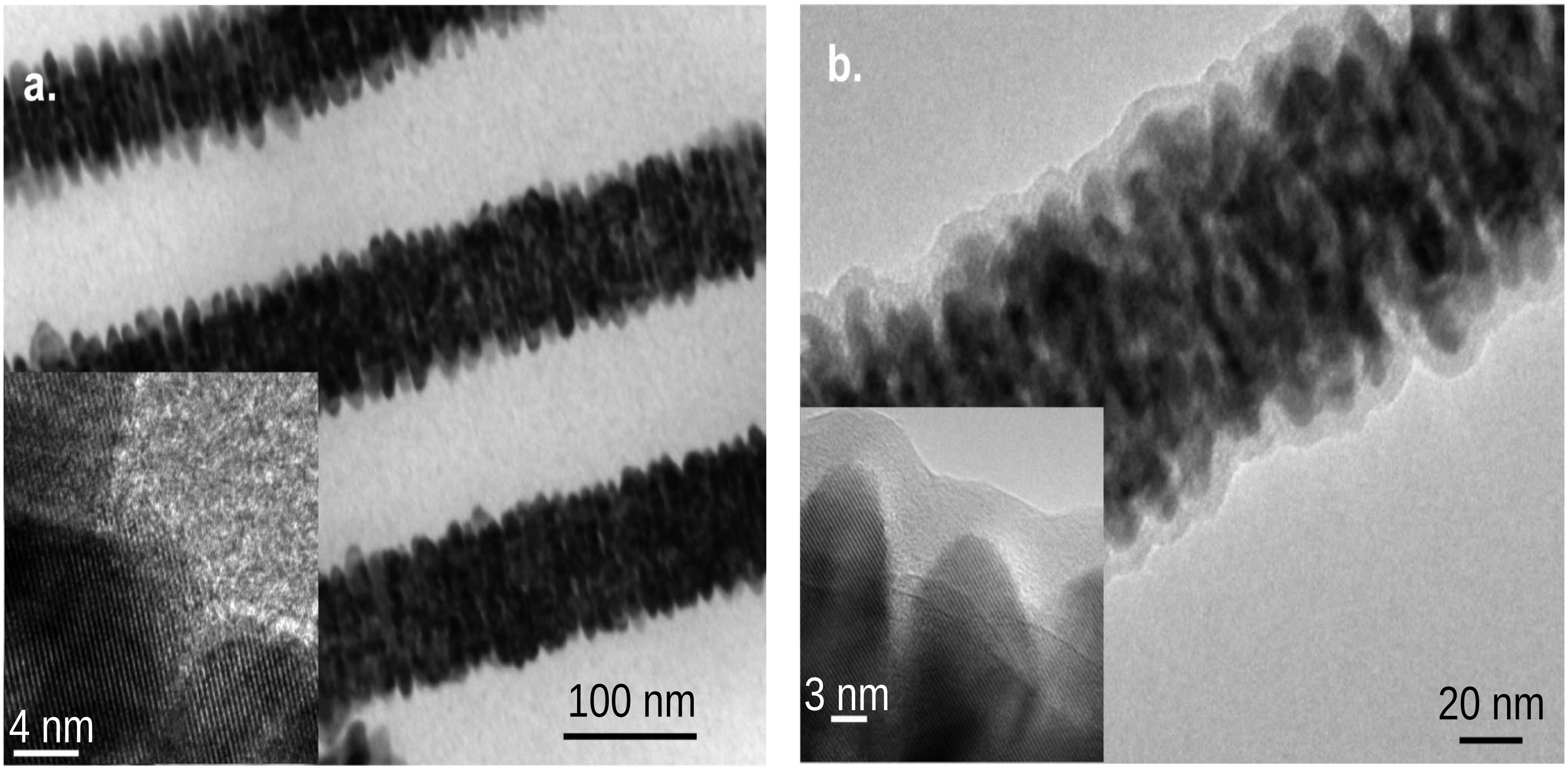
I. 0.76 g $Pb(acac)_2 . 3H_2O$ + 2 mL oleic acid/10 mL DPE $\xrightarrow[N_2]{150\ ^{0}C/30\ min.}$ Pb oleate

II. Pb oleate $\xrightarrow{4\ mL\ of\ 0.16\ M\ TOPSe/TOP}$ $\xrightarrow{15\ mL\ of\ DPE/250^{0}C}$ PbSe

III. PbSe $\xrightarrow{Al_2O_3}$ $PbSe@Al_2O_3$ $\xrightarrow[250^{0}C/4h]{700mTorr\ N_2}$

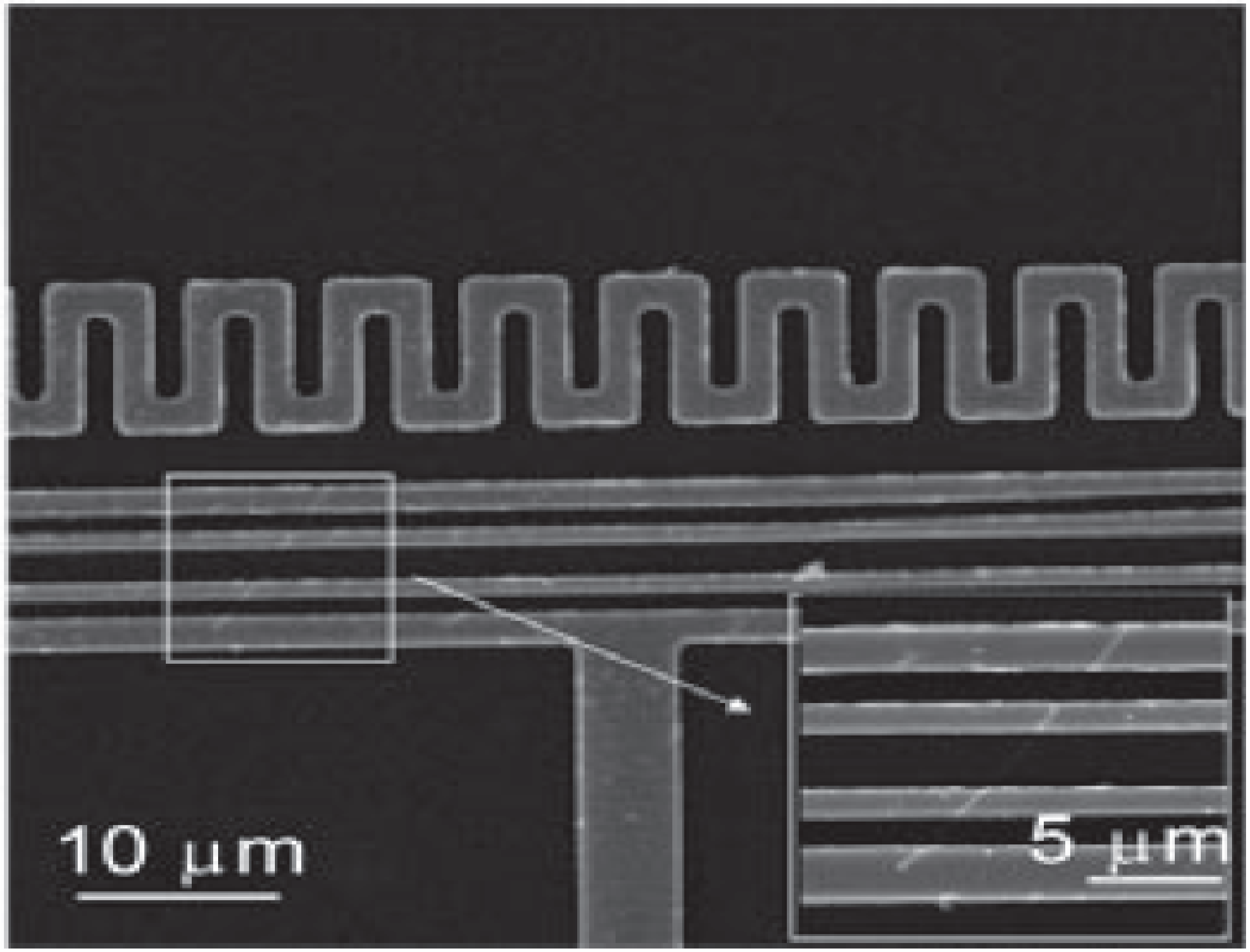
Cho, K.; Talapin, D. V.; Gaschler, W.; Murray, C. B. *J. Am. Chem. Soc.* **2005**, *127, 7140.*

Characterization



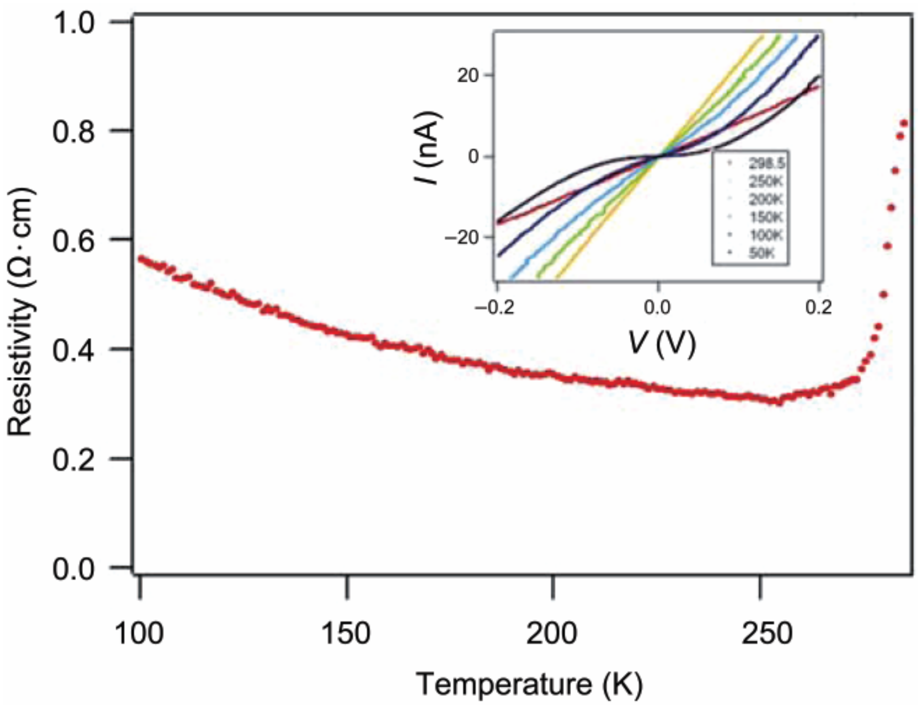
TEM images of PbSe nanowires: (a) as synthesized PbSe nanowires, (b) PbSe nanowire coated with ALD alumina. Insets are HRTEM images of the corresponding nanowires.

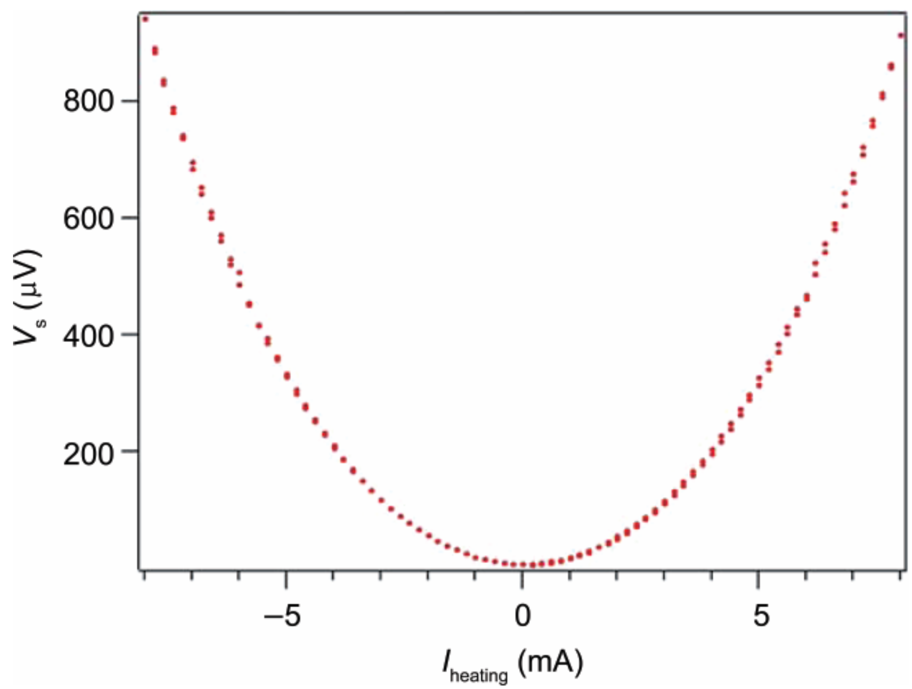
Fabrication of Single Nanowire



SEM image of a device used for individual nanowire thermoelectric measurements. The device was fabricated on a Si/SiO2 chip with a coil electrode designed to generate a temperature gradient. Inset: SEM image of the device with a single PbSe nanowire contacted by four 1 nm/100 nm/30 nm Ti/Pd/Au electrodes

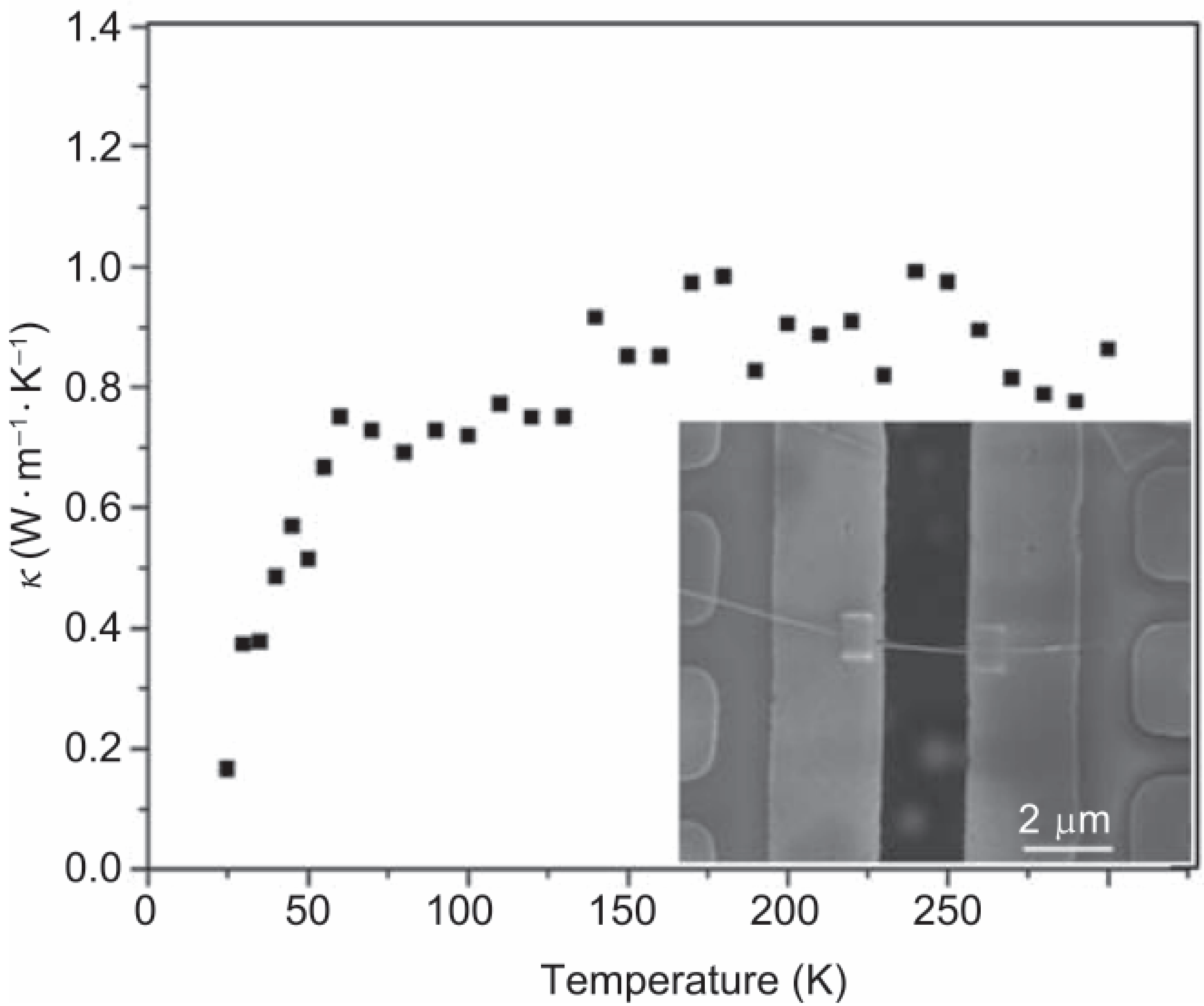
Electrical Studies





Themoelectrical measurements of single as-made PbSe nanowires. (a) Temperature dependent resistivity measurement. Inset: four-point probe measurement of I–V at different temperatures. (b) Thermal voltage measured across a single PbSe nanowire

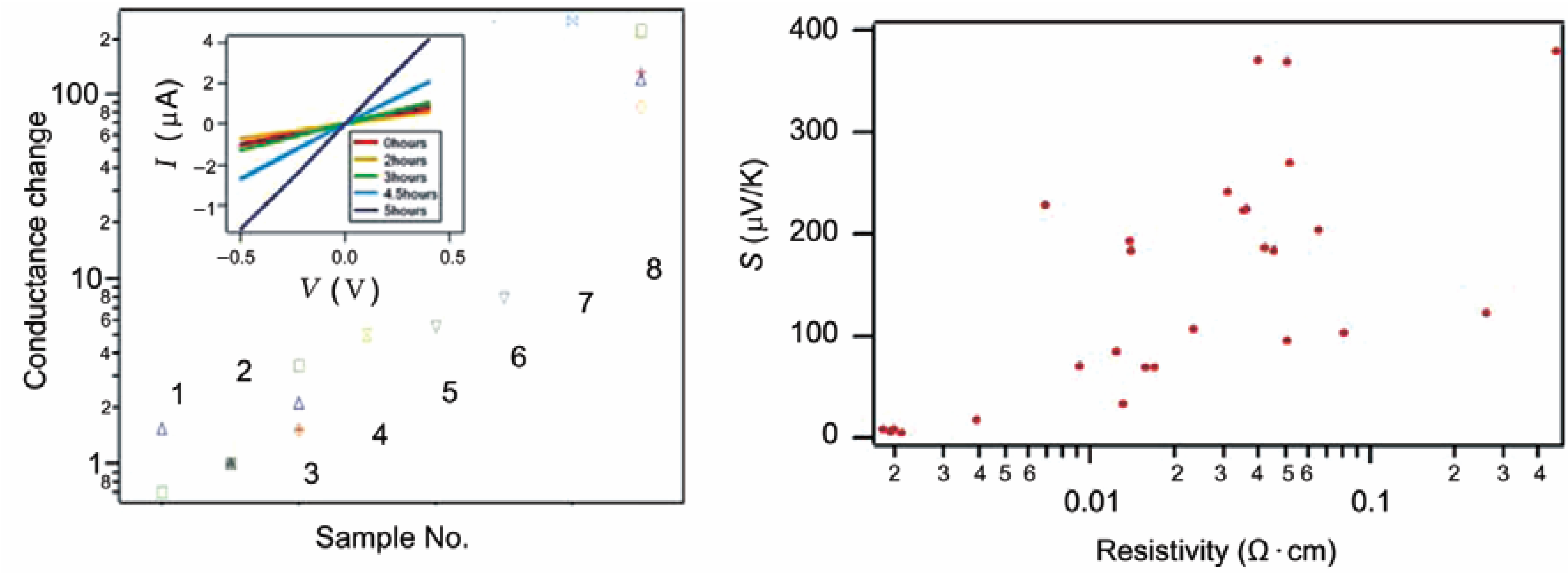
Electrical Studies



Thermal conductivity of a single PbSe nanowire as a function of the temperature.

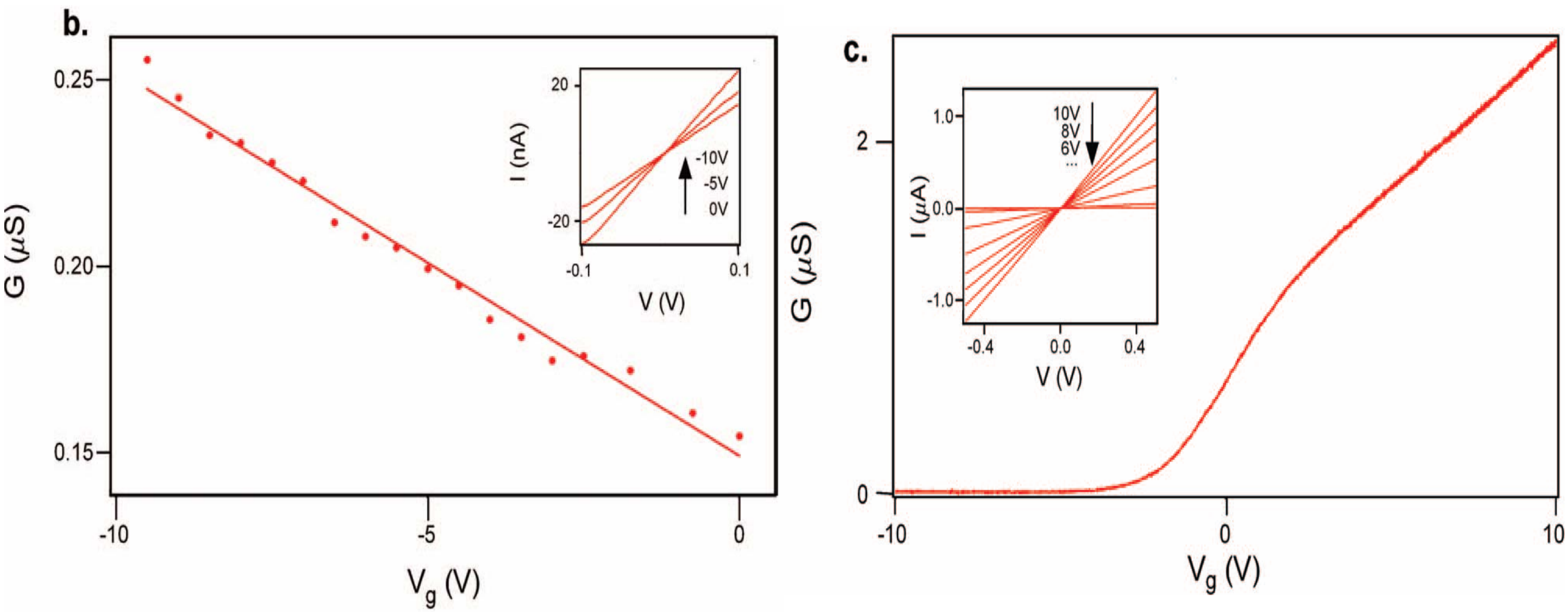
Inset: SEM image of the measured device

Electrical conductivity and Seebeck studies



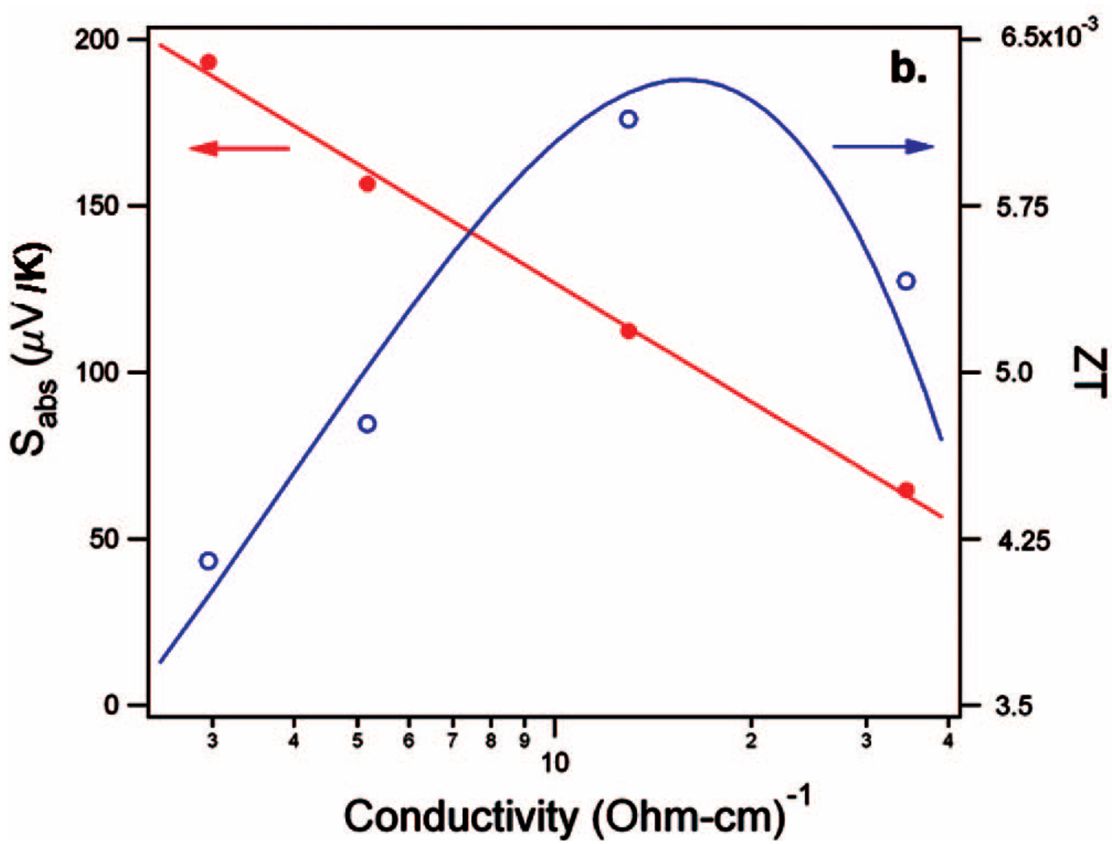
Thermoelectrical measurements of the PbSe nanowire devices after thermal annealing. (a) Ratio of conductivity change under the following annealing conditions. Sample #1. before annealing; #2. 180 °C, 2 h; #3. 180 °C, 10 h; #4. 200 °C, 0.5 h; #5. 200 °C, 1 h; #6. 200 °C, 4 h; #7. 200 °C, 7 h; #8. 250 °C, 7 h. Inset: I–V curves of a single PbSe nanowire annealed at 200 °C for different durations. (b) Seebeck coeffi cient of annealed nanowires as a function of their resistivity.

Electrical Studies



(b) Conductance of a as-synthesized single PbSe nanowire as a function of gate voltage (Vg). Inset: I-V behavior of the same PbSe nanowire taken at Vg) -10, -5, and 0 V. (c) Conductance of a single PbSe nanowire coated with Al_2O_3 as a function of Vg. Inset: I-V behavior of the same coated nanowire at Vg) 10, 8, 6, 4, 2, 0, and -2 V.

Thermoelectric Studies



Thermoelectric power and figure-of-merit of an individual Al_2O_3 coated PbSe nanowire. Seebeck coefficient (red) and the estimated room temperature ZT (blue) as a function of the nanowire conductivity, defined by the applied gate voltage.

Summary

- *A novel strategy to control the thermoelectric properties of individual PbSe nanowires using a field-effect gated device.*

- *Tuned the Seebeck coefficient of single PbSe nanowires from 64 to 193* $\mu V \cdot K^{-1}$.

- *This is the first demonstration of field effect modulation of the thermoelectric figure of merit in a single semiconductor nanowire.*

- *This novel strategy for thermoelectric property modulation especially important in optimizing the thermoelectric properties of semiconductors where reproducible doping is difficult to achieve.*

Thank You