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

Material Challenges for Clean Energy in the New Millennium

-M.S. Dresselhaus
Massachusetts Institute of Technology
The Energy Revolution

Material Challenges for Clean Energy in the New Millennium
-M.S. Dresselhaus
Massachusetts Institute of Technology

2008
14 Terawatts

2050
30 Terawatts
**THERMOELECTRIC DEVICES**
for energy conversion and conservation

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

- **Seebeck Coefficient**
- **Conductivity**
- **Temperature**
- **Thermal Conductivity**

**ZT \sim 3** for desired goal

**Difficulties in increasing ZT in bulk materials:**

\[S \uparrow \iff \sigma \downarrow\]

\[\sigma \uparrow \iff S \downarrow \text{ and } \kappa \uparrow\]

⇒ **A limit to Z is rapidly obtained in conventional materials**

⇒ **So far, best bulk material** \((\text{Bi}_{0.5}\text{Sb}_{1.5}\text{Te}_3)\) **has** \(ZT \sim 1\) **at** 300 K

**Low dimensional physics gives additional control:**

- **Enhanced density of states due to quantum confinement effects**
  ⇒ **Increase** \(S\) **without reducing** \(\sigma\)
- **Boundary scattering at interfaces can reduce** \(\kappa\) **more than** \(\sigma\)
- **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 µV·K⁻¹.

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

I. $0.76 \text{ g Pb(acac)}_2 \cdot 3\text{H}_2\text{O}$
   +
   $2 \text{ mL oleic acid/10 mL DPE}$
   $\rightarrow$ $150^\circ\text{C}/30 \text{ min.}$
   $\rightarrow$ $\text{Pb oleate}$

II. $\text{Pb oleate}$
   $\rightarrow$ $4 \text{ mL of 0.16 M TOPSe/TOP}$
   $\rightarrow$ $15 \text{ mL of DPE/250^\circC}$
   $\rightarrow$ $\text{PbSe}$

III. $\text{PbSe}$
   $\rightarrow$ $\text{Al}_2\text{O}_3$
   $\rightarrow$ $\text{PbSe@Al}_2\text{O}_3$
   $\rightarrow$ $700\text{mTorr N}_2$
   $\rightarrow$ $250^\circ\text{C}/4\text{h}$

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

Thermoelectrical 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
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 coefficient of annealed nanowires as a function of their resistivity.
(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 Al₂O₃ 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 power and figure-of-merit of an individual $\text{Al}_2\text{O}_3$ 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·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