2020 UCR/HBCU Joint Kickoff Meeting

Ceramic-based Ultra-High-Temperature Thermocouples in Harsh Environments

DE-FOA-0002193

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Collaborating with

Department of Chemical Engineering, University of Wyoming

October 21, 2020

Outline

1. Introduction of Project Team Members
2. Short Background on Thermocouples
3. Discussion of Technical Aspects of the Project
4. Comments and Questions

Project Team: Members

Morgan State University

- Yucheng Lan (PI).
- Numbers of grad: 1; Numbers of undergrad: 2.

University of Wyoming

- Dr. Hertanto Adidharm (co-PI) and Dr. Maohong Fan (co-PI)
- Numbers of student: 1

Project Team: Related Previous Work on Thermoelectrics

Science AAAS

High-Thermoelectric Performance of Nanostructured Bismuth Antimony Telluride Bulk Alloys
Bed Poudel, *et al.*
Science **320**, 634 (2008);
DOI: 10.1126/science.1156446

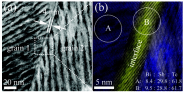
NANO LETTERS

Letter

Structure Study of Bulk Nanograined Thermoelectric Bismuth Antimony Telluride

Yucheng Lan, Bed Poudel, Yi Ma, Dezhi Wang, Mildred S. Dresselhaus, Gang Chen, and Zhifeng Ren

Nano Lett., **2009**, 9 (4), 1419-1422• DOI: 10.1021/nl803235n • Publication Date (Web): 25 February 2009



PRL **102,** 196803 (2009) PHYSICAL REVIEW LETTERS week ending 15 MAY 2009

Increased Phonon Scattering by Nanograins and Point Defects in Nanostructured Silicon with a Low Concentration of Germanium

G. H. Zhu,[1] H. Lee,[2] Y. C. Lan,[1] X. W. Wang,[1] G. Joshi,[1] D. Z. Wang,[1] J. Yang,[1] D. Vashaee,[3] H. Guilbert,[1] A. Pillitteri,[1] M. S. Dresselhaus,[4] G. Chen,[2,*] and Z. F. Ren[1,*]

[1]*Department of Physics, Boston College, Chestnut Hill, Massachusetts 02467, USA*
[2]*Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
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[4]*Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*

(Received 26 November 2008; published 14 May 2009)

The mechanism for phonon scattering by nanostructures and by point defects in nanostructured silicon (Si) and the silicon germanium (Ge) alloy and their thermoelectric properties are investigated. We found that the thermal conductivity is reduced by a factor of 10 in nanostructured Si in comparison with bulk crystalline Si. However, nanosize interfaces are not as effective as point defects in scattering phonons with wavelengths shorter than 1 nm. We further found that a 5 at. % Ge replacing Si is very efficient in scattering phonons shorter than 1 nm, resulting in a further thermal conductivity reduction by a factor of 2, thereby leading to a thermoelectric figure of merit 0.95 for $Si_{95}Ge_5$, similar to that of large grained $Si_{80}Ge_{20}$ alloys.

DOI: 10.1103/PhysRevLett.102.196803 PACS numbers: 73.50.Lw, 84.60.Rb, 85.80.Fi

Materials Views www.MaterialsViews.com ADVANCED FUNCTIONAL MATERIALS www.afm-journal.de

FEATURE ARTICLE

Enhancement of Thermoelectric Figure-of-Merit by a Bulk Nanostructuring Approach

By *Yucheng Lan, Austin Jerome Minnich, Gang Chen,** and *Zhifeng Ren**

Recently a significant figure-of-merit (*ZT*) improvement in the most-studied existing thermoelectric materials has been achieved by creating nanograins and nanostructures in the grains using the combination of high-energy ball milling and a direct-current-induced hot-press process. Thermoelectric transport measurements, coupled with microstructure studies and theoretical modeling, show that the *ZT* improvement is the result of low lattice thermal conductivity due to the increased phonon scattering by grain boundaries and structural defects. In this article, the synthesis process and the relationship between the microstructures and the thermoelectric properties of the nanostructured thermoelectric bulk materials with an enhanced *ZT* value are reviewed. It is expected that the nanostructured materials described here will be useful for a variety of applications such as waste heat recovery, solar energy conversion, and environmentally friendly refrigeration.

where S, σ, κ, and T are the Seebeck coefficient, the electrical conductivity, the thermal conductivity, and the absolute temperature at which the properties are measured, respectively. The efficiency of a thermoelectric device is directly related to ZT. For power generation, the efficiency is

$$\eta = \frac{T_h - T_c}{T_h} \frac{\sqrt{1+Z\overline{T}} - 1}{\sqrt{1+Z\overline{T}} + T_c/T_h} \quad (2)$$

and for air-conditioning and refrigeration, the coefficient of performance is

$$COP = \frac{T_c}{T_h - T_c} \frac{\sqrt{1+Z\overline{T}} - T_h/T_c}{\sqrt{1+Z\overline{T}} + 1} \quad (3)$$

pnas.org/content/110/33/13261

PNAS Proceedings of the National Academy of Sciences of the United States of America

Keyword, Author, or DOI

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NEW RESEARCH IN Physical Sciences | Social Sciences

RESEARCH ARTICLE

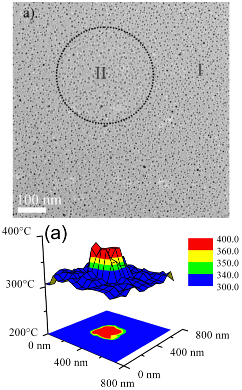
High thermoelectric performance by resonant dopant indium in nanostructured SnTe

Qian Zhang, Bolin Liao, Yucheng Lan, Kevin Lukas, Weishu Liu, Keivan Esfarjani, Cyril Opeil, David Broido, Gang Chen, and Zhifeng Ren

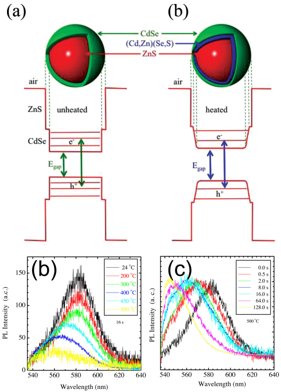
PNAS August 13, 2013 110 (33) 13261-13266; https://doi.org/10.1073/pnas.1305735110

Edited* by Ching-Wu Chu, University of Houston, Houston, TX, and approved July 5, 2013 (received for review March 25, 2013)

Project Team: Related Previous Work on Thermosensing



Ag-base thermosenors at nanoscale.



CdS-based thermal history sensing.

Thermal sensors.

Project Team: Facilities at Morgan

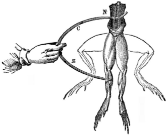
Setaram TAG 24-24 simultaneous digital thermoanalyzer.

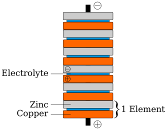
- Hitachi S-5500 cold field-emission scanning electron microscope.
- Physical Property Measurement System (PPMS).
- Scintag PAD-V high precision automated X-ray diffractometer, Rigaku MiniFlex desktop X-ray diffractometer.
- Atomic force microscopes (AFM).
- LECO HR-1B-2 hydrothermal system.

Project Team: Facilities at UW

- FEI G2-F20 TEM.
- FEI FEG450 SEM with EDS.
- DXR2Xi Raman Imaging Microscope.
- SmartLab X-ray diffractometer.
- MFP-3D Origin AFM.
- Thermogravimetric Analyzers (TGA).

Background: Thermoelectrics





Luigi Galvani (1737 – 1798) and experiment frog legs.

Alessandro Volta (1745 – 1827) and a voltaic pile.

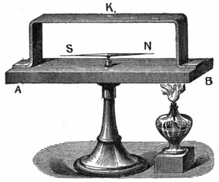
Italian physicist. Pioneer of bioelectricity.

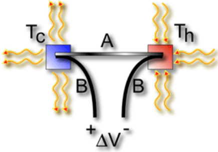
Italian physicist and chemist. Pioneer of electricity and power.

en.wikipedia.org

Background: Seebeck Effect

Thomas Johann Seebeck (1770 – 1831). German physicist. Discover of thermoelectric effects.

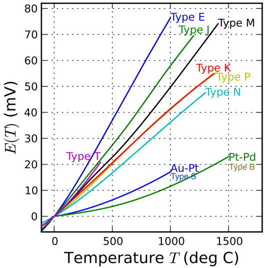


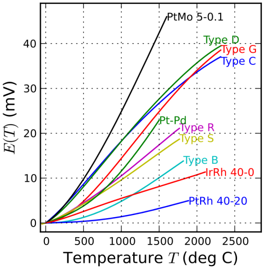


$$\Delta V = S(T_h - T_c)$$

S: Seebeck coefficient; V: electromotive force (Seebeck voltage); T_h: temperature of hot end; T_c: temperature of cold end.

Background: Alloy-based Thermocouples





Type	Combination*	T
E	chromel – constantan	-50 – 740
J	Fe – constantan	-40 - 750
K	chromel – alumel	-200 - 1350
M	82%Ni / 18%Mo – 99.2%Ni / 0.8%Co	1400
N	Nicrosil / Nisil	-270 – 1300
T	copper – constantan	-200 – 350

*: by weight. T: Temperature range ($^\circ$C).

Type	Combination*	T
B	70%Pt / 30%Rh – 94%Pt / 6%Rh	50 - 1820
R	87%Pt / 13%Rh – Pt	0 - 1600
S	90%Pt / 10%Rh – Pt	630 - 1600
C	95%W/5%Re – 74%W/26%Re	2329
D	97%W/3%Re – 75%W/25%Re	2490
G	W – 74%W/26%Re	2,300
P	55%Pd/31%Pt/14%Au – 65%Au/35%Pd	500 – 1400

*: by weight. T: Temperature range ($^\circ$C).

instrumentationtools.com; en.wikipedia.org

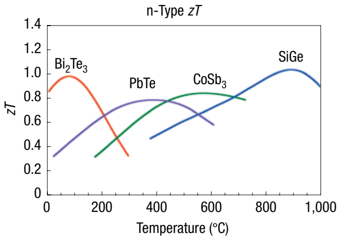
Background: High-Temperature Alloy-based Thermocouple Assemblies

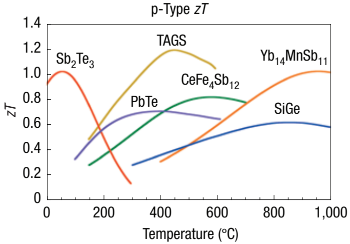
- Cost. Noble metals, such as Pt and Rh, are used.
- Slow responsive.
- Bulky.

Background: Seebeck Coefficient and Semiconducting Thermoelectric Materials

$$S = \frac{8\pi^2\kappa_B^2}{3eh^2} m^* T \left(\frac{\pi}{3n}\right)^{2/3}$$

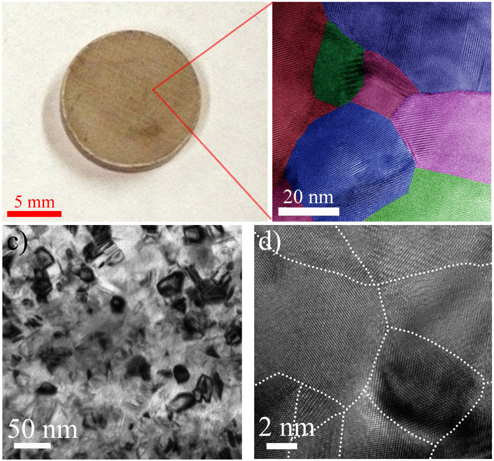
- S is Seebeck efficient.
- κ_B is the Boltzmann constant.
- m^* is the effective mass the carrier.
- T is temperature.
- e is the unit charge.
- h is the Planck's constant.
- n is the carrier concentration.





Snyder and Toberer, Nat. Mater. **7** (2008) 105; M. Cutler, *et al.*, Phys. Rev. **133** (1964) A1143.

Background: Advanced Semiconducting Thermoelectric Materials



Nanostructered thermoelectric materials.

- Top: Bi_2Te_3 thermoelectric nanocomposites with its microstructurres.
- Bottom: Microstructures of $Si_{95}Ge_5$ thermoelectric nanocomposites.

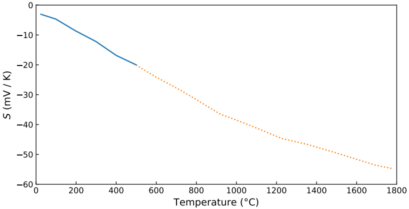
Adv. Func. Mater. **20** (2010) 357; Phy. Rev. Lett. **12** (2009) 196803; Nano. Lett. **9** (2009) 1419.

Project: Goals and Potential Significance of Results

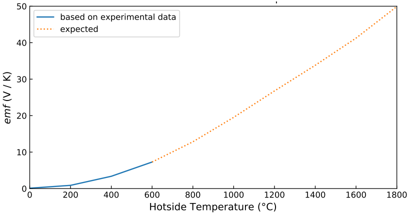
A new kind of semiconducting thermocouples working in harsh environments:

- High stability at high temperature.
- Resistance to oxidization, erosion, and shock.
- Simple structure and easy maintenance.
- Low Cost.

Project: Semiconducting Thermoelectric Ceramic



Seebeck coefficient S of proposed semiconducting ceramic.

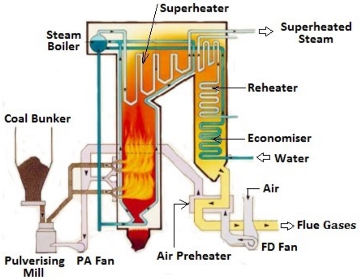


Predicated *emf* of proposed thermocouples.

Working at high temperatures, with high chemical stability and high erosion resistance.

Project: Relevancy to Fossil Energy

Bowen Steam Plant. A coal-fired power station in Georgia.



Pulverized coal-fired boiler in thermal-power-plants.

- Coal combustion at $1,300 - 1,700\ ^\circ\mathrm{C}$.
- Coal-fired thermal power plant: emit CO_2, SO_2, NO_x, solid waste under high temperature / high pressure.
- Overall coal plant efficiency: $32 - 42$ %. Efficiency: $35 - 38$ % at $570\ ^\circ\mathrm{C}$ and 170 bar, 42 % at $600\ ^\circ\mathrm{C}$ and 220 bar, 48 % at $600\ ^\circ\mathrm{C}$ and 300 bar.

Thermal sensors work under harsh environment to control temperature accurately. The proposed thermocouples will be good substitutes.

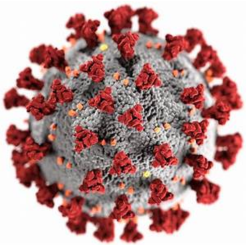
en.wikipedia.org; coalhandlingplants.com

Project: Milestones and Schedule

- Ceramic *synthesis* and structural *characterization*.
- Seebeck *coefficient* measurements of semiconducting ceramics.
- Fabrication of *thermocouples* and *emf* measurements.
- *Stability* characterization of thermocouples

Budget: $\$$ 500K.

Project: Project Risks and Risk Management Plan



COVID-19 and pandemic

scottcountyiowa.gov

Comments and Questions ?