Enhanced Waste Heat - Energy Conversion Through Nanostructured Thermoelectrics

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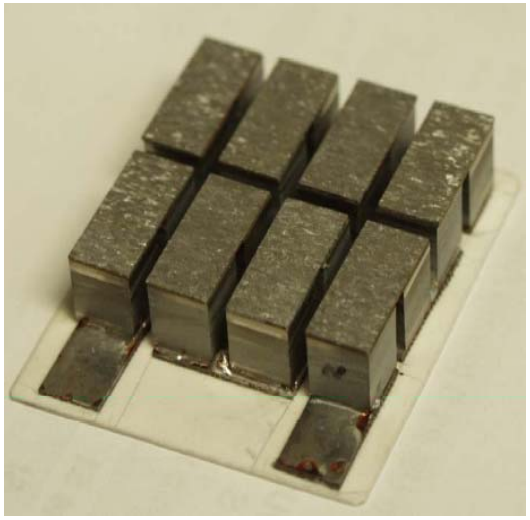
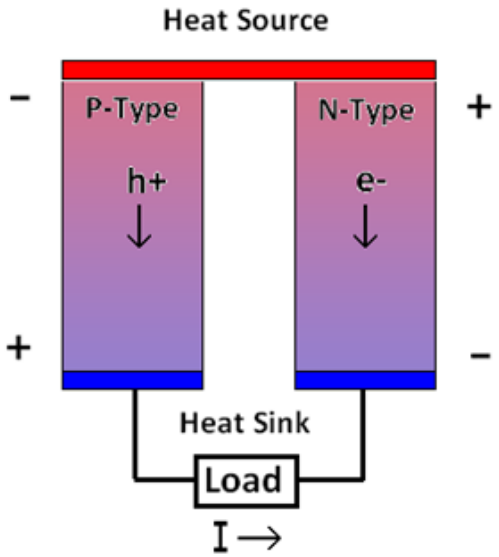
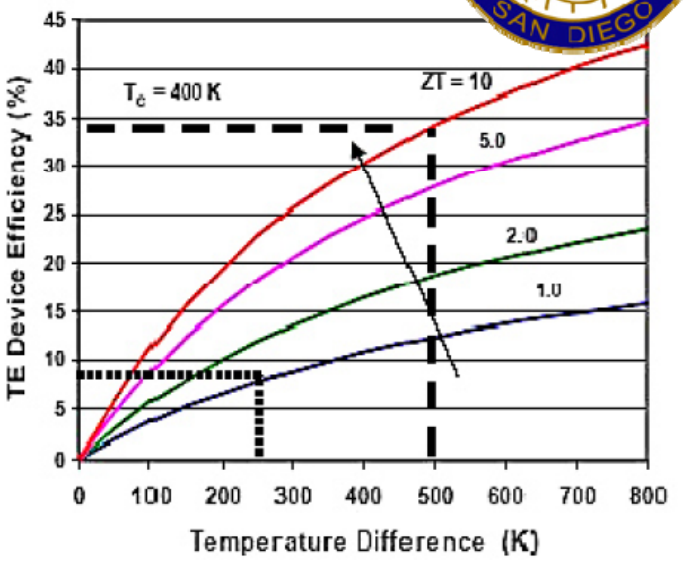
Thermoelectricity



MSU's thermocouple module





T. Hendricks, and W.T. Choate, "Engineering Scoping Study of Thermoelectric Generator Systems for Industrial Waste Heat Recovery", PNNL (2006).

- Solid state conversion of "heat flow" to "electrical current", vice versa.
  - Seebeck effect = Temperature difference induce electron flow

- Assembled as "couple" of P- and N-type legs
- Must also have high σ and low κ

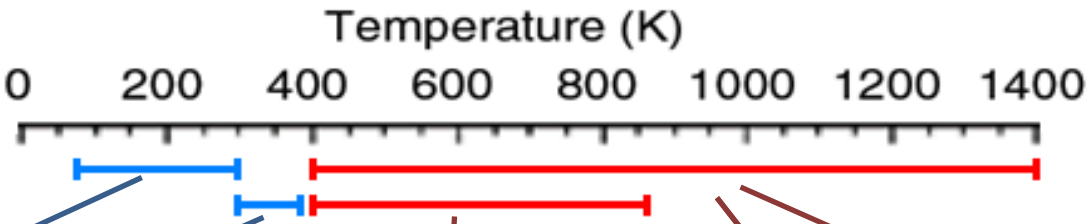
Efficiency:

$$\varepsilon = \left[\frac{T_H - T_C}{T_H}\right]\left[\frac{\sqrt{1+Z\overline{T}}-1}{\sqrt{1+Z\overline{T}}-T_C/T_H}\right]$$

Figure of Merit:

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

Applications



Optoelectronics cooling
Cryogenics application

U.S. DOE: Vehicle Zonal AC. Eliminate R-134A refrigerant

Electronics chip cooling

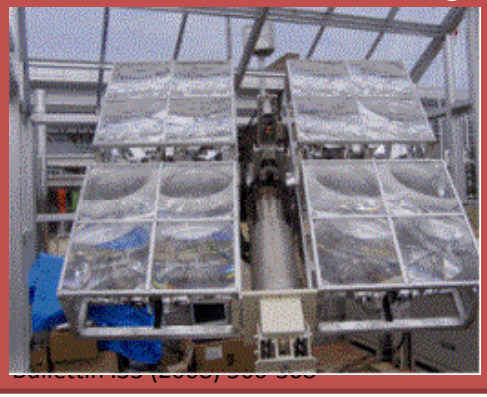
Nextreme's TE spot cooling flip-chip

U.S. DOE goal:
ZT = 1.7 at 700K

U.S. DOE: Vehicle Waste Heat Recovery from exhaust

Hi-Z 330W vehicle exhaust manifold

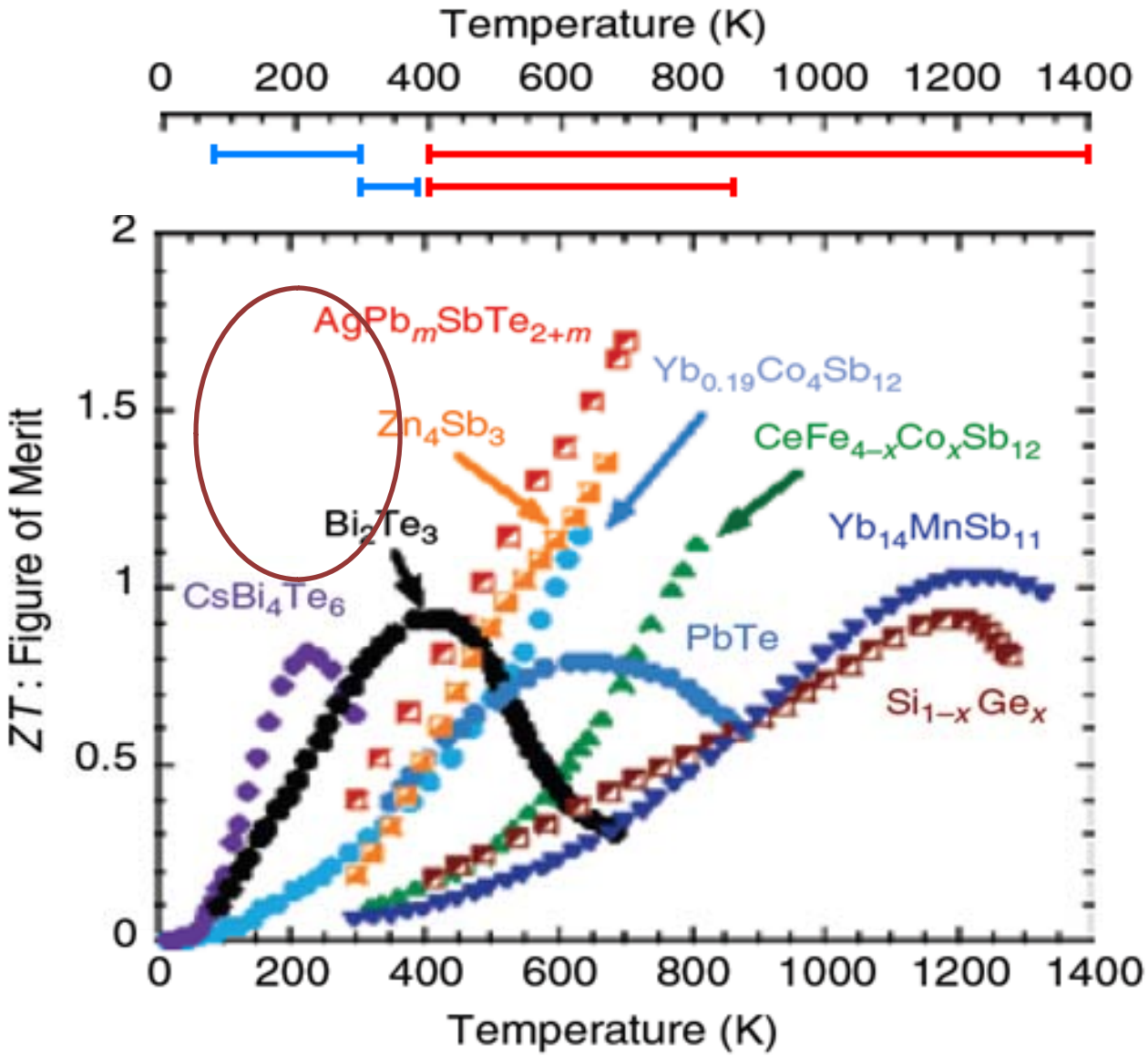
Solar–thermal from IR heating



PNNL: Industrial Waste Heat Recovery from high grade heat source (Aluminum, Glass, Cement processing), and low grade heat source (waste gas)

Nuclear power for healthy heart

Current Technology



T.M. Tritt, H. Bottner, and L. Chen, MRS Bulletin.33 (2008) 366-368

2nd –gen, ZT~1.5
-LAST-m
-Skutterudites
-Zintl phase
Difficult to produce

- Nanostructured material

1st –gen, ZT~1
Commercially available
Binary alloys

Current Technology

Insulator — Semiconductor — Metal

1,000 — 167-180 — 10 uV/K

S

10^{12} — 10^{18} 10^{19} — 10^{22} cm^{-3}

$\sigma = ne\mu$

S and σ mutually related.
Max. $S^2\sigma$ occurs at fixed S.

Challenge: increase σ while preserving S.

Polymer — 2nd 1st — Diamond

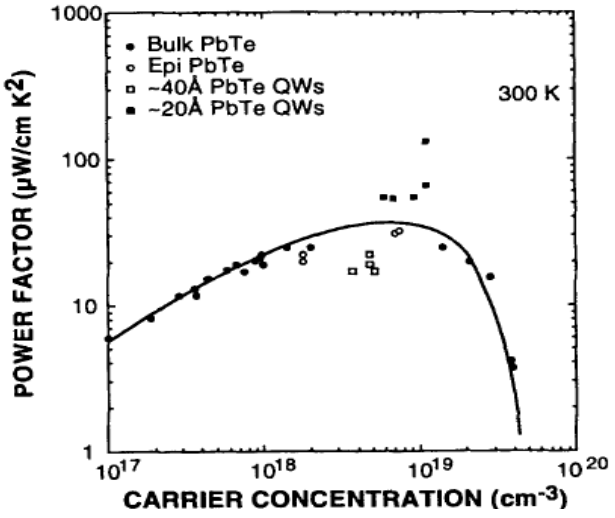
0.01 — 0.2 1-3 — 3000 W/mK

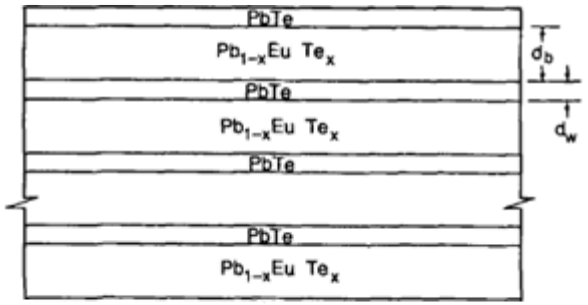
k

2nd-gen material lower k than 1st-gen.
k also reduced by nanostructures.

Nanostructured TE

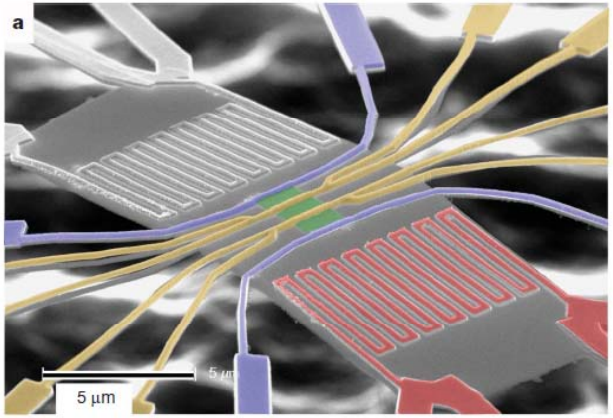
1993: Enhancement of *peak $S^2\sigma$* via electron confinement effect
1996: Enhancement reported in PbTe QWs





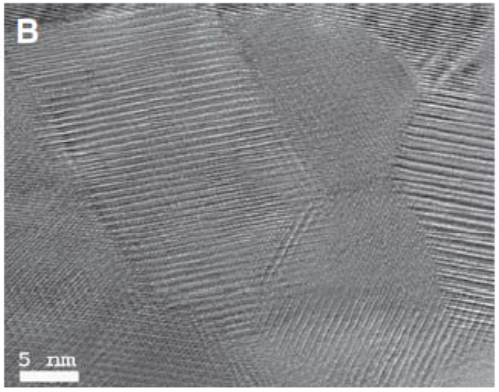
T.C. Harman, D.L. Spears, and M.J. Manfra, Journal of Electronic Materials. 25 (1996) 1121-1127.

2001: *ZT = 2.4 at 300K*, Bi_2Te_3
Superlattice, phonons scattering at layers' interface



2008: *ZT = 1 at 200K*
20 nm Si nanowires
Due to reduced κ

A.I. Boukai, Y. Bunimovich, J. Tahir-Kheli, J.-K. Yu, W.A.G. III, and J.R. Heath, Nature. 451 (2008) 168.

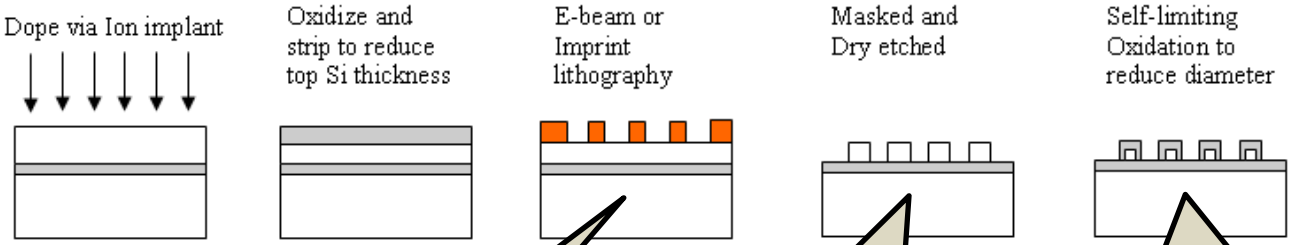


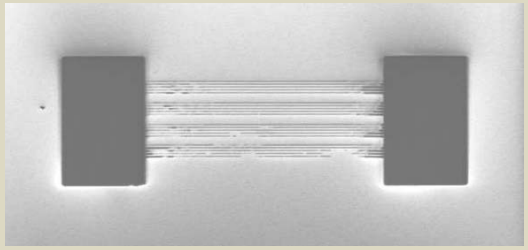
2008: *ZT = 1.4 at 373K*
"nanocrystaline"
BiSbTe

B. Poudel, Q. Hao, Y. Ma, Y. Lan, A. Minnich, B. Yu, X. Yan, D. Wang, A. Muto, D. Vashaee, X. Chen, J. Liu, M.S. Dresselhaus, G. Chen, and Z. Ren, Science. 320 (2008) 634.

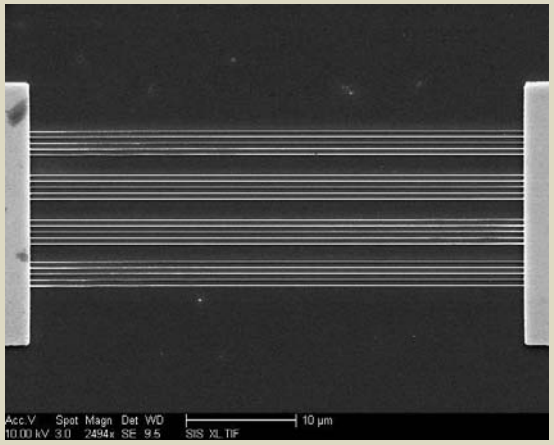
Fabrication of Si NWs

- Reduced κ has been demonstrated, but $S^2\sigma$ enhancement not yet observed
- Our calculation indicates sub 5 nm wires needed
- Standard semiconductor lithographic technique used to fabricates nanowires

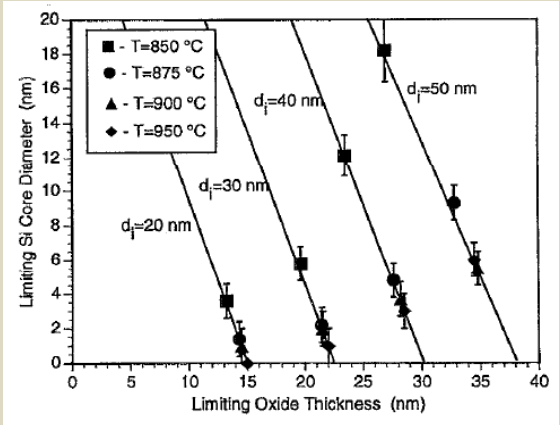




Nano Imprint Lithography for large-scale reproduction



40 nm Si wires on SiO_2 substrate

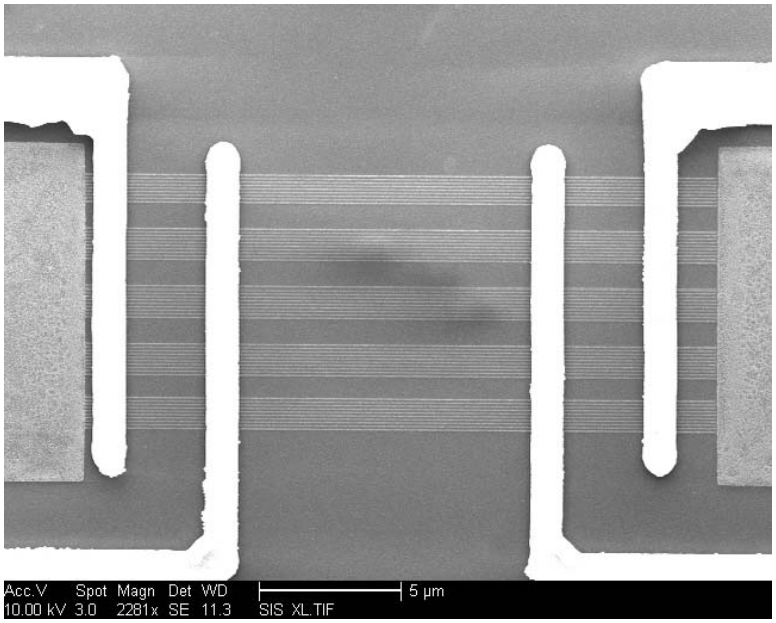


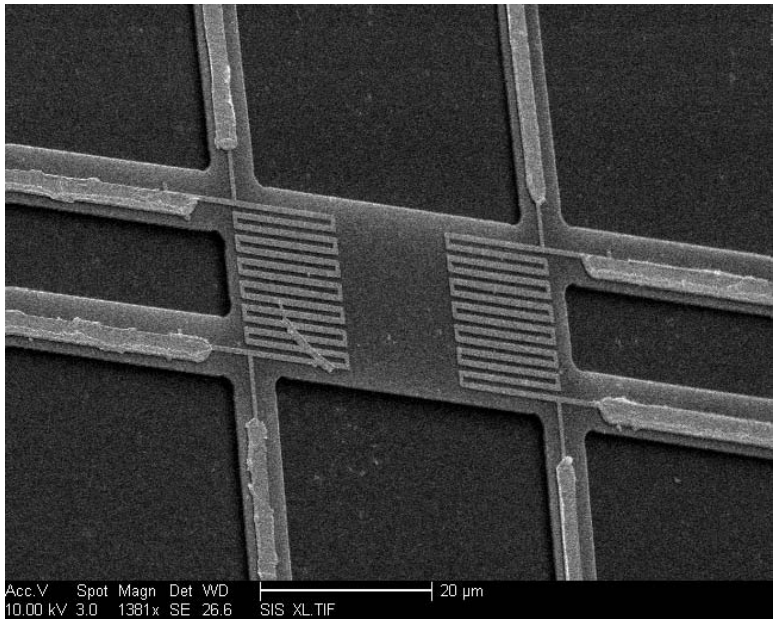
Sub 5 nm wire obtained by self-limiting oxidation under 950 ˚C

Measurement

Preliminary resistance measurement have been done, but metallization is an issue.

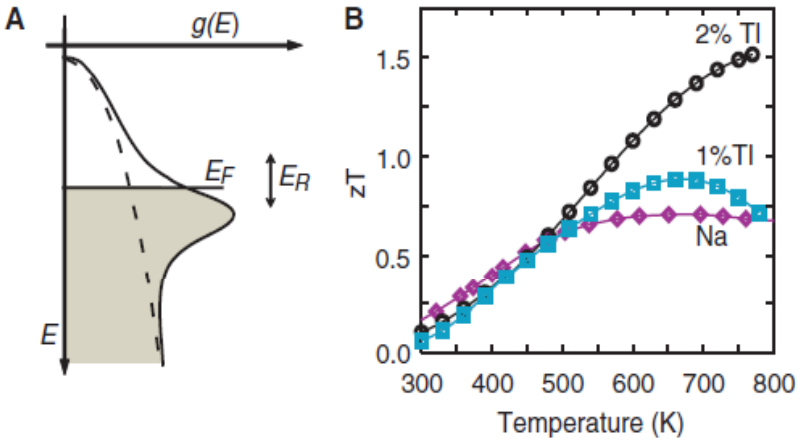
Micro Ni heater has been tested for use in Seebeck measurement.





TE properties of Dilute Ni III-VI

2008: Addition of Tl significantly changed PbTe's electronic structure resulting in large increase in peak $S^2\sigma$.

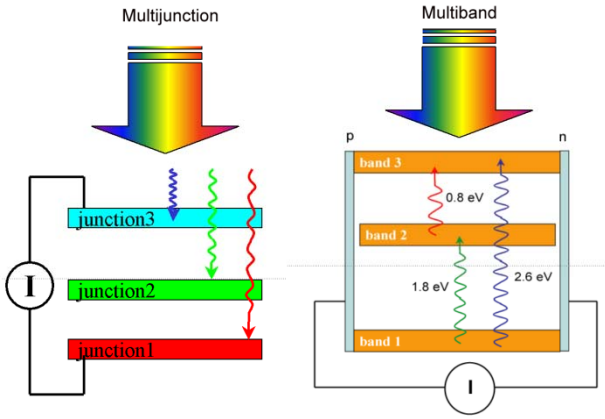


J.P. Heremans, V. Jovovic, E.S. Toberer, A. Saramat, K. Kurosaki, A. Charoenpakdee, S. Yamanaka, and G.J. Snyder, Science. 321 (2008) 554.

Dilute Nitride grown by MBE of Prof. Charles Tu (UCSD-ECE) group.

Addition of Nitrogen has similar effect in III-VI semiconductor (GaAs, GaP). "Dilute Nitride" can increase photo absorption and the efficiency of solar cell.

Nitrogen "level" create "multi band" material that mimics multi junction solar cell.



Last word

Advantage of TE technology:

Solid state -
1. Reliable/Maintenance free
2. Scalable
3. Silent
4. Reversible functionality

Problem: Materials not efficient enough. Require ZT~2.

There are available materials but no reproducible on a large scale yet.

Use of nanostructures is one approach to increasing ZT.

Promise of higher ZT by increasing power factor or reduce k.

Trade chemical complexity for a physical complexity

Si nanowire: No Ge. “Cheaper”

Problem with integration, production – just like most nanodevices.