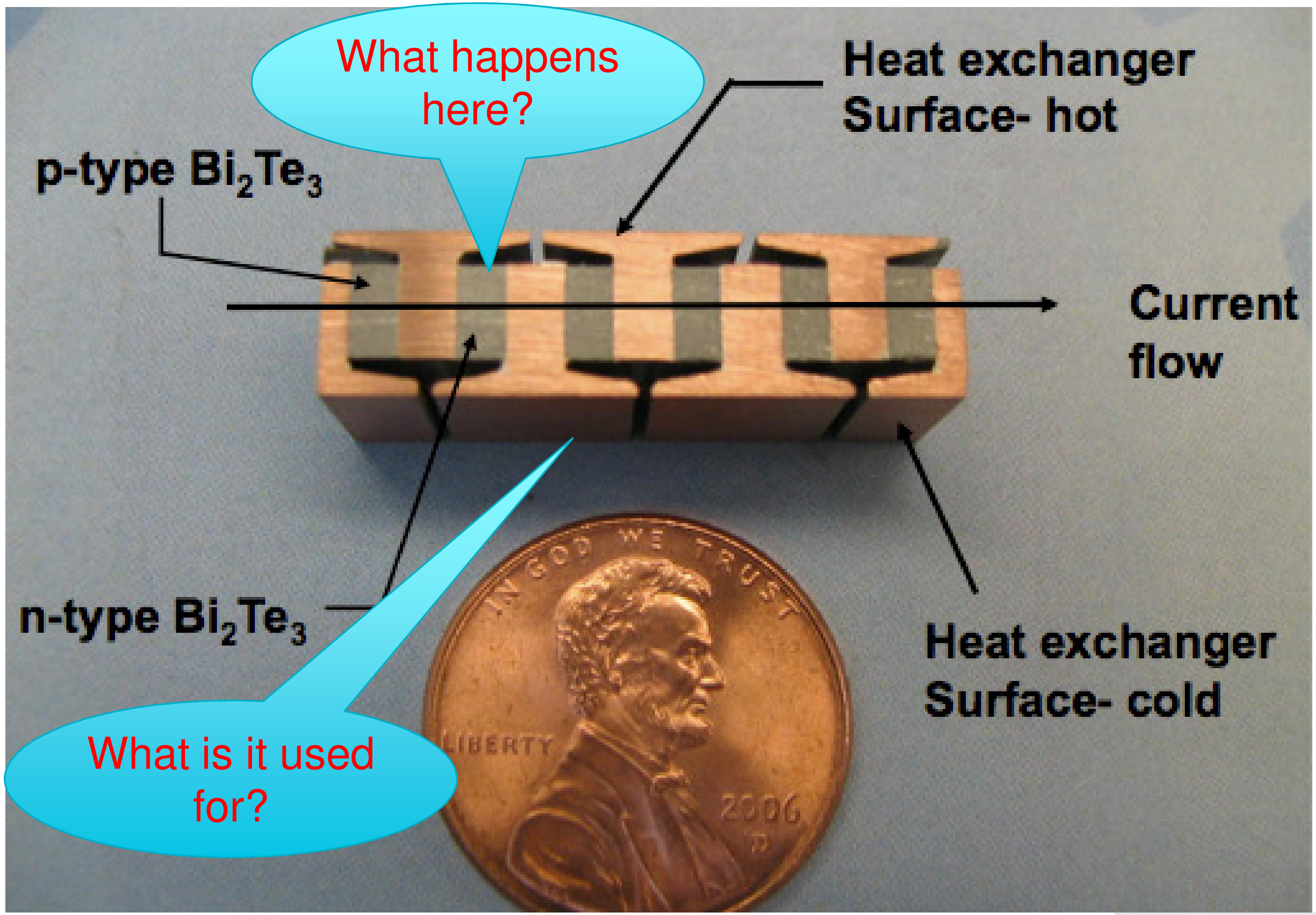
Thermoelectrics



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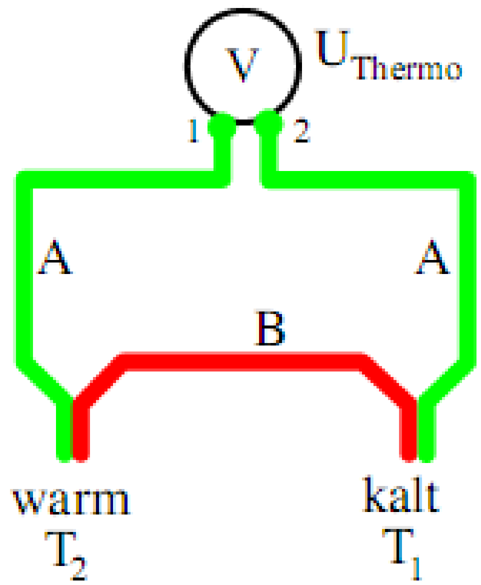
What is the relation between temperature and electricity?

Experiment: Thermo-voltages



Observations:

- DC voltage is generated
- Electrical polarity depends on the temperature polarity
- Voltage is proportional to the temperature difference
- Proportionality depends on both materials connected

$$U = (S_A - S_B)(T_1 - T_2)$$

Seebeck-coefficient

Electrical measurement of temperature differences

Offset voltage in many electrical measurements

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Origin of thermovoltages

Imbalance of the temperature dependence of the work function

Electrical current and heat current

Validity of Ohm's law:

electrical field

$$\boxed{F = \frac{j}{\sigma}}$$

current density

electrical conductivity

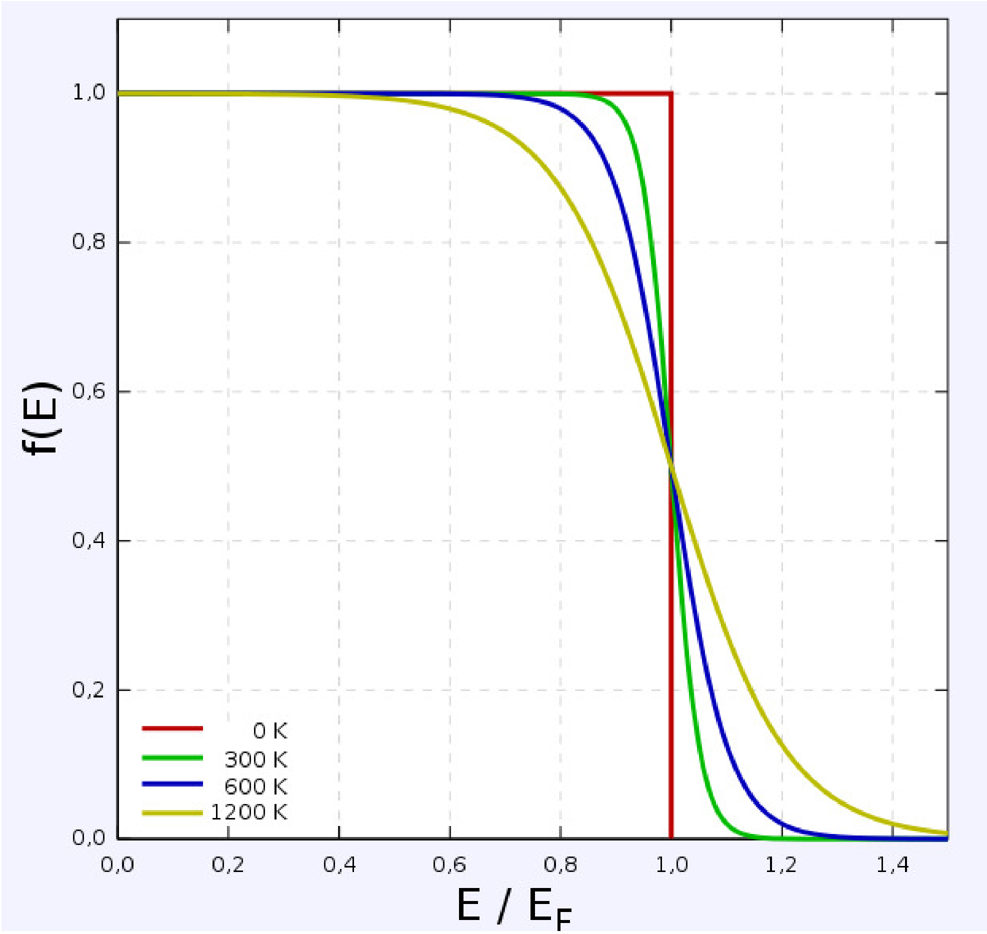
Electrons in electrical conductors have
- a certain kinetic energy and momentum
- different directions of propagation
- a distribution of different momentum

Electrical current microscopically means:
- charges are accelerated in an electrical field
- scattering events stops the accelerated motion quickly
- the equal distribution of all directions of propagation is disturbed
- the center of all electrons is moving slowly through the conductor

Distribution of energies of the electrons

A temperature gradient or a gradient of the electrochemical potential moves the charges resulting in an electrical field opposite to the external field

$$F = \frac{j}{\sigma} + S \cdot \frac{dT}{dz} - \frac{1}{e} \cdot \frac{d\mu}{dz}$$



Seebeck-effekt ("Thermoforce", thermo-voltage) is created by thermal diffusion of charges

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How can you boil you soup?

- With electrons
  Scattering and diffusion forms
  a Fermi-Dirac distribution

$$f(E) = \frac{1}{\exp\left(\frac{E - E_F}{k_B T}\right) + 1}$$

- With phonons
  Scattering and diffusion forms
  a Bose-Einstein distribution

$$n(q) = \frac{1}{\exp\left(\frac{\hbar\omega_q}{k_B T}\right) - 1}$$

- With photons
  Thermal radiation according to
  Stefan Boltzmann

$$P(T) = \sigma \cdot A \cdot T^4 \cdot \mathrm{Wcm}^{-2}$$

3 ways to transfer heat

How can you boil you soup?

•With electrons

Scattering and diffusion forms a Fermi-Dirac distribution

”Bandgap engineering“
Quantum electronics, semiconductor heterostructures

•With phonons

Scattering and diffusion forms a Bose-Einstein distribution

”Phononic bandgap engineering“

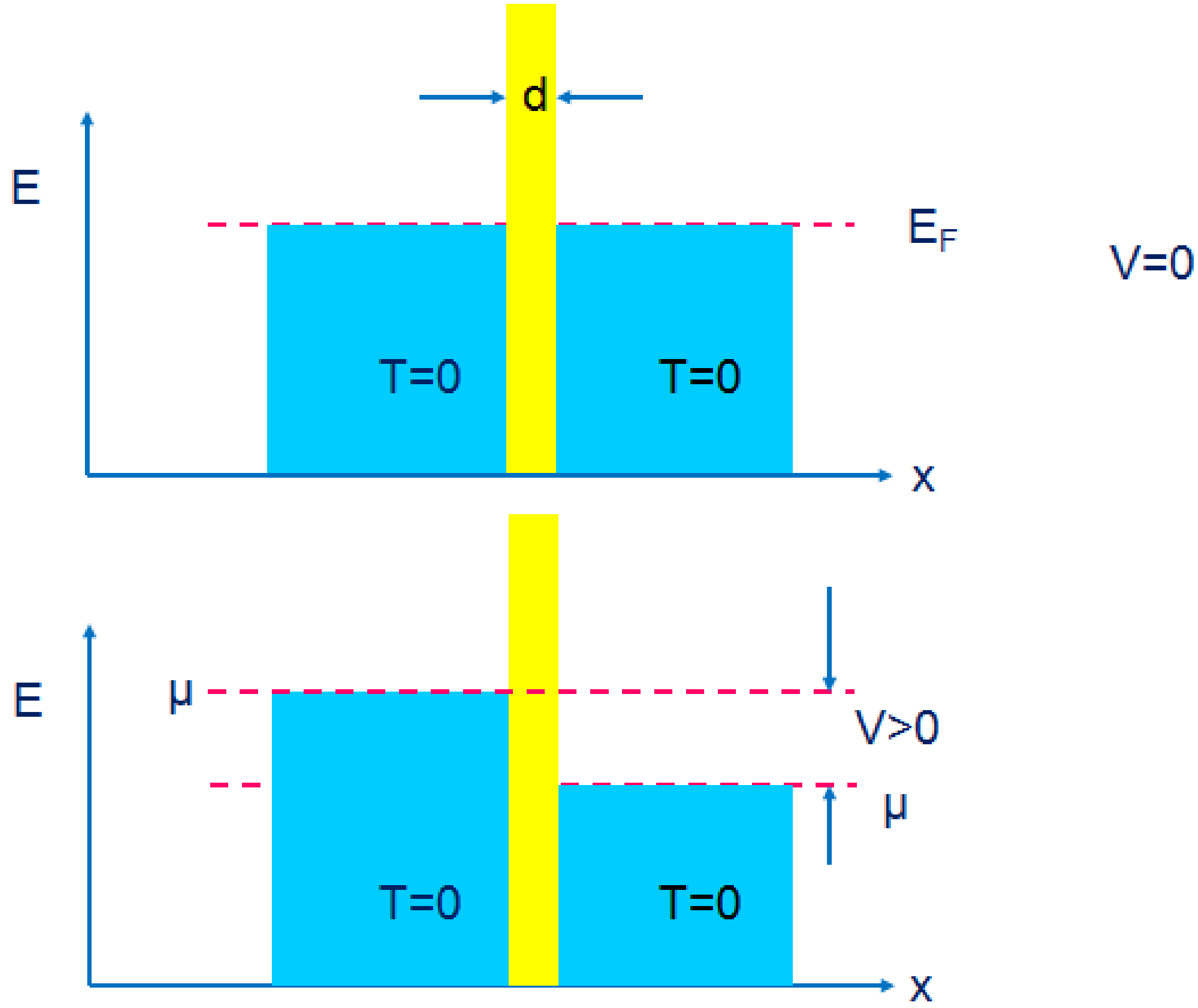
•With photons

Thermal radiation according to Stefan Boltzmann

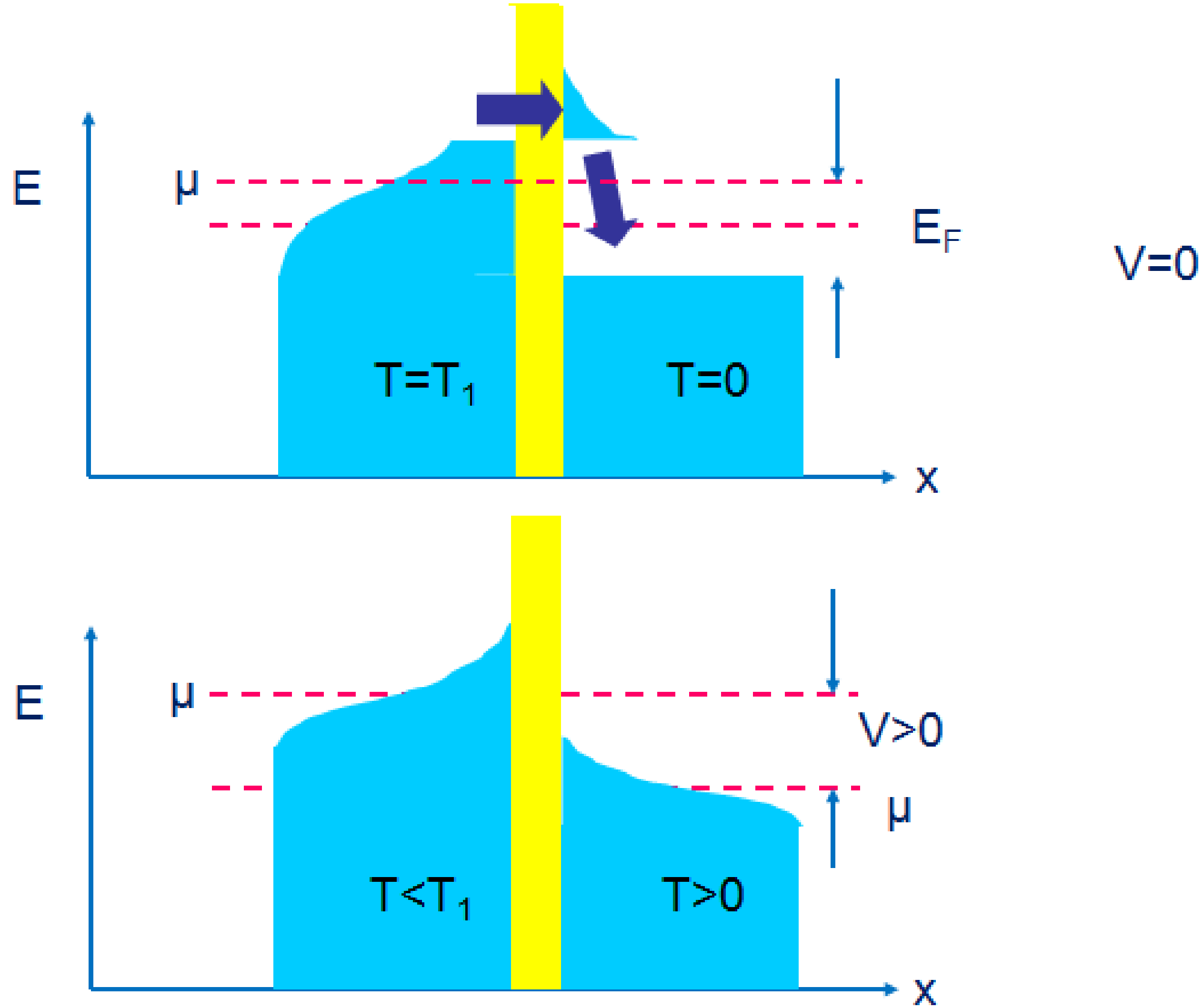
”Photonic bandgap engineering“
Photonic crystal

➡ **Nanotechnology!**

Transport through a tunnel-barrier



Transport through a tunnel-barrier



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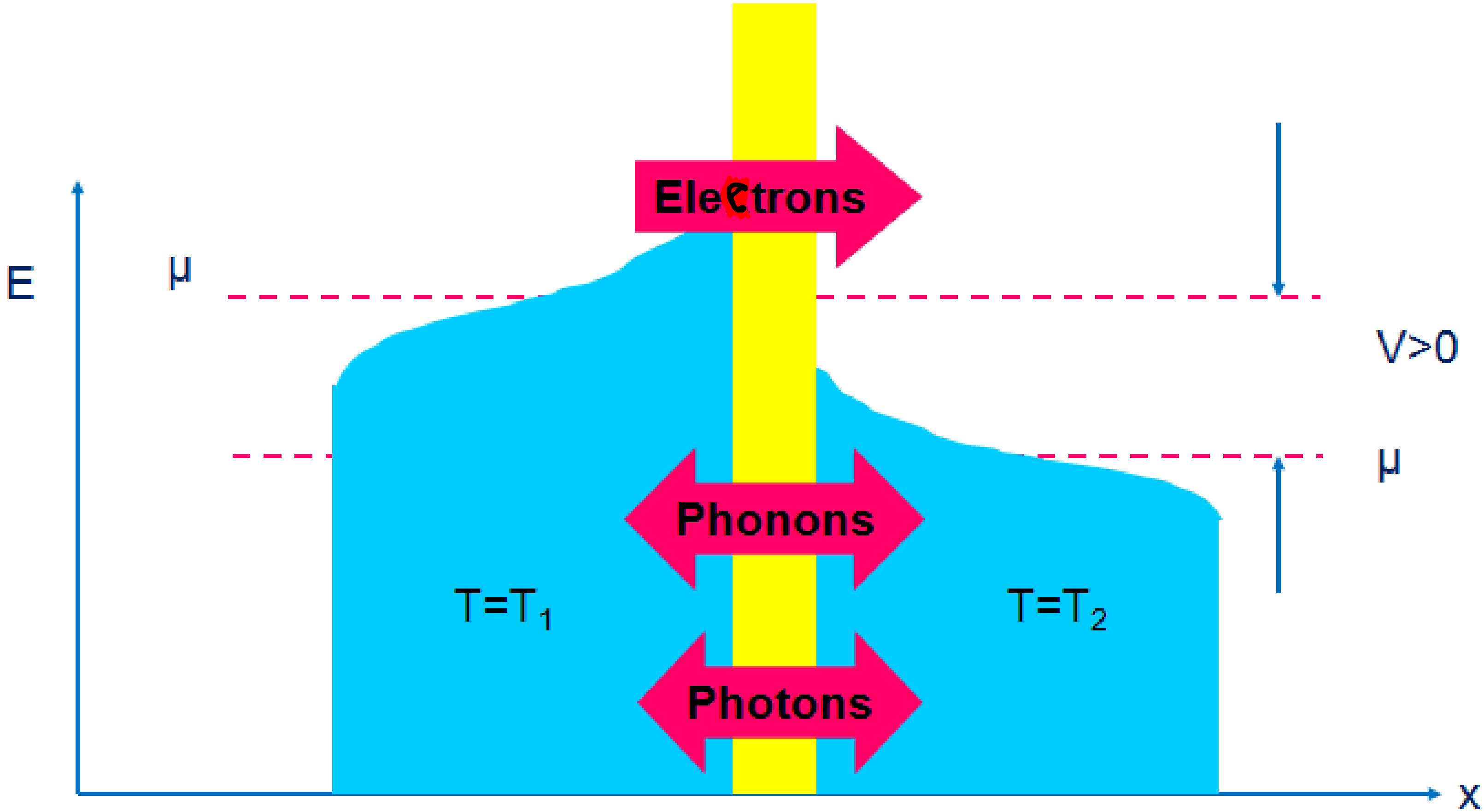
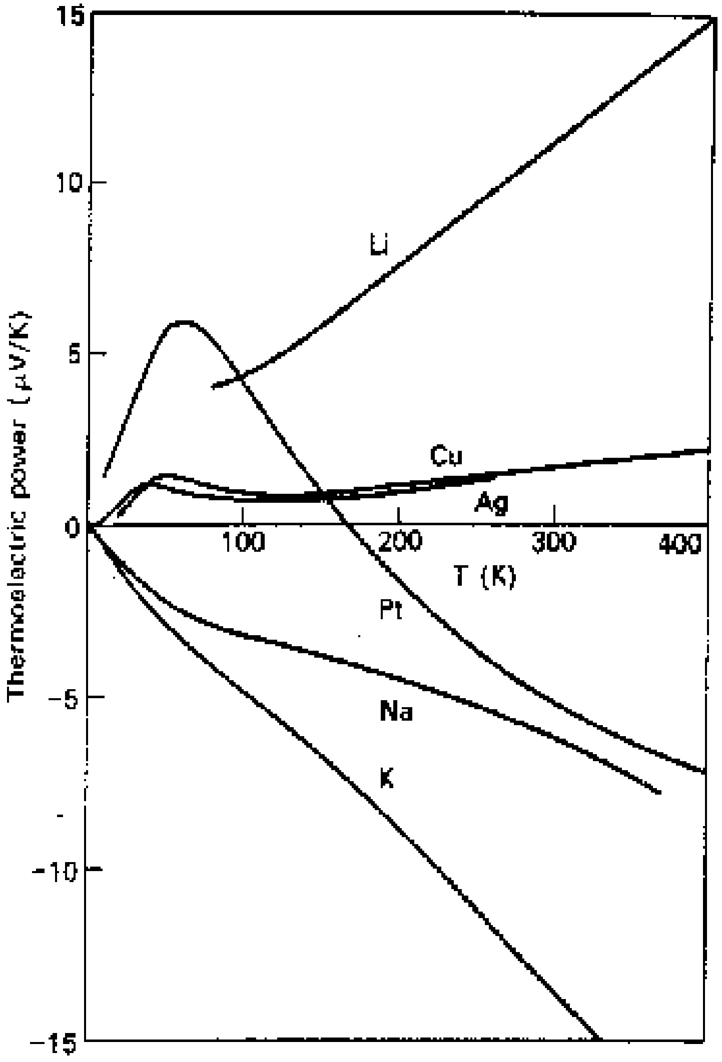
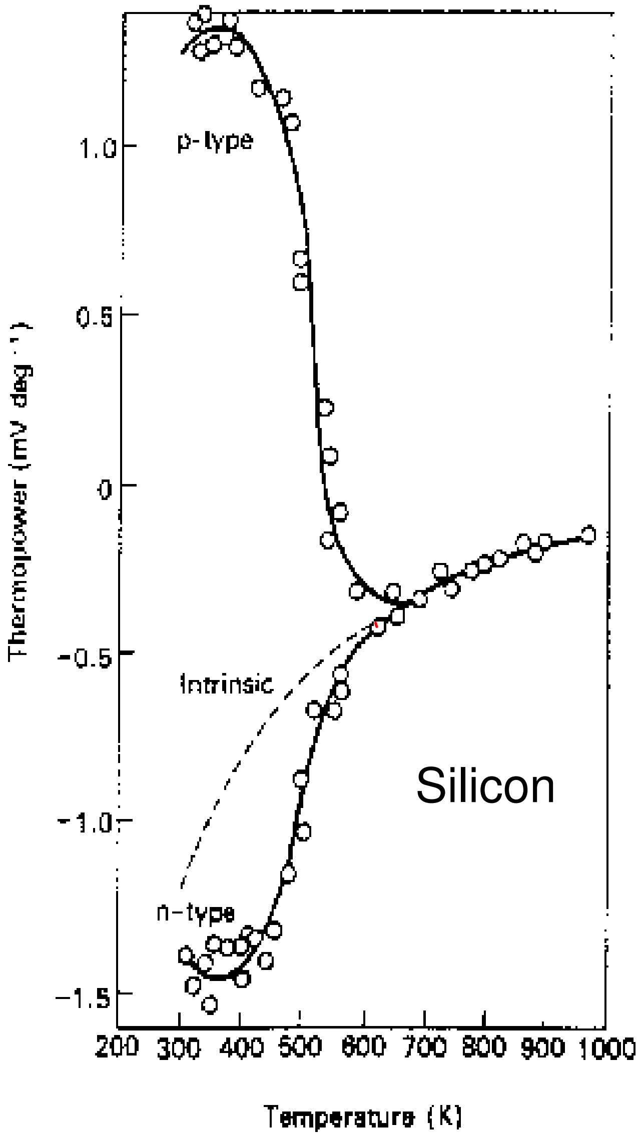
Transport through a tunnel-barrier



- **Gradient is compensated by the flux of phonons and photons**
- **Tunnel-barrier may consist of vacuum**

Seebeck-coefficients for metals and silicon





$$[S] = \mathrm{V/K} = \frac{\text{energy}}{\text{charge} \cdot \text{temperature}}$$

Peltier-effect (1832), Thompson-effect (1851)

Electrical current flowing through an interface is linked to a heat current

$$\frac{dW}{dt} = (\Pi_A - \Pi_B) \cdot I$$

metal A	metal B	← I

Peltier-coefficients

Relation of Peltier- and Seebeck-coefficient

$$\Pi = S \cdot T$$

•Heat current can be either positive or negative depending on the direction of the electrical current (contrary to Joule's heat)
•Each electron carries a certain amount of energy (heat)

$$E_c - E_F + \frac{3}{2} k_B T$$

Quality of TE-materials

$$ZT = S^2 \sigma T / k$$

"Figure of merit"

Seebeck-coefficient

electrical conductivity

Thermal conductivity

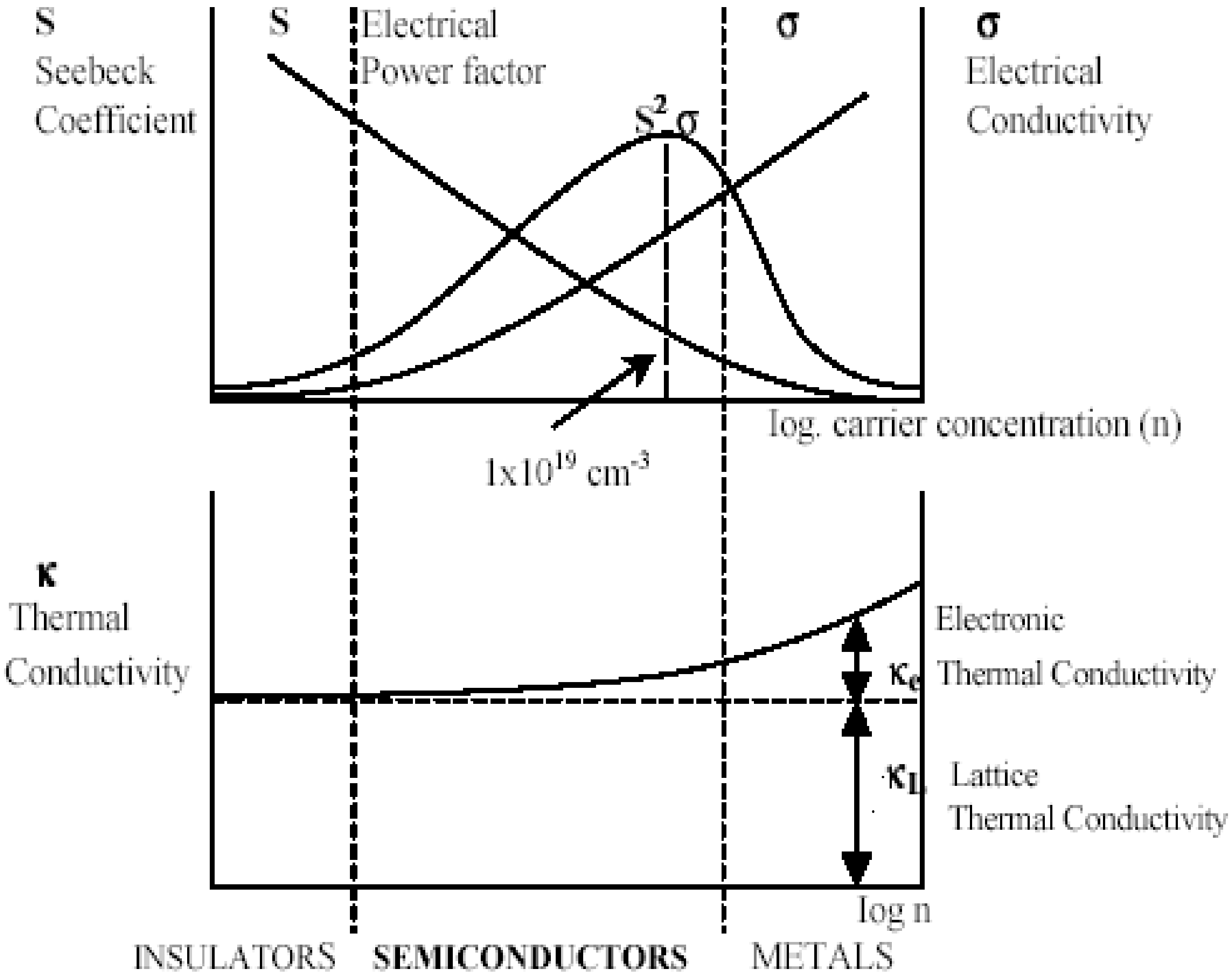
Aim: Materials with high electrical and low thermal conductivity

Approach: Block phonon transport, enhance electron transport

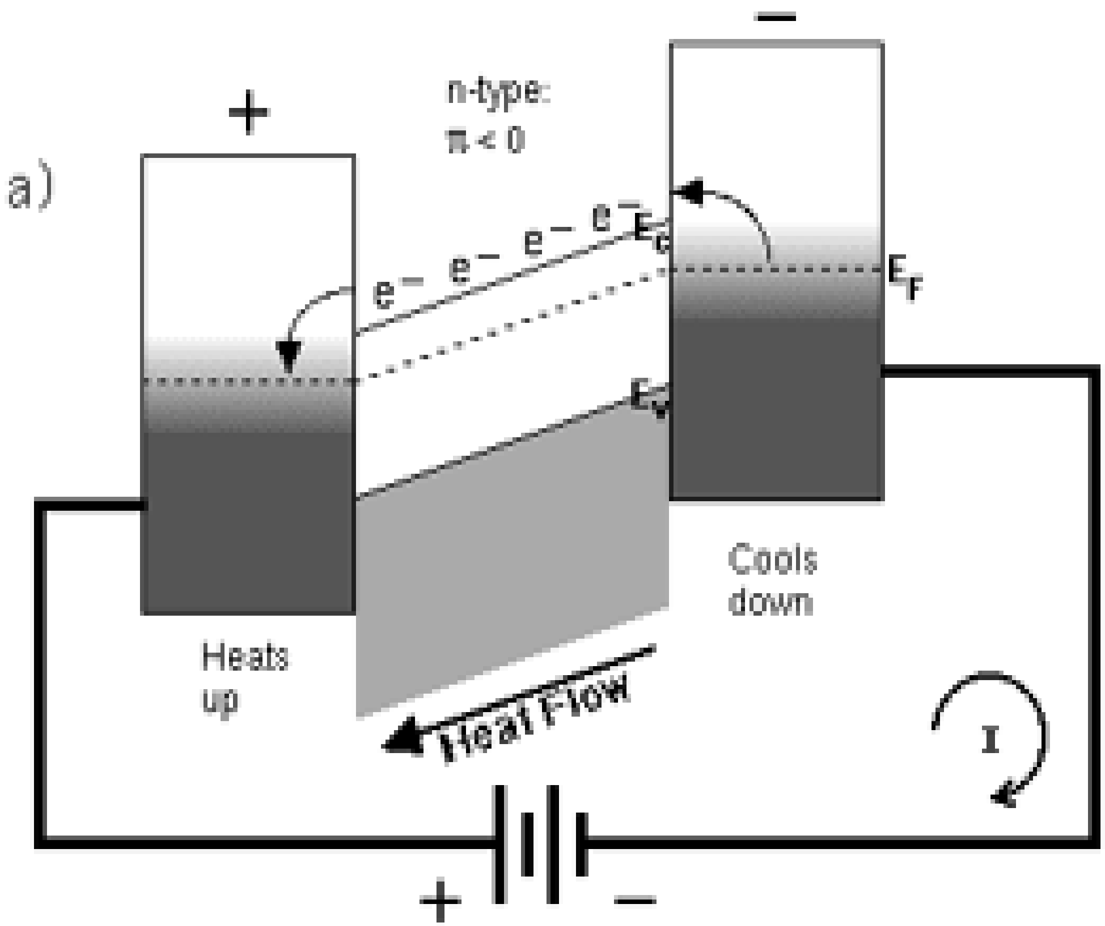
Contradiction to Wiedemann-Franz law! $k/\sigma = LT$

Which materials are suitable?

Optimum carrier density for a high Seebeck-coefficient for moderately to highly doped semiconductors



Flow of electrons and heat n-doped



Heat and electrical current flow in opposite directions

Hot electrons flow from the hot side to the cold side

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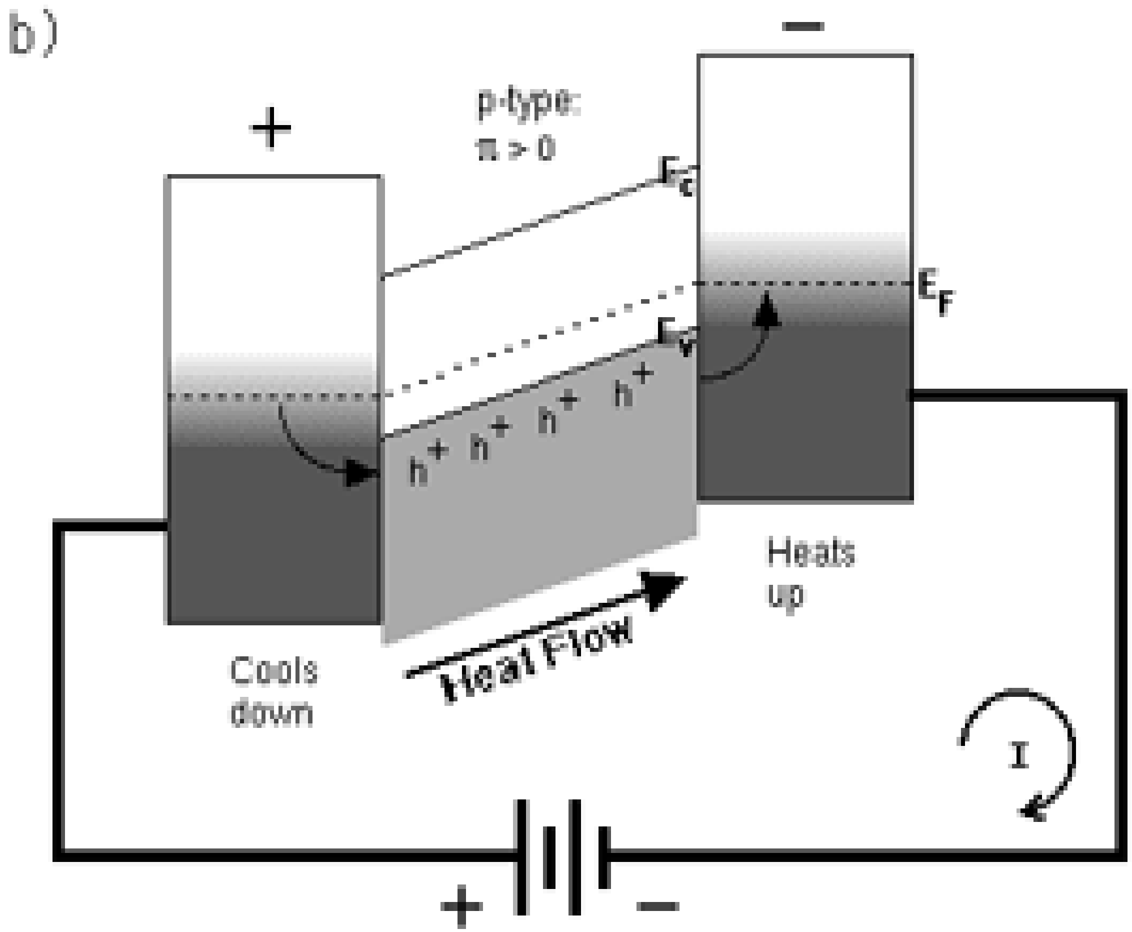
Flow of electrons and heat p-doped

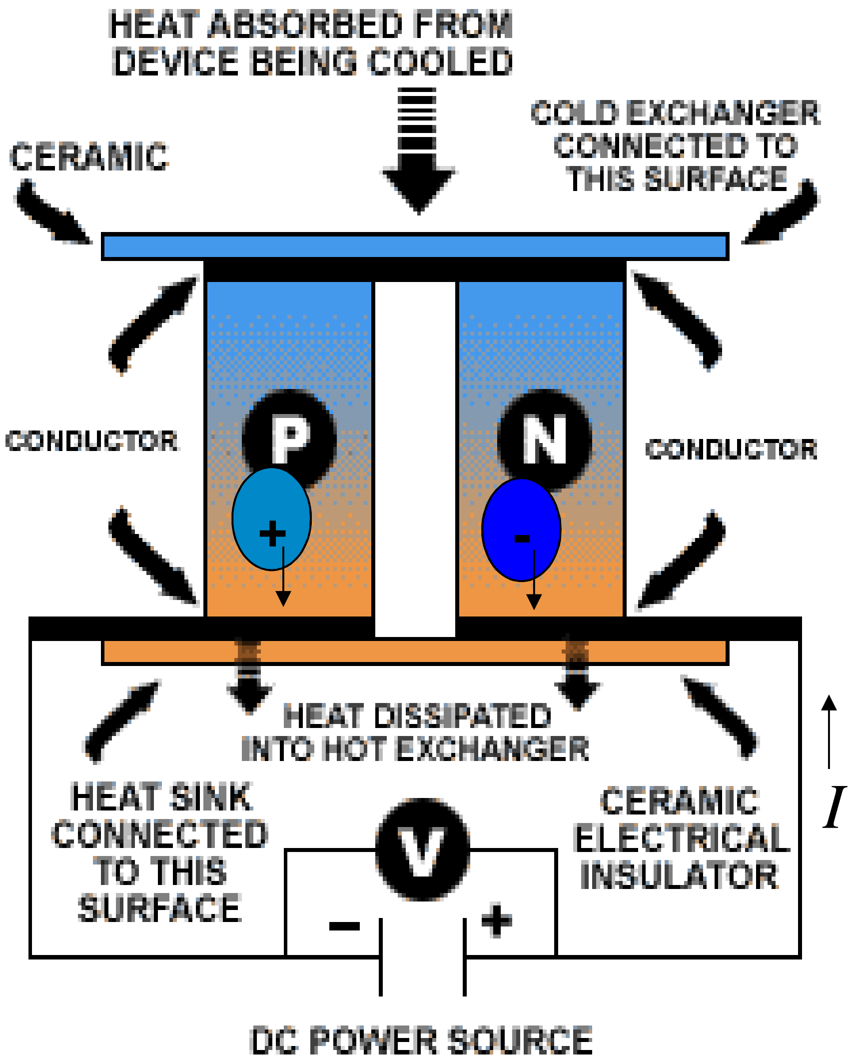


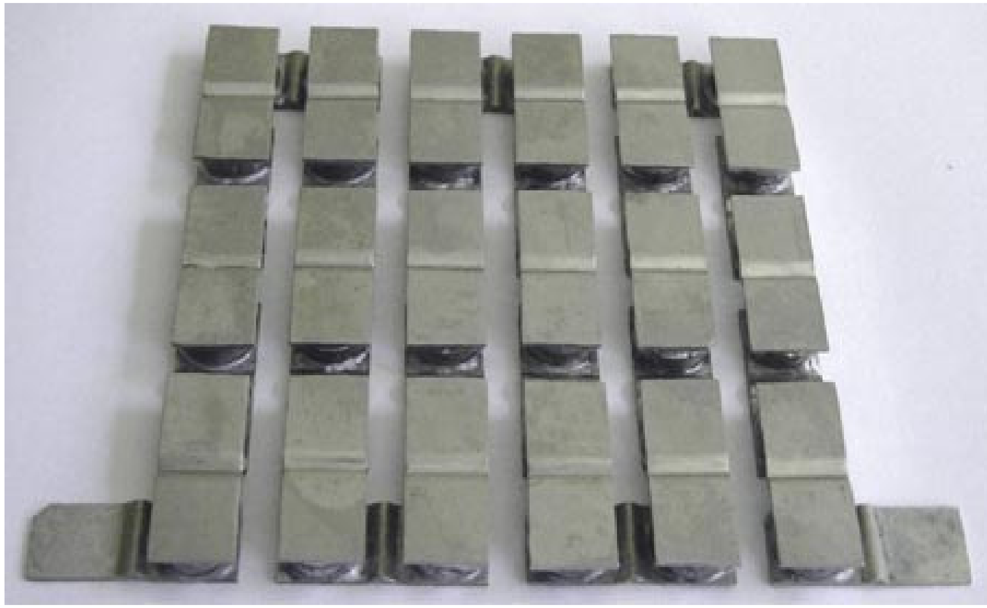
Heat and electrical current flow in the same direction

Hot holes flow from the hot side to the cold side

Commercial thermoelectrical cooler

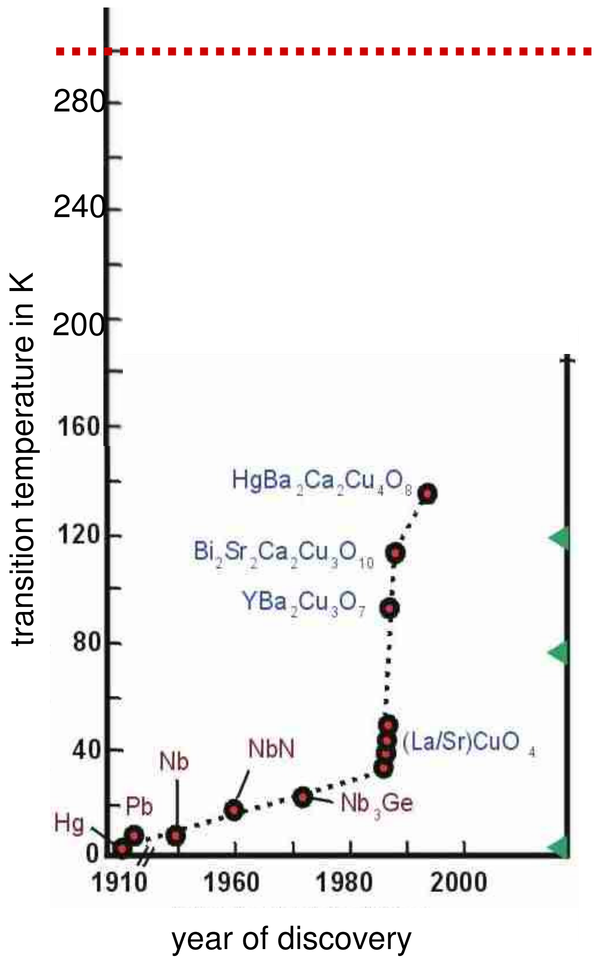
- High doping leads to low electrical resistance
- Very high currents and low voltages are not useful for applications
- Electrical and thermal connections are necessary (electrical series, thermal parallel)



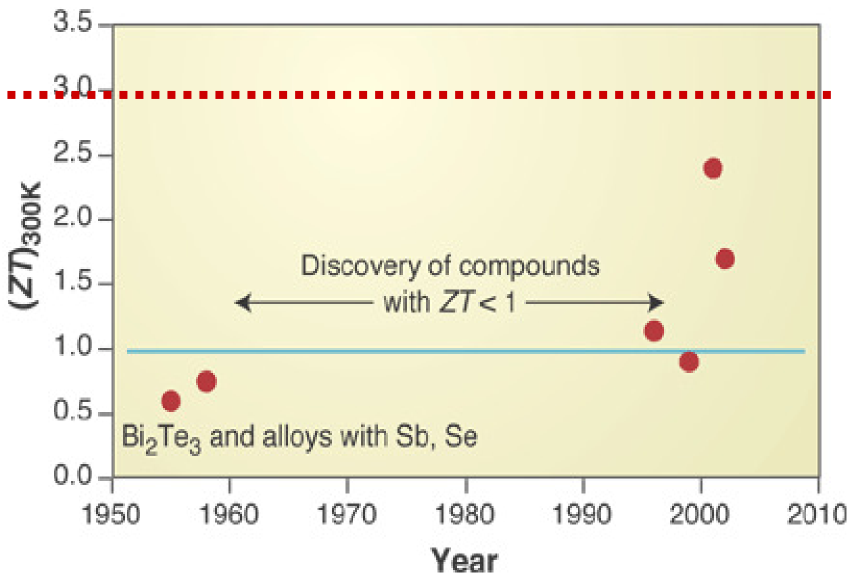


Advances in thermoelectrics: Level for commercial relevance

Superconductors



Thermoelectrical materials



New materials may replace classical cooling cycles

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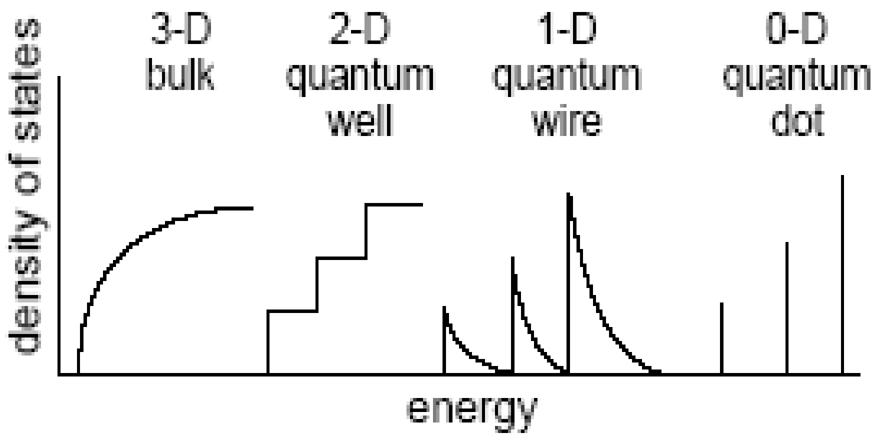
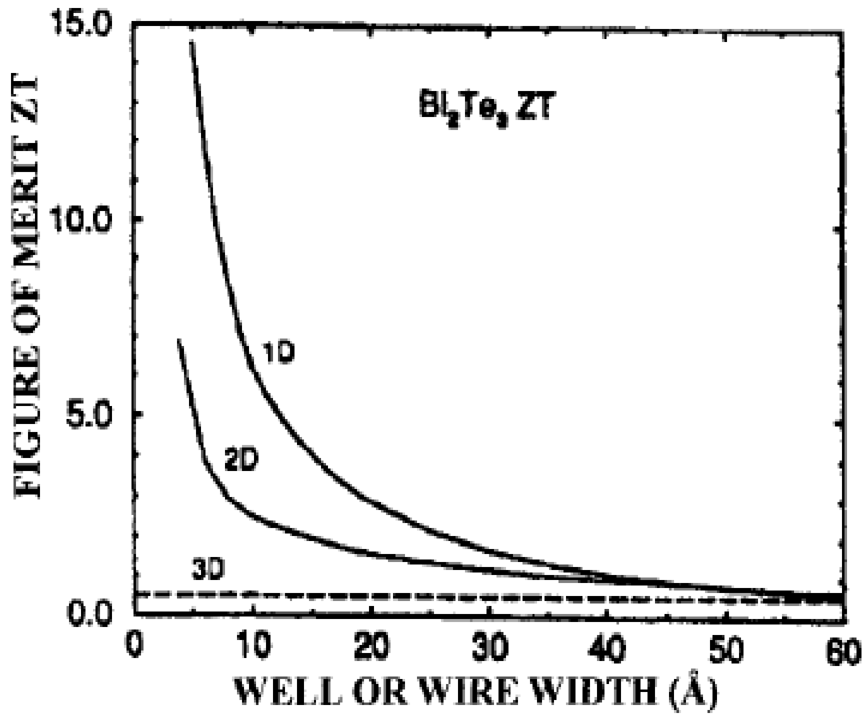
Theoretical limits using nanostructures

Seebeck-coefficient depends on the density of states

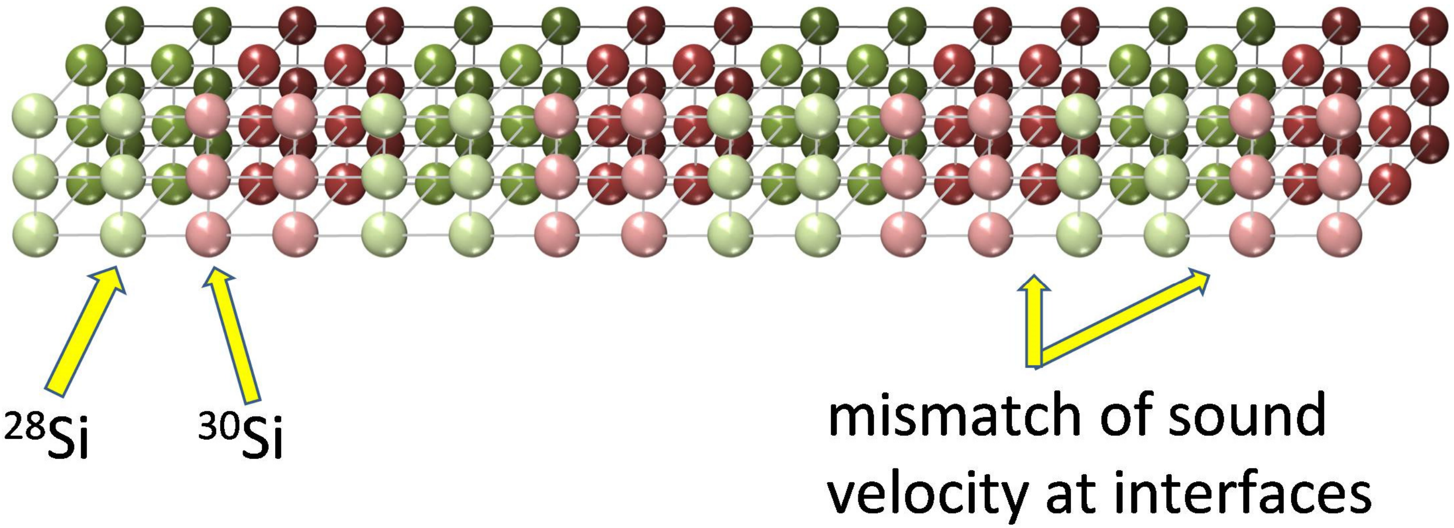
$$S \approx \frac{1}{g(E)} \frac{\partial g(E)}{\partial E}\bigg|_{E=E_F}$$



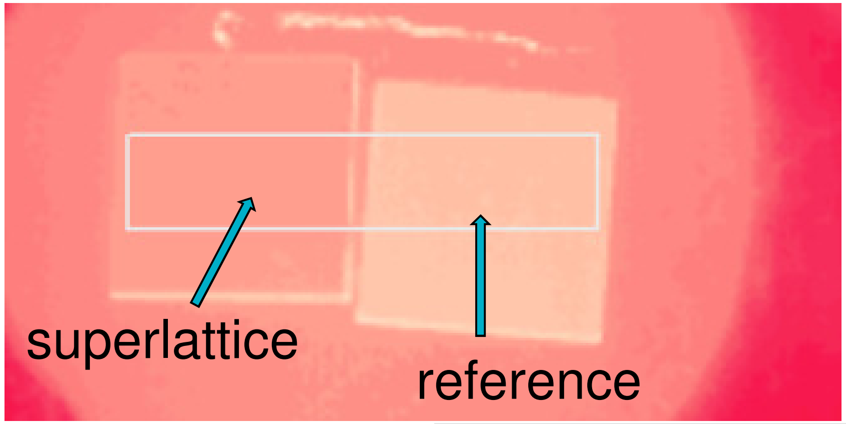


Dependence on the dimensionality and size

Tailoring phonon transport and density of states



- Thermal conductivity of silicon significantly reduced
- Electrical conductivity not altered



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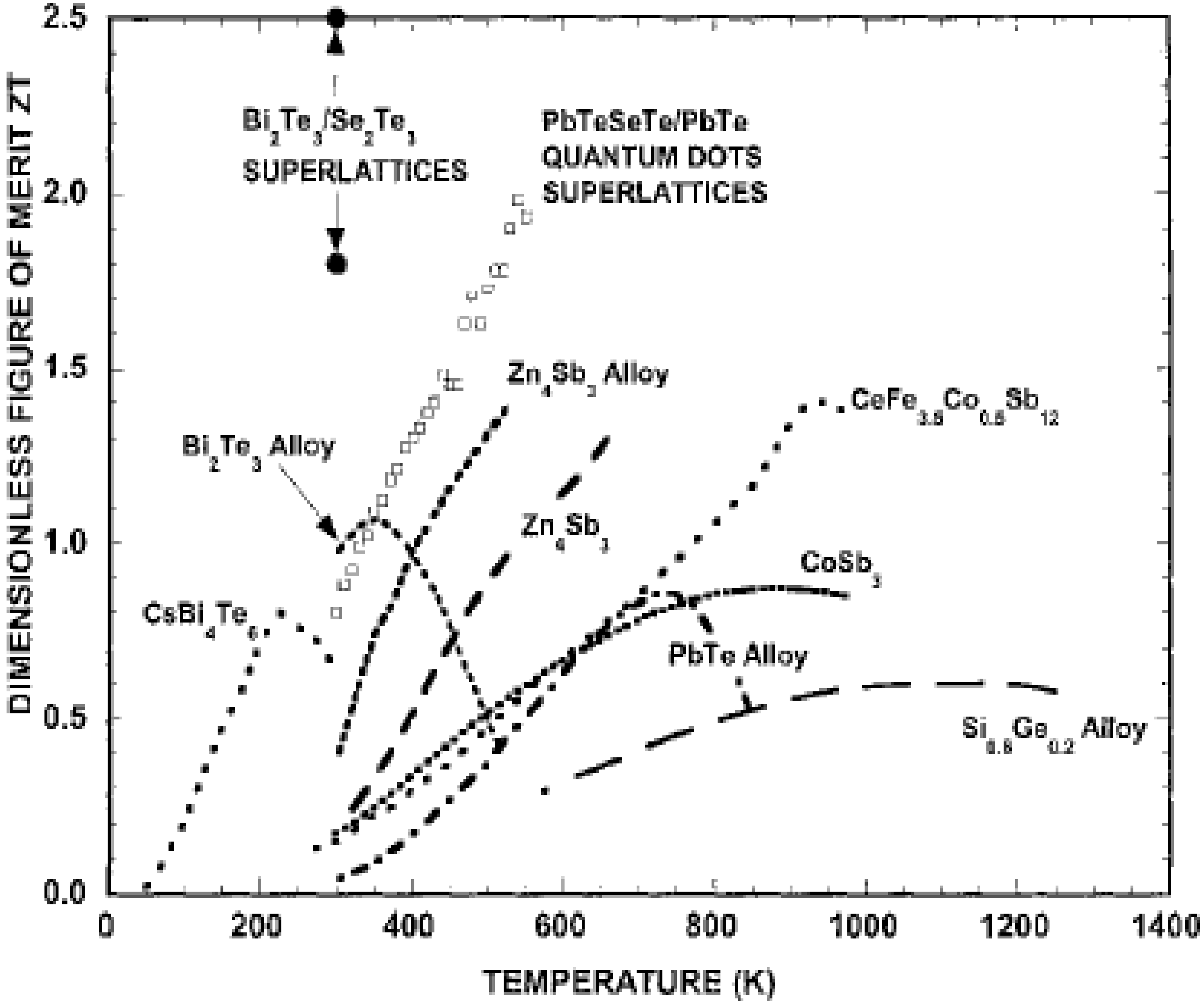
Experimental results



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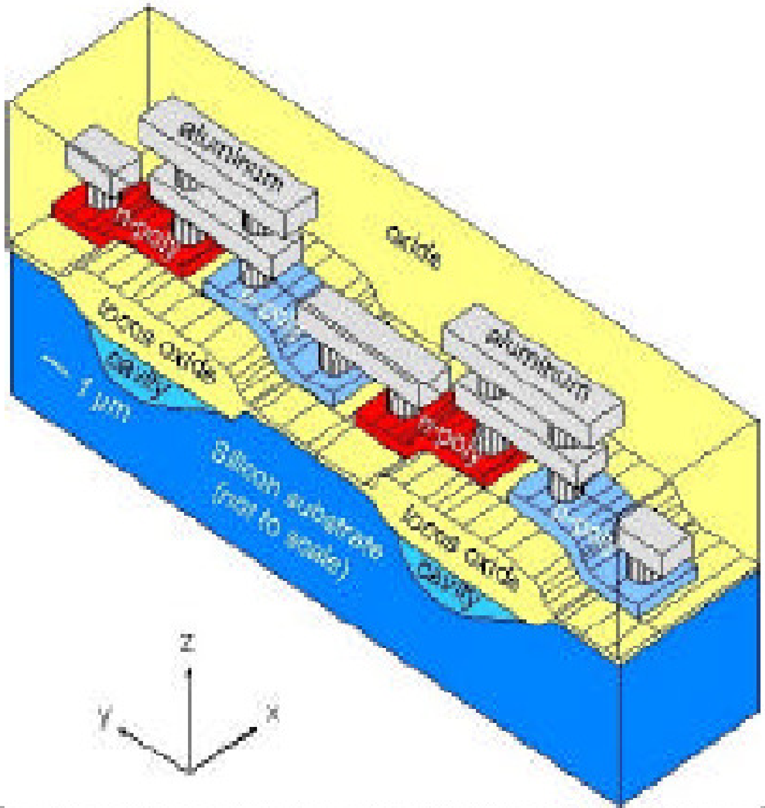
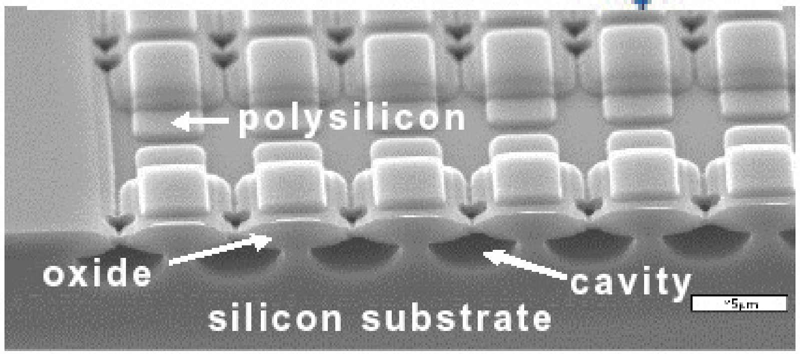
Applications

Thermoelectric generator
"smart clothes"

Power: 1 µW/cm²

@ ΔT=5K





Applications

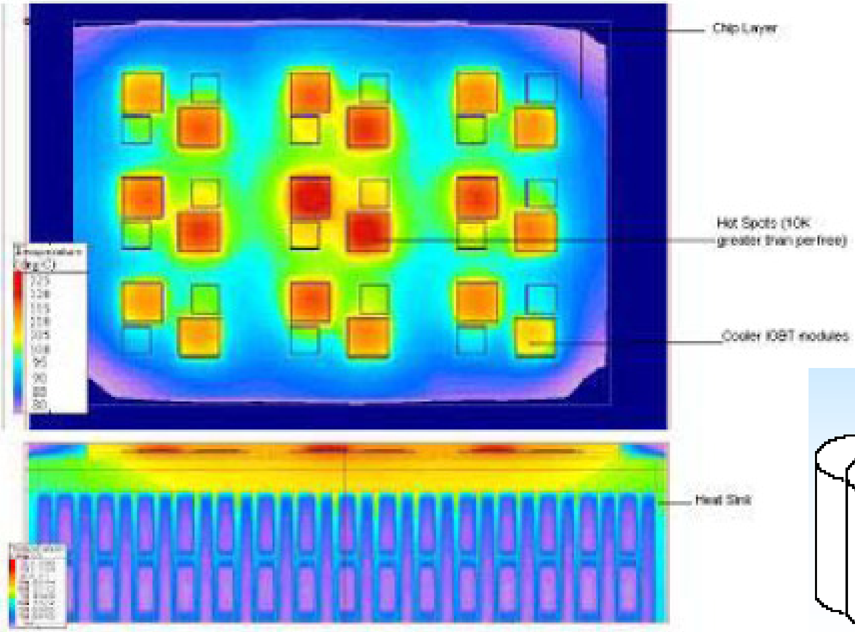
beer!

food

chocolate

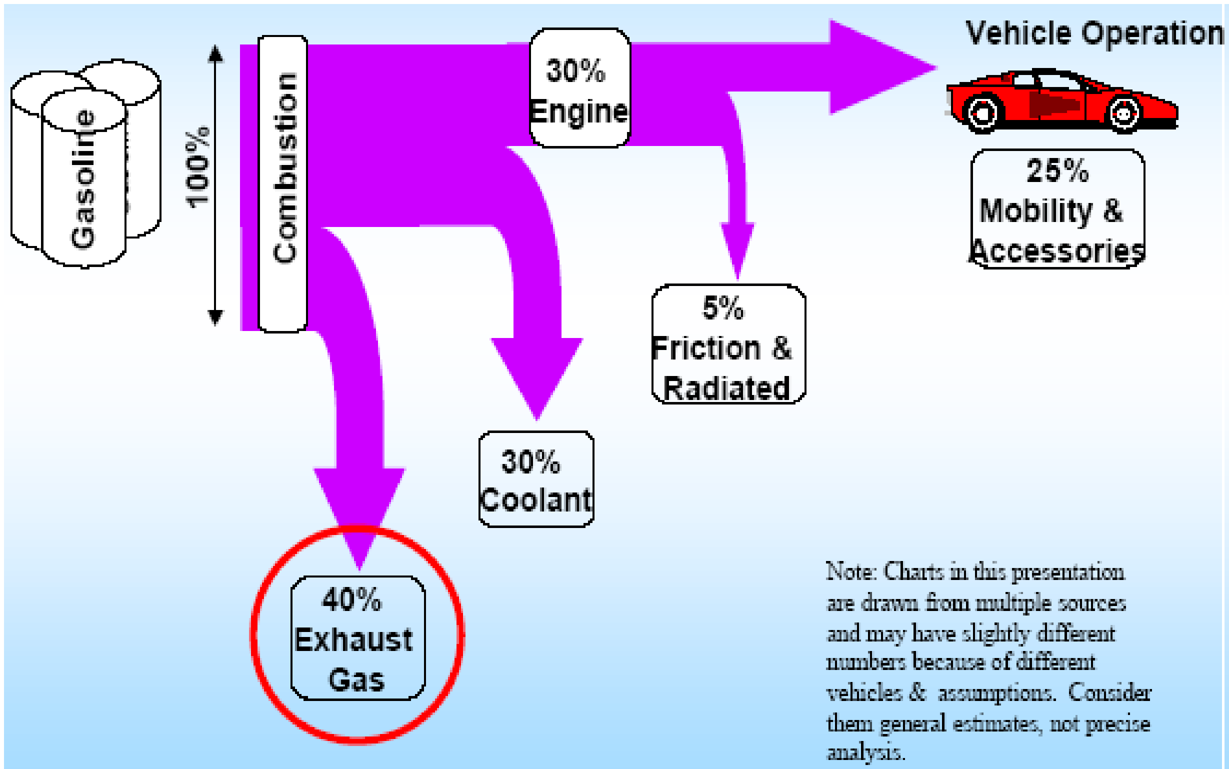
air-conditioned seats

Applications

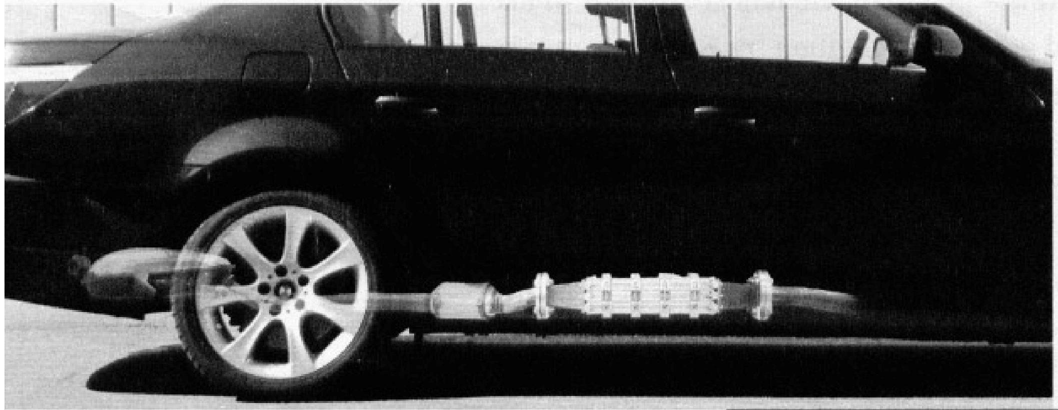


cooling of hot-spots in ICs or
for power electronics

Recycling of waste-heat
using TEGs



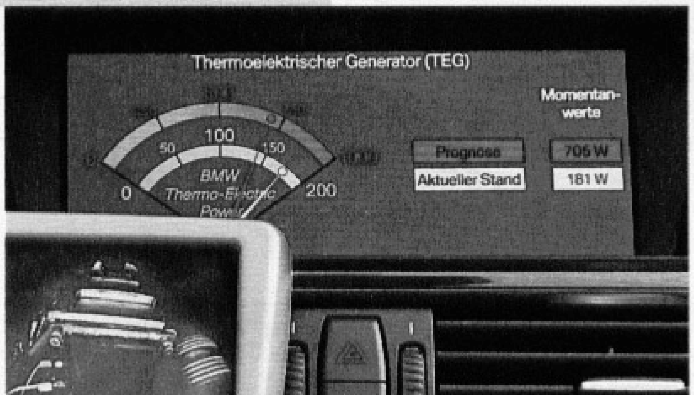
Applications



Aus Wärme Strom gewinnen

TECHNOLOGIE. BMW treibt sein Programm »EfficientDynamics«, mit dem alle Modelle schrittweise sparsamer werden, weiter voran. Neben dem vorausschauenden Auto, das je nach zu erwartender Verkehrssituation Motoraggregate zu- oder abschaltet, setzt BMW auf den thermoelektrischen Generator (TEG). Mit der in der Raumfahrt genutzten Technologie wandelt das Auto ungenutzt aus dem Auspuff ausgestoßene Wärme in elektrische Energie um, die in die Batterie eingespeist wird. Durch Fortschritte bei Material und Werkstoffen soll die bislang geringe Leistungsfähigkeit in den nächsten fünf Jahren deutlich verbessert werden. Die Lichtmaschine wird dann seltener eingesetzt, was in der Serie bis zu fünf Prozent Kraftstoff einsparen könnte.

Noch Zukunftsmusik: Ein thermoelektrischer Generator am Auspuff macht aus Wärme Strom (o.). Im Versuchsfahrzeug werden die Werte der aktuellen Stromproduktion angezeigt (r.)



12 ADACmotorwelt 6/2008

Cooperation BASF and BMW

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Maximum efficiency

Theoretical efficiency

$$\eta_{max} = \underbrace{\frac{T_1 - T_2}{T_1}}_{\text{Carnot efficiency}} \cdot \underbrace{\frac{\sqrt{1 + ZT_M} - 1}{\sqrt{1 + ZT_M} + \frac{T_2}{T_1}}}_{\text{TE efficiency}}$$

Summary

Thermoelectrics

- needs advanced materials / metamaterials
- links fundamental research closely to applications
- can be used for heat-conversion, cooling and heating
- may beat techniques such as Sterling engines or Rankine cycles
- is complicated