

Micro Electro Mechanical Systems for mechanical engineering applications

Lecture 7: Device examples (2): electrothermal transduction

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Generalized Classifications

Input \ Output	Mechincal (mechano-)	Thermal (thermo-)	Electrical (electro-)	Magnetic (magneto-)	Radiant (photo- or Radio-)	Chemical (chemo-)
Input						
Mechanical	Acoustics fluidics	Cooling Effects	Piezoelectric Piezoresistor	Piezomagnetic	Photo Elasticity	
Thermal	Bi-metallic		Seebeck effect (TC's)			
Electrical	Piezoelectric	Peltier effect (TC's)			Electro-luminescence	
Magnetic	Magnetometer	Thermo-Magnetic				Electrolysis
Radiant		Thermo-Pile	Photo-electric			
Chemical		Calorimeter		Nuclear Magnetic resistance		

Madou, Fundamentals of Microfabrication, 2003

Electrothermal Sensing (1)

- Thermoelectrics
 - Thermocouples
 - metals
 - semiconductors
 - Thermopiles (multiple thermocouples)
- Thermoresistors
 - Metal thermoresistors
 - Thermistors
 - semiconductor oxides
 - Intrinsic semiconductors
- Semiconductor devices
 - Thermodiodes
 - Thermotransistors

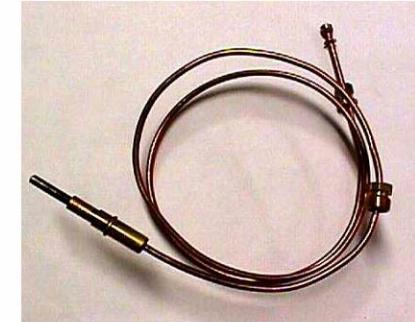
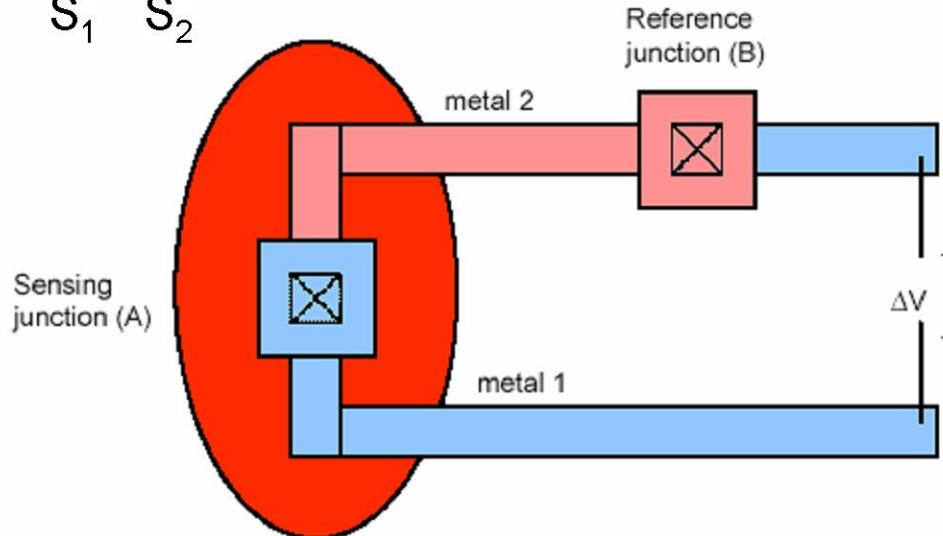
Electrothermal Sensing (2)

- 3 thermoelectric effects:
 - Seebeck effect: voltage generated by changes in Fermi level & diffusion potential of bi-metal junctions
 - Peltier effect: heat released/absorbed when current passed through bi-metal junction
 - Thomson (Kelvin) effect: current passed along single conductor in a temperature gradient produces heat

- Seebeck effect: thermocouples
 - 2 different metals w/ 2 junctions held at different temperatures generate an e.m.f., resulting in electrical current flow

Thermocouples

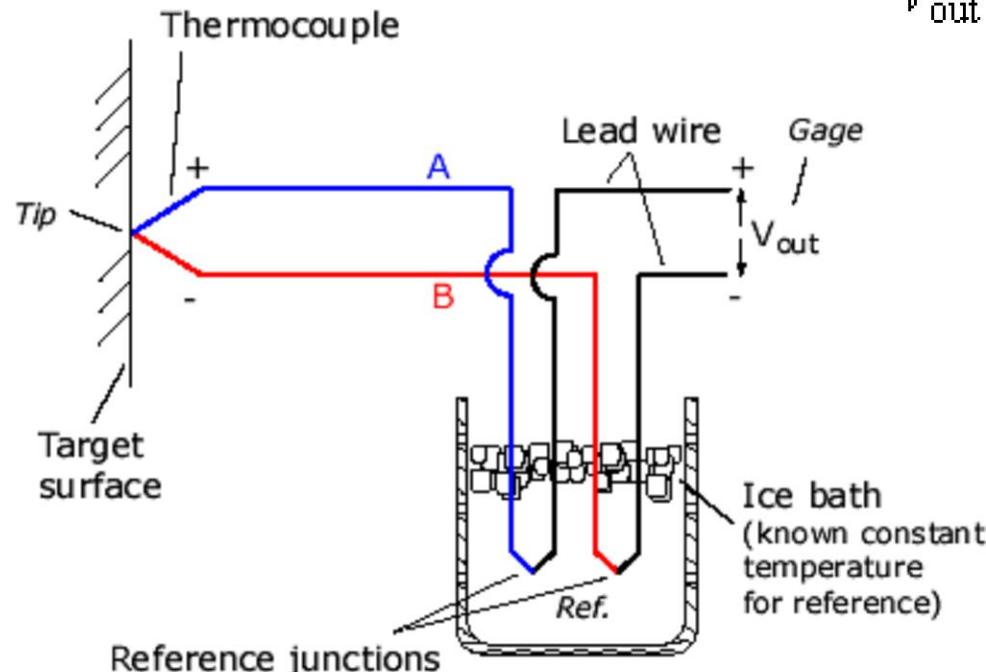
- $\Delta V = (P_1 - P_2)(T_A - T_B)$
 $S_1 \quad S_2$



- $P_{1,2}$ = seebeck coefficient of metal 1 & 2 measured relative
 S_1 or S_2 standard

metal	P [$\mu\text{V/K}$]
Au	+9.20
Ag	+8.85
Al	+5.30
Ni	-15.50

Thermocouples



$$\begin{aligned}V_{out} &= \int_{Gage}^{Ref} S_{Lead}(T) \frac{dT}{dx} dx + \int_{Ref}^{Tip} S_A(T) \frac{dT}{dx} dx \\&\quad + \int_{Tip}^{Ref} S_B(T) \frac{dT}{dx} dx + \int_{Ref}^{Gage} S_{Lead}(T) \frac{dT}{dx} dx \\&= \int_{T_{Ref}}^{T_{Tip}} S_A(T) dT + \int_{T_{Tip}}^{T_{Ref}} S_B(T) dT \\&= \int_{T_{Ref}}^{T_{Tip}} [S_A(T) - S_B(T)] dT\end{aligned}$$

http://www.efunda.com/designstandards/sensors/thermocouples/thmcple_theory.cfm

Thermoresistors

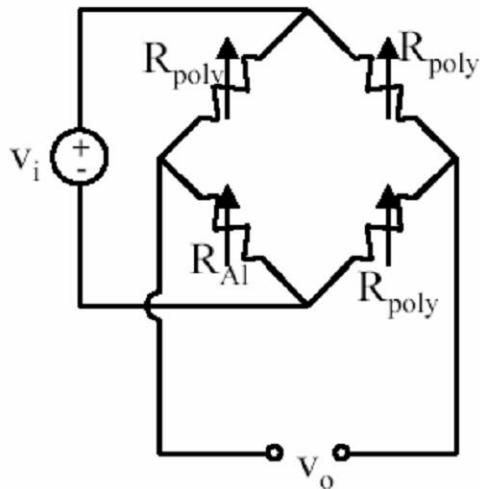
■ Temperature coefficient of resistivity ($\alpha = \text{TCR}$):

$$\rho = \rho_o(1 + \alpha T + \beta T^2) \quad \text{for metals} \rightarrow \alpha = \frac{1}{\rho_o} \frac{d\rho}{dT}$$

metal	resistivity [Ωcm]	TCR [$10^{-4}/\text{K}$]
Pt	10.6e-6	39.2
Nichrome	101e-6	1.7
Ni	6.84e-6	68.1
Al	2.83e-6	38
Au	2.4e-6	40
Cr	1.26e-5	30
Ti	3.84e-5	38
W	4.9e-6	45
Cu	1.72e-6	41
Fe	9.71e-6	65.1
poly-Si	10.6e-6	-12 to 12

- Wheatstone bridge circuit for output measurement
- Pt is preferred due to high linearity, calibration standards
- poly-Si can be used, but low TCR and doping-dependent

Thermoresistors (Con't)



$$V_o = V_i \left(\frac{R_{Al}}{R_{Al} + R_{poly}} - \frac{1}{2} \right)$$

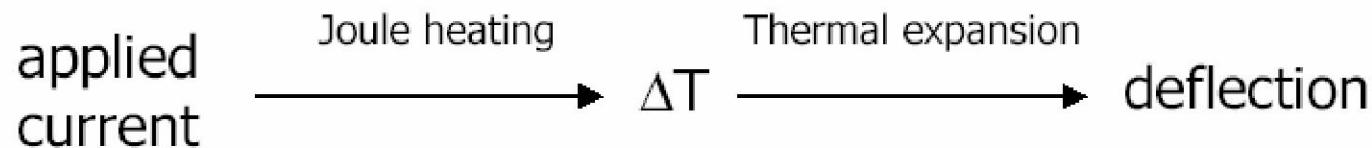
$$\begin{aligned}\frac{dV_o}{dT} &= \frac{\partial V_o}{\partial R_{Al}} \frac{\partial R_{Al}}{\partial T} + \frac{\partial V_o}{\partial R_{poly}} \frac{\partial R_{poly}}{\partial T} \\&= V_i \left(\frac{1}{R_{Al} + R_{poly}} - \frac{R_{Al}}{(R_{Al} + R_{poly})^2} \right) \frac{\partial R_{Al}}{\partial T} + V_i \left(\frac{-R_{Al}}{(R_{Al} + R_{poly})^2} \right) \frac{\partial R_{poly}}{\partial T} \\&= V_i \left(\frac{1}{2R_o} + \frac{1}{4R_o} \right) \frac{\partial R_{Al}}{\partial T} - V_i \left(\frac{1}{4R_o} \right) \frac{\partial R_{poly}}{\partial T} \\&= \frac{V_i}{4} (\alpha_{r,Al} - \alpha_{r,poly})\end{aligned}$$

$\frac{dR}{dT} = R_o \alpha_r$

$R_{poly,o} = R_{Al,o} = R_o$

Electrothermal Actuation (1)

- Thermal expansion via Joule heating:



- Applications:
 - valves
 - motors
 - optical positioning
 - high-force actuators

Electrothermal Actuation (2)

- Thermal biomorphs
 - 2 materials with dissimilar CTE
 - uniform ΔT results in differential expansion
 - strain compatibility between layers produces deflection
 - temperature can result from applied Joule heating or ambient ΔT

- U-beam compliant thermal microactuators
 - single material with varying geometry
 - differential temperature results in differential expansion
 - temperature controlled via Joule heating

Actuation Comparison

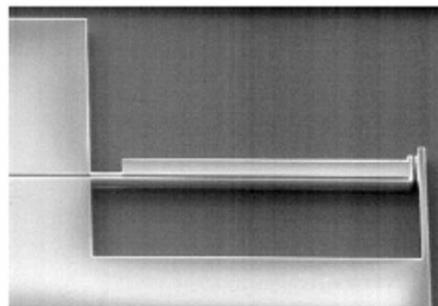
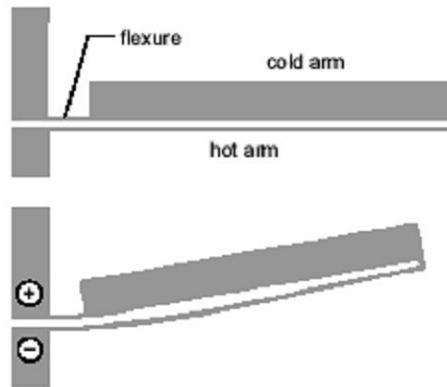
<i>Actuator</i>	<i>fractional stroke (%)</i>	<i>Max. Pressure (MPa)</i>	<i>Energy Density (J/cm³)</i>	<i>Efficiency</i>	<i>Speed</i>
electrostatic	N/A	0.025	0.004	high	fast
electromagnetic	N/A	0.1	0.025	low	fast
piezoelectric	0.2	35	0.035	high	fast
magnetostriuctive	0.2	70	0.07	low	fast
electrostrictive	4	0.21	0.032	high	fast
thermal	50	10	25.5	low	slow
SMA	8	400	16	low	slow

- CTE for common MEMS materials:

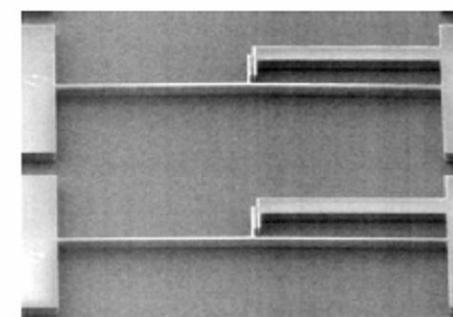
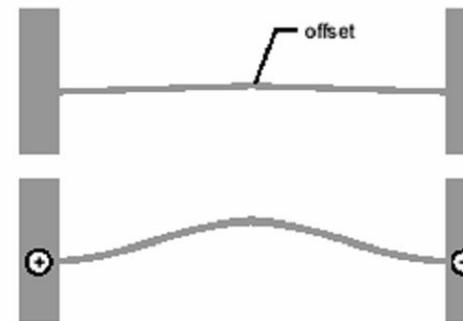
Material	$\alpha \times 10^{-6}$ [1/K]	σ_{res} [MPa]	E [GPa]
SCS	2.5	0	166
poly-Si	2.4	-10	166
Al	24	82 (sputtered)	69
Au	14	50 (evaporated)	80
SiO_2 (PECVD)	0.35	50	62
SiO_2 (SOG)	0.35	-200	62
SiC	1.6	45	448
Pt	8.8	847	150
Ni	12.8	?	210
Cr	5.0	850	248
Ti	8.6	~ 0	103

Other Electrothermal Actuators

- U-beam



- V-beam



Thermoelectric Effects: References

Thermo-electrics: Basic principles and New Materials Development by Nolas, Sharp and Goldsmid

Thermoelectric Refrigeration by Goldsmid

Thermodynamics by Callen. Sections 17-1 to 17-5

Outline

- Thermoelectric Effects
- Thermoelectric Refrigeration
- Figure of Merit (Z)
- Direct Thermal to Electric Power Generation

Applications

Beer Cooler



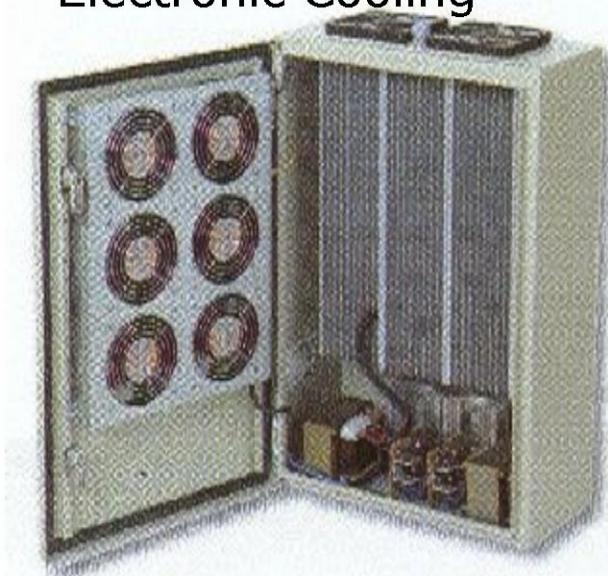
Cryogenic IR Night Vision



Thermally-Controlled Car Seat



Electronic Cooling

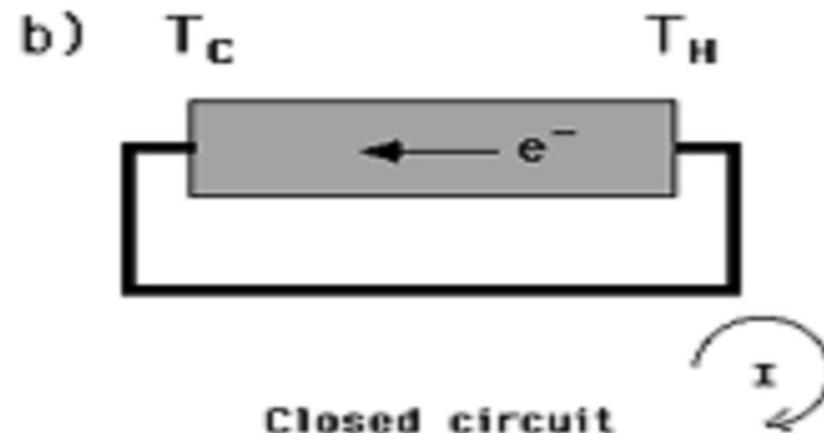
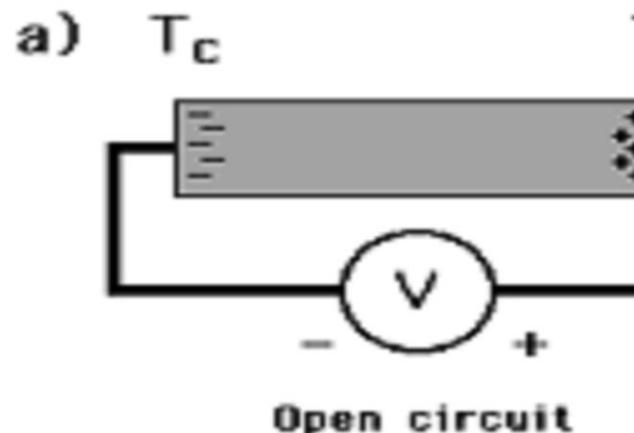


Basic Thermoelectric Effects

- Seebeck effect
- Peltier Effect
- Thomson effect

Seebeck Effect

- In 1821, Thomas Seebeck found that an electric current would flow continuously in a closed circuit made up of two dissimilar metals, if the junctions of the metals were maintained at two different temperatures.



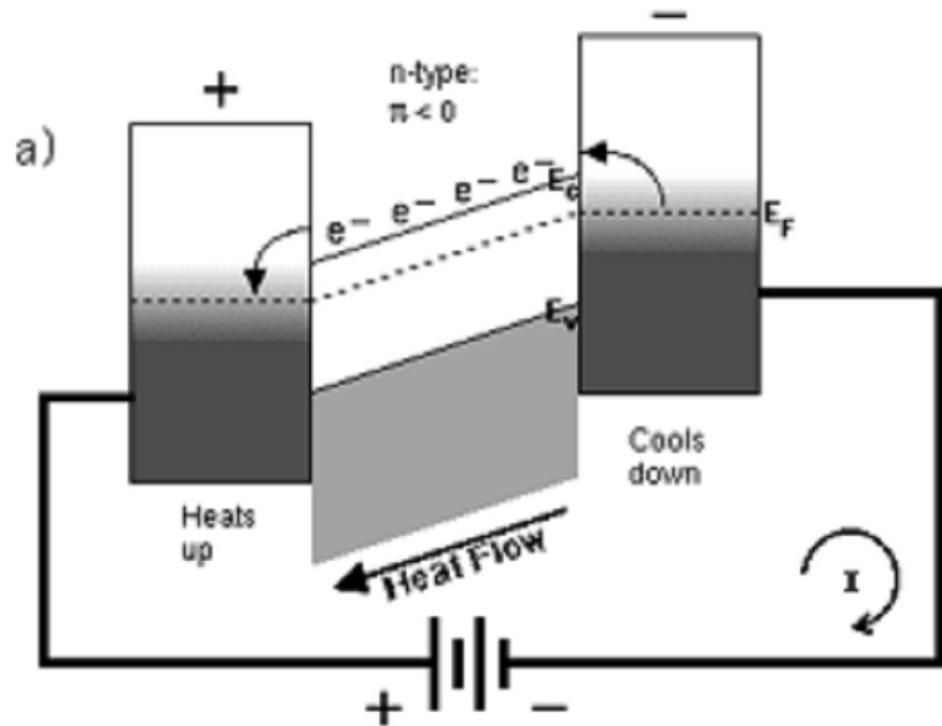
$$S = dV / dT;$$

S is the Seebeck Coefficient with units of Volts per Kelvin

S is positive when the direction of electric current is same as the direction of thermal current

Peltier Effect

- In 1834, a French watchmaker and part time physicist, Jean Peltier found that an electrical current would produce a temperature gradient at the junction of two dissimilar metals.



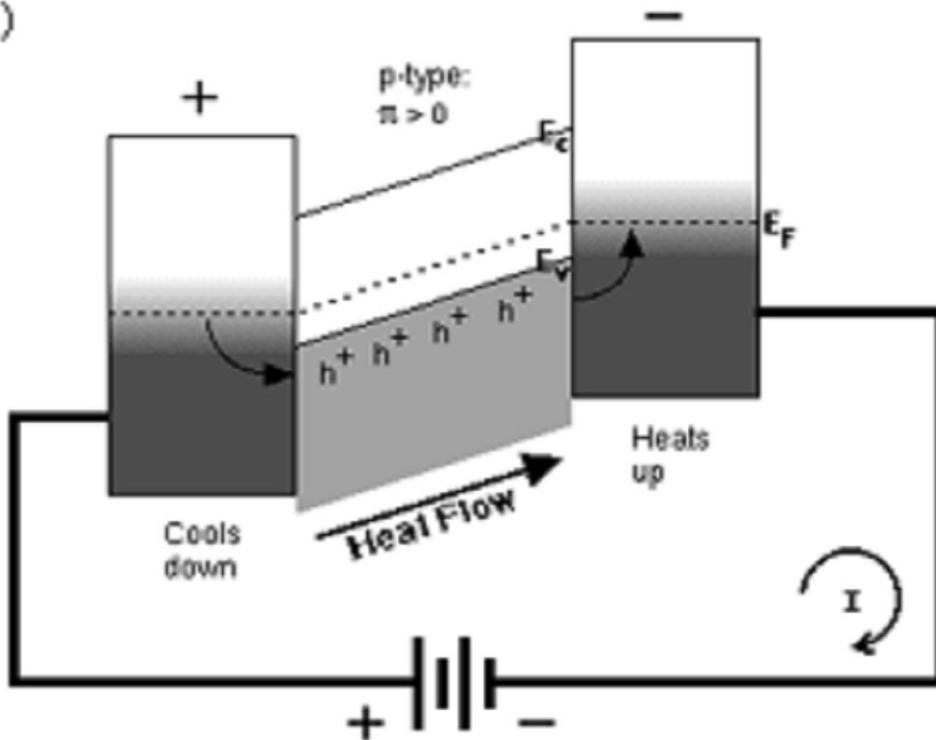
$\Pi < 0$; Negative Peltier coefficient

High energy electrons move from right to left.

Thermal current and electric current flow in opposite directions.

Peltier Cooling

b)



$\Pi > 0$; Positive Peltier coefficient

High energy holes move from left to right.

Thermal current and electric current flow in same direction.

$q = \Pi * j$, where q is thermal current density and j is electrical current density.

$$\Pi = S * T \text{ (Volts)}$$

T is the Absolute Temperature

Thomson Effect

- Discovered by William Thomson (Lord Kelvin)
- When an electric current flows through a conductor, the ends of which are maintained at different temperatures, heat is evolved at a rate approximately proportional to the product of the current and the temperature gradient.

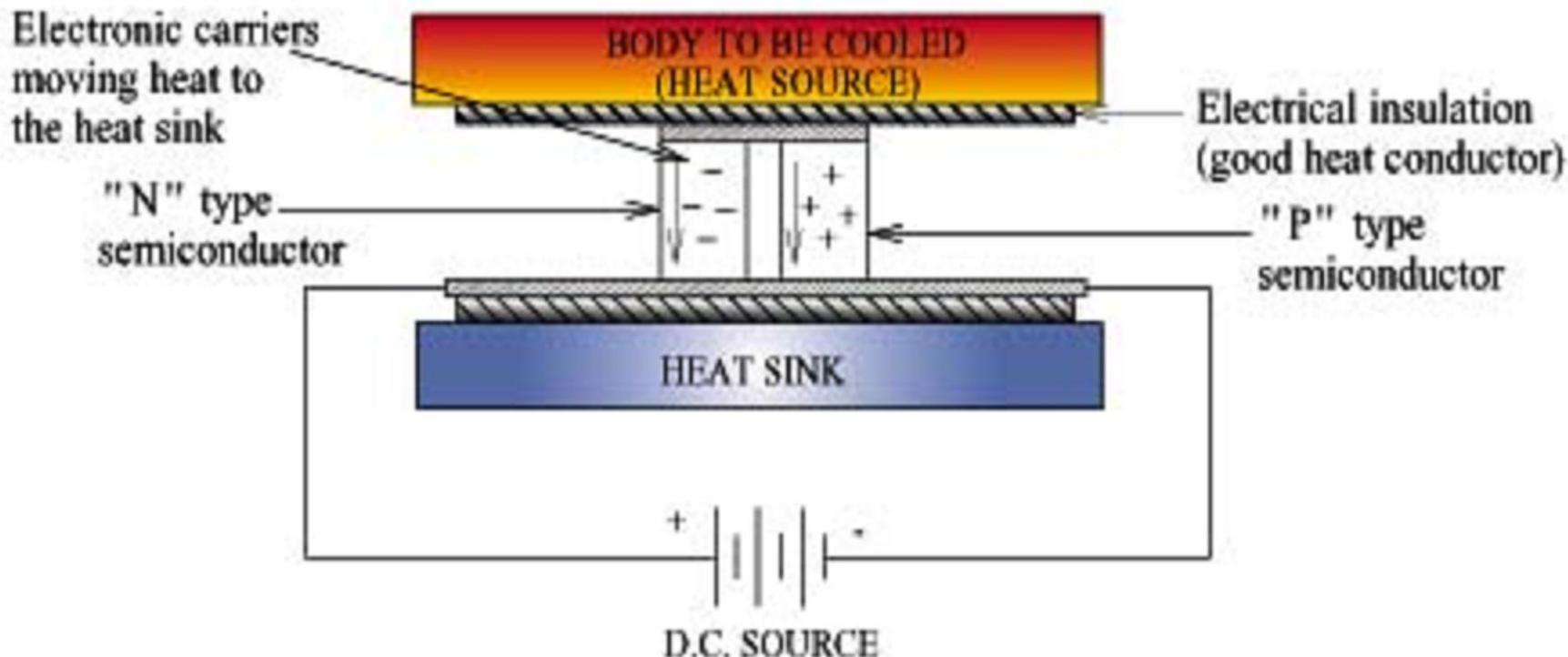
$$\frac{dQ}{dx} = \tau I \frac{dT}{dx}$$

τ is the Thomson coefficient in Volts/Kelvin

→ Seebeck coeff. S is temperature dependent

Relation given by Kelvin: $\tau = T \frac{dS}{dT}$

Thermoelectric Refrigeration



The rate of heat flow from one of the legs ($i=1$ or 2) :

$$q_i|_{x=0} = S_i IT - k_i A_i \frac{dT}{dx}|_{x=0} \quad (1)$$

Thermoelectric Refrigeration (Con't)

The rate of heat generation per unit length due to Joule heating is given by:

$$\begin{aligned} I^2 R_x &= Q_x \text{ (Joule's law)} \quad I^2 \cdot \frac{\Delta x}{\sigma_i A_i} = - \left(k_i A_i \frac{dT}{dx} \Big|_{x+\Delta x} - k_i A_i \frac{dT}{dx} \Big|_x \right) \\ &\Rightarrow \frac{I^2}{\sigma_i A_i} = -k_i A_i \frac{d^2 T}{dx^2} \end{aligned} \quad (2)$$

Eqn 2 is solved using the boundary conditions $T = T_c$ at $x=0$ and $T = T_h$ at $x=l$. Thus it is found that:

$$-k_i A_i \frac{dT}{dx} = \frac{I^2 [x - l/2]}{\sigma_i A_i} - \frac{k_i A_i (T_h - T_c)}{l} \quad (3)$$

The total heat removed from source will be sum of q_1 and q_2

$$q_c = (q_1 + q_2) \Big|_{x=0} \quad (4)$$

$$\text{Eqs. 1, 3, 4} \rightarrow q_c = (S_2 - S_1)IT_c - K\Delta T - 0.5I^2R$$

K: Thermal conductance of the two legs

R: Electrical Resistance of the two legs

Thermoelectric Refrigeration (Con't)

The electrical power is given by:

$$w = (S_2 - S_1)I\Delta T + I^2 R$$

COP is given by heat removed per unit power consumed

$$\Phi = \frac{q_c}{w} = \frac{(S_2 - S_1)IT_c - K\Delta T - 0.5I^2R}{I[(S_2 - S_1)\Delta T + IR]}$$

Differentiating w.r.t I we get max. value of COP

$$\phi_{\max} = \frac{T_c}{T_h - T_c} \frac{\sqrt{1+zT_m} - T_h/T_c}{\sqrt{1+zT_m} + 1}$$

where

$$z = \frac{(S_2 - S_1)^2}{KR} \quad \text{and} \quad T_m = (T_h + T_c)/2$$

A similar approach can be used to obtain the maximum degree of cooling and maximum cooling power.

Thermoelectric Refrigeration (Con't)

It is obvious that Z will be maximum when RK will have minimum value.
This occurs when:

$$\frac{A_1/l_1}{A_2/l_2} = \sqrt{\frac{\sigma_2 k_2}{\sigma_1 k_1}}$$

When this condition is satisfied Z becomes:

$$Z = \frac{(S_2 - S_1)^2}{[(k_1/\sigma_1)^{1/2} + (k_2/\sigma_2)^{1/2}]^2}$$

Further, if $S_2 = -S_1 = S$, $k_1 = k_2 = k$, $\sigma_1 = \sigma_2 = \sigma$

$$Z = \frac{S^2 \sigma}{k}$$

ZT_m vs. COP

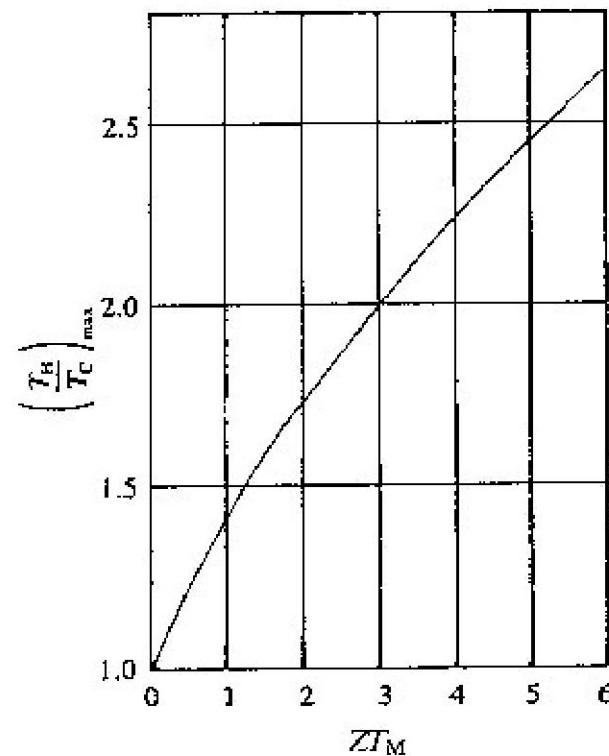


Fig. 1.6. Maximum ratio of hot to cold junction temperature as a function of the dimensionless figure of merit

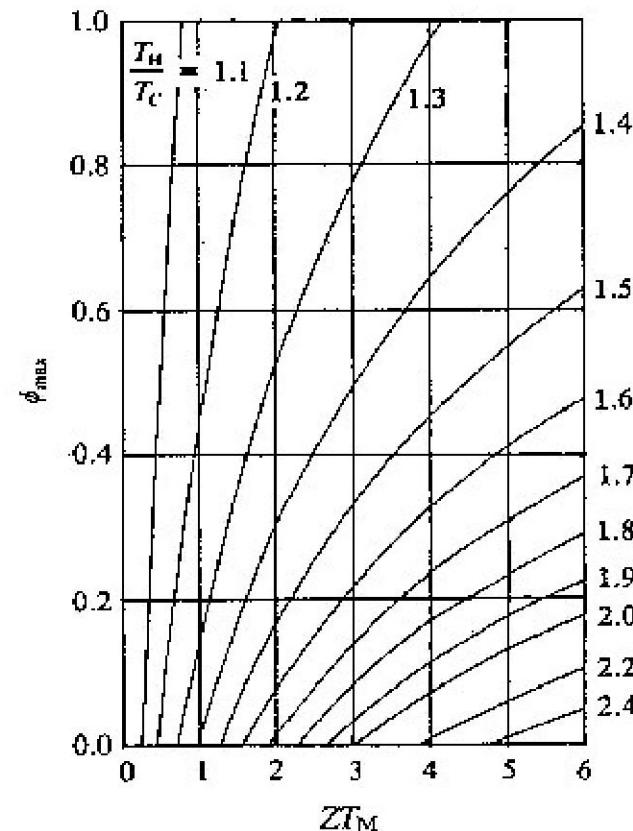
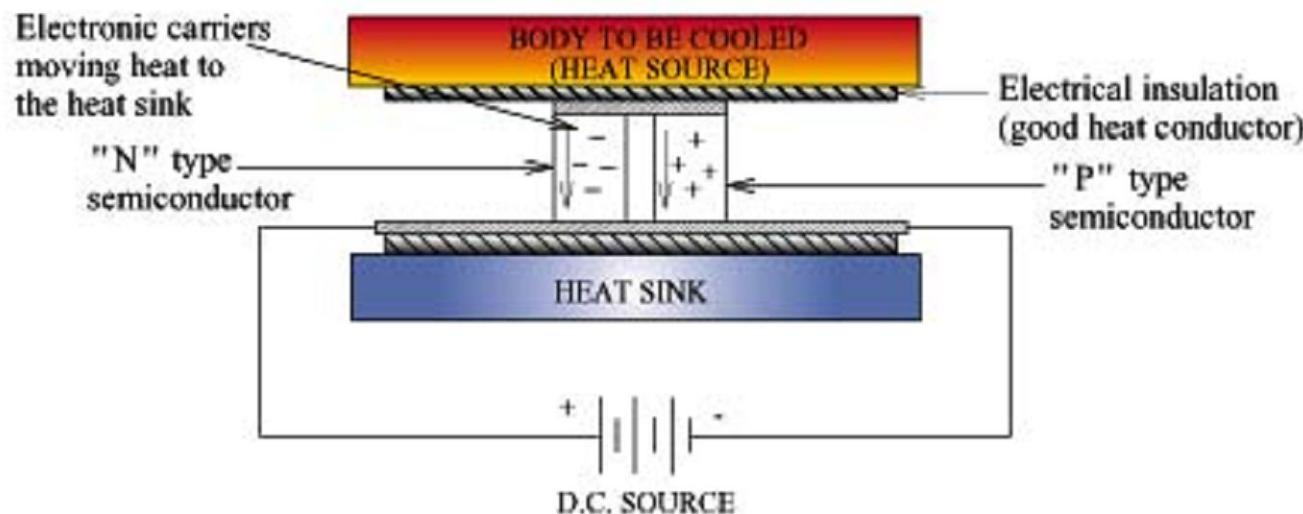


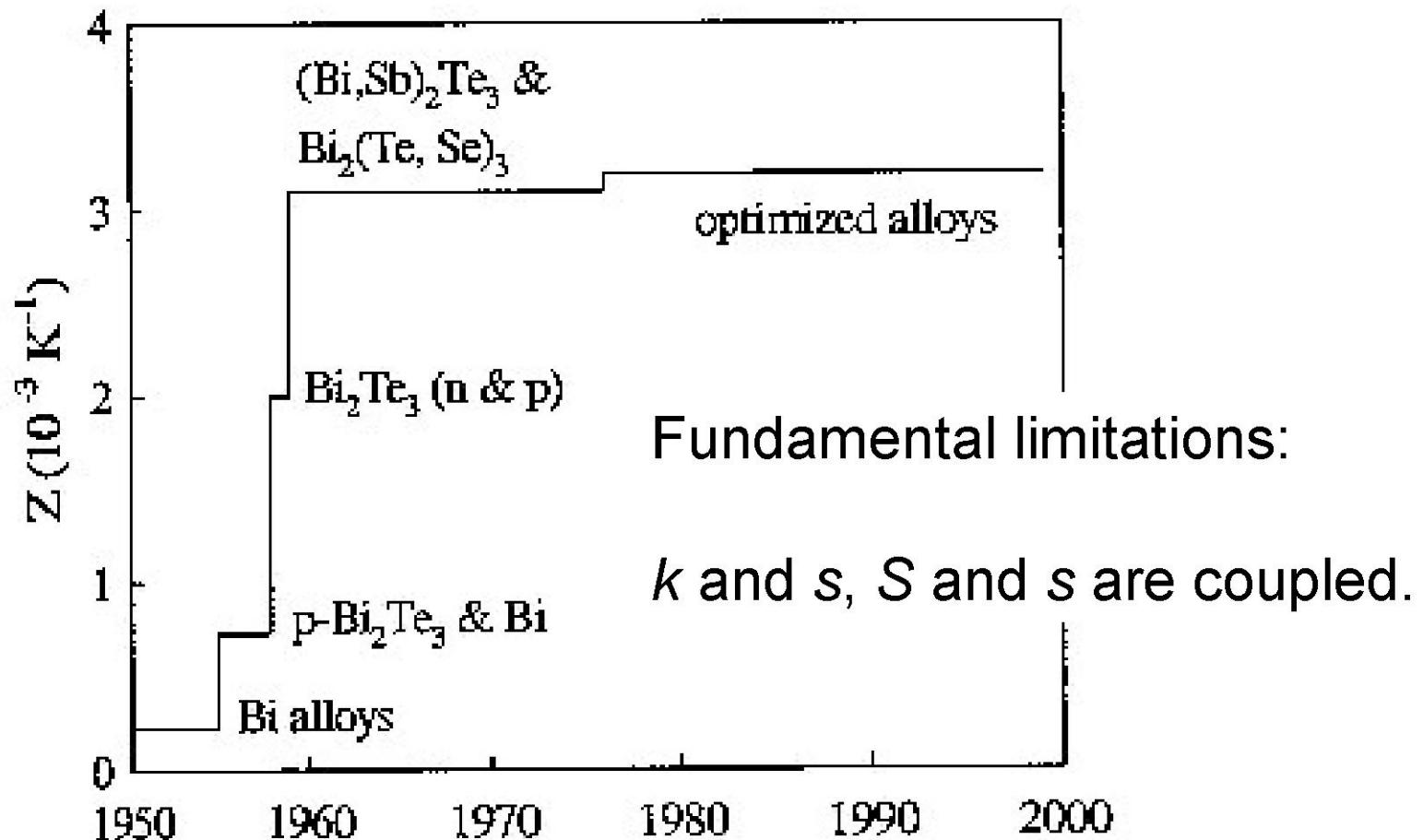
Fig. 1.7. Maximum coefficient of performance as a function of the dimensionless figure of merit for different ratios of hot to cold junction temperature

Criteria

- For greatest cooling efficiency we need a material that:
 - conducts electricity well (like metal)
 - conducts heat poorly (like glass)
-
- Bismuth telluride is the best bulk TE material with $ZT=1$
 - To match a refrigerator, $ZT= 4 - 5$ is needed
 - To efficiently recover waste heat from car, $ZT = 2$ is needed



Progress in ZT



Thermoelectric Power Generation

- Used in Space shuttles and rockets for compact source of power.
- Diffusive heat flow and Peltier effect are additive i.e. both reduce the temperature gradient.
- The efficiency of power generation is given by:

$$\eta = \frac{w}{q_H} = \frac{I[(S_2 - S_1)\Delta T - IR]}{(S_2 - S_1)IT_c - k\Delta T - 0.5I^2R}$$

where: w is the power delivered to the external load

Q_H is the positive heat flow from source to sink