Lecture 9 (week 9: 14 April 2025)

Transport properties of solids

- Electrical conductivity
- Thermal conductivity
- Thermoelectric effects

Exercises – Series 9, cross-coupled effects, thermoelectromechanics

Use of constitutive equations: tips and recommendations

$$D_i = \varepsilon_0 K_{ij} E_j + d_{in}\sigma_n + p_i \delta T$$

$$\varepsilon_n = d_{in} E_i + s_{nm}\sigma_m + \alpha_n \delta T$$

$$\delta S = p_i E_i + \alpha_m \sigma_m + \frac{C}{T}\delta T$$

- **What do you need to find?**
- **What are the boundary conditions?**
- **Maybe, some input data are redundant? (some effects are not permitted because of symmetry…)**

This reasoning helps selecting right equations

Exercises – Series 9, cross-coupled effects, thermoelectromechanics

Use of constitutive equations

$$D_i = \varepsilon_0 K_{ij} E_j + d_{in} \sigma_n + p_i \delta T$$

$$\varepsilon_n = d_{in} E_i + s_{nm} \sigma_m + \alpha_n \delta T$$

$$\delta S = p_i E_i + \alpha_m \sigma_m + \frac{C}{T} \delta T$$

- **Choose a suitable set of equations (previous slide)**
- **Identify the tensor structure, use symmetry, boundary conditions and input data to simplify equations as much as possible**
- **check about the coordinate system of your problem, rotate the tensors if needed**
- **combine equations, get the answer**

Exercises – Series 9, cross-coupled effects, thermoelectromechanics: solutions and comments

In all the exercises, the material used is $BaTiO_3$ in its tetragonal phase $4mm$. The 4-fold axis is always directed along the x_3 axis. You may use the table of values for $BaTiO_3$ given below if needed.

s_{11}	$8.05 \times 10^{-12}\ \mathrm{m^2/N}$	d_{15}	$392 \times 10^{-12}\ \mathrm{C/N}$
s_{12}	$-2.35 \times 10^{-12}\ \mathrm{m^2/N}$	d_{31}	$-35 \times 10^{-12}\ \mathrm{C/N}$
s_{13}	$-5.24 \times 10^{-12}\ \mathrm{m^2/N}$	d_{33}	$86 \times 10^{-12}\ \mathrm{C/N}$
s_{33}	$15.7 \times 10^{-12}\ \mathrm{m^2/N}$	K_{33}	150
C	$2.42 \times 10^{6}\ J/(m^3 \cdot K)$	p_3	$-5 \times 10^{-4}\ C/(m^2 \cdot K)$
α_3	$3.5 \times 10^{-5}\ 1/K$		

Some data are usable, others maybe redundant or irrelevant…

Exercises from Week 8

- 9.1. The effect of mechanical conditions on the pyroelectric response is measured

- 9.2 The effect of mechanical conditions on the capacitance is investigated

    - For both exercises one needs to check mechanical boundary conditions (clamped/free - what components of ε and σ are zero/nonzero)

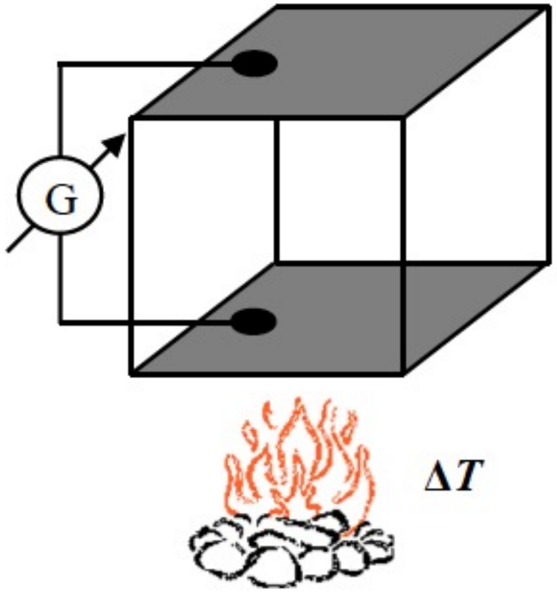
Exercise 8.1

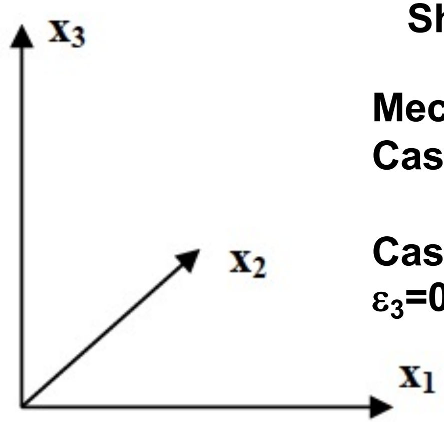
9.1. The effect of mechanical conditions on the pyroelectric response is measured. To do it, the (001) surfaces of the parallelepiped $BaTiO_3$ sample are covered with electrodes, and the change of the surface charge, driven by the temperature change, is measured (**Fig.1**).

In measurement (**a**), the sample is kept mechanically free.

In measurement (**b**), the sample is kept mechanically free in the x_1 and x_2 directions, while the motion in the x_3 direction is blocked.

Find the difference between the pyroelectric coefficients $p_{(a)}$ and $p_{(b)}$ measured these two ways (provide the answer in the analytical form)





Electric boundary conditions:
Short circuit, E_3=0

Mechanical boundary conditions:
Case(a): $\sigma_i = 0$

Case (b) only $\sigma_3 \neq 0$
ε_3=0

Exercise 8.1

$$D_i = \varepsilon_0 K_{ij} E_j + d_{ij}\sigma_j + p_i \Delta T,$$

$$\varepsilon_i = d_{ji} E_j + s_{ij}\sigma_j + \alpha_i \Delta T.$$

In both cases, the electric field $E_3 = 0$ since the (001) electrodes are electrically connected. In order to simplify the equation for D_3, we use the $4mm$ symmetry restrictions for tensor K_{ij} ($K_{31} = K_{32} = 0$), thus $K_{31}E_1 = K_{32}E_2 = 0$. The equation for D_3 attains the following form:

$$D_3 = d_{3j}\sigma_j + p_3 \Delta T$$

In case **(a)**, the sample is mechanically free, implying all $\sigma_j = 0$. Then, $D_3 = p_3 \Delta T$, and

$$p_{(a)} = \frac{D_3}{\Delta T} = p_3.$$

In case **(b)**, the sample is kept mechanically free in x_1 and x_2 directions, implying $\sigma_1 = \sigma_2 = \sigma_4 = \sigma_5 = \sigma_6 = 0$, and $\sigma_3 \neq 0$. Then, equation for D_3 rewrites as

$$D_3 = d_{33}\sigma_3 + p_3 \Delta T$$

To find σ_3, we use the constitutive equation for $\varepsilon_3 = 0$, which must not change during the measurement (note that $E_3 = 0$):

$$\varepsilon_3 = d_{j3}E_j + s_{33}\sigma_3 + \alpha_3 \Delta T = d_{13}E_1 + d_{23}E_2 + s_{33}\sigma_3 + \alpha_3 \Delta T$$

Result:

$$D_3 = \left(p_3 - \frac{d_{33}\alpha_3}{s_{33}}\right)\Delta T,$$

$$p_{(b)} = \frac{D_3}{\Delta T} = p_3 - \frac{d_{33}\alpha_3}{s_{33}}.$$

Thus, in **(a)** and **(b)** the measured pyroelectric responses are different. Specifically,

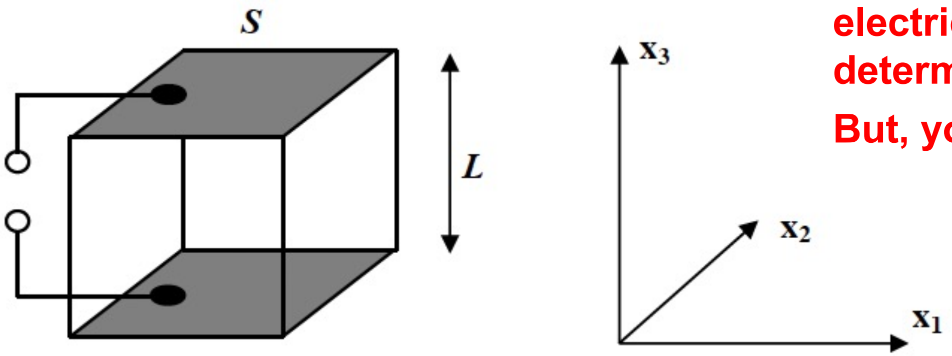
$$p_{(a)} - p_{(b)} = \frac{d_{33}\alpha_3}{s_{33}}$$

Exercise 8.2

The effect of mechanical conditions on the capacitance is investigated. To do it, the (001) surfaces of the parallelepiped $BaTiO_3$ sample (distance between the (001) faces is L , the area of each (001) face is S) are covered with electrodes (**fig.2**), and the capacitance of the sample is measured.

In measurement **(a)**, the sample is kept mechanically free.

In measurement (**b**), the sample is kept mechanically free in the x_1 and x_2 directions (i.e., in plane of capacitor), while the distance between electrodes L is forced to not change.



electrical boundary conditions are not determined!

But, you do not need them do define *C*

$$C = \frac{\Delta Q}{\Delta V} = \frac{\Delta D_3 \cdot S}{\Delta E_3 \cdot L}$$

Show that the two measured capacitances $C_{(a)}$ and $C_{(b)}$ have different values. Calculate the relative difference between them $\frac{C_{(a)}-C_{(b)}}{C_{(a)}}$. All measurements are done at constant temperature.

Exercise 8.2

$$D_i = \varepsilon_0 K_{ij} E_j + d_{ij}\sigma_j,$$
$$\varepsilon_i = d_{ji} E_j + s_{ij}\sigma_j.$$

$$(K_{31} = K_{32} = 0)$$

$$D_3 = \varepsilon_0 K_{33} E_3 + d_{3j}\sigma_j.$$

(a), the sample is mechanically free, implying all $\sigma_j = 0$. Then, $D_3 = \varepsilon_0 K_{33} E_3$, and

$$C_{(a)} = \frac{D_3 \cdot S}{E_3 \cdot L} = \varepsilon_0 K_{33} \frac{S}{L}.$$

In case **(b)**, the sample is kept mechanically free in x_1 and x_2 directions, implying $\sigma_1 = \sigma_2 = \sigma_4 = \sigma_5 = \sigma_6 = 0$, and $\sigma_3 \neq 0$. Then, equation for D_3 rewrites as

$$D_3 = \varepsilon_0 K_{33} E_3 + d_{33}\sigma_3.$$

$$\varepsilon_3 = d_{j3} E_j + s_{33}\sigma_3 = d_{13} E_1 + d_{23} E_2 + d_{33} E_3 + s_{33}\sigma_3$$

$$\varepsilon_3 = d_{33} E_3 + s_{33}\sigma_3 = 0 \quad \Rightarrow \quad \sigma_3 = -\frac{d_{33}}{s_{33}} E_3,$$

$$D_3 = \left(\varepsilon_0 K_{33} - \frac{d_{33}^2}{s_{33}}\right) E_3,$$

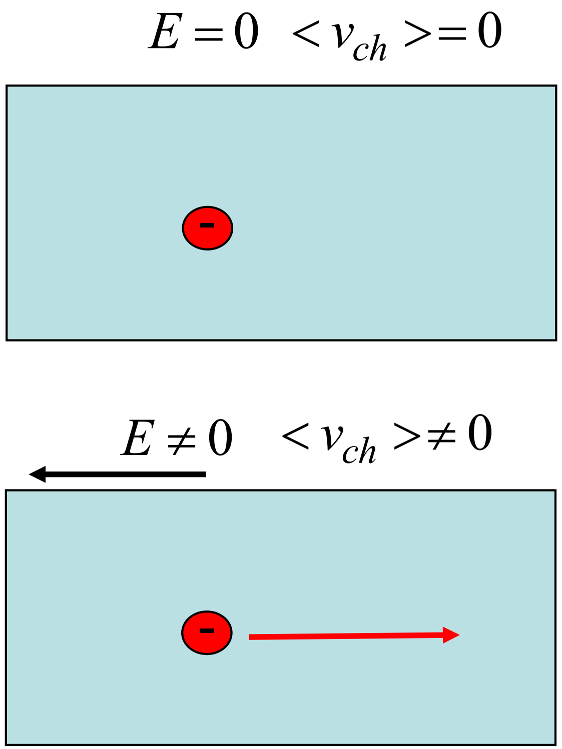
$$C_{(b)} = \frac{D_3 \cdot S}{E_3 \cdot L} = \left(\varepsilon_0 K_{33} - \frac{d_{33}^2}{s_{33}}\right) \frac{S}{L}.$$

Thus, in **(a)** and **(b)** the measured capacitances are different. Specifically,

$$\frac{C_{(a)} - C_{(b)}}{C_{(a)}} = \frac{d_{33}^2 / s_{33}}{\varepsilon_0 K_{33}} = 0.35$$

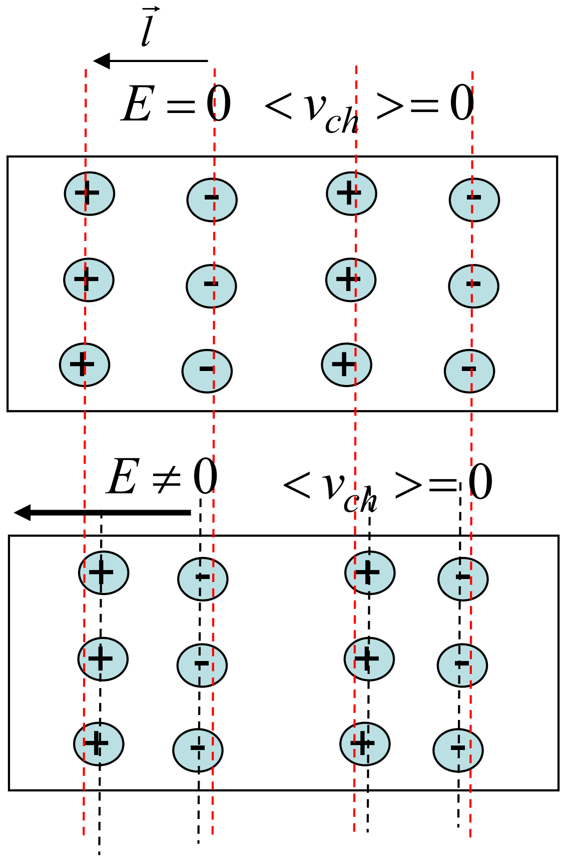
Electric response of solids: transport vs. dielectric response

Conductivity



Displacements of the charges are much *larger* that the interatomic distance

Polarization



Displacements of the charges are much *smaller* that the interatomic distance

Both described by 2nd rank tensor, but there are differences!

Electric response of solids, formal description

Conductivity

Polarization

$$\vec{J} = \frac{\sum_i q_i \vec{v}_i}{V}$$

$$\vec{P} = \frac{\sum_i q_i \delta\vec{x}_i}{V}$$

Linear response

$$J_i = \tau_{ij} E_j$$

$$P_i = \chi_{ij} E_j$$

Conductivity tensor

$$\tau_{ij}$$

Dielectric susceptibility tensor

$$\chi_{ij}$$

can be shown

$$\tau_{ij} = \tau_{ji}$$

$$\chi_{ij} = \chi_{ji}$$

Transport property vs. equilibrium property

Dielectric response
- equilibrium property

$$D_i = \varepsilon_o K_{ij} E_j$$

$$K_{ij} = K_{ji}$$

Energy at fixed *E*

$$dW = E_i dD_i \qquad W = \frac{1}{2} E_j D_j$$

Electrical Conductivity
- transport property

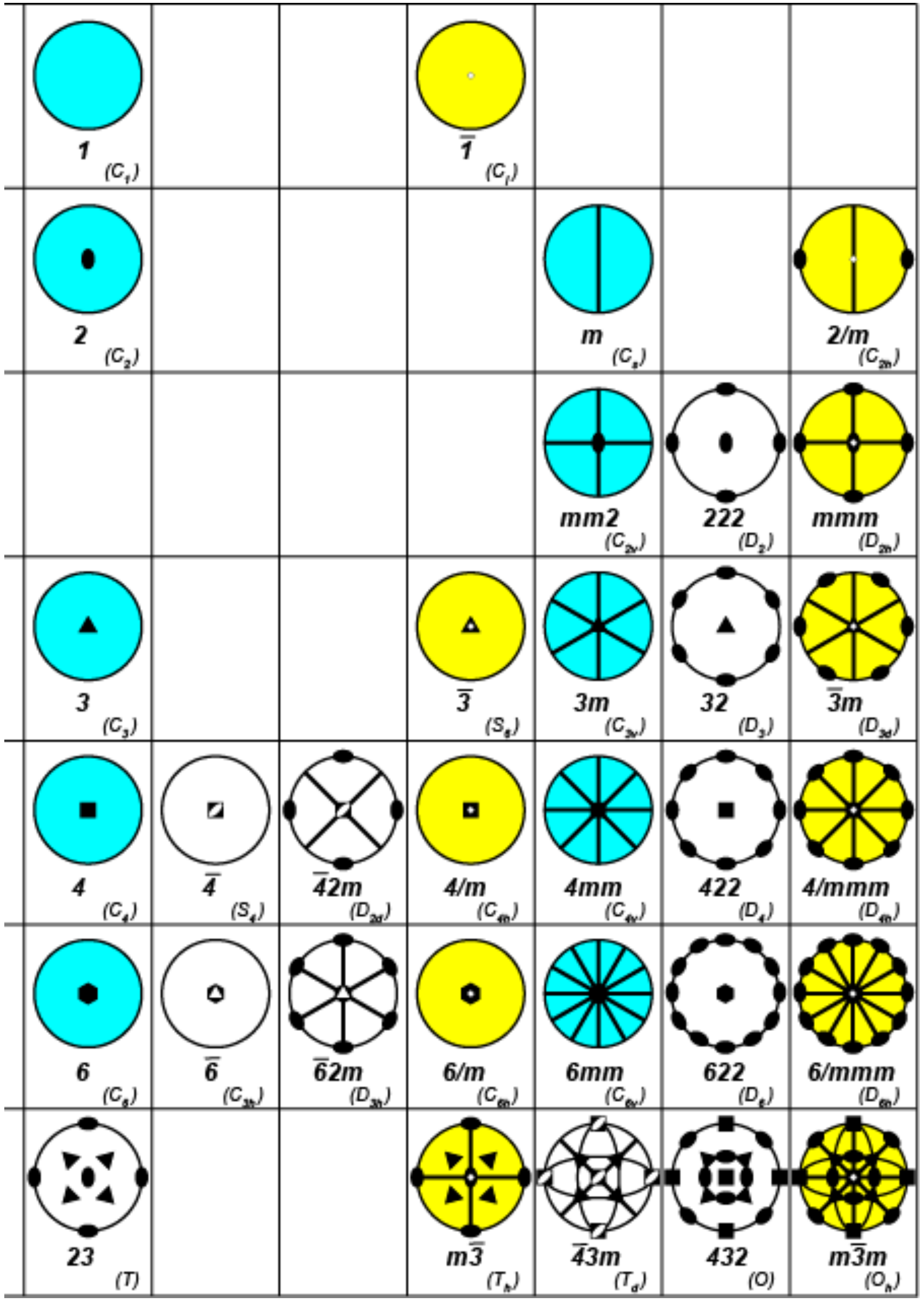
$$J_i = \tau_{ij} E_j$$

$$\tau_{ij} = \tau_{ji}$$

Energy loss at fixed *E*

$$\frac{dW}{dt} = -E_j J_j$$

Conductivity : Effect of Neumann in conventional axes



$$\begin{pmatrix} \tau_{11} & \tau_{12} & \tau_{13} \\ & \tau_{22} & \tau_{23} \\ & & \tau_{33} \end{pmatrix}$$

$$\begin{pmatrix} \tau_{11} & 0 & \tau_{13} \\ & \tau_{22} & 0 \\ & & \tau_{33} \end{pmatrix}$$

$$\begin{pmatrix} \tau_{11} & 0 & 0 \\ & \tau_{22} & 0 \\ & & \tau_{33} \end{pmatrix}$$

$$\begin{pmatrix} \tau_{1} & 0 & 0 \\ & \tau_{1} & 0 \\ & & \tau_{3} \end{pmatrix}$$

$\infty \quad \infty m \quad \infty 2$

$\infty / m \quad \infty / mm$

$$\begin{pmatrix} \tau & 0 & 0 \\ & \tau & 0 \\ & & \tau \end{pmatrix}$$

$\infty\infty \quad \infty\infty m$

Anisotropy of conductivity

$$J_i = \tau_{ij} E_j$$

Current is always parallel to the field only if

$$\tau_{ij} = \tau \delta_{ij}$$

In anisotropic materials current is NOT ALWAYS parallel to the field !

mm2

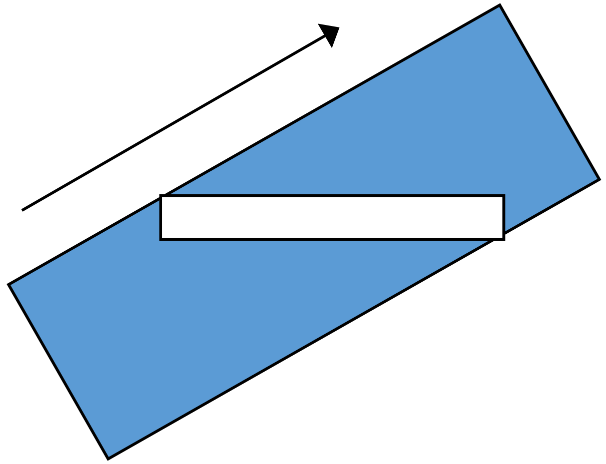
$$\begin{pmatrix} \tau_{11} & 0 & 0 \\ & \tau_{22} & 0 \\ & & \tau_{33} \end{pmatrix}$$

2

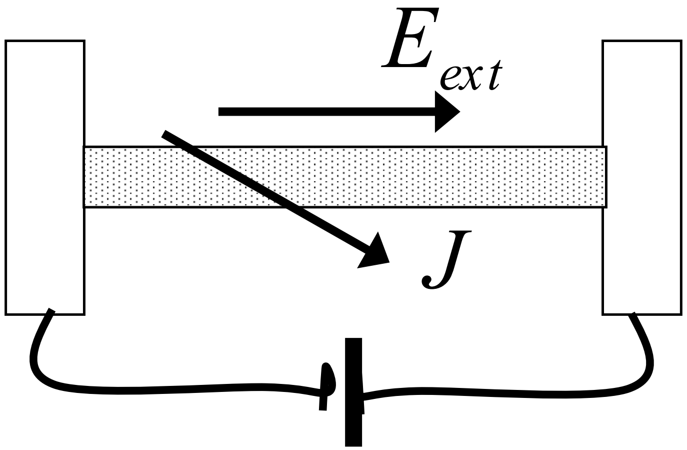
$$\begin{pmatrix} \tau_{11} & 0 & \tau_{13} \\ & \tau_{22} & 0 \\ & & \tau_{33} \end{pmatrix}$$

Transversal voltage

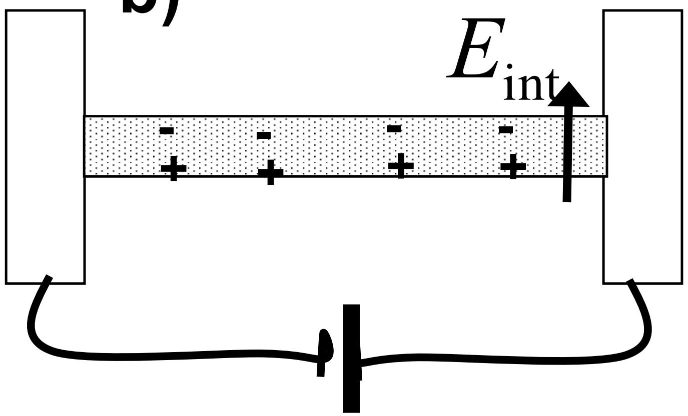
$4/mmm$ $Bi_4Ti_3O_{12}$ 4



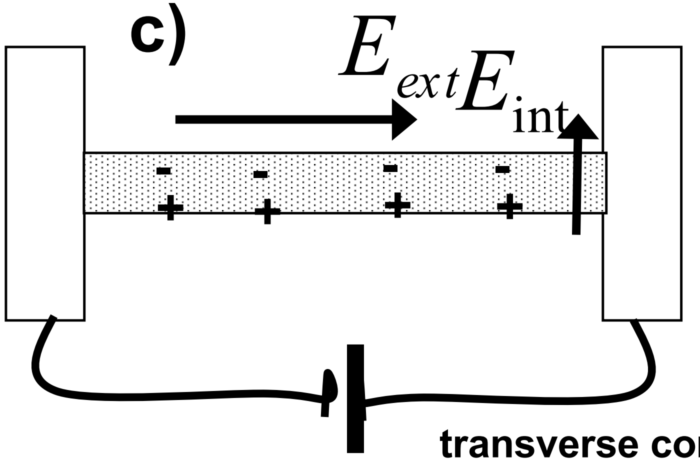
a) (first moment, transient response)



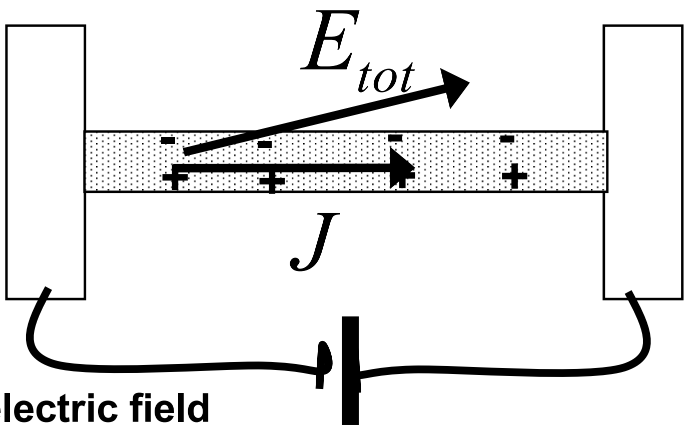
b)



c)



d) (steady-state current response)



transverse component of the electric field

Transversal voltage

Example $Bi_4Ti_3O_{12}$

Made of less conductive layers TiO_2 and more conductive layers Bi_2O_3

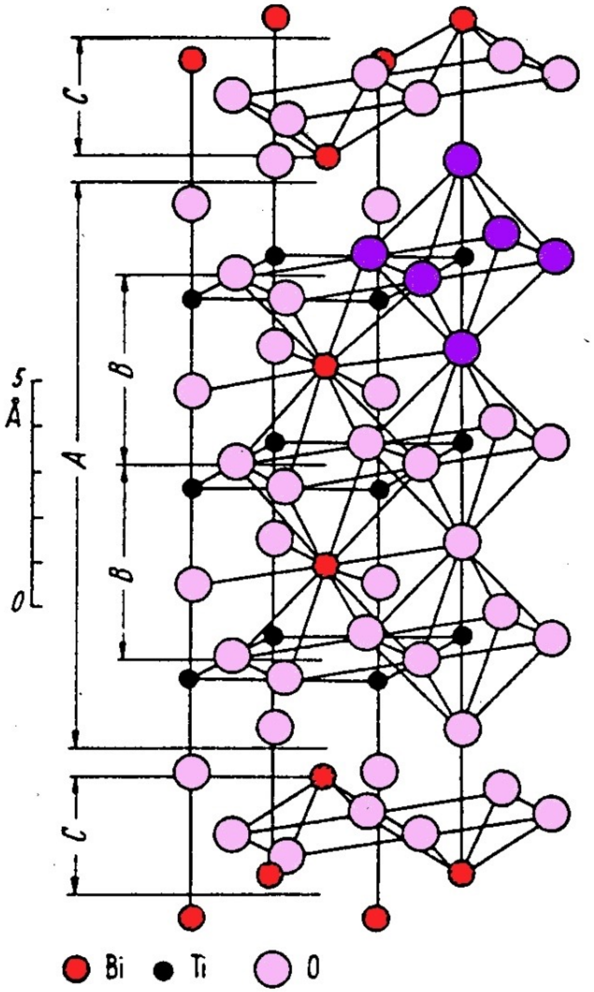
4/mmm

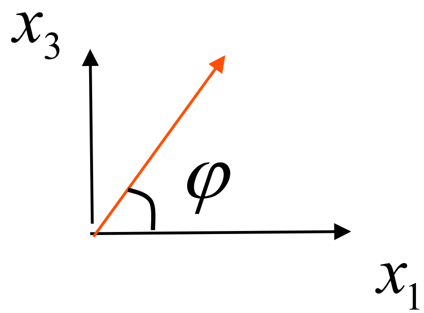
$$T = 800^0\text{C}$$

$$a = 0.25\,(\Omega\text{m})^{-1}$$

$$b = 0.016\,(\Omega\text{m})^{-1}$$

$$\underline{\tau} = \begin{pmatrix} a & 0 & 0 \\ 0 & a & 0 \\ 0 & 0 & b \end{pmatrix}$$

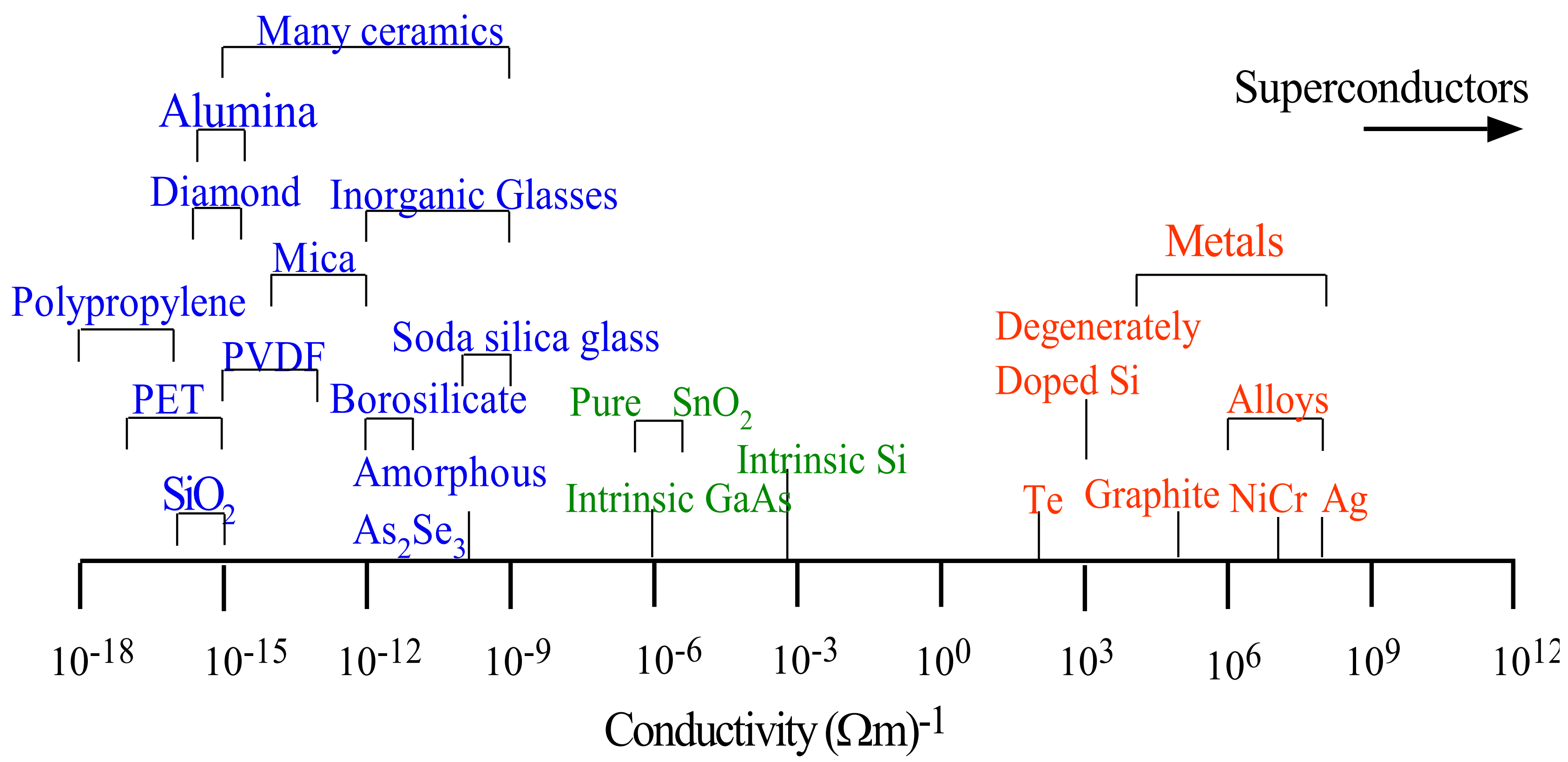




$$\left.\frac{E_\perp}{E_{\uparrow\uparrow}}\right|_{\max} \approx 2$$

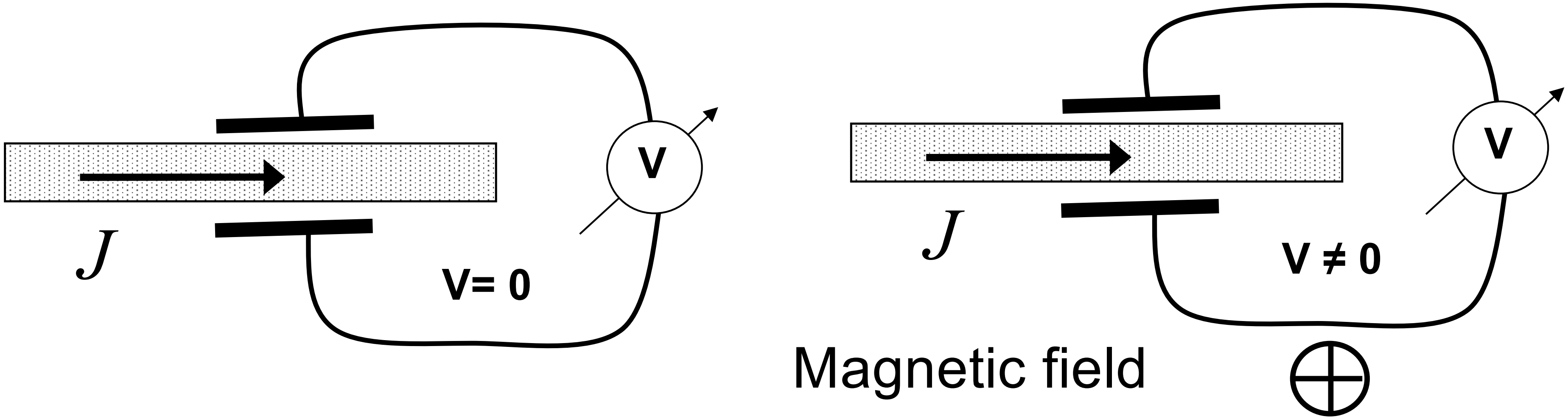
$$\varphi|_{\max} \approx 4^0$$

Spread of conduction



Transversal voltage and Hall effect

$m\bar{3}m$ **Cu** isotropic conductor



Lorentz force:

F=q **(v** x **B)**

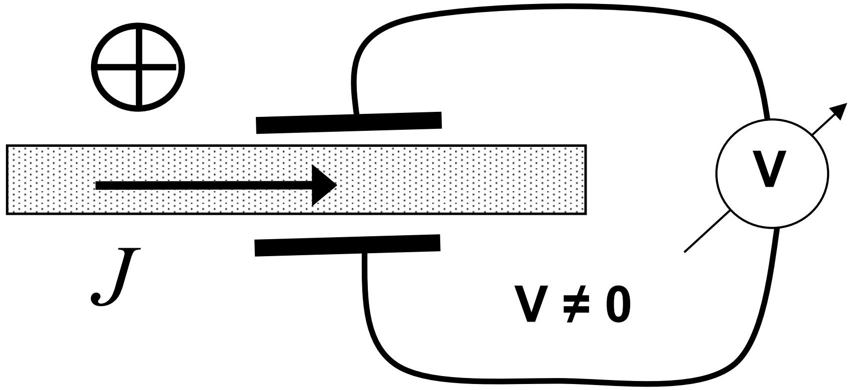
Hall voltage:

V_H=($I_x$$B_z$)/(ntq), where n-charge density, t-thickness, q-charge

Hall effect

Isotropic conductor

Magnetic field



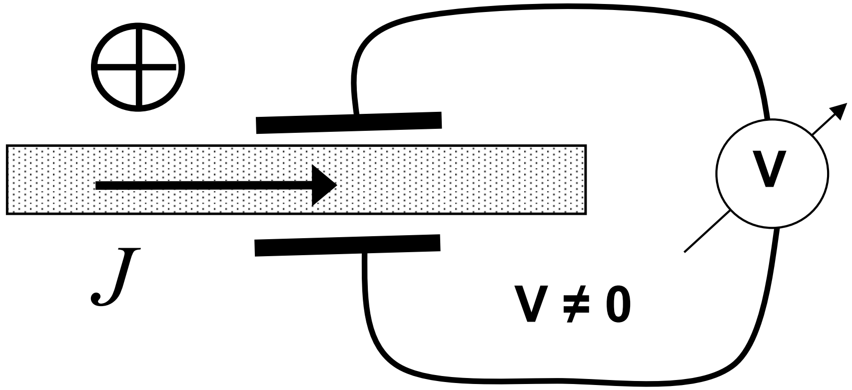
1. Magnetic field modify the symmetry of the system allowing the transverse voltage in isotropic conductor

2. Transport effect → current

Hall effect: tensor aspect

Isotropic conductor

Magnetic field



Hall effects is controlled by a 3rd rank pseudo-tensor

$$E_i = R_{ijk} B_j J_k$$

Thermoelectric transport effects

Thermal conductivity

Energy dissipation

$$h_i = -k_{ij}\frac{\partial T}{\partial x_j}$$

$$k_{ji} = k_{ij}$$

$$\frac{dW}{dt} = \frac{h_i}{T}\frac{\partial T}{\partial x_j}$$

k_{ij} (kappa) – thermal conductivity tensor, h_i – heat flux

Analogy to electrical conductivity

$$E_i = -\frac{\partial \varphi}{\partial x_j}$$

$$J_i = -\tau_{ij}\frac{\partial \varphi}{\partial x_j}$$

$$\frac{dW}{dt} = J_j\frac{\partial \varphi}{\partial x_j}$$

$$\frac{\partial \varphi}{\partial x_j} \Rightarrow \frac{\partial T}{\partial x_j}$$

$$J_i \Rightarrow \frac{h_i}{T}$$

Thermoelectricity

Electrical Conductivity

$$J_i = \tau_{ij} E_j$$

Thermal Conductivity

$$h_i = -k_{ij} \frac{\partial T}{\partial x_j}$$

Thermoelectricity

$$J_i = \tau_{ij} E_j + a_{ij} \frac{\partial T}{\partial x_j}$$

$$h_i = b_{ij} E_j - k_{ij} \frac{\partial T}{\partial x_j}$$

Cross effects:

There should be a component of current proportional to the temperature gradient!

Thermoelectricity vs. piezoelectricity

Piezoelectricty

$$D_i = \varepsilon_0 K_{ij} E_j + d_{ijk} \sigma_{jk}$$

$$\varepsilon_{ij} = d_{kij} E_k + s_{ijkl} \sigma_{kl}$$

Maxwell relations

Thermoelectricity

$$J_i = \tau_{ij} E_j + a_{ij} \frac{\partial T}{\partial x_j}$$

$$h_i = b_{ij} E_j - k_{ij} \frac{\partial T}{\partial x_j}$$

??????????

Onsager relations for thermo-electric transport phenomena

$$\tau_{ij} = \tau_{ji}$$

$$k_{ji} = k_{ij}$$

$$b_{ij} = -Ta_{ji}$$

Maxwell relations cannot be applied because the energy does not characterize the state of the material in a transport phenomenon

Onsager relations can be obtained from considerations in terms of the energy dissipation in a process

Onsager relations express the equality of certain ratios between flows and forces

Themoelectricity vs. piezoelectricity

Piezoelectricty

$$D_i = \varepsilon_0 K_{ij} E_j + d_{ijk} \sigma_{jk}$$

$$\varepsilon_{ij} = d_{kij} E_k + s_{ijkl} \sigma_{kl}$$

Maxwell relations

Thermoelectricity

$$J_i = \tau_{ij} E_j + a_{ij} \frac{\partial T}{\partial x_j}$$

$$h_i = -T a_{ji} E_j - k_{ij} \frac{\partial T}{\partial x_j}$$

Onsager relations

Standard description of thermoelectricity

Changing variables:
Instead of field use current and temperature

$$J_i = \tau_{ij} E_j + a_{ij} \frac{\partial T}{\partial x_j}$$

$$h_i = -T a_{ji} E_j - k_{ij} \frac{\partial T}{\partial x_j}$$

$$E_i = \rho_{ij} J_j + \Sigma_{ij} \frac{\partial T}{\partial x_j}$$

$$h_i = T \Sigma_{ji} J_j - \tilde{k}_{ij} \frac{\partial T}{\partial x_j}$$

$$\rho_{ij} = \tau^{-1}{}_{ij}$$

$$\Sigma_{ij} = -\rho_{il} a_{lj}$$

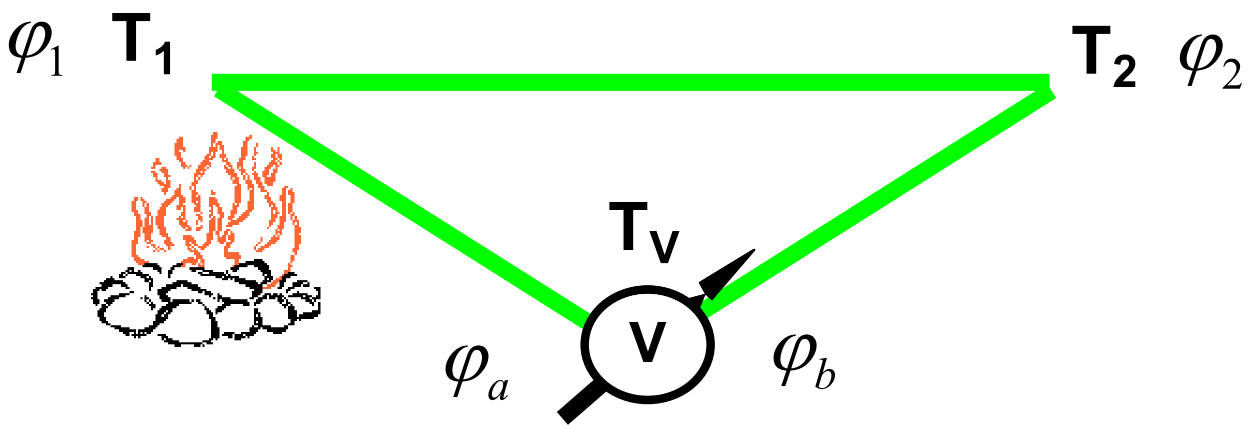
$$\tilde{k}_{ij} = k_{ij} - T a_{si} \rho_{sl} a_{lj}$$

Σ_{ij} **Thermoelectric tensor (Seebeck coefficients)**

In general $\Sigma_{ij} \neq \Sigma_{ji}$

Thermoelectric effect - example

Seebeck effect



$$E = \rho J + \Sigma \frac{\partial T}{\partial x}$$

$$J = 0 \qquad E = -\frac{\partial \varphi}{\partial x}$$

$$\frac{\partial}{\partial x}(\varphi + \Sigma T) = 0$$

$$\varphi + \Sigma T = const$$

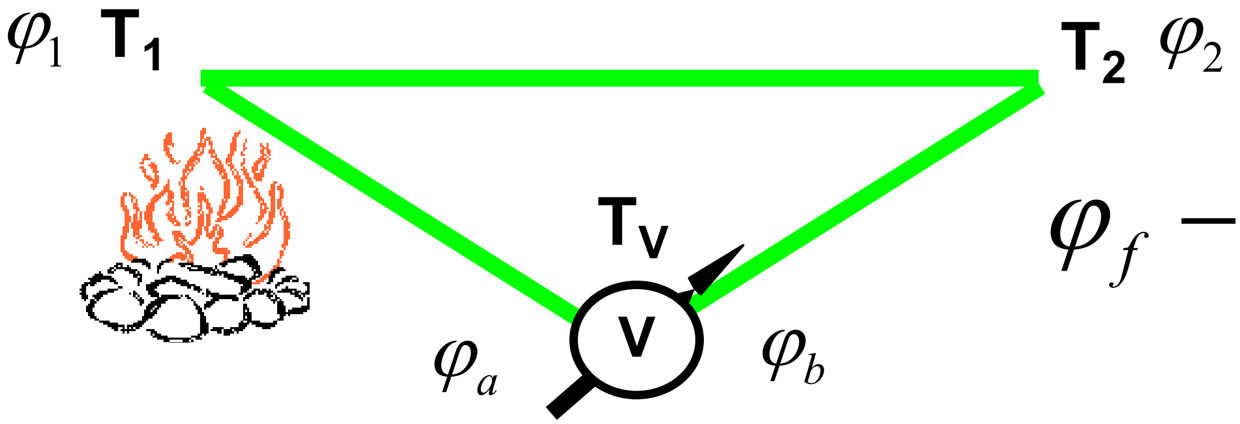
$\varphi_b - \varphi_a$ **?**

$$\varphi_f - \varphi_i = -\Sigma(T_f - T_i)$$

For simplicity Seebeck koefficients are considered T-independent

Thermoelectric effect - example

Seebeck effect



$$\varphi_f - \varphi_i = -\Sigma(T_f - T_i)$$

$$\varphi_b - \varphi_2 = -\Sigma(T_V - T_2)$$

$$\varphi_b - \varphi_1 = -\Sigma(T_V - T_2) - \Sigma(T_2 - T_1)$$

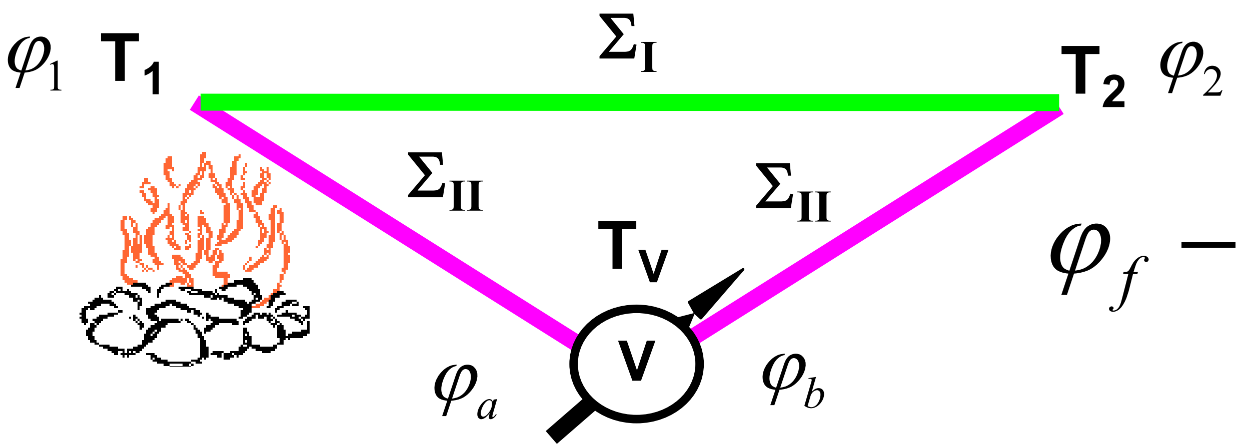
$$\varphi_b - \varphi_a = -\Sigma(T_V - T_2) - \Sigma(T_2 - T_1) - \Sigma(T_1 - T_V) = 0$$

Σ cannot be measured this way

This is rigorous for small $T_1 - T_2$, since Σ is temperature dependent.

Thermoelectric effect - example

Seebeck effect



$$\varphi_f - \varphi_i = -\Sigma(T_f - T_i)$$

$$\varphi_b - \varphi_2 = -\Sigma_{II}(T_V - T_2)$$

$$\varphi_b - \varphi_1 = -\Sigma_{II}(T_V - T_2) - \Sigma_I(T_2 - T_1)$$

$$\varphi_b - \varphi_a = -\Sigma_{II}(T_V - T_2) - \Sigma_I(T_2 - T_1) - \Sigma_{II}(T_1 - T_V) = (\Sigma_{II} - \Sigma_I)(T_2 - T_1)$$

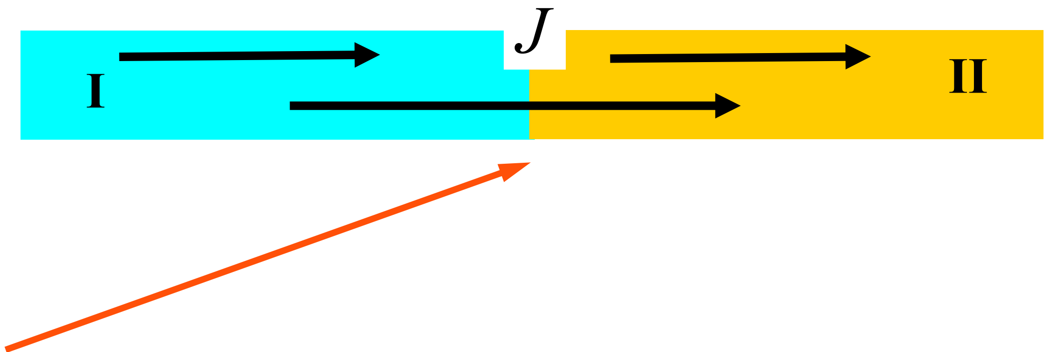
This is rigorous for small $T_1 - T_2$, since Σ is temperature dependent.

Thermoelectric effect - example

Peltier effect

$$h = T\Sigma J - \tilde{k}\frac{\partial T}{\partial x}$$

$$h^{I} = T\Sigma^{I} J \qquad h^{II} = T\Sigma^{II} J$$



$T = \mathrm{const}$

$$\frac{dQ}{dt} = S(h^{I} - h^{II}) = STJ(\Sigma^{I} - \Sigma^{II}) = T(\Sigma^{I} - \Sigma^{II})I$$

Thermoelectric Peltier and Seebeck effects

• We can regard the Peltier effect as the back-action counterpart to the Seebeck effect :

-if a thermoelectric circuit is closed then the Seebeck effect will drive a current

- this current in turn will always transfer heat from the hot to the cold junction (via the Peltier effect)

- relationship between Peltier and Seebeck effects is seen in the connection between their coefficients

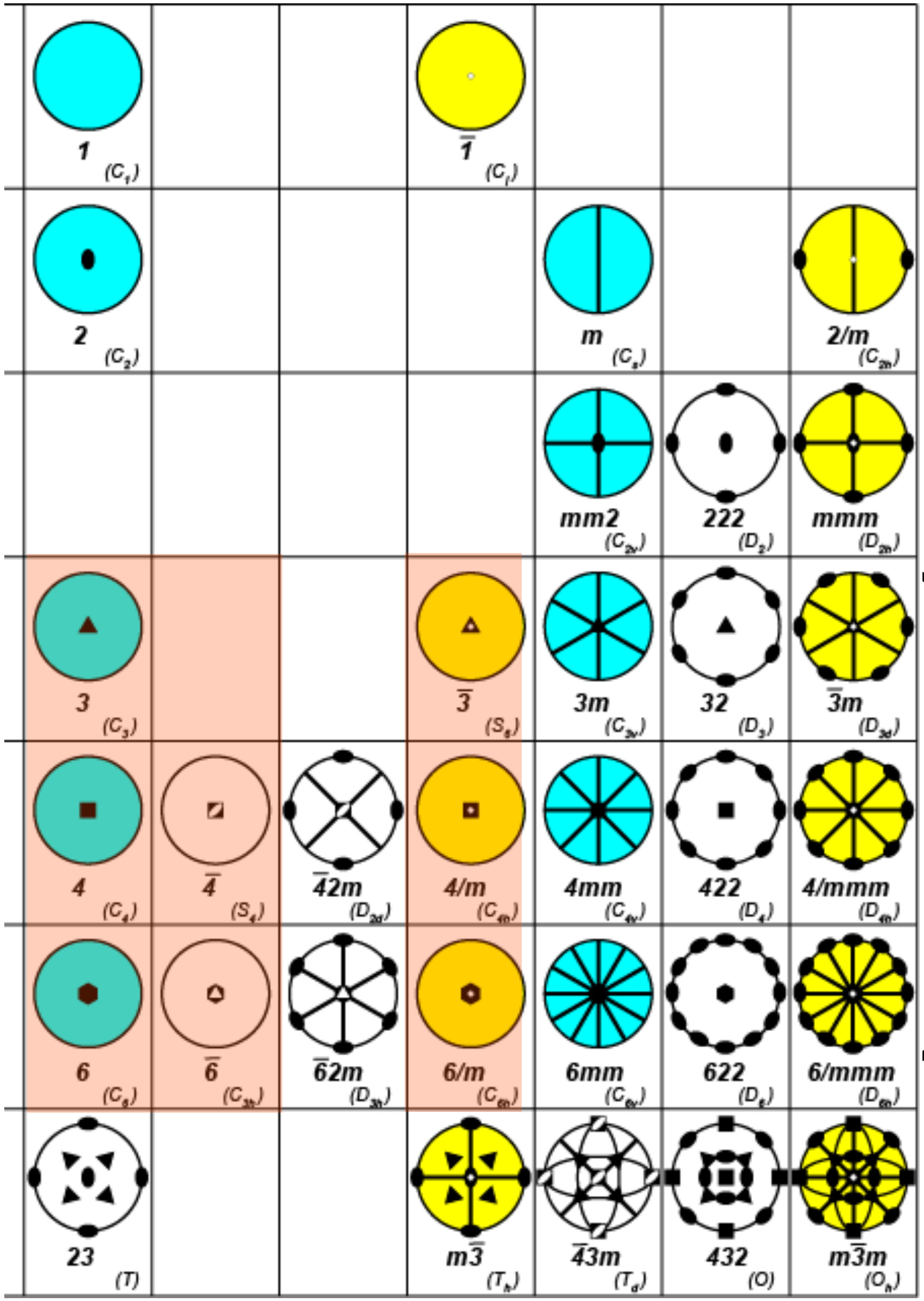
• Applications:

-small refrigerators /coolers (Peltier effect) –compact, no fluids

-temperature sensors (Seebeck effects) - thermocouples

All symmetries

There is no physical reason to expect Seebeck tensor to be symmetrical



$$\begin{pmatrix} \Sigma_{11} & \Sigma_{12} & \Sigma_{13} \\ \Sigma_{21} & \Sigma_{22} & \Sigma_{23} \\ \Sigma_{31} & \Sigma_{32} & \Sigma_{33} \end{pmatrix}$$

$$\begin{pmatrix} \Sigma_{11} & \Sigma_{12} & 0 \\ \Sigma_{21} & \Sigma_{22} & 0 \\ 0 & 0 & \Sigma_{33} \end{pmatrix}$$

$$\begin{pmatrix} \Sigma_{11} & 0 & 0 \\ 0 & \Sigma_{22} & 0 \\ 0 & 0 & \Sigma_{33} \end{pmatrix}$$

$$\begin{pmatrix} \Sigma_{11} & 0 & 0 \\ 0 & \Sigma_{11} & 0 \\ 0 & 0 & \Sigma_{33} \end{pmatrix} \leftarrow \infty/mm \quad \infty 2 \quad \infty m$$

$$\begin{pmatrix} \Sigma_{11} & \Sigma_{12} & 0 \\ -\Sigma_{12} & \Sigma_{11} & 0 \\ 0 & 0 & \Sigma_{33} \end{pmatrix} \quad \infty \quad \infty/m$$

$$\begin{pmatrix} \Sigma & 0 & 0 \\ 0 & \Sigma & 0 \\ 0 & 0 & \Sigma \end{pmatrix} \leftarrow \infty\infty \quad \infty\infty m$$

Seebeck coefficients of selected metals

$m\bar{3}m$	**Σ at 0 °C (μV K^{-1})**	**Σ at 27 °C (μV K^{-1})**
Al	1.6	1.8
Au	-1.79	-1.94
Cu	-1.70	-1.84
Na		5
Pd	9.00	9.99
Pt	4.45	

Bi_2Te_3 n-type	**Σ at 54 °C**
rhombohedral	287 μV K^{-1}

at room temperature

$$\Delta T = 100 \text{ K}$$

$$\Delta\varphi \cong 10^{-1} - 10^{-3} \text{ V}$$

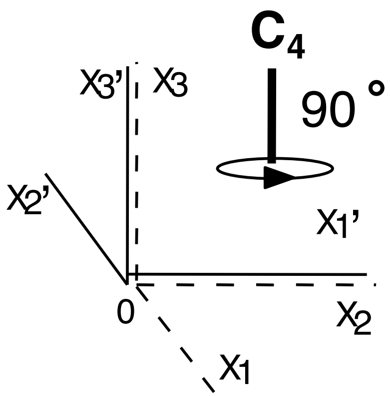
Useful numbers, temperature ranges:

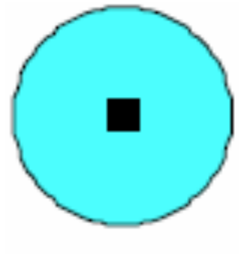
https://www.omega.com/en-us/colorcodes

Convention in engineering: Seebeck coefficient S = - Σ

Applications of Neumann equation

Example: Σ_{12}?





4

$$\begin{pmatrix} \Sigma_{11} & \Sigma_{12} & 0 \\ -\Sigma_{12} & \Sigma_{11} & 0 \\ 0 & 0 & \Sigma_{33} \end{pmatrix}$$

rotation $4_z(90^0)$

$$p_1' = p_2$$
$$p_2' = -p_1$$
$$p_3' = p_3$$

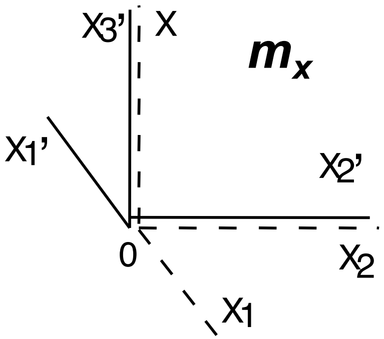
$$p_1' p_2' = -p_2 p_1 \Rightarrow \Sigma_{12}' = -\Sigma_{21}$$

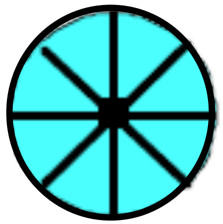
Neumann equation

$$\Sigma_{12} = -\Sigma_{21}$$

Applications of Neumann equation

Example: Σ_{12}-?





$$\begin{pmatrix} \Sigma_{11} & 0 & 0 \\ 0 & \Sigma_{11} & 0 \\ 0 & 0 & \Sigma_{33} \end{pmatrix}$$

$4mm$

plane m_x

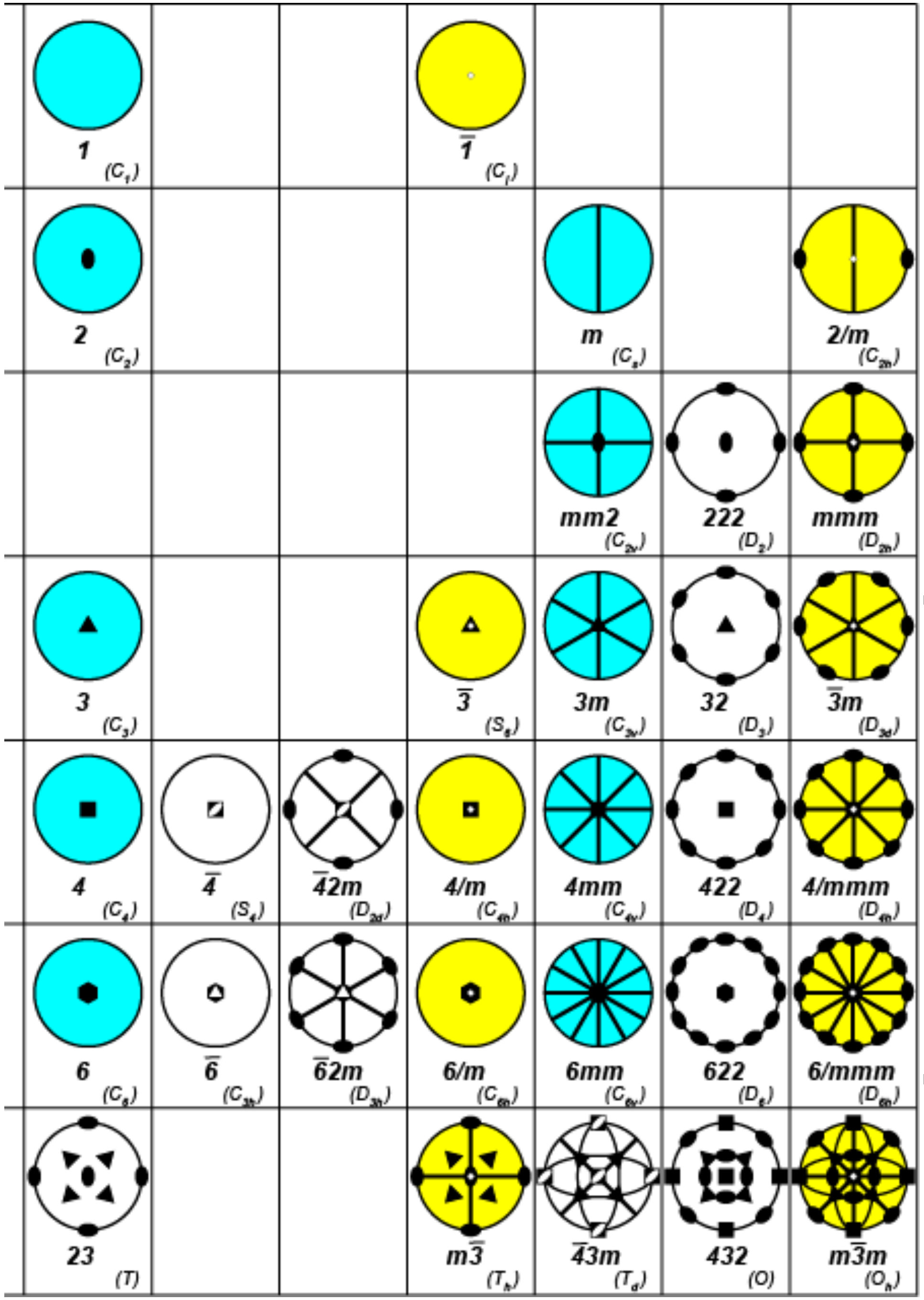
$$p_1' = -p_1$$
$$p_2' = p_2$$
$$p_3' = p_3$$

$$p_1' p_2' = -p_1 p_2 \Rightarrow \Sigma_{12}' = -\Sigma_{12}$$

Neumann equation

$$\Sigma_{12} = -\Sigma_{12} = 0$$

Thermoelectric anisotropy and axis choice



9 $\Rightarrow$ 6

5 $\Rightarrow$ 4

3

2-3

$$\Sigma_{ij} \neq \Sigma_{ji}$$

1

Equilibrium and transport properties

Equilibrium

Dielectric response K_{ij}

Elasticity c_{ijkl} s_{ijkl}

Heat capacity C

Piezoelectricity and converse piezoelectricity d_{ijk}

Pyroelectricity and electrocaloric p_i

Thermal expansion and piezocaloric α_{ji}

Maxwell relations

Transport

Electrical conductivity τ_{ij}

Thermal conductivity k_{ij}

Seebeck and Peltier effect Σ_{ij}

Hall effect R_{ijk}

Onsager relations

Essential

1. The symmetry of a material can be translated into the symmetry of its transport properties.

2. Thermoelectric effects: Peltier and Seebeck effects

3. Transport properties give an examples of a non-symmetric second rank tensor - Thermoelectric tensor (Seebeck coefficients)