Magnetism (Spins) Seen in a New Light

Muhammad Sabieh Anwar

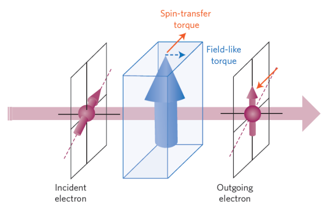
S S E

LUMS School of Science & Engineering

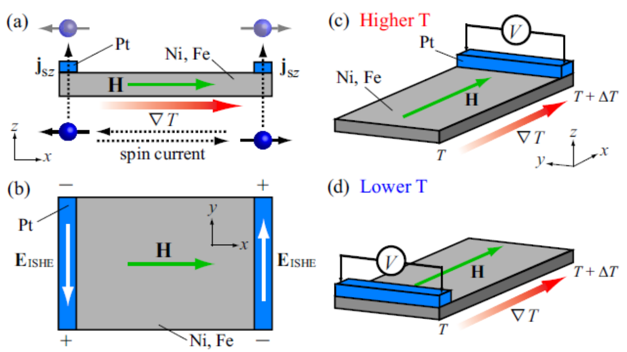
Spring College on Optics, LUMS, 2016

Classes of Spintronic Effects

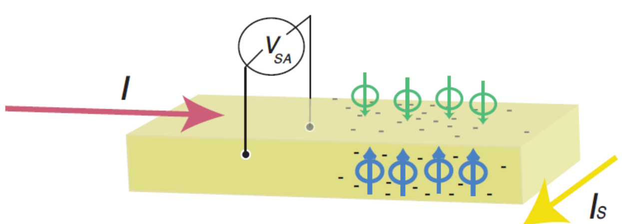
Current induced torque or Spin transfer torque



Spin Caloritronics



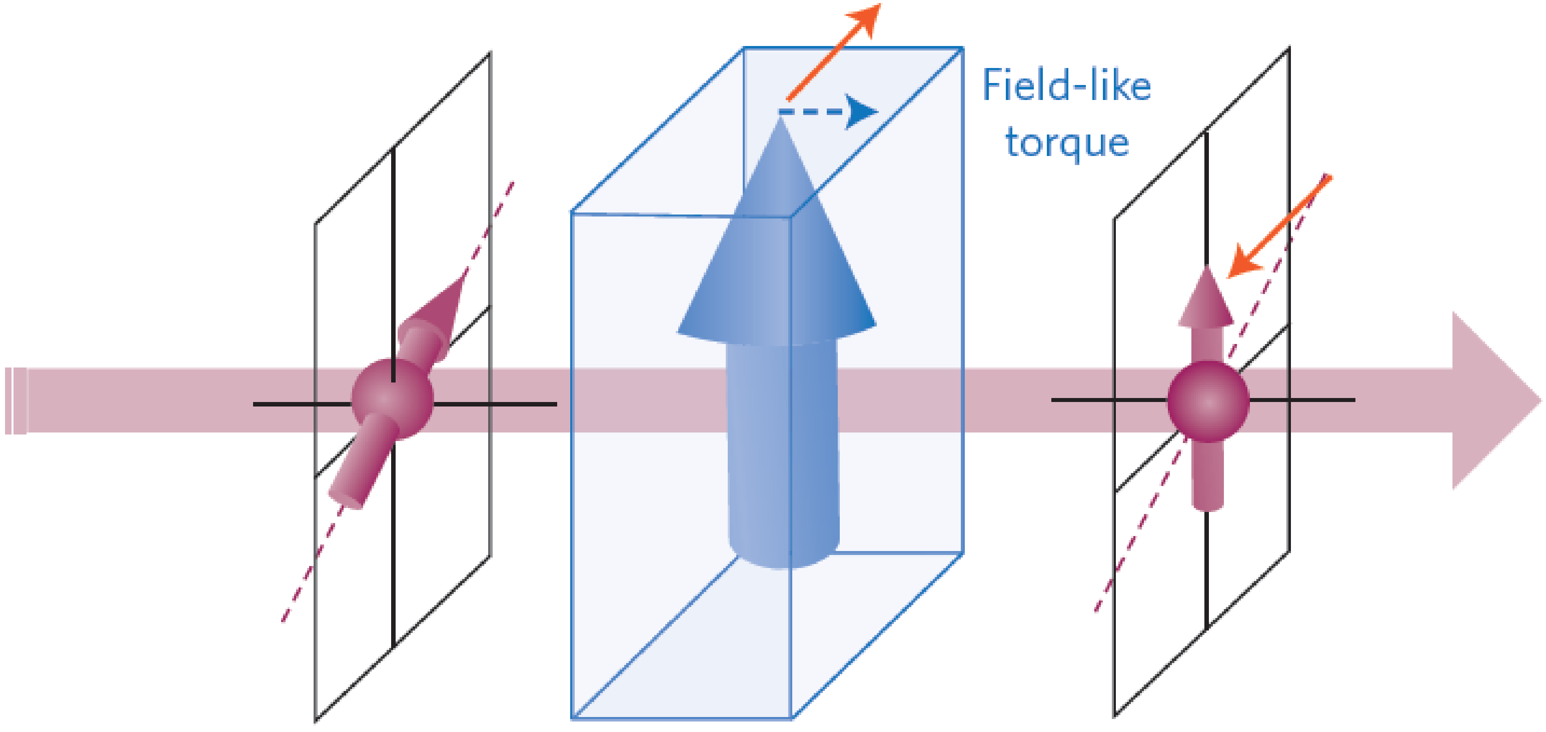
Spin Hall effect family



Si spintronics

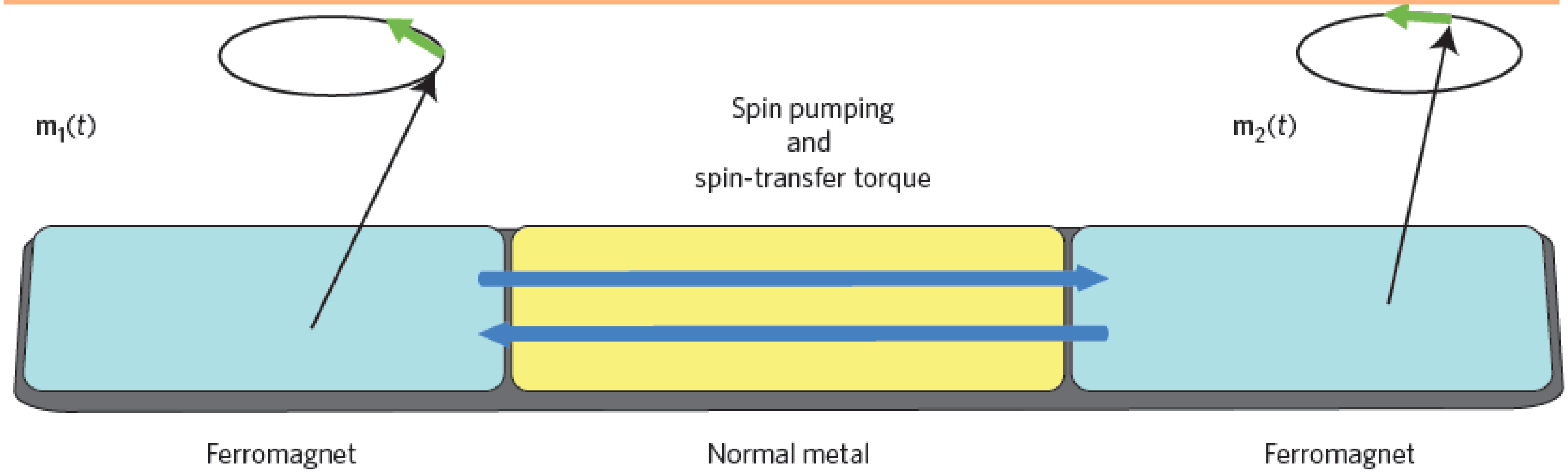
Graphene and topological insulators

Current induced torque or Spin transfer torque



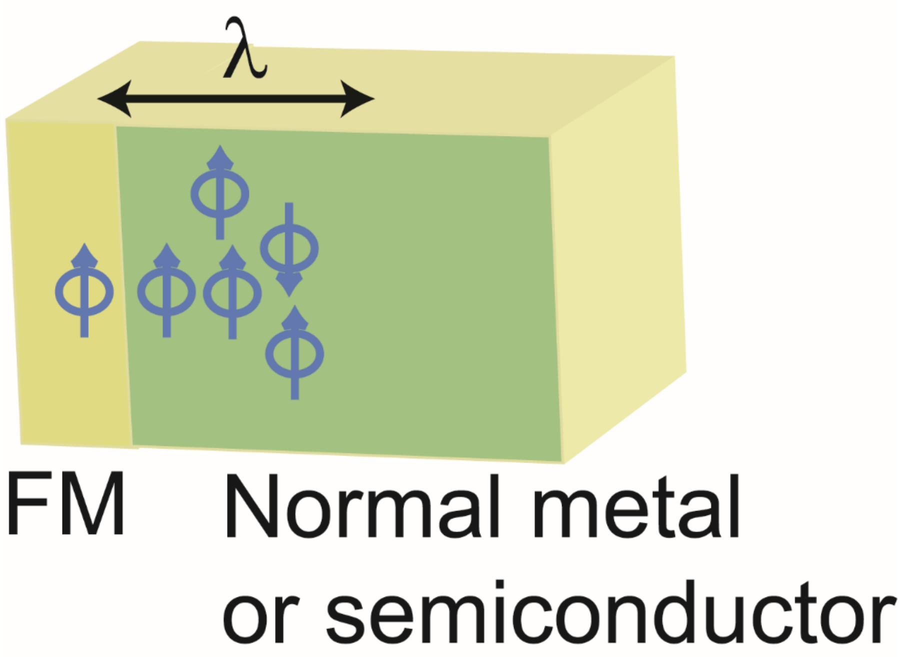
A. Brataas, A.D. Kent and H.Ohno,
Nature Materials 11, 372 (2012).

Spin pumping

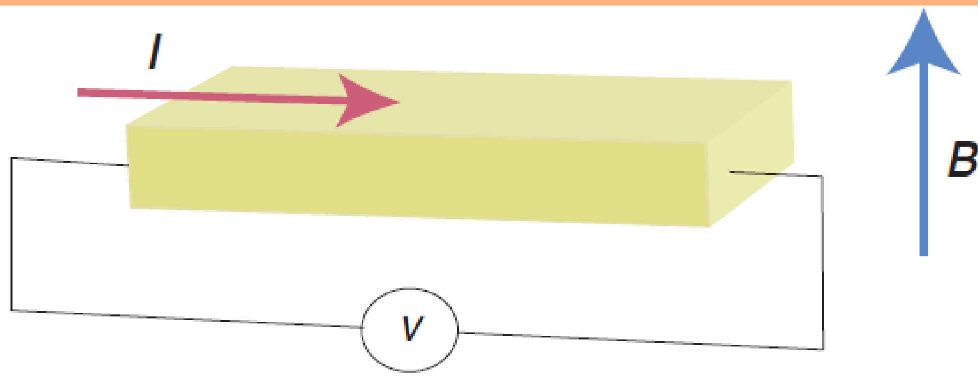


A. Brataas, A.D. Kent and H.Ohno, **Nature Materials 11**, 372 (2012).

Spin injection



Conventional Magnetoresistance

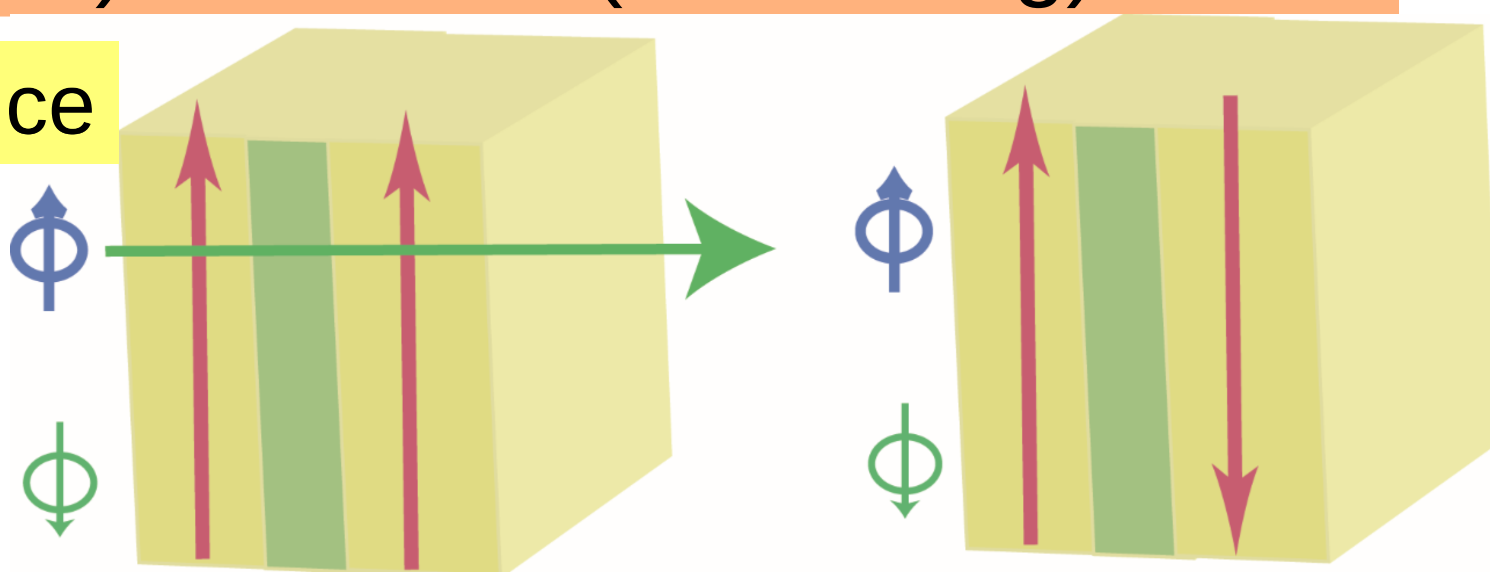


I =conduction current.
B =magnetic field.
V =detected electrical voltage.

(Giant) GMR and (Tunnelling) TMR

Mott Device

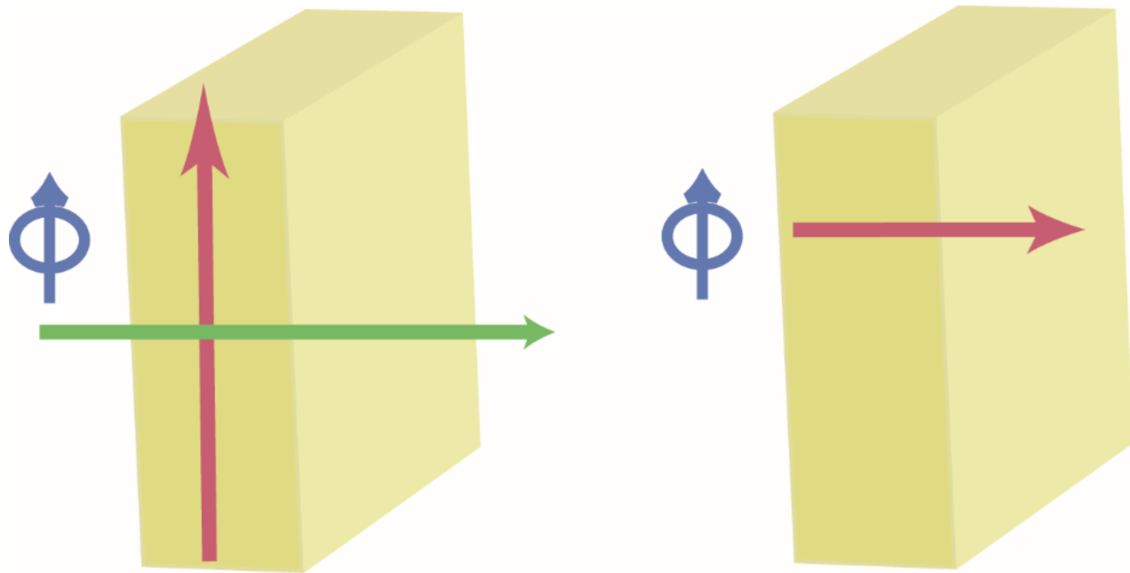
Spin valve



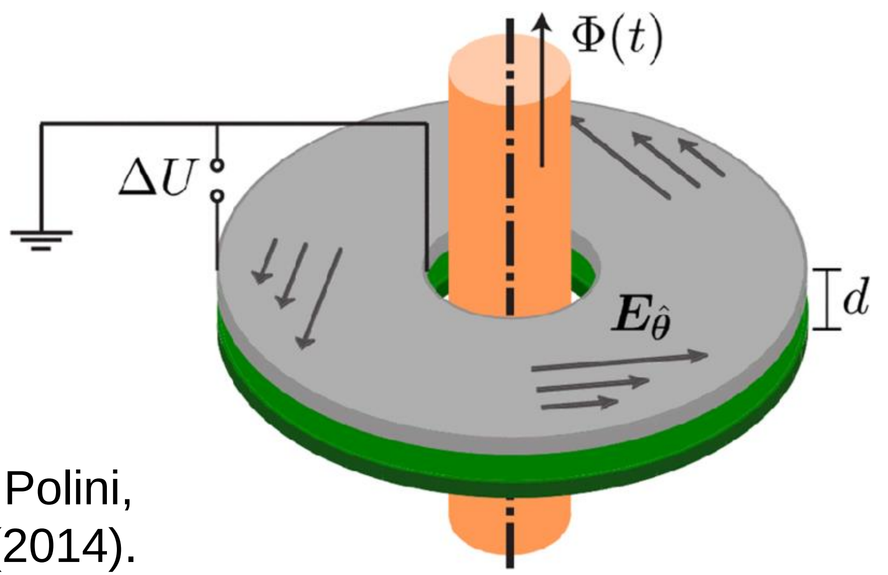
(Anisotropic) AMR

Dirac Device

Spin valve



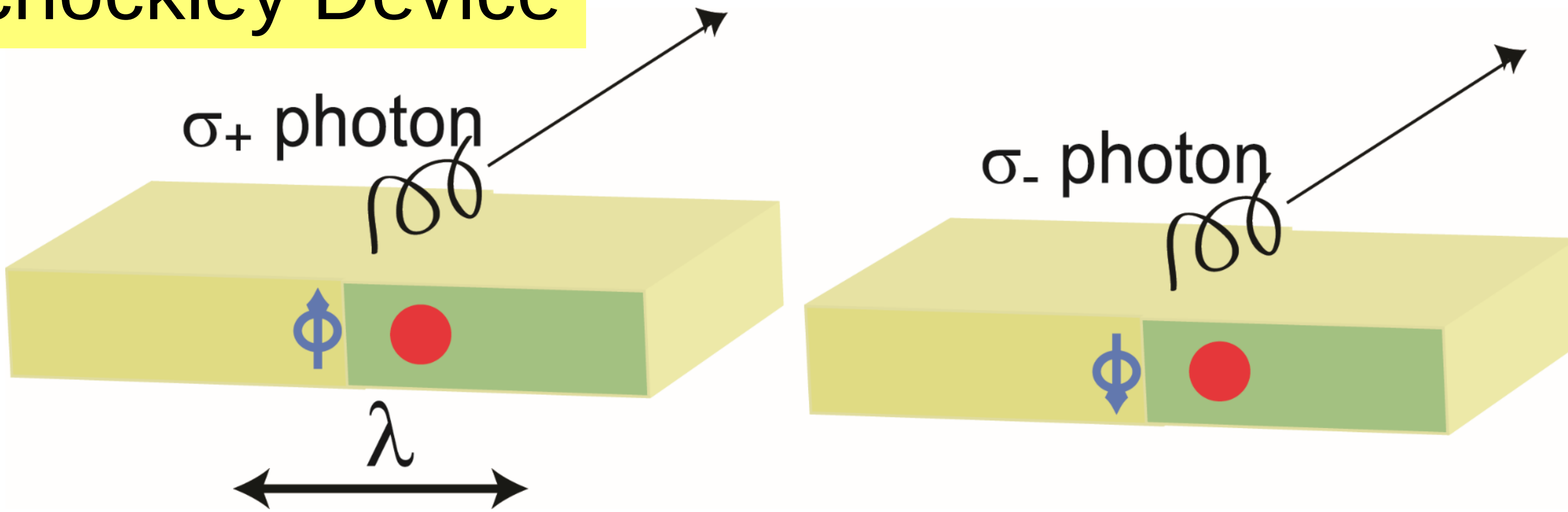
Corbino disk

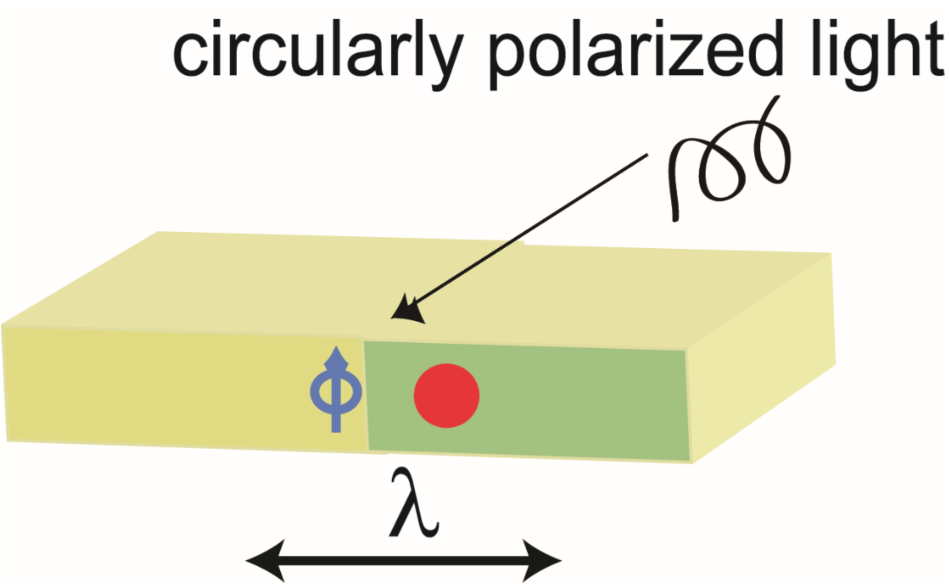


A. Tomadin, G. Vignale and M. Polini,
Phys. Rev. Lett. 113, 235901 (2014).

Bipolar spintronics: light and spin

Schockley Device

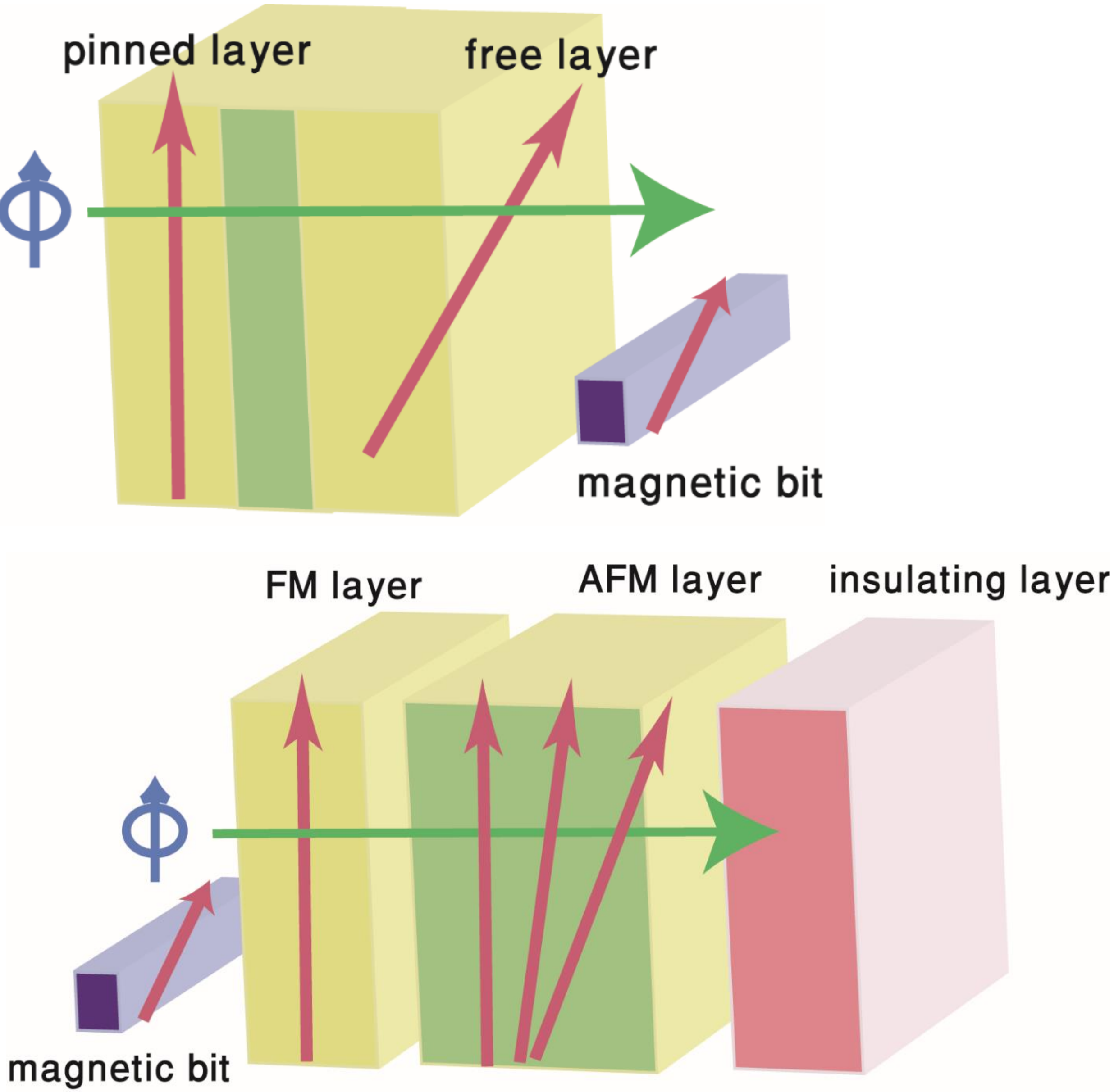


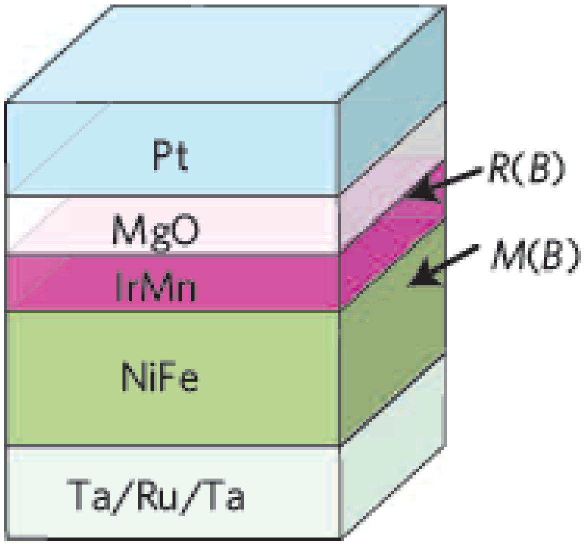


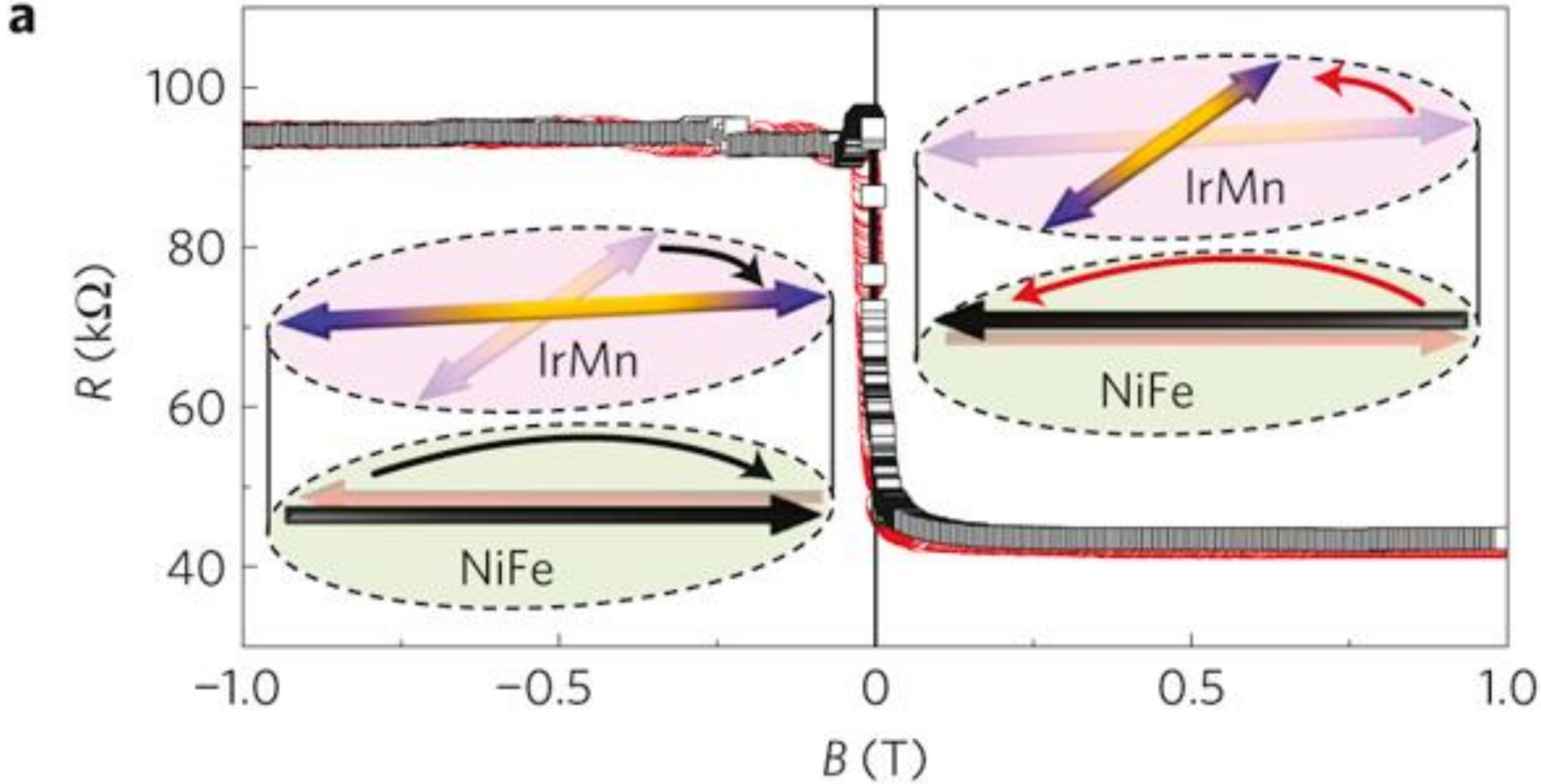
Spin LED and spin lasers.

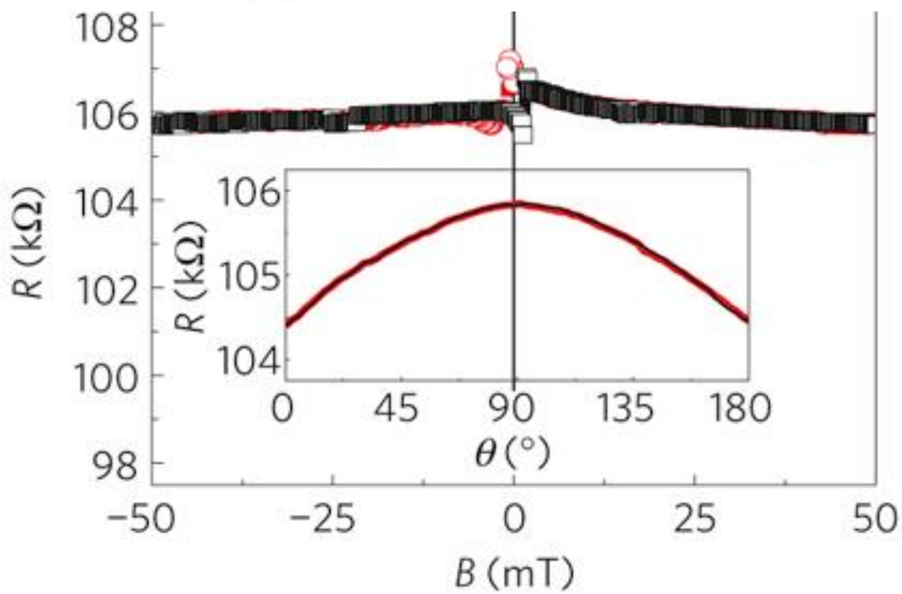
Photoexcitation of spin currents.

Role of antiferromagnets in spintronics



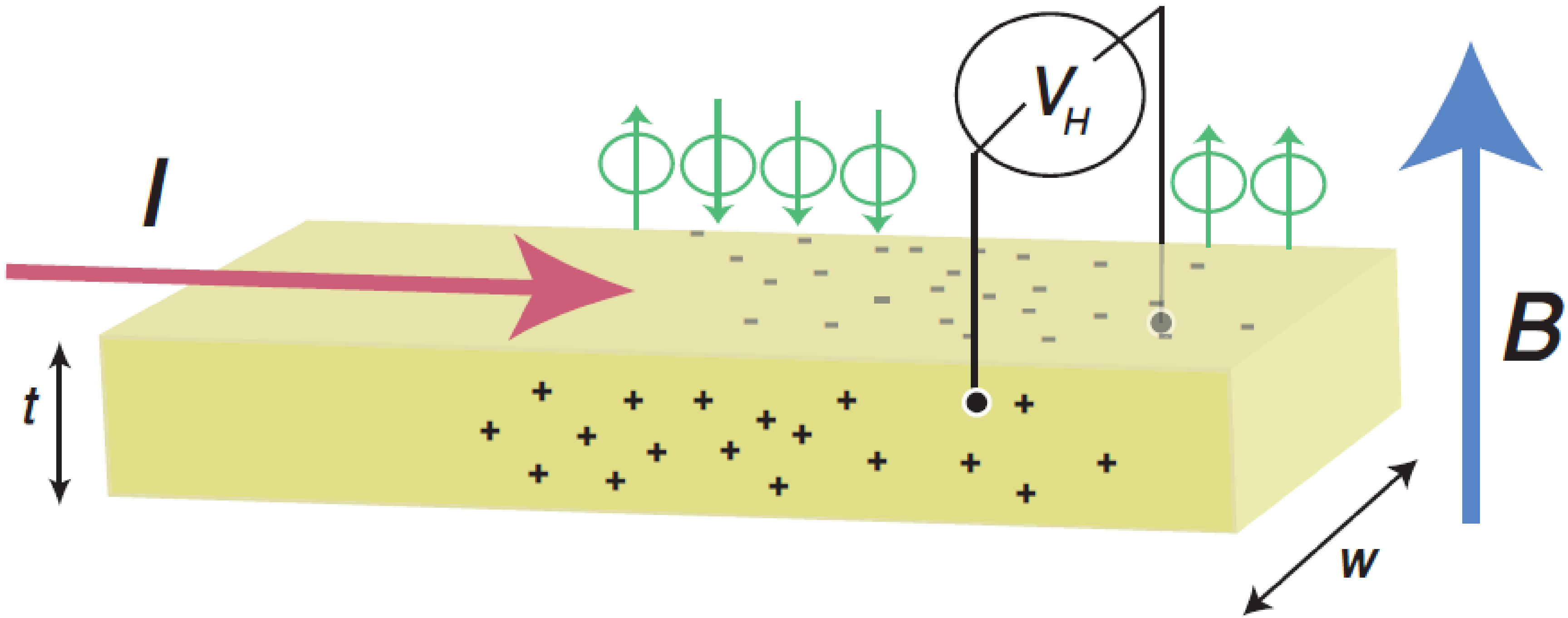






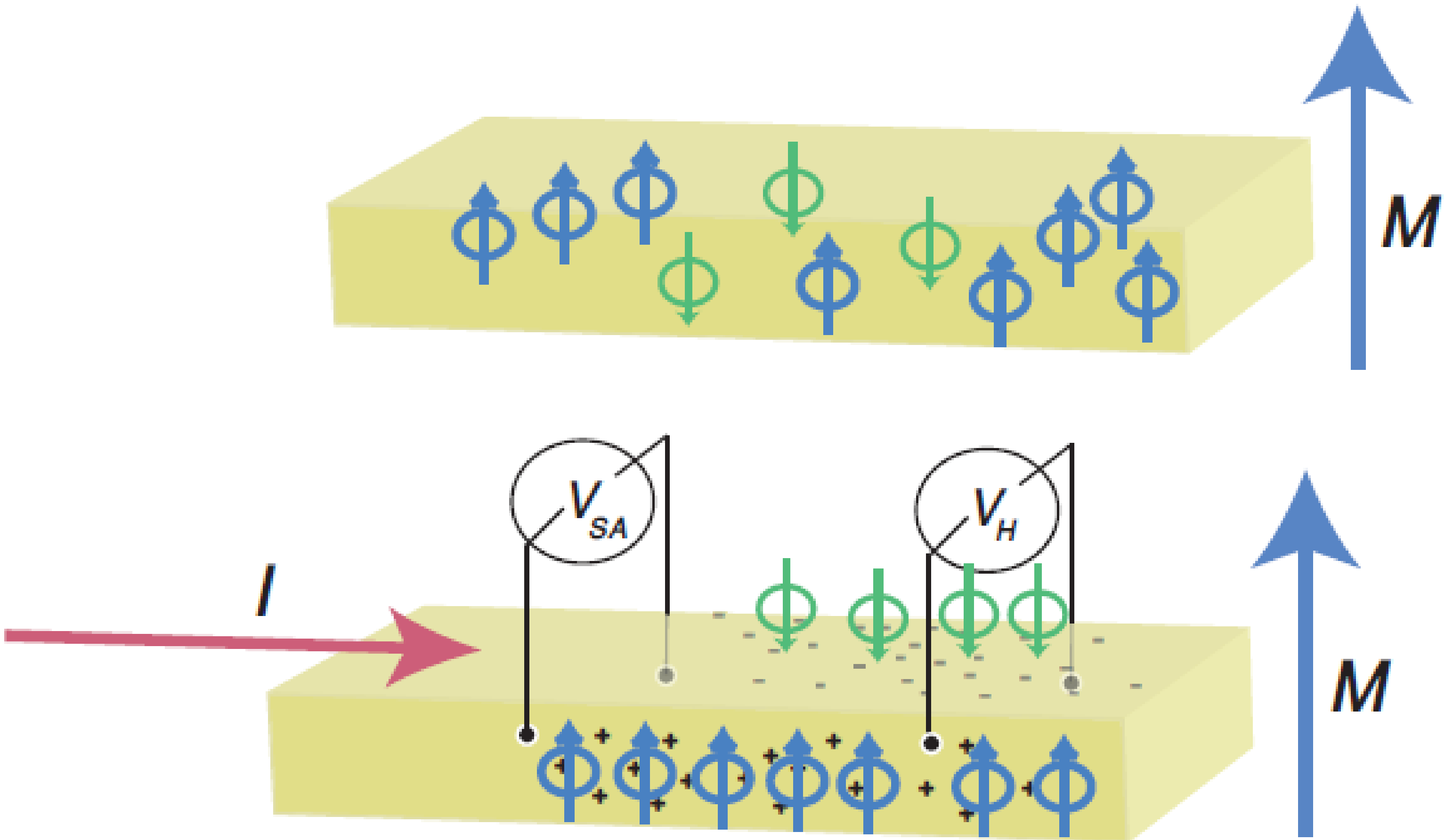
B.G. park *et al*,
Nature Mat. 10, 347 (2011).

The Conventional Hall Effect



$qv_D B =$Lorentz force, where v_d is the drift velocity.
$qE_H =$Hall electric field.
$V_H = E_H w = \frac{IB}{tnq} =$Hall voltage where n is the volume density of charge carriers.

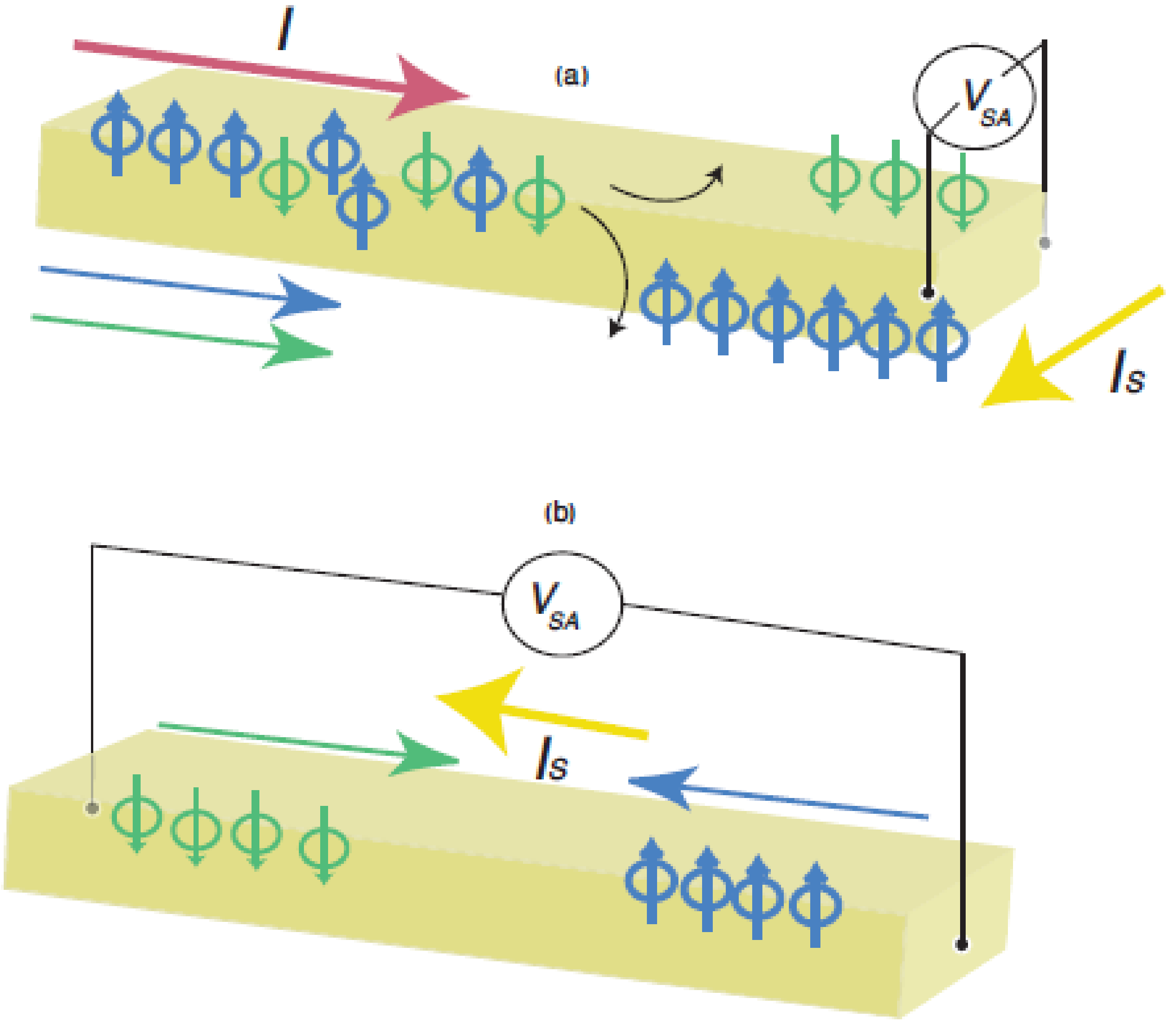
The Anomalous Hall Effect



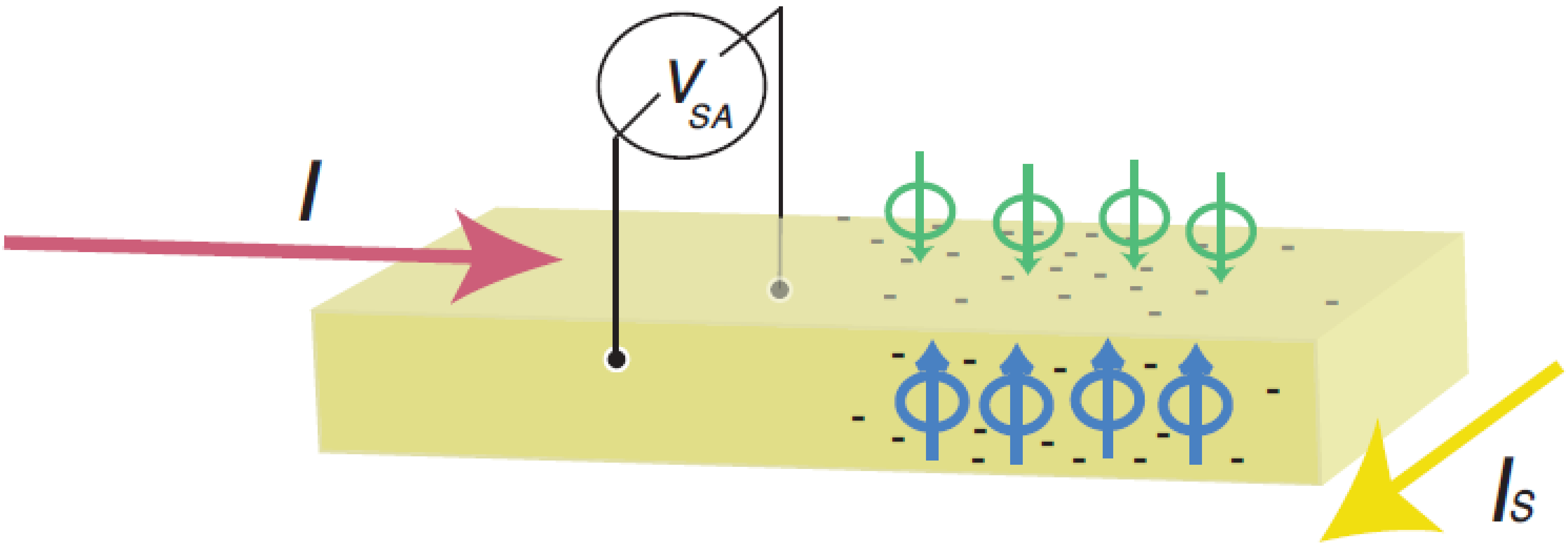
V_{SA} =Spin accumulation voltage.

Both a charge and spin differential exist.

Charge and Spin Current

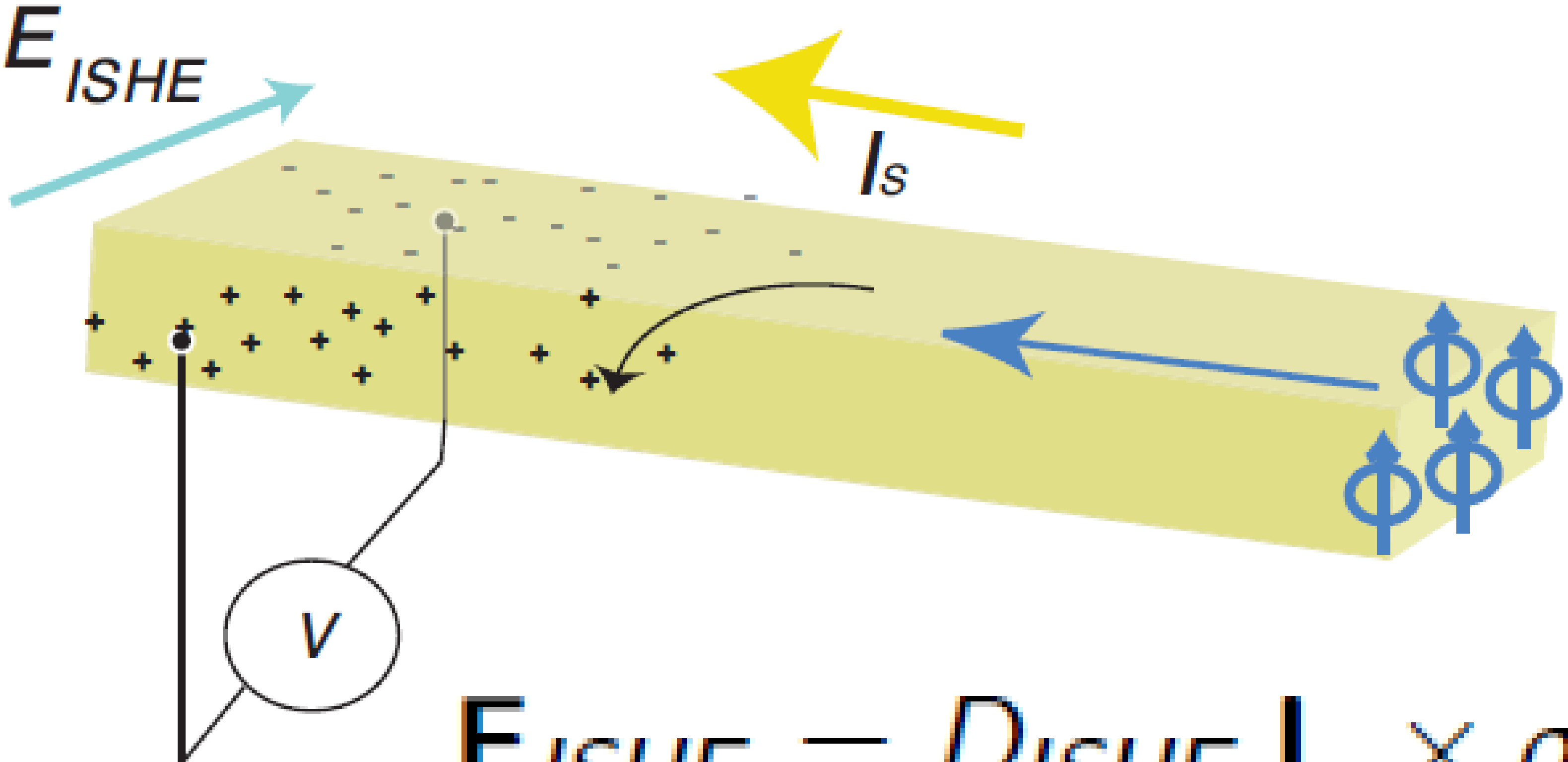


Pure Spin Hall Effect



There is no charge accumulation or electric Hall voltage. For the pure spin Hall effect, the material need not be ferromagnetic.

Inverse Spin Hall Effect

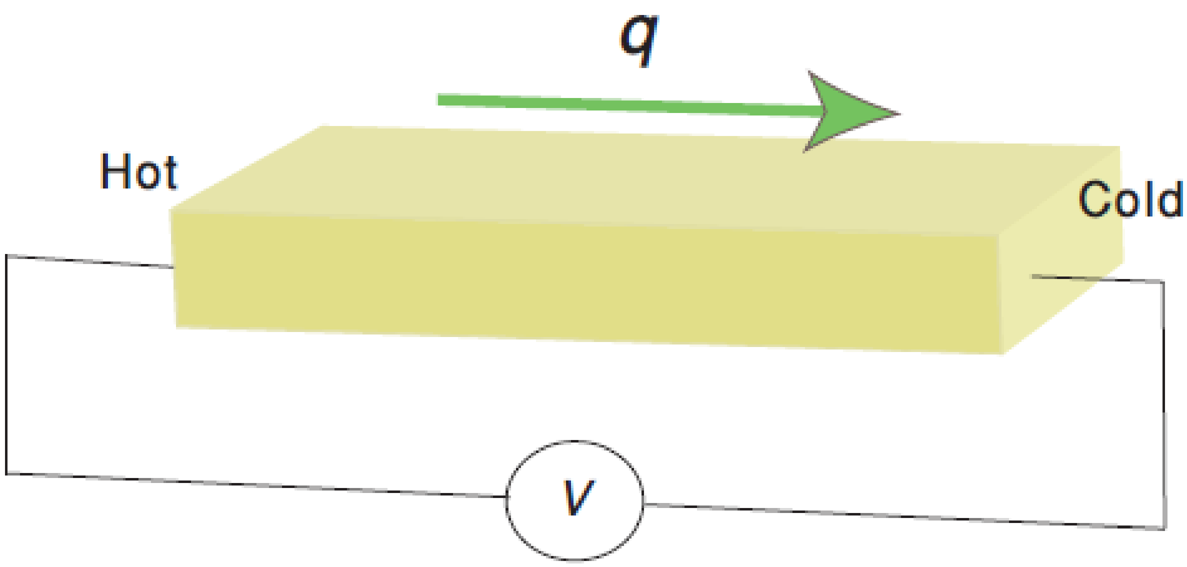


$$\mathbf{E}_{ISHE} = D_{ISHE}\,\mathbf{J}_s \times \boldsymbol{\sigma}$$

Electrical detection of spin currents.

Spin Caloritronic Effects

Conventional Seebeck Effect

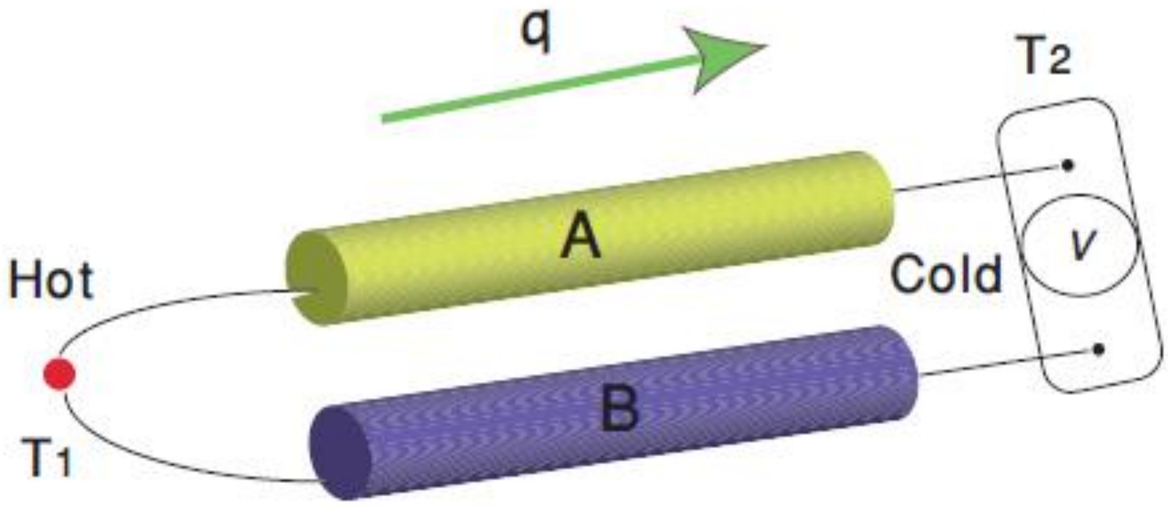


$q = -\kappa \nabla T$ =heat flux.

V =detected electrical voltage.

$S = V/\Delta T$ is called the Seebeck coefficient and is a measure of the thermopower.

Thermocouple

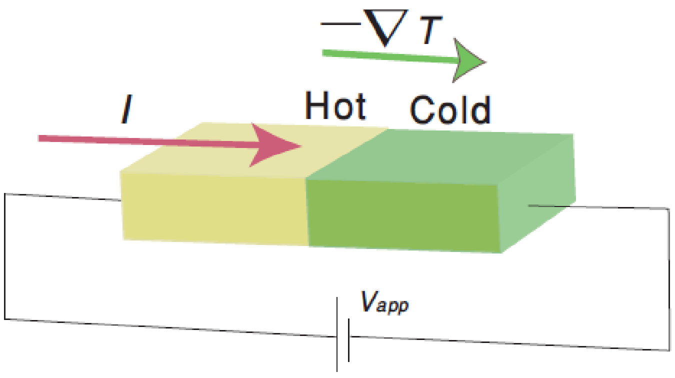


The detected electrical voltage is,

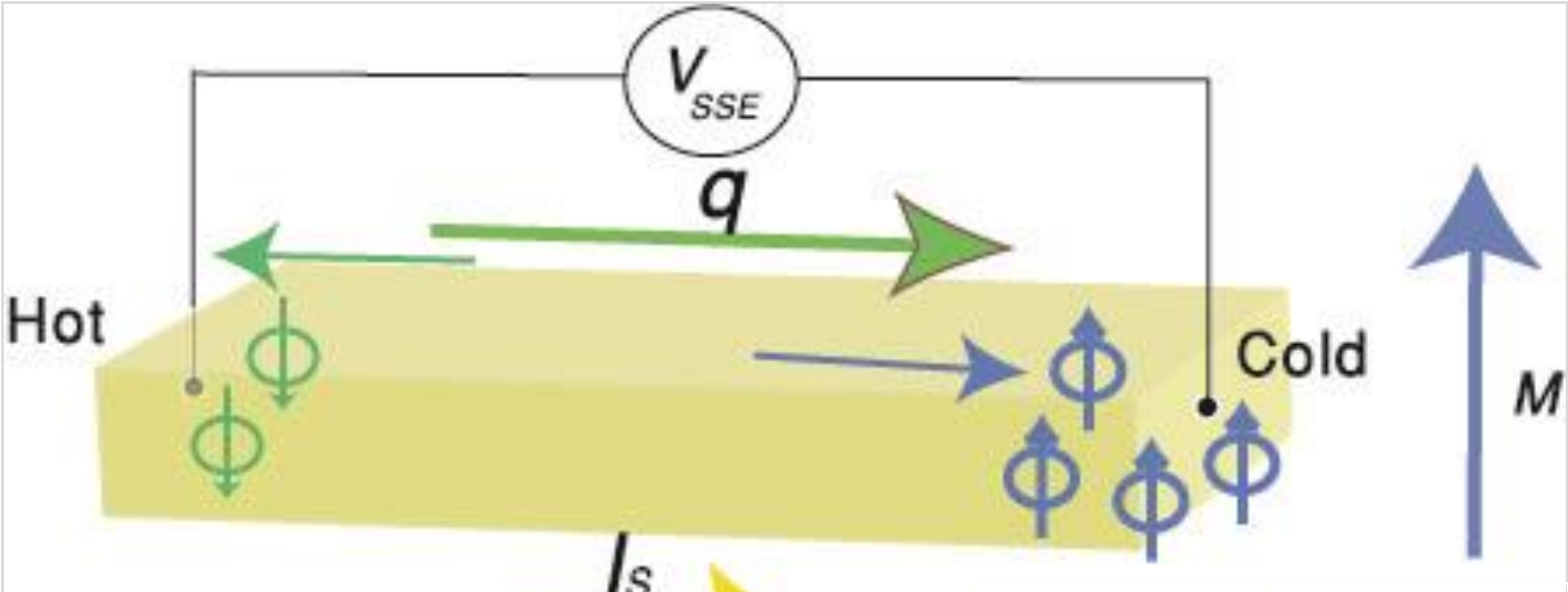
$V = \int_{T_2}^{T_1} S_A(T)\,dt + \int_{T_1}^{T_2} S_B(T)\,dt = \int_{T_2}^{T_1} (S_A(T) - S_B(T))\,dt$,

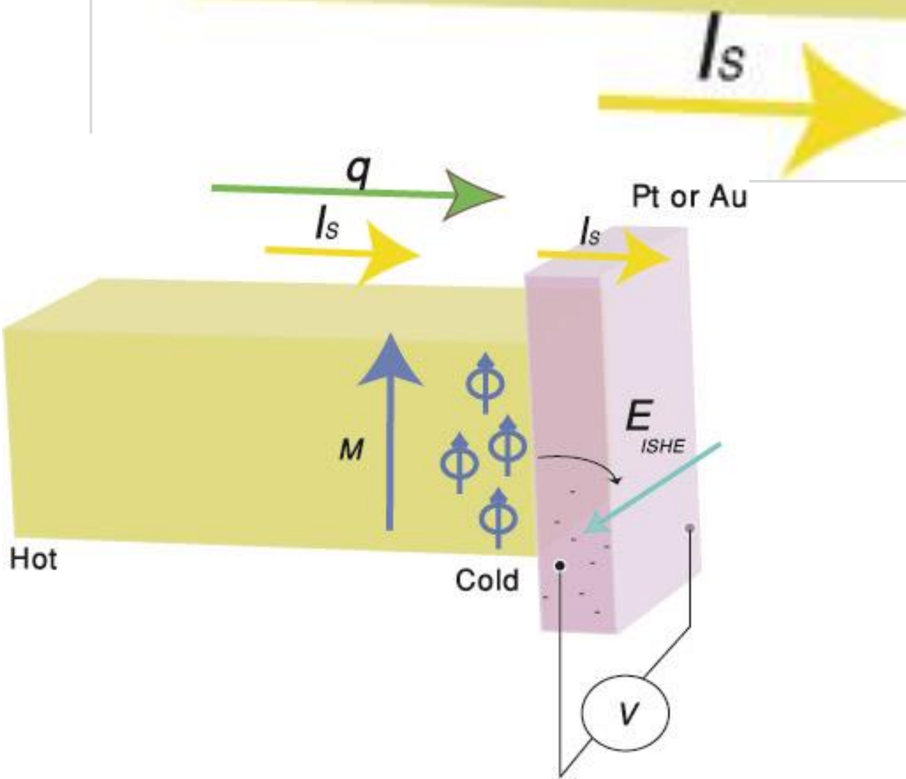
dependent on the difference in the Seebeck coefficients of the two dissimilar metals.

Peltier Effect



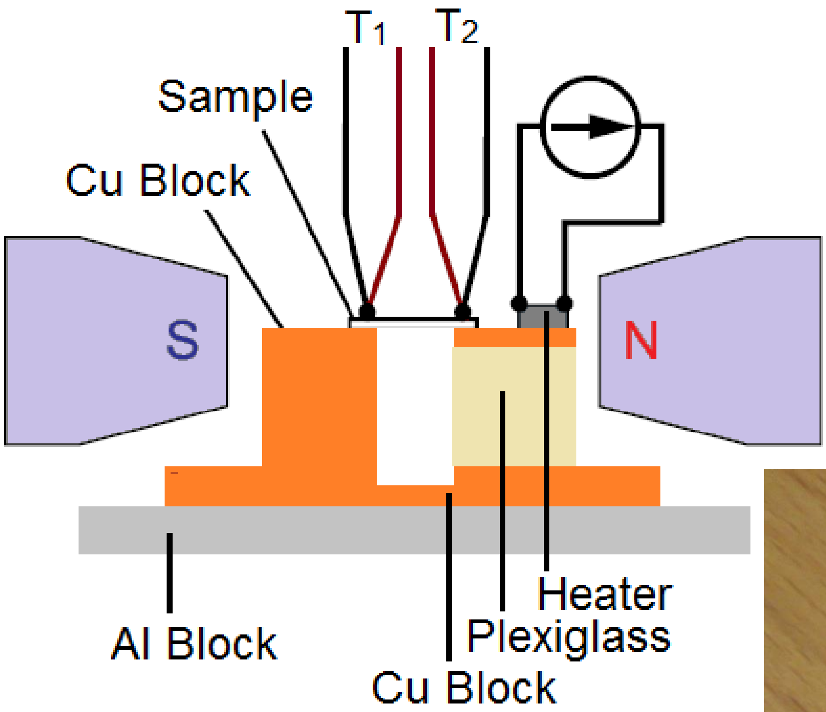
Spin Seebeck Effect

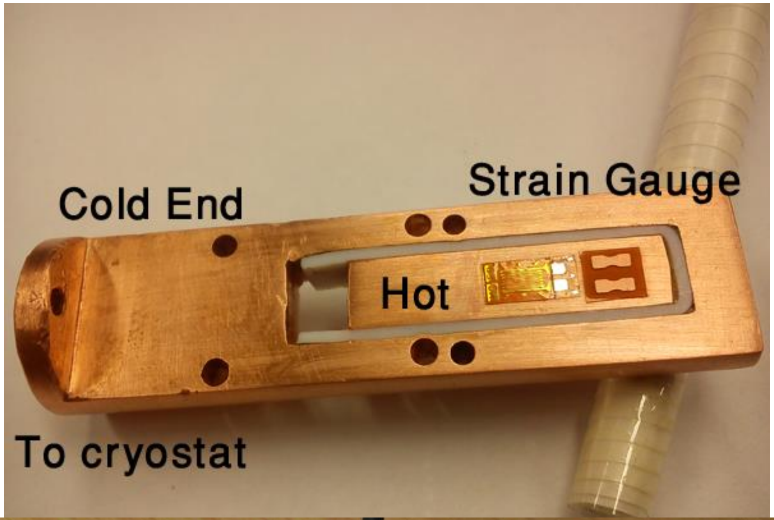


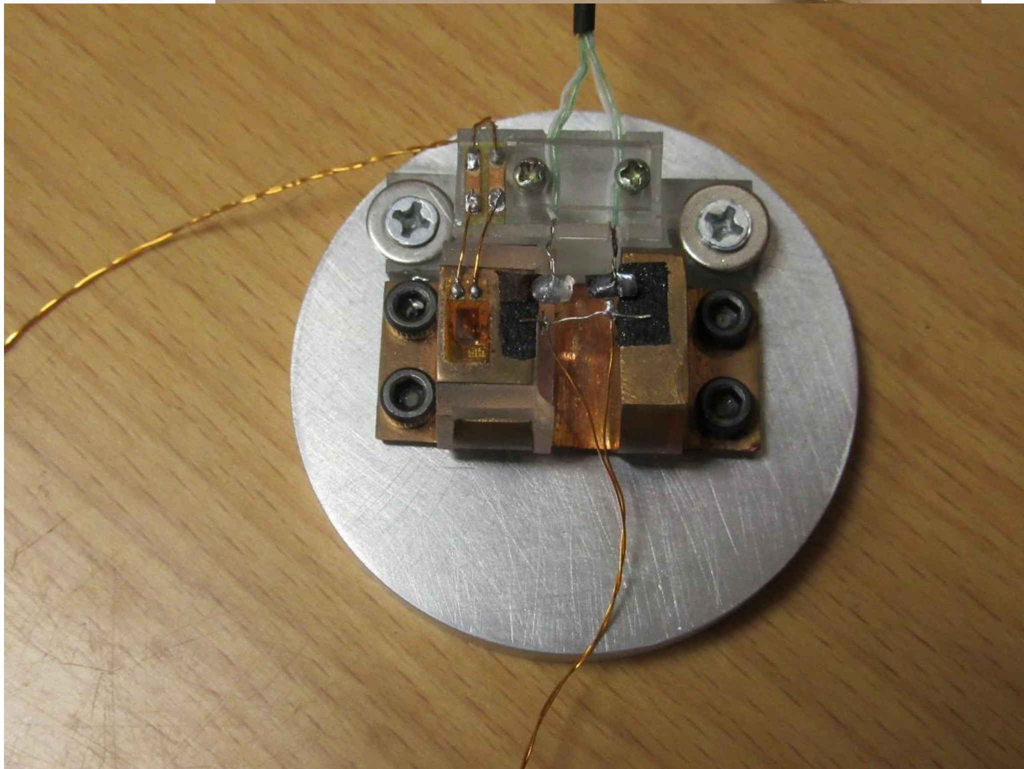


Metal	✓ **Uchida et al. (2008)**
Semiconductor	✓ Jaworski et al. (2010)
Insulator	✓ Uchida et al. (2010)
Ferrites	✓ D. Meier et al. (2015)

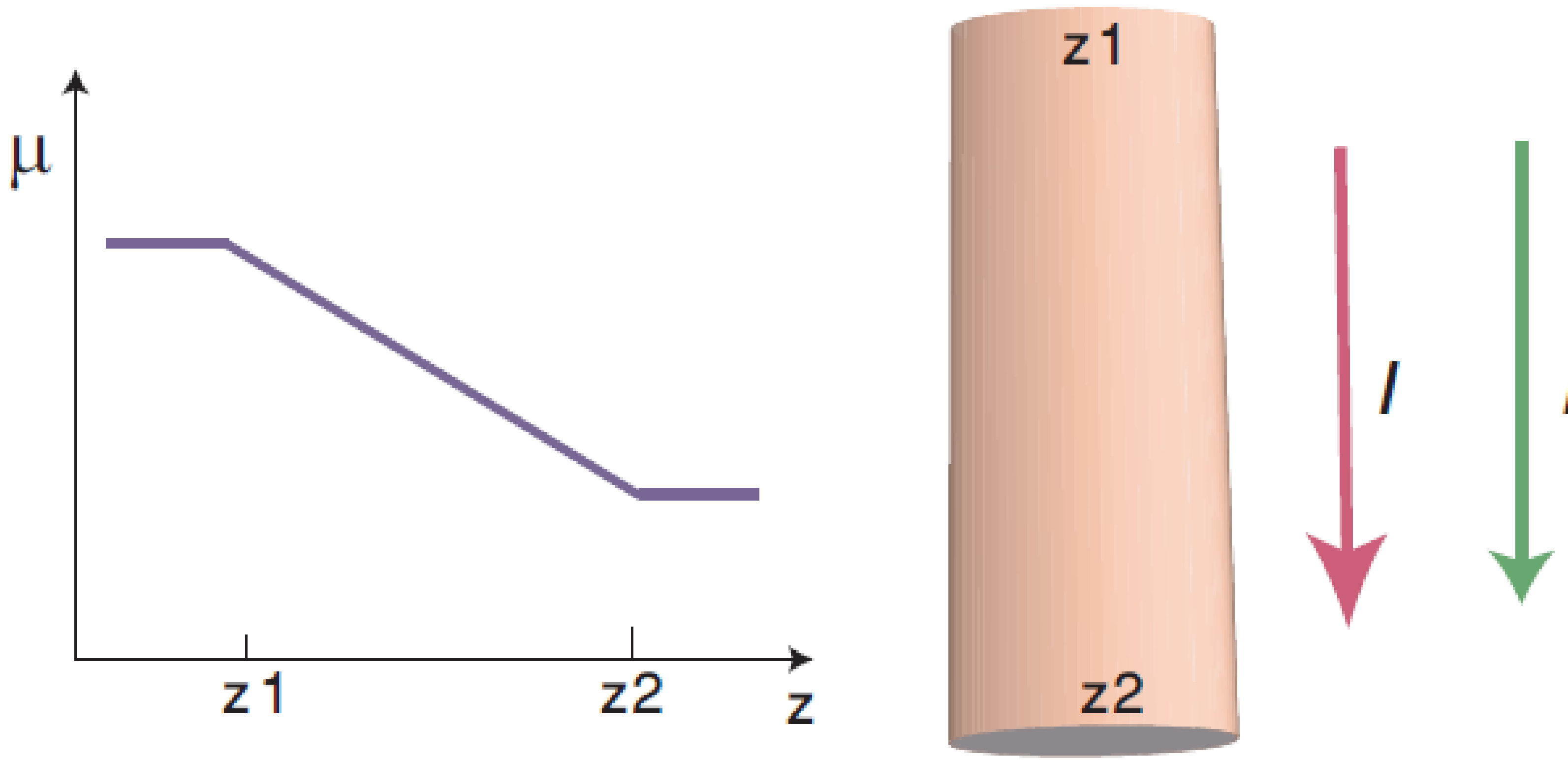
Thermospin generators





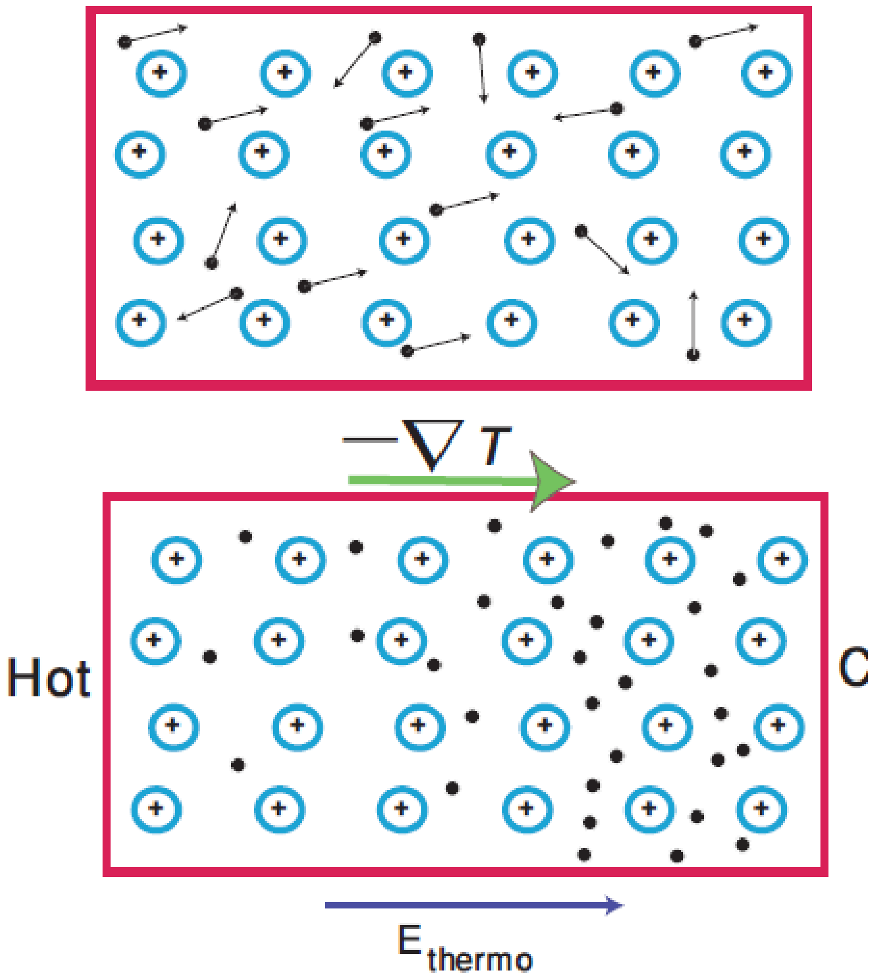


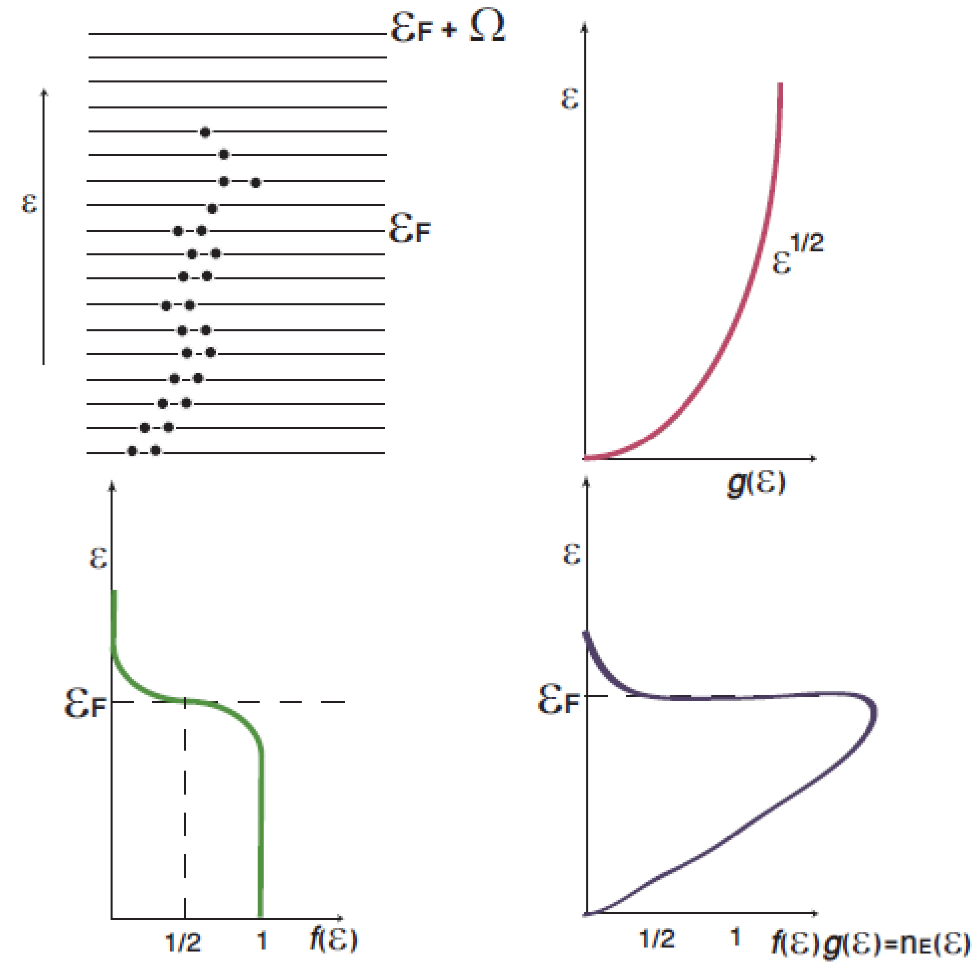
Charge current flow along chemical potential gradient



The chemical potential (energy) is $\mu = \mu^c - e\phi_e$ where $E = -\nabla\phi_e$ is the electric field driving the charge current and ϕ_e is the electric potential. The charge flows "downhill" on the chemical potential curve.

Mechanism of the Seebeck effect





Average energies dependent on temperature

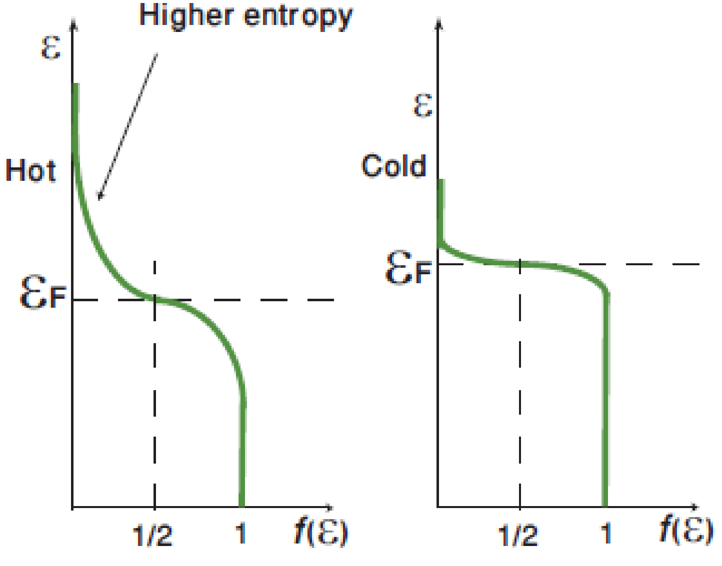
$$n = \frac{8\pi\sqrt{2}m_e^{3/2}}{h^3}\int_0^\infty \frac{\varepsilon^{1/2}d\varepsilon}{1+\exp\left((\varepsilon-\varepsilon_F)/kT\right)}$$

At 0 K, the upper limit in the integral is ε_{F0}. Therefore,

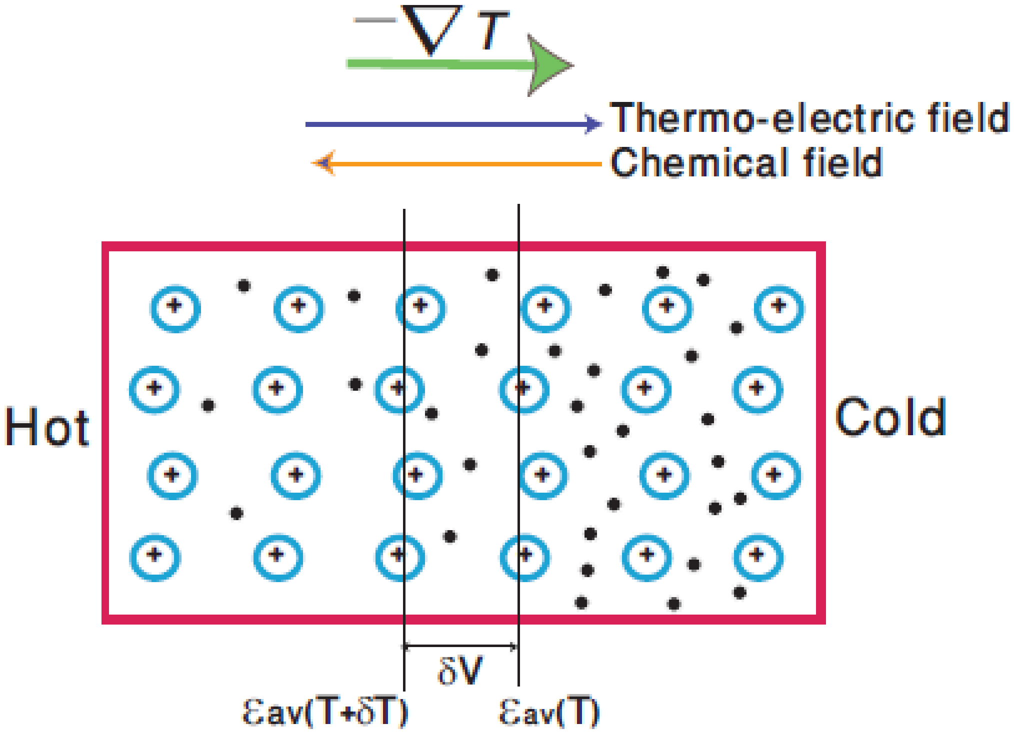
$$\varepsilon_{F0} = \frac{h^2}{4m_e}\left(\frac{3n}{\sqrt{2}\pi}\right)^{2/3}$$

$$\varepsilon_F(T) = \varepsilon_{F0}\left(1 - \frac{\pi^2}{12}\left(\frac{kT}{E_{F0}}\right)^2\right)$$

$$\varepsilon_{av}(T) = \frac{\int \varepsilon n_\varepsilon(\varepsilon)d\varepsilon}{\int n_\varepsilon(\varepsilon)d\varepsilon} = \frac{3}{5}\varepsilon_{F0}\left(1 + \frac{5\pi^2}{12}\left(\frac{kT}{\varepsilon_{F0}}\right)^2\right)$$



Seebeck effect as a field gradient



Energy lost= Energy gained.

$\varepsilon_{av}(T+\delta T)-\varepsilon_{av}(T)=e\delta V$, hence,

$e\delta V\approx\frac{\varepsilon_{F0}}{2}\left(\frac{\pi k}{\varepsilon_{F0}}\right)^2 T\delta T$

Seebeck coefficient $S=\frac{\delta V}{\delta T}\approx\frac{1}{2\varepsilon_{F0}}(\pi k)^2 T$

Seebeck effect as the gradient of electronic entropy

Chemical potential:

$\mu = \mu^c - e\phi_e$ where μ^c depends on n and T.

$\nabla\mu = \nabla\mu^c - e\nabla\phi_e = \nabla\mu^c + eE_{thermoelectric}$.

In thermodynamic equilibrium,

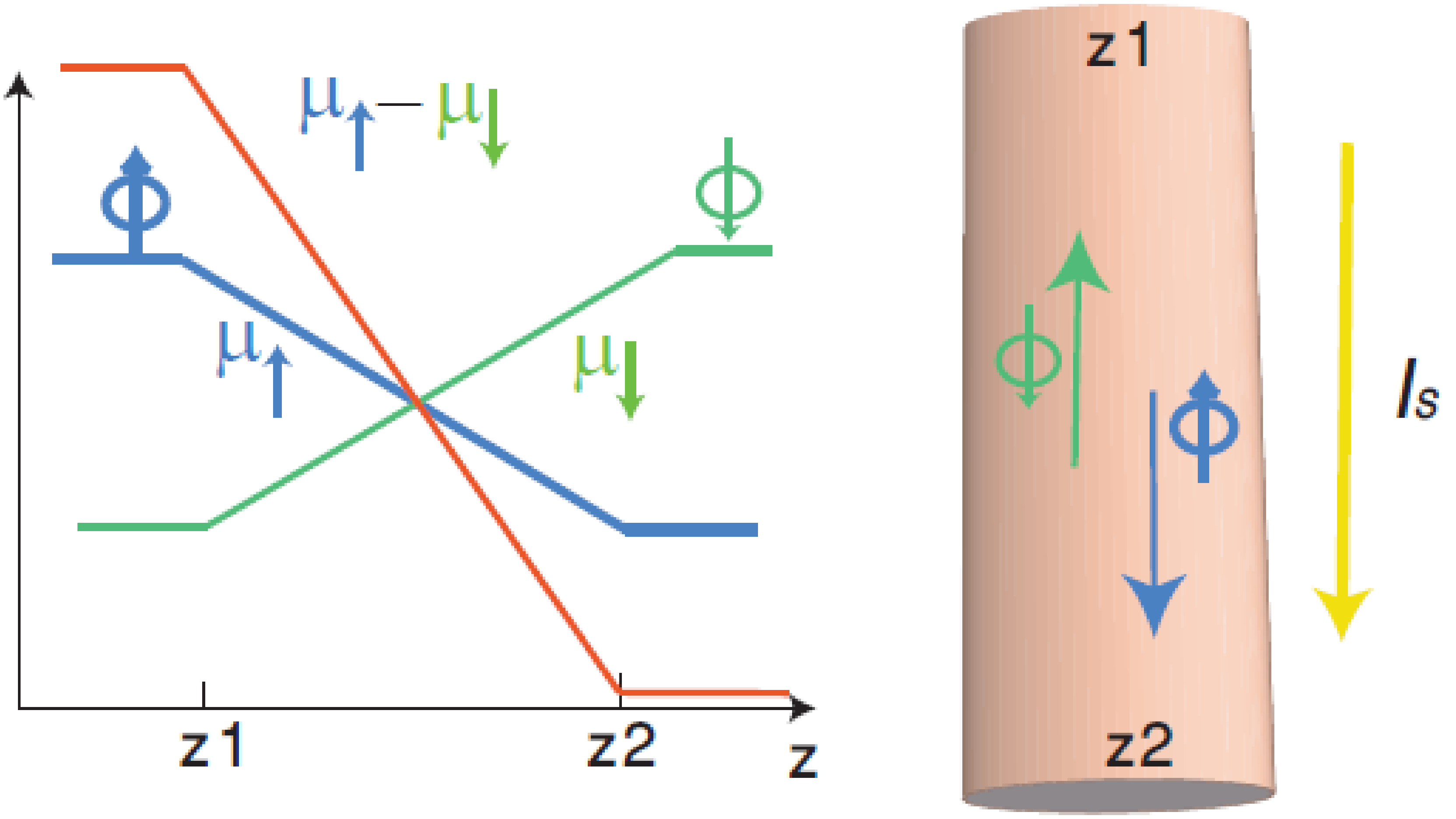
$\nabla\mu^c = \left(\frac{\partial\mu^c}{\partial n}\nabla n + \frac{\partial\mu^c}{\partial T}\nabla T\right) = -eE_{thermoelectric}$

$E_{chemical} = -\frac{1}{e}\left(\frac{\partial\mu^c}{\partial n}\nabla n + \frac{\partial\mu^c}{\partial T}\nabla T\right)$.

The field associated with the chemical potential is a sum of density and entropic terms.

The Seebeck coefficient is the gradient of the electronic entropy.

Mechanism of the spin Seebeck effect (1)



Mechanism of the spin Seebeck effect (2)

The $\uparrow$ and $\uparrow$ have different spin Seebeck coefficients.

$\nabla\mu_\uparrow = \nabla\mu^c_\uparrow - e\nabla\phi_e$ and $\nabla\mu_\downarrow = \nabla\mu^c_\downarrow - e\nabla\phi_e$

Now, $\nabla\mu_\uparrow = \frac{\partial\mu^c_\uparrow}{\partial n_\uparrow}\nabla n_\uparrow + \frac{\partial\mu^c_\uparrow}{\partial T}\nabla T - e\nabla\phi_e$ and likewise for the other spin.

The density gradients $\nabla n_\uparrow$ and $\nabla n_\downarrow$ decay within the spin diffusion length. Hence only the entropic terms matter for long samples, $L >> L_{SD}$. Hence,

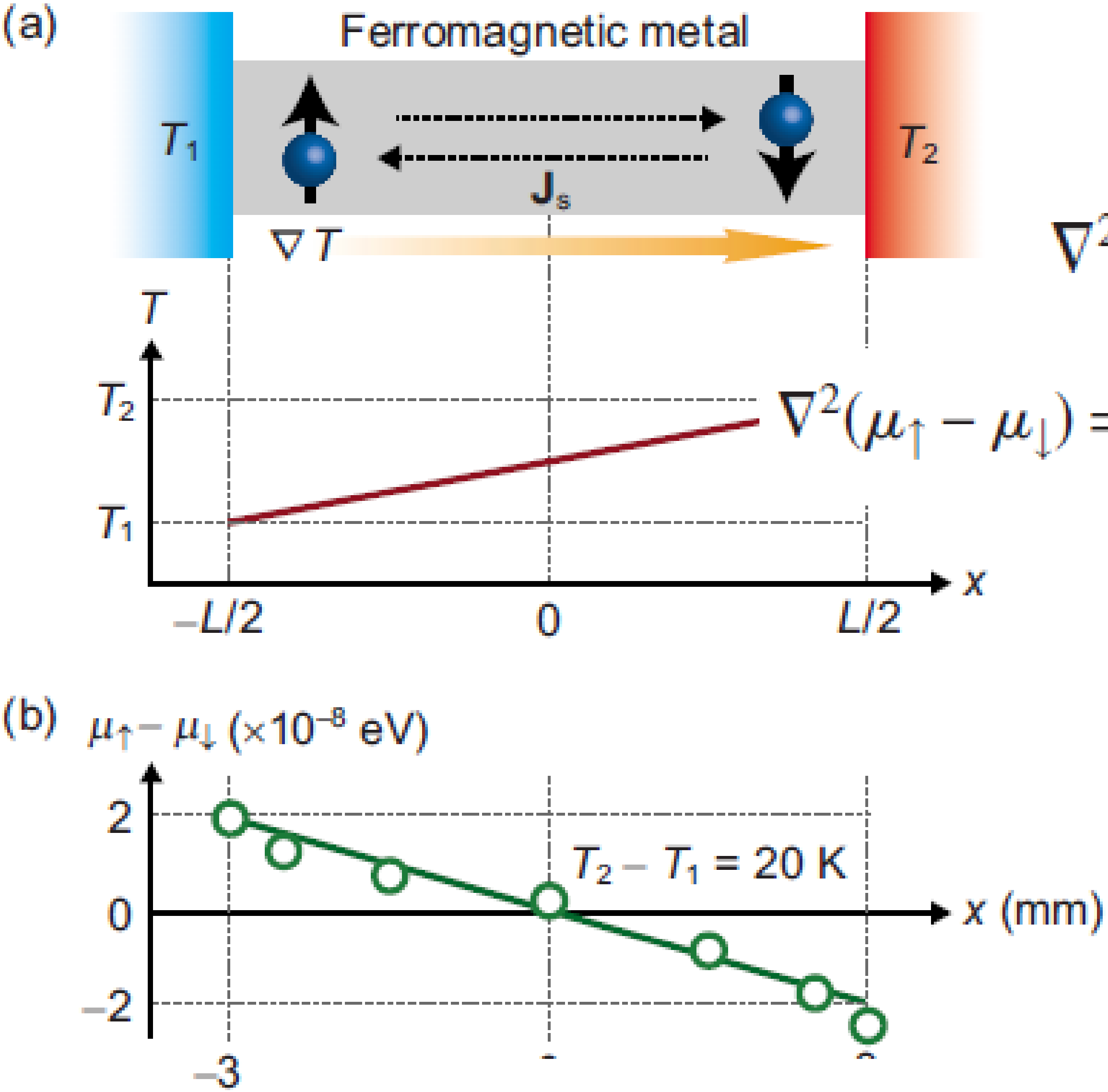
$\nabla(\mu_\uparrow - \mu_\downarrow) = (\frac{\partial\mu^c_\uparrow}{\partial T} - \frac{\partial\mu^c_\downarrow}{\partial T})\nabla T = eS_{SSE}\nabla T$, where,

$S_{SSE} = 1/e(\frac{\partial\mu^c_\uparrow}{\partial T} - \frac{\partial\mu^c_\downarrow}{\partial T})$.

The gradient of the chemical potential difference is caused by an entropic gradient. The sub-band entropies are different for the $\uparrow$ and $\uparrow$ spins.

The spin voltage at the ends of the sample is $\pm S_{SSE}\Delta T/2$.

Variation of the electrochemical potential

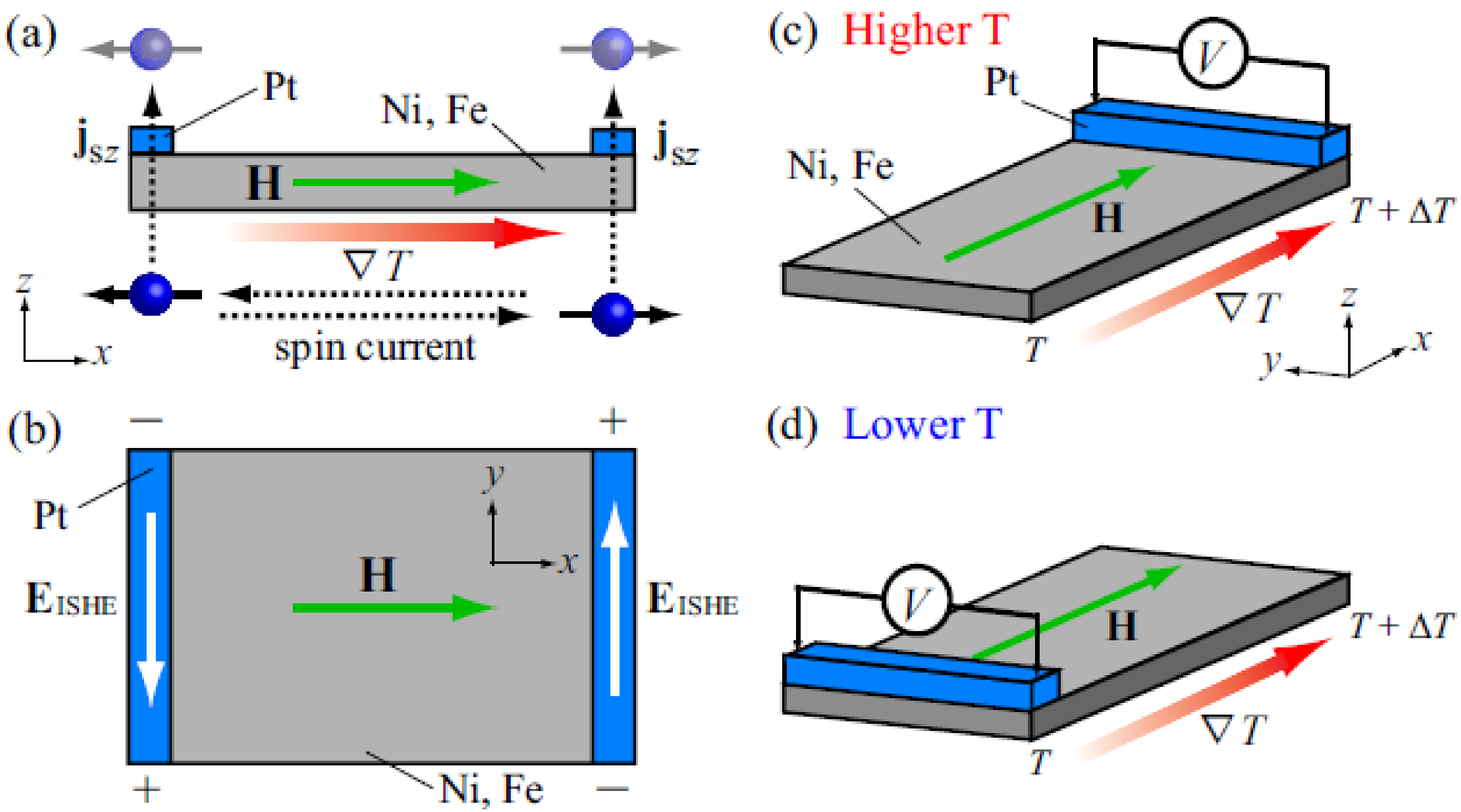


$$\nabla^2(\mu_\uparrow - \mu_\downarrow) = \frac{1}{\lambda^2}(\mu_\uparrow - \mu_\downarrow)$$

$$\nabla^2(\mu_\uparrow - \mu_\downarrow) = \frac{1}{\lambda^2}(\mu_\uparrow - \mu_\downarrow) - \frac{e}{\lambda^2} S_S (\nabla T) x$$

$$\mu_\uparrow - \mu_\downarrow = e S_S (\nabla T) x - e\lambda [S_S - (S_\uparrow - S_\downarrow)] \frac{\sinh(x/\lambda)}{\cosh(L/2\lambda)} \nabla T$$

Electrical Detection of the SSE

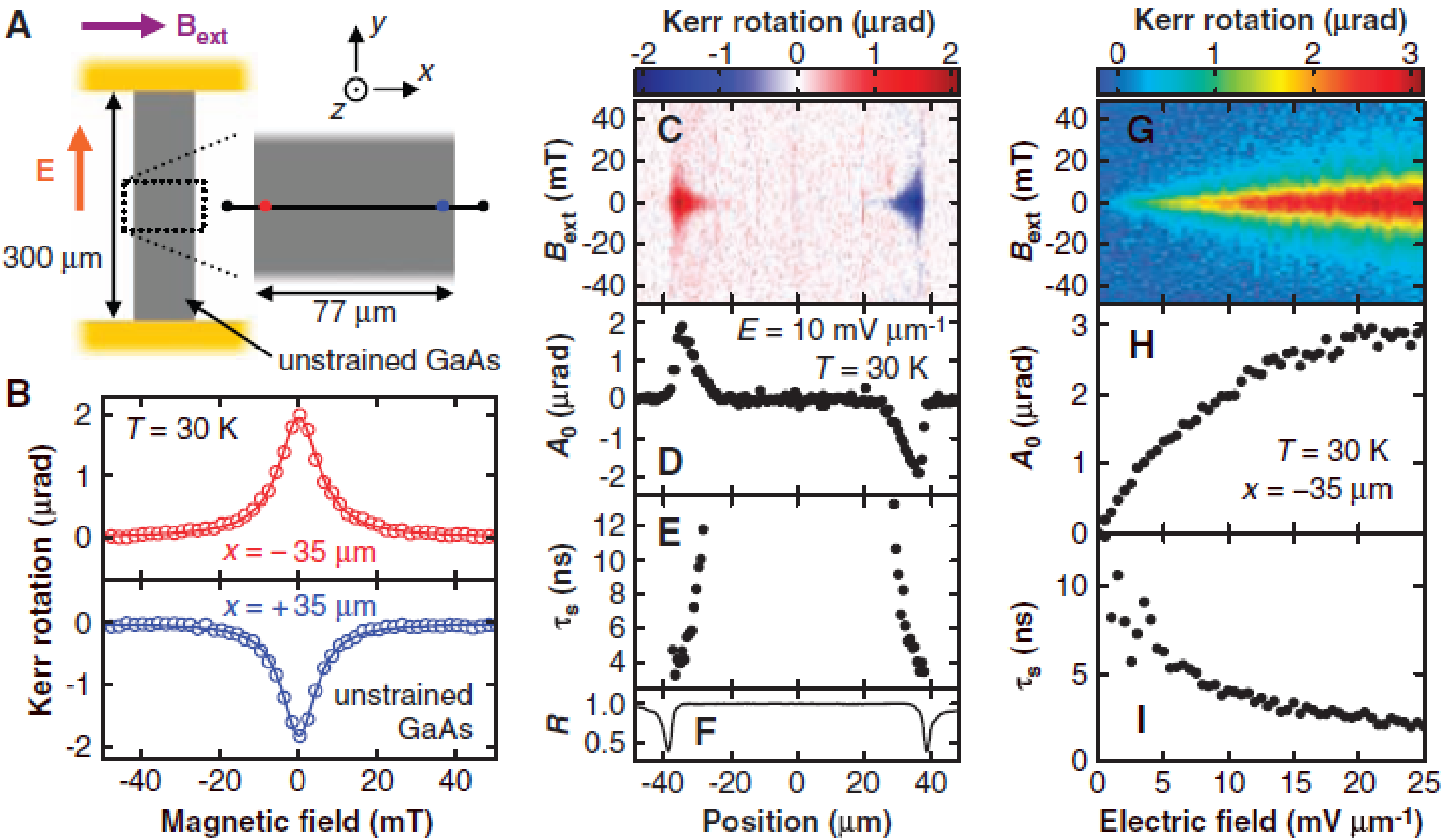


T. Ota et al, **J. Phys.: Conf. Series 200**, 062020 (2010).

Measurement and Imaging of Electron Spin

- Electron spin resonance
- Ferromagnetic resonance
- Brillouin light scattering (BLS)
- Magnetic force microscopy
- Magneto-optical techniques

Observation of SHE



Y. K. Kato et al, **Science 306**, 1910 (2004).

Basics of Magneto-Optic Effects

Constitutive magnetic properties at optical frequencies

$$\overrightarrow{M}(\vec{k},\omega) = \chi_m(\vec{k},\omega)\overrightarrow{H}(\vec{k},\omega)$$

$$\overrightarrow{B}(\vec{k},\omega) = \mu_o \overrightarrow{H}(\vec{k},\omega) + \mu_o \overrightarrow{M}(\vec{k},\omega)$$

$$\mu = \mu_o(1+\chi_m)$$

$$\chi_m(\omega) = 0$$

Magneto-electric coupling at optical frequencies

$$\vec{P}(\omega,\vec{H}_o) = \varepsilon_o \chi(\omega,\vec{H}_o)\vec{E}(\omega)$$

$$= \varepsilon_o \chi(\omega)\vec{E}(\omega) + \varepsilon_o \Delta\chi(\omega,\vec{H}_o)\vec{E}(\omega)$$

$$\vec{D}(\omega,\vec{H}_o) = \varepsilon(\omega,\vec{H}_o)\vec{E}(\omega)$$

$$= \varepsilon(\omega)\vec{E}(\omega) + \Delta\varepsilon(\omega,\vec{H}_o)\vec{E}(\omega)$$

$$\varepsilon(\omega,\vec{H}_o)$$

$$\varepsilon(\omega,\vec{M})$$

Properties of the electric permittivity tensor

$$\varepsilon_{ij}(\omega,\overrightarrow{H}_o) = \varepsilon_{ji}(\omega,-\overrightarrow{H}_o)$$

$$\varepsilon_{ij}(\omega,\overrightarrow{H}_o) = \varepsilon*_{ji}(\omega,\overrightarrow{H}_o)$$

$$\varepsilon_{ij}'(\omega,\overrightarrow{H}_o) = \varepsilon_{ji}'(\omega,-\overrightarrow{H}_o) = \varepsilon_{ij}'(\omega,-\overrightarrow{H}_o) = \varepsilon_{ji}'(\omega,\overrightarrow{H}_o)$$

$$\varepsilon_{ij}''(\omega,\overrightarrow{H}_o) = -\varepsilon_{ji}''(\omega,\overrightarrow{H}_o) = -\varepsilon_{ij}''(\omega,-\overrightarrow{H}_o) = -\varepsilon_{ji}''(\omega,-\overrightarrow{H}_o)$$

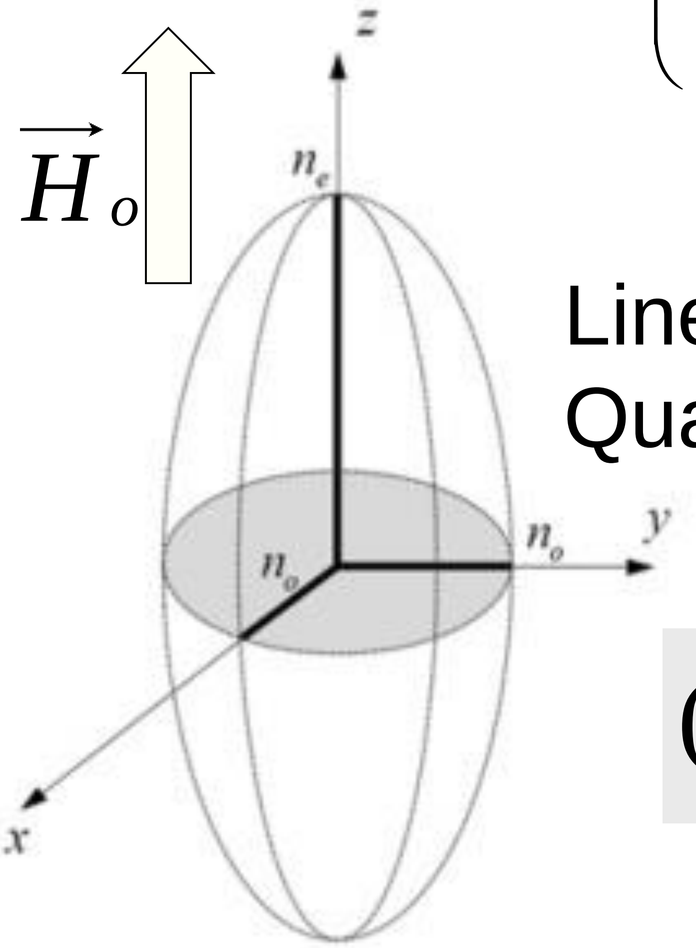
$$\varepsilon_{ij}(\omega,\overrightarrow{H}_o) = \varepsilon_{ij}(\omega) + \Delta\varepsilon_{ij}(\overrightarrow{H}_o)$$

$$= \varepsilon_{ij}(\omega) + i\varepsilon_o\sum_k f_{ijk}H_{ok} + \varepsilon_o\sum_{kl} c_{ijkl}H_{ok}H_{ol}$$

where $f_{ijk} = -f_{jik}$ and $c_{ijkl} = c_{jikl} = c_{ijlk} = c_{jilk}$ are real.

Example: uniaxial crystal of a magnetic non-ordered material inside a magnetic field

$$\varepsilon(\vec{H}_o) = \varepsilon_o \begin{pmatrix} n_o^2 + c_\perp H_{oz}^2 & ifH_{oz} & 0 \\ -ifH_{oz} & n_o^2 + c_\perp H_{oz}^2 & 0 \\ 0 & 0 & n_e^2 + c_\parallel H_{oz}^2 \end{pmatrix}$$



Linear effects: Faraday and Kerr

Quadratic effects: Cotton-Mouton

$$(c_\perp - c_\parallel) H_{oz}^2 > \left| n_o^2 - n_e^2 \right|$$

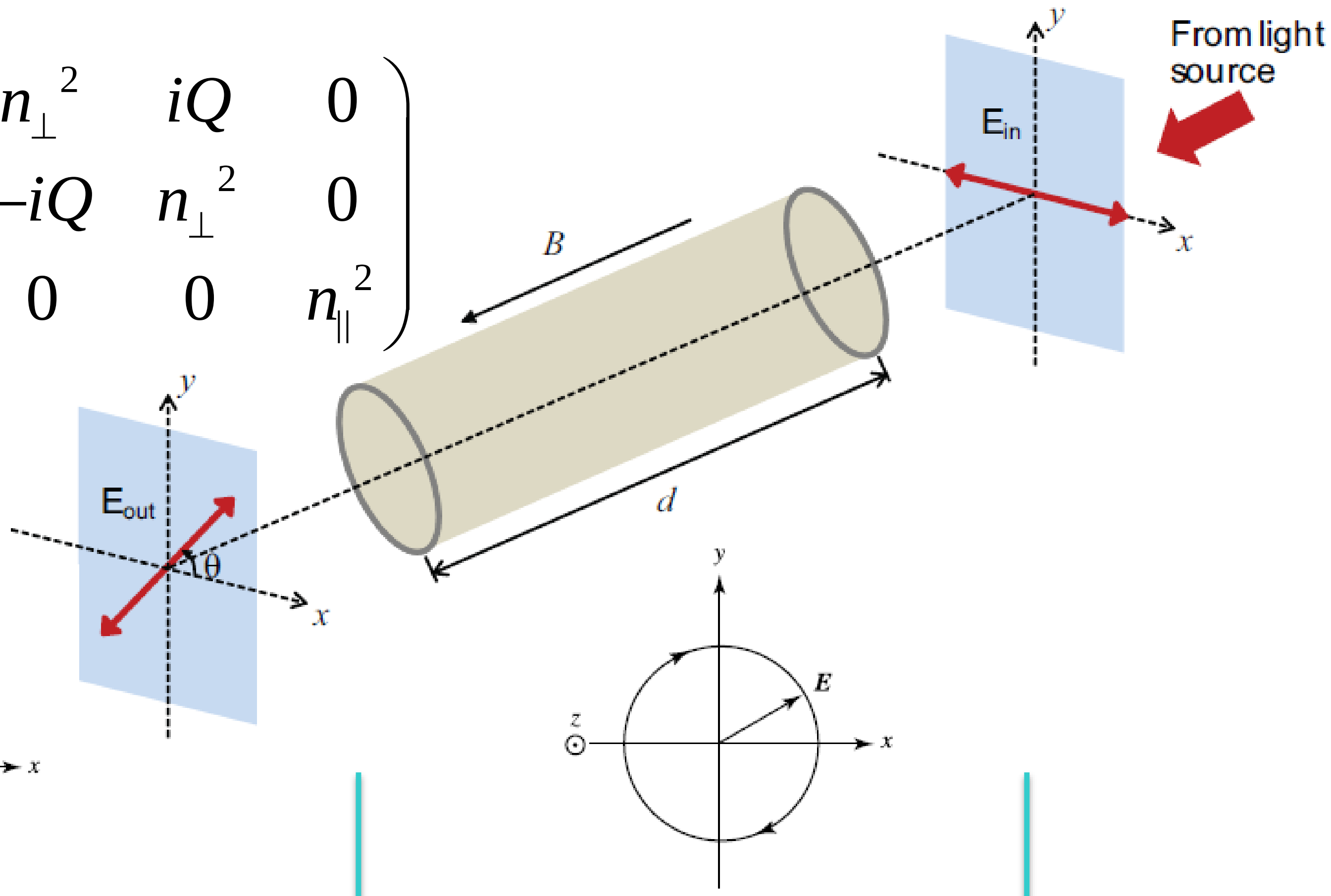
Example: uniaxial crystal of a magnetically ordered material with some magnetization

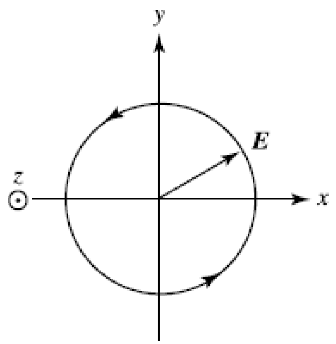
$$\varepsilon(\vec{M}) = \varepsilon_o \begin{pmatrix} n_\perp{}^2 & iQ & 0 \\ -iQ & n_\perp{}^2 & 0 \\ 0 & 0 & n_{\|}{}^2 \end{pmatrix}$$

$n_\perp{}^2(M^2)$ $\quad$ $n_{\|}{}^2(M^2)$ $\quad$ $Q(M)$

Magneto-optic Faraday Effect

$$\varepsilon(\overrightarrow{M}) = \varepsilon_o \begin{pmatrix} n_\perp^2 & iQ & 0 \\ -iQ & n_\perp^2 & 0 \\ 0 & 0 & n_{||}^2 \end{pmatrix}$$





$$\varepsilon_+ = \varepsilon_o(n_\perp^2 - Q)$$

$$\hat{e}_+ = \frac{1}{\sqrt{2}}(\hat{x} + i\hat{y})$$

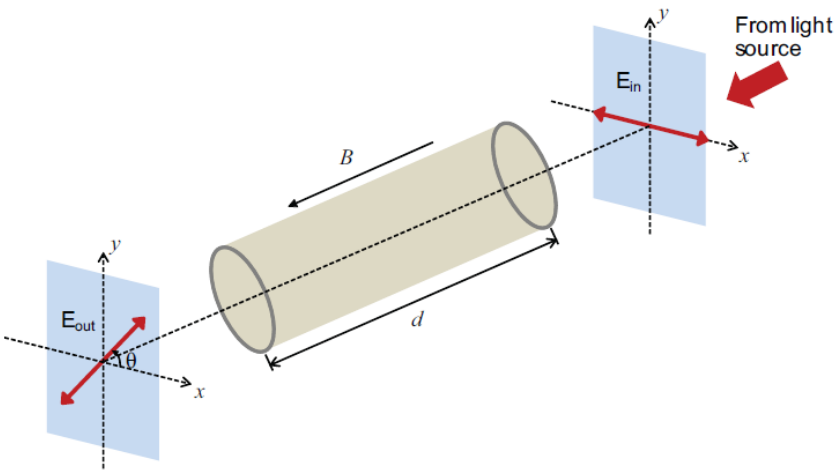
$$\varepsilon_- = \varepsilon_o(n_\perp^2 + Q)$$

$$\hat{e}_- = \frac{1}{\sqrt{2}}(\hat{x} - i\hat{y})$$

$$\varepsilon_z = \varepsilon_o(n_{||}^2)$$

$$\hat{Z}$$

The Faraday Rotation Angle



$$\vec{k}_{\pm} = \frac{\omega}{c_o}\sqrt{n_{\perp}{}^2 \mp Q}\;\hat{z}$$

$$\vec{E}_{in} = E_o\hat{x} = \frac{E_o}{\sqrt{2}}\left(\hat{e}_+ + \hat{e}_-\right)$$

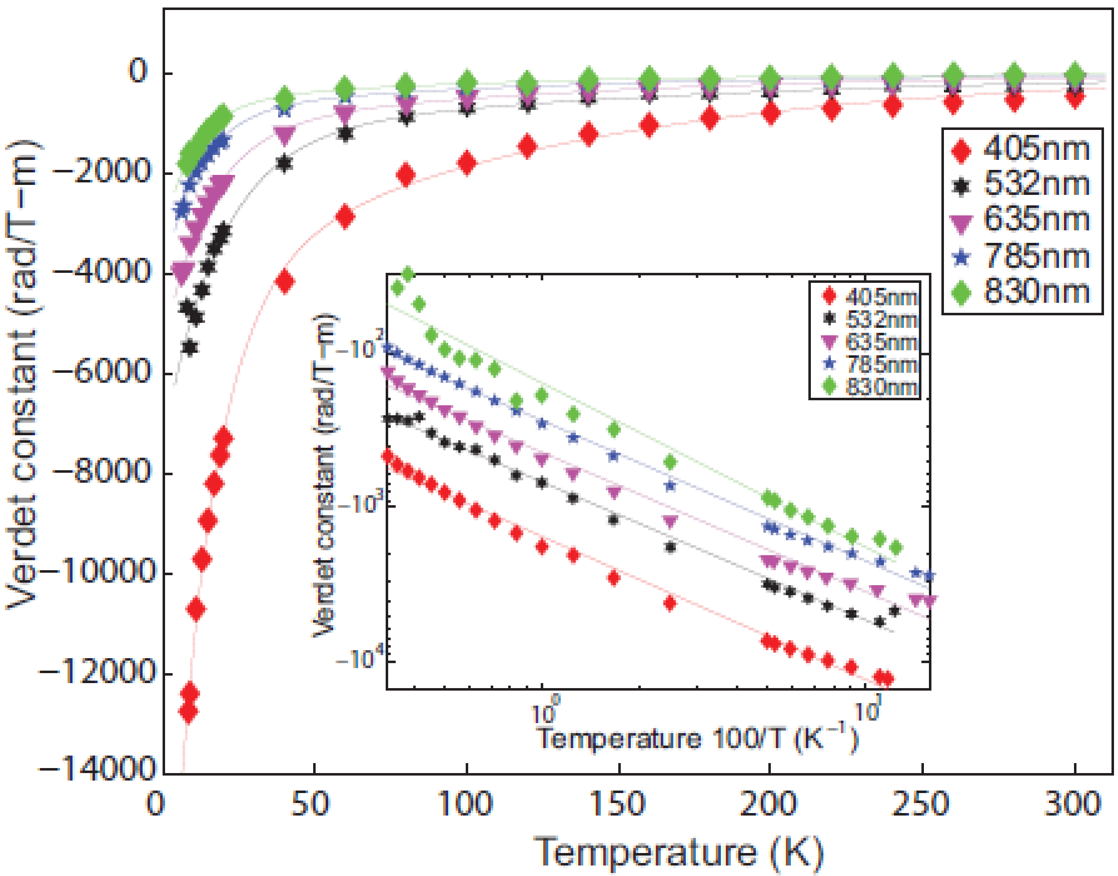
$$\vec{E}_{out} = \frac{E_o}{\sqrt{2}}\left(\hat{e}_+ e^{ik_+ d} + \hat{e}_- e^{ik_- d}\right)$$

$$= \frac{E_o e^{i(k_+ + k_-)d/2}}{\sqrt{2}}\left(\hat{x}\cos(\Delta k d/2) + \hat{y}\sin(\Delta k d/2)\right)$$

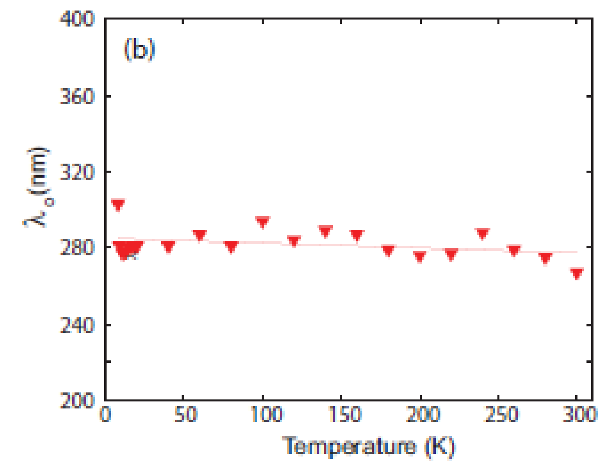
where $\Delta k = k_+ - k_- = -\frac{\omega}{c_o}\left(\sqrt{n_{\perp}{}^2 + Q} - \sqrt{n_{\perp}{}^2 + Q}\right) \approx -\frac{\omega Q}{c_o n_{\perp}}$

$$\theta_F = -\frac{\omega Q d}{2 c_o n_{\perp}}$$

Magneto-optic rotary dispersion and properties of paramagnetic ions imbedded in a diamagnetic matrix



$4f^n$-$4f^{n-1}5d$ electronic transition

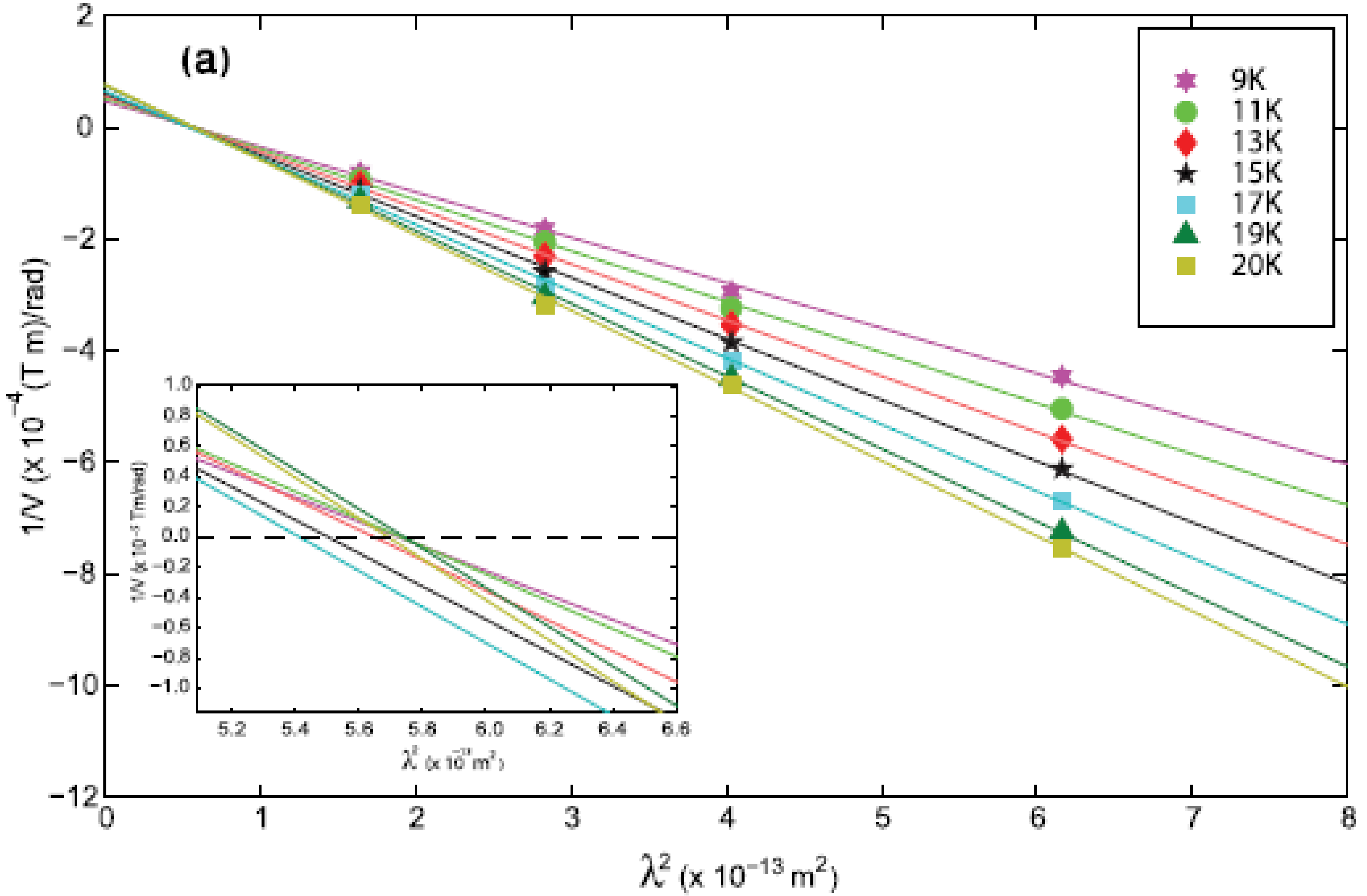


$$V = \frac{4\pi^2\nu^2\chi}{g\mu_B ch}\sum_{ij}\frac{f_{ij}}{\nu^2-\nu_{ij}^2}$$

A. Shaheen, H. Majeed, and M.S. Anwar, **Applied Optics** 52, 5549-5554 (2015).

$$V(\lambda,T) = -\frac{4\pi^2\lambda_o^2 N_{\mathrm{RE}}\mu_o g J(J+1)\mu_B}{3k_B Thc}\frac{f_o}{\lambda^2-\lambda_o^2}$$

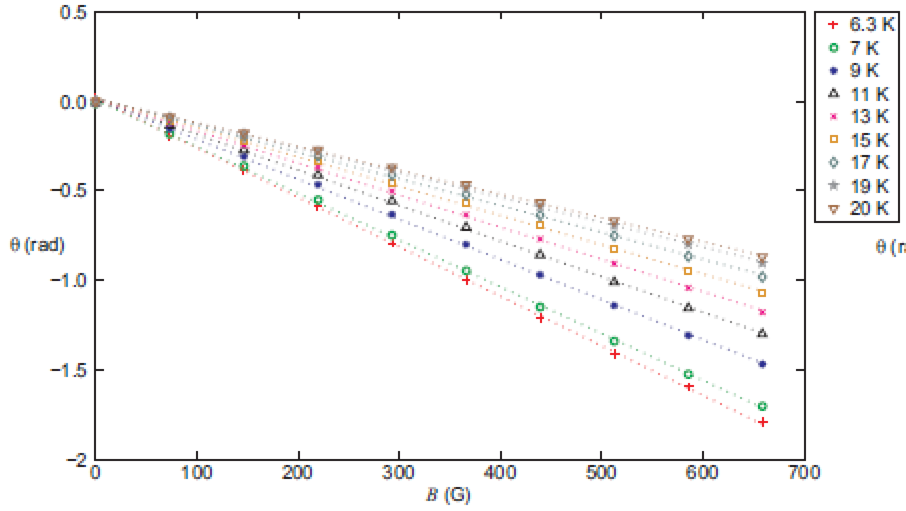
Calculating the oscillator strength for paramagnetic rare earth ions



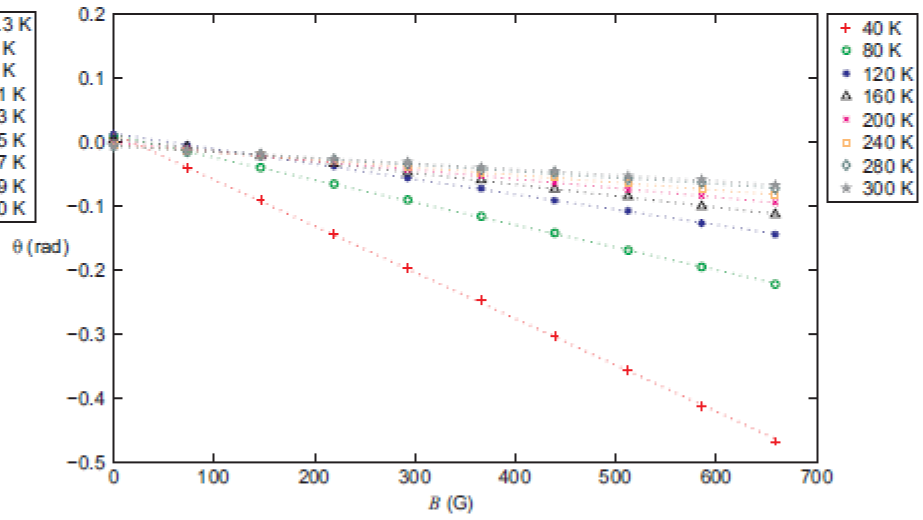
$$f_o = \frac{3chk_B p_1}{4\pi^2 N \mu_o \mu_B J(J+1) g_J}$$

$$f_o = 6.0 \times 10^{-38} \text{ erg cm}^3 \text{ or } 6.0 \times 10^{-51} \text{ J m}^3.$$

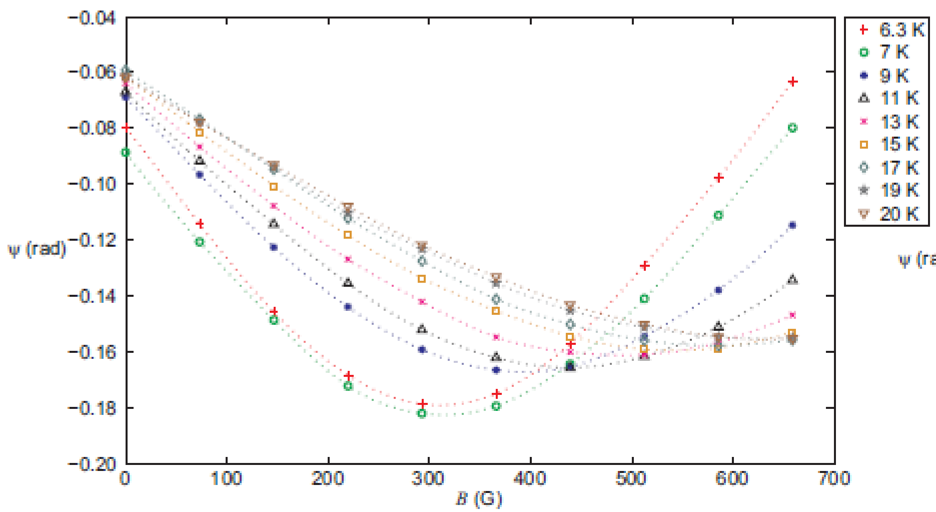
Unambiguous Determination of Faraday Rotation and Ellipticity from paramagnetic terbium gallium garnet crystal



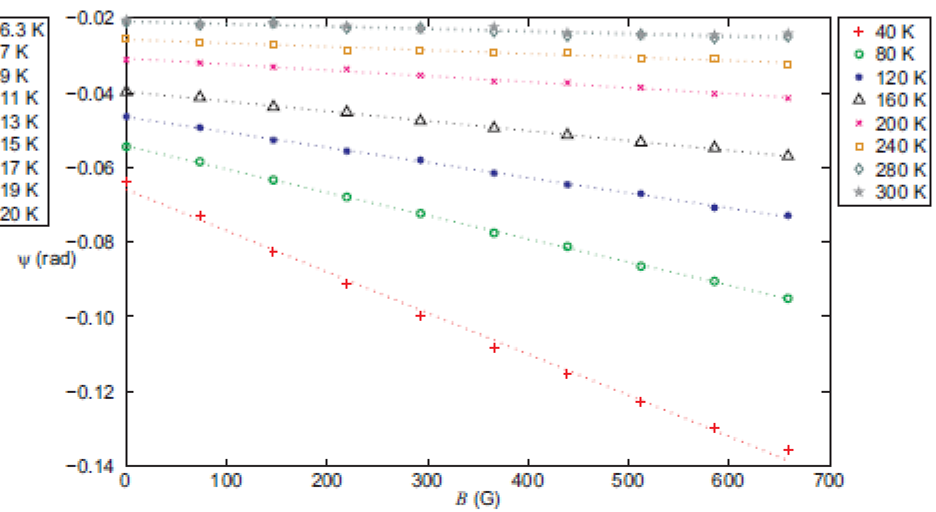
(a)



(b)

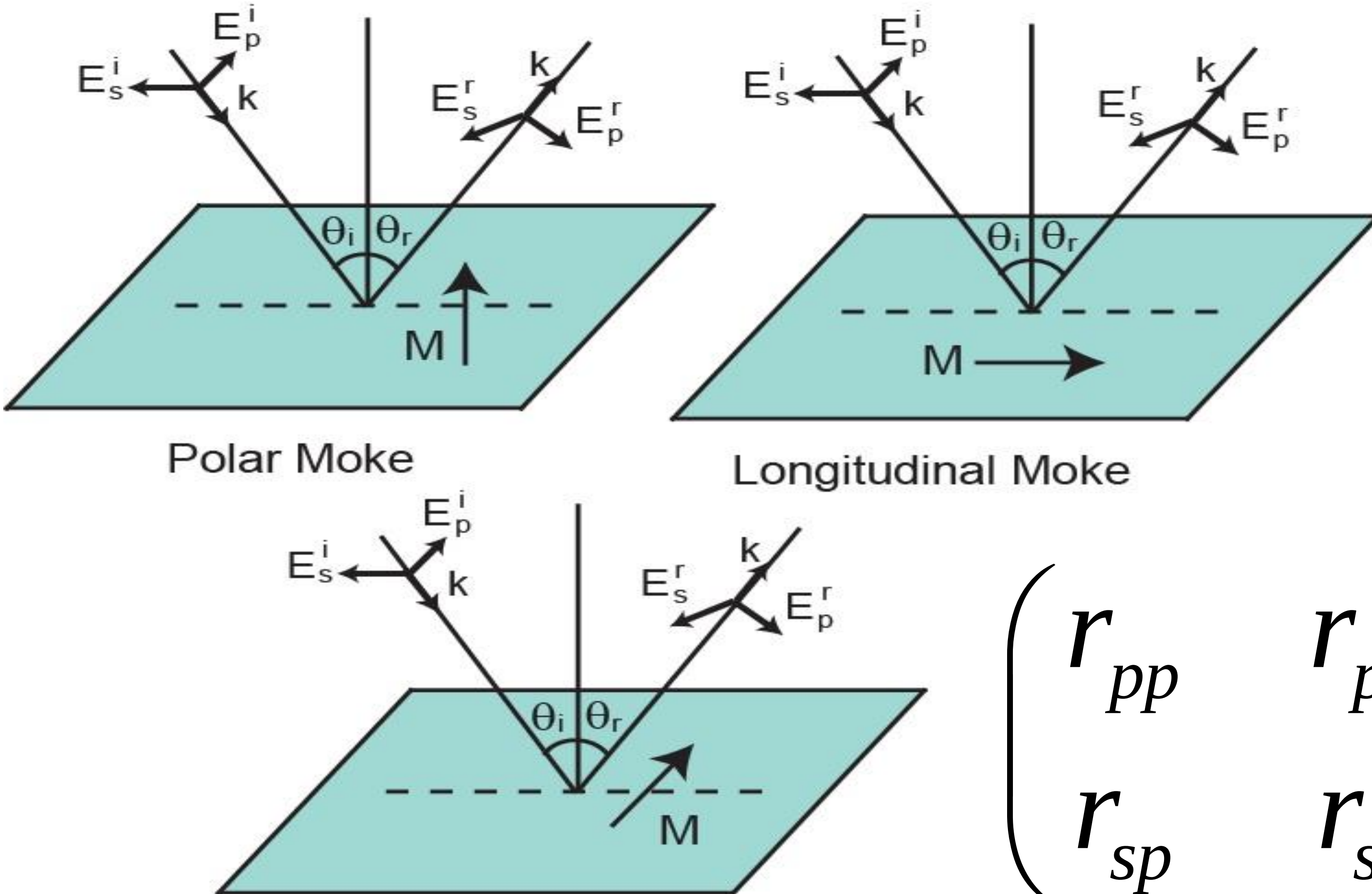


(c)



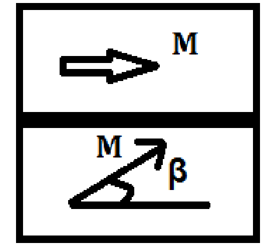
(d)

Magneto-optic Kerr Effect

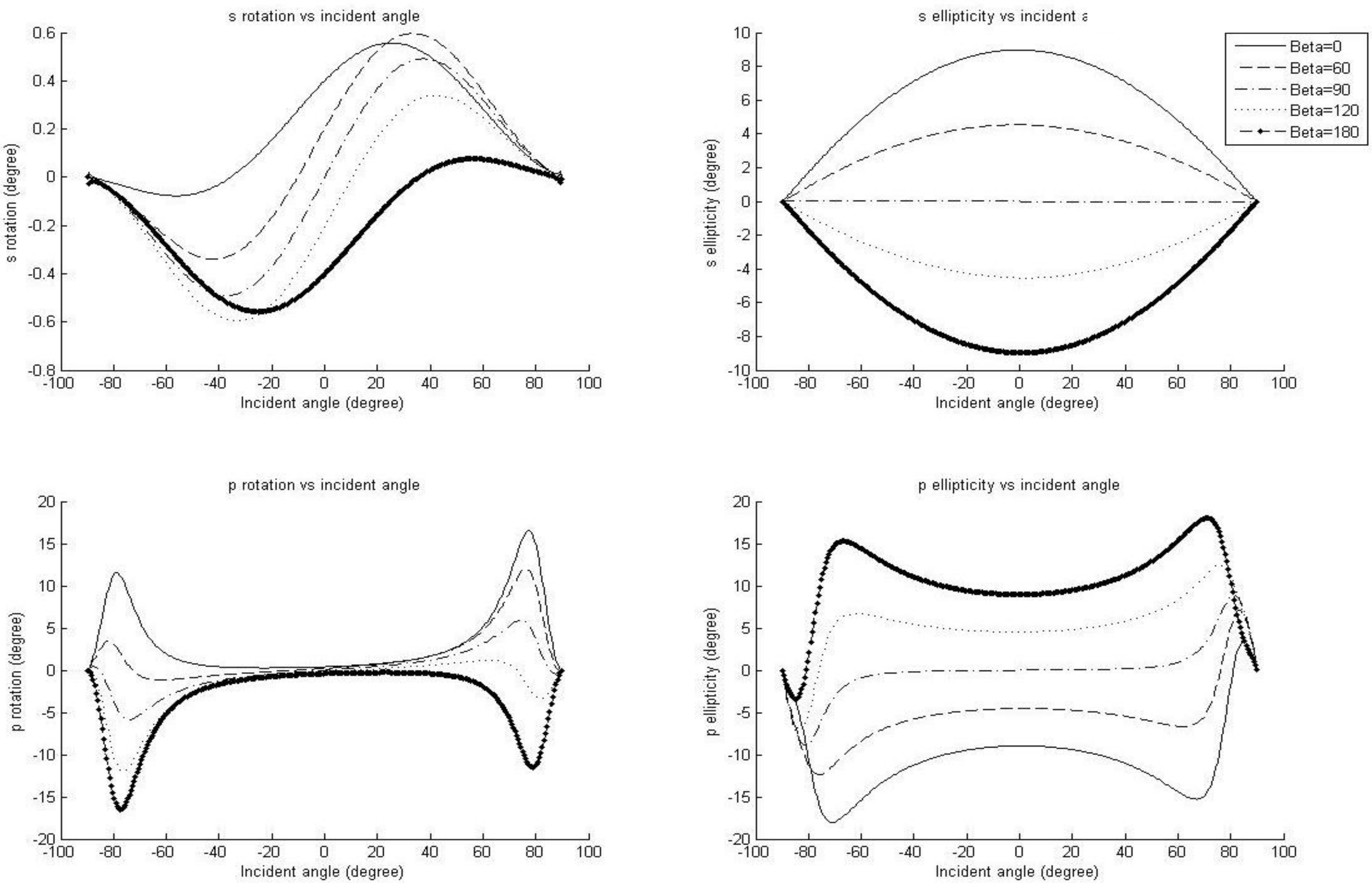


$$\begin{pmatrix} r_{pp} & r_{ps} \\ r_{sp} & r_{ss} \end{pmatrix}$$

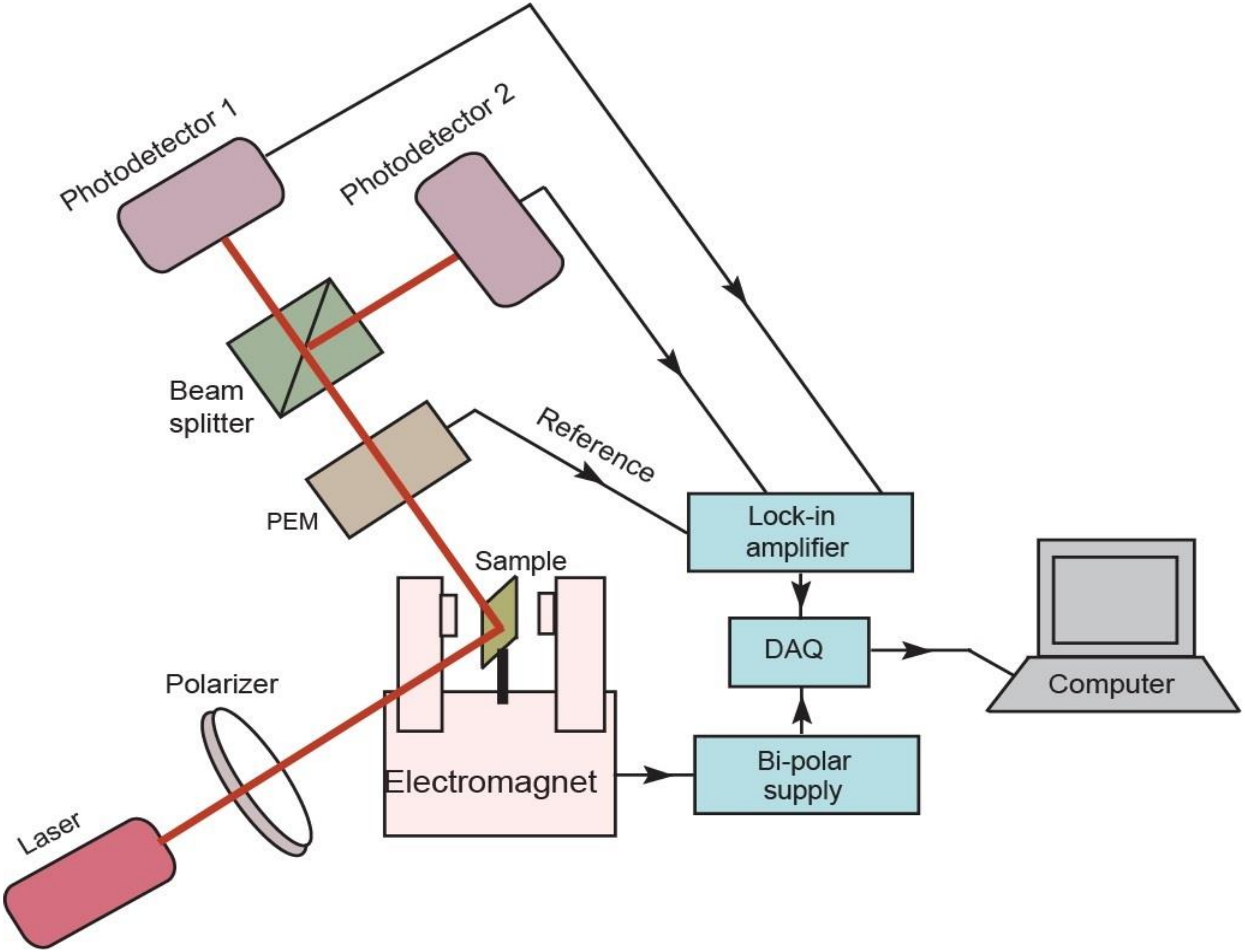
Magneto-optic scattering from heterostructures



4.

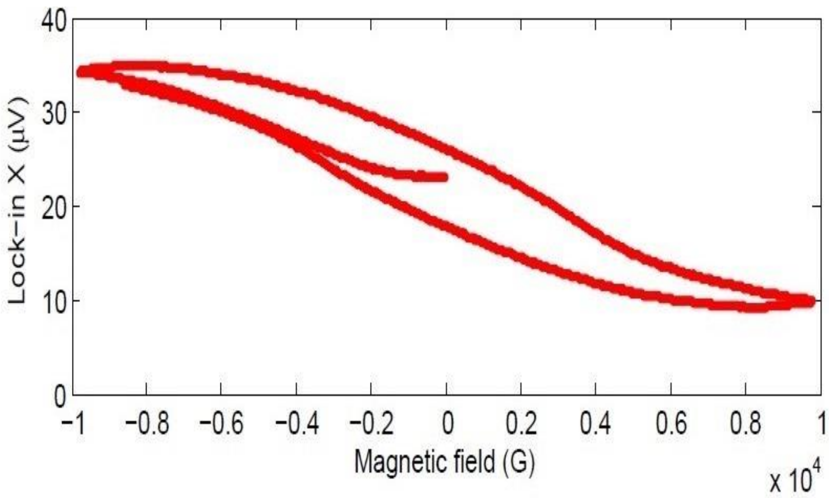


Scheme of balanced polar MOKE detection

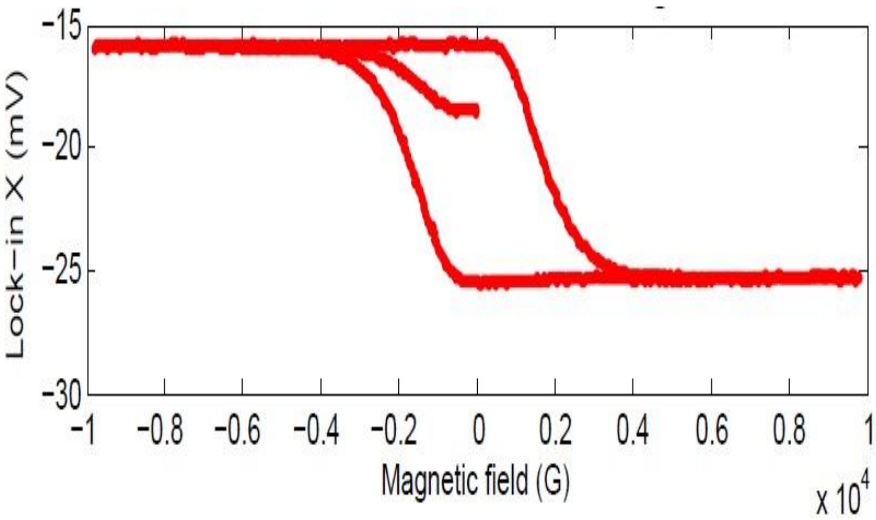



Laser
Polarizer
Iris
PEM
PBS
Iris
Photodetector 1
Photodetector 2

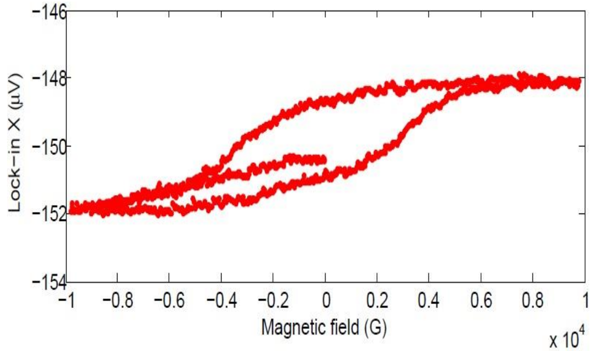
Polar MOKE
Co/CoO
(Balanced detection)



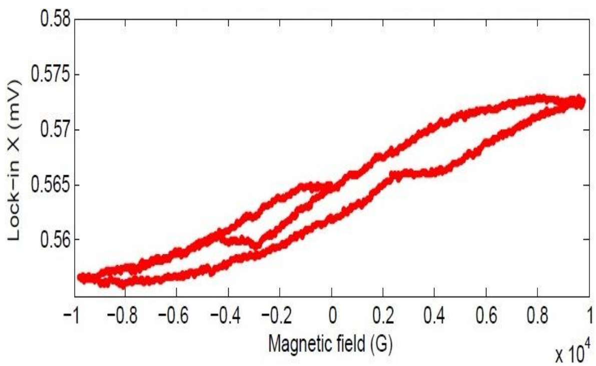
Longitudinal MOKE
Co/CoO
(Balanced detection)



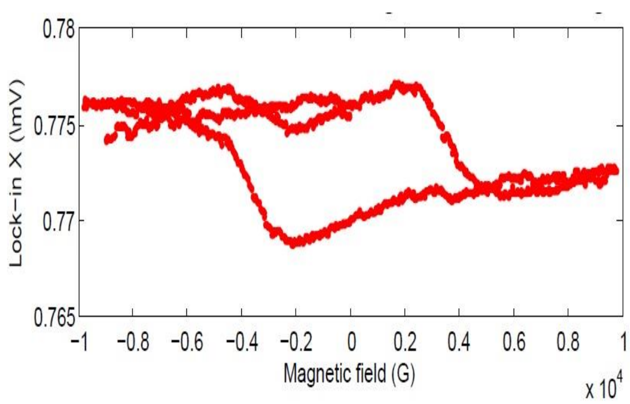
Polar MOKE
Parallel polarizers
(single ended)



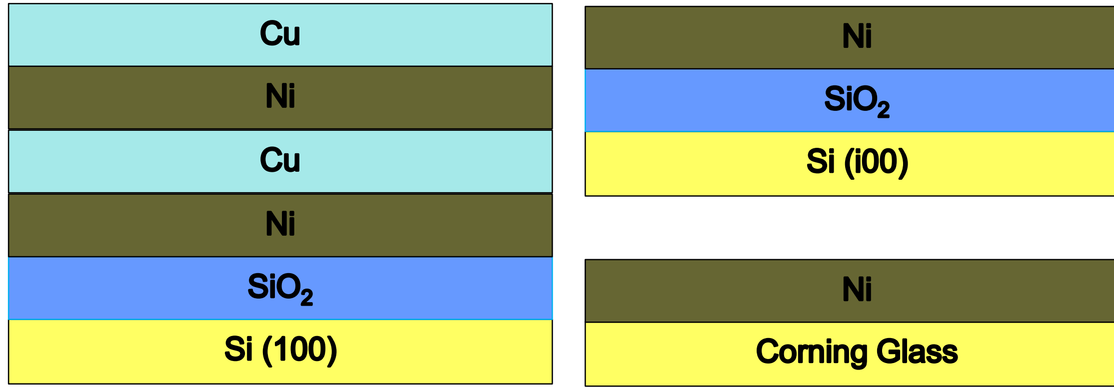
Crossed polarizers

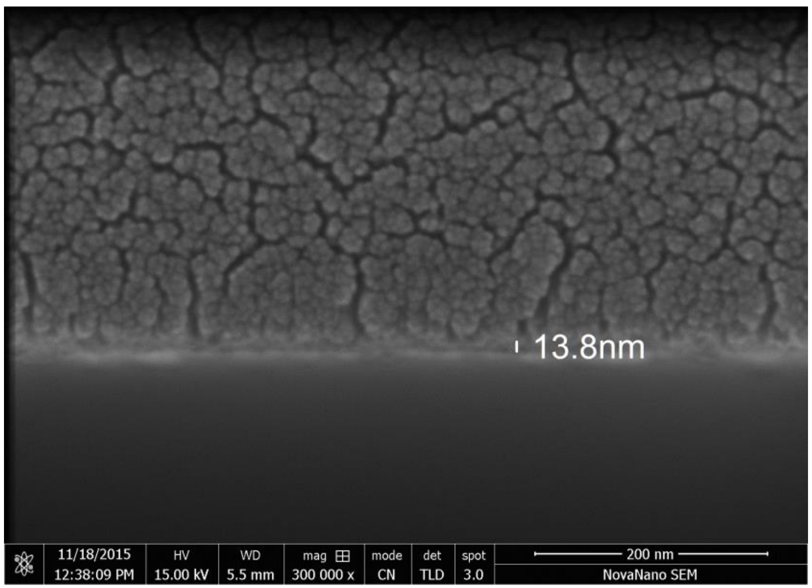


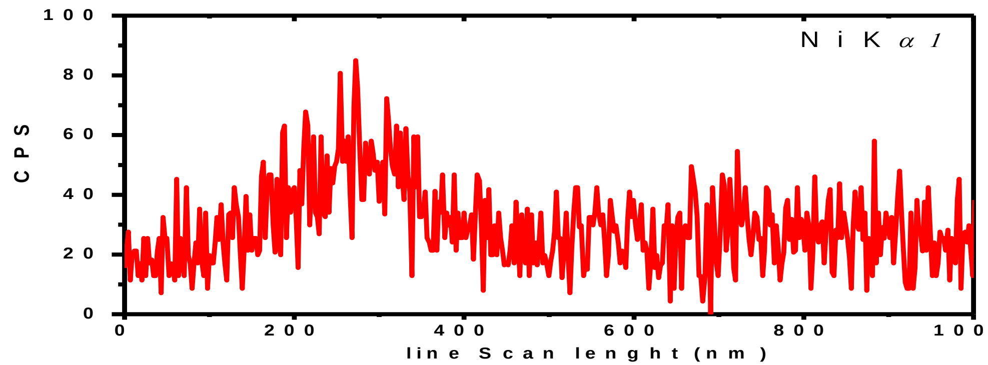
Analyzer at 45 deg.

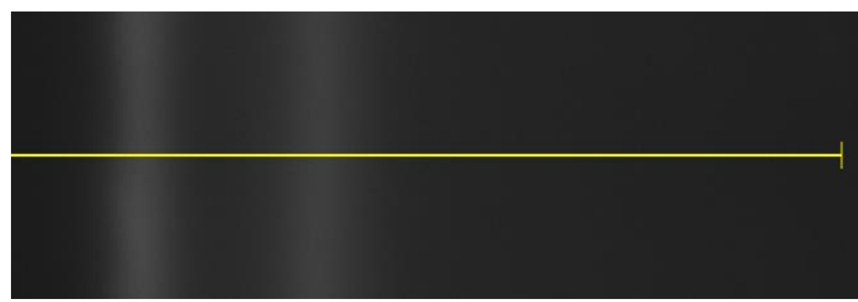


Experimental scheme

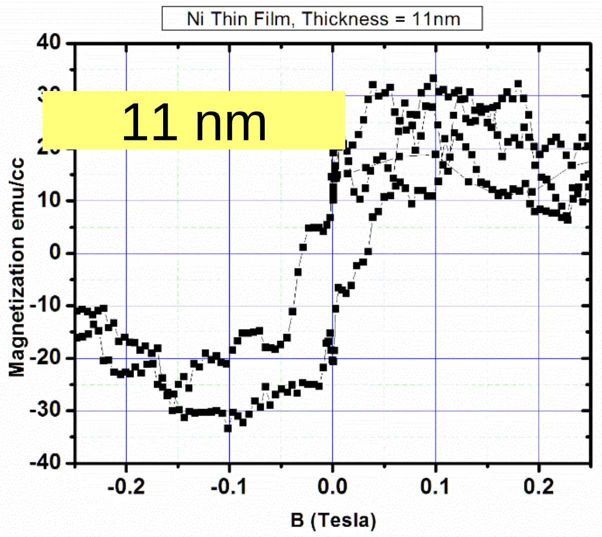


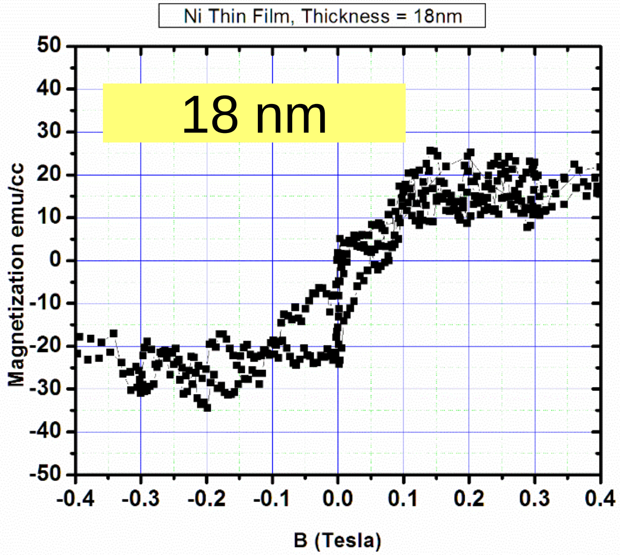


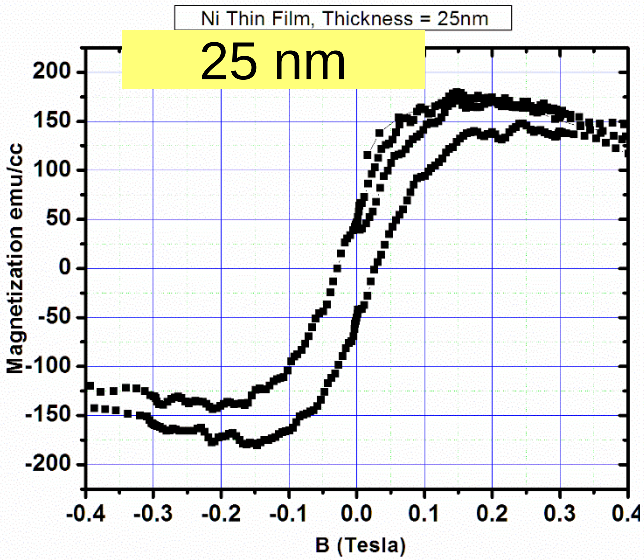


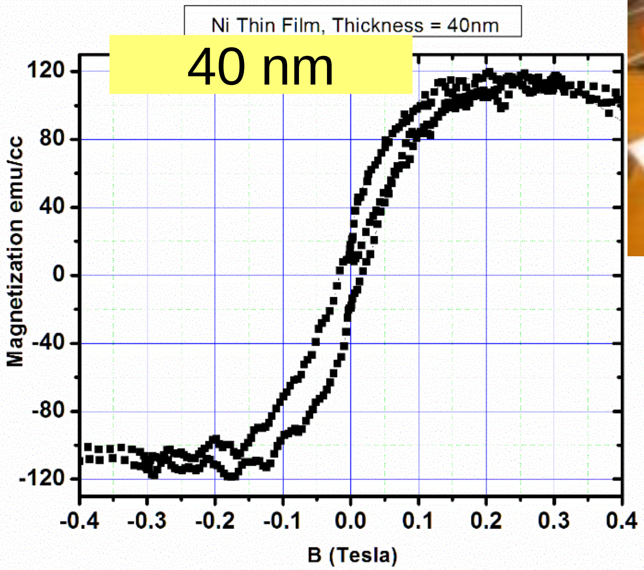


Synthesis and structural characterization


Ni Thin Film, Thickness = 11nm
11 nm
Magnetization emu/cc
B (Tesla)

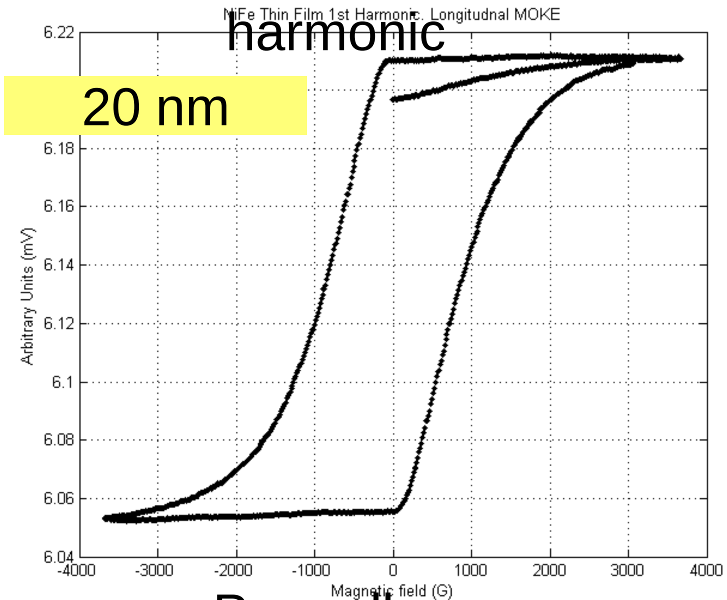

Ni Thin Film, Thickness = 18nm
18 nm
Magnetization emu/cc
B (Tesla)

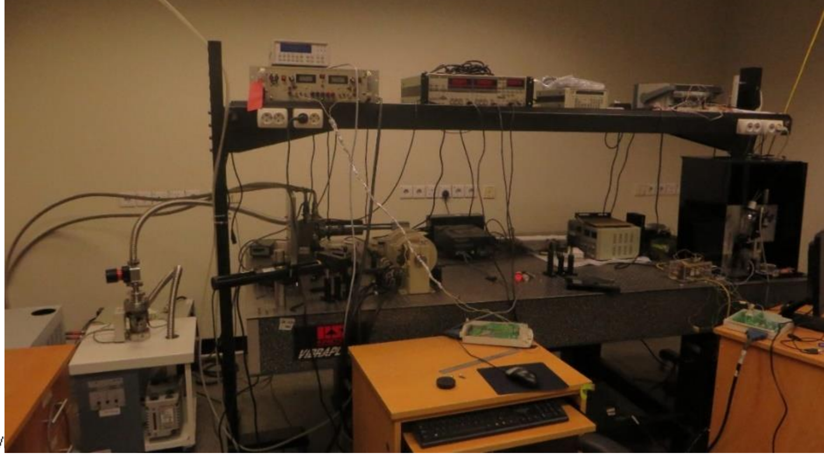

Ni Thin Film, Thickness = 25nm
25 nm
Magnetization emu/cc
B (Tesla)


Ni Thin Film, Thickness = 40nm
40 nm
Magnetization emu/cc
B (Tesla)

Permalloy, longitudinal, first harmonic

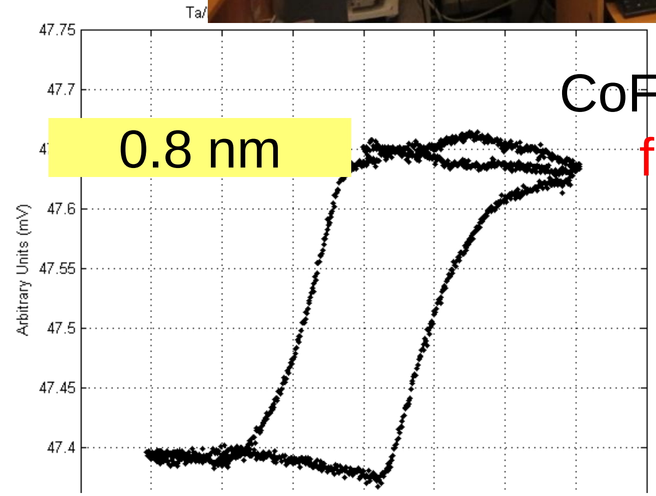
20 nm





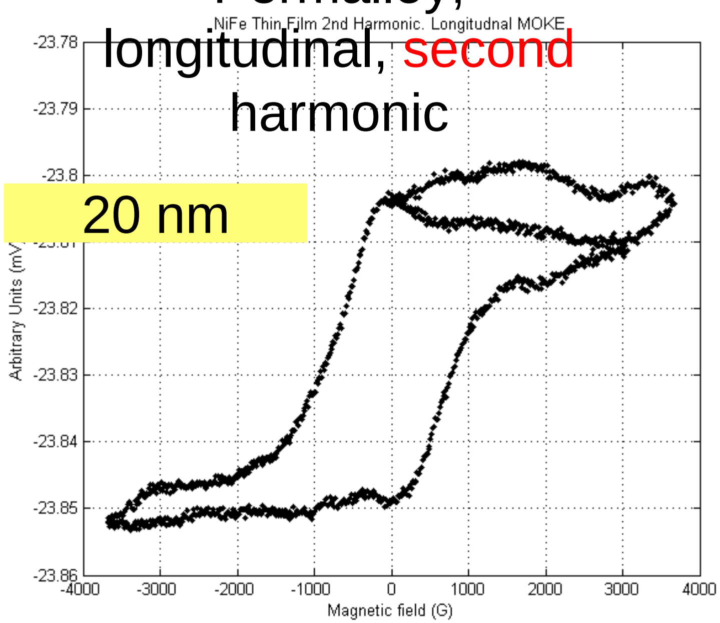
CoFeB, longitudinal first harmonic

0.8 nm



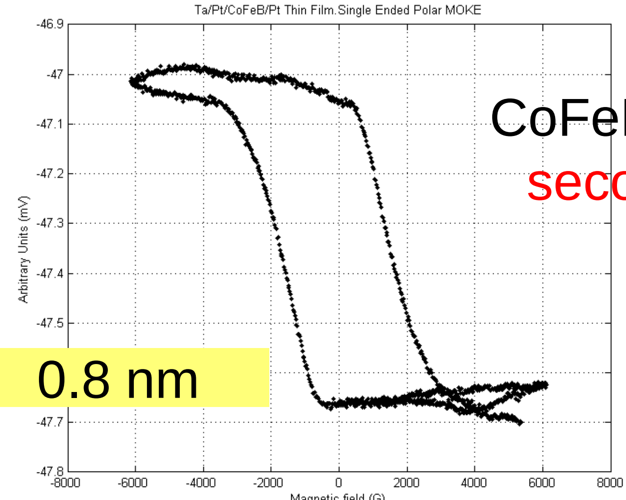
Permalloy, longitudinal, second harmonic

20 nm

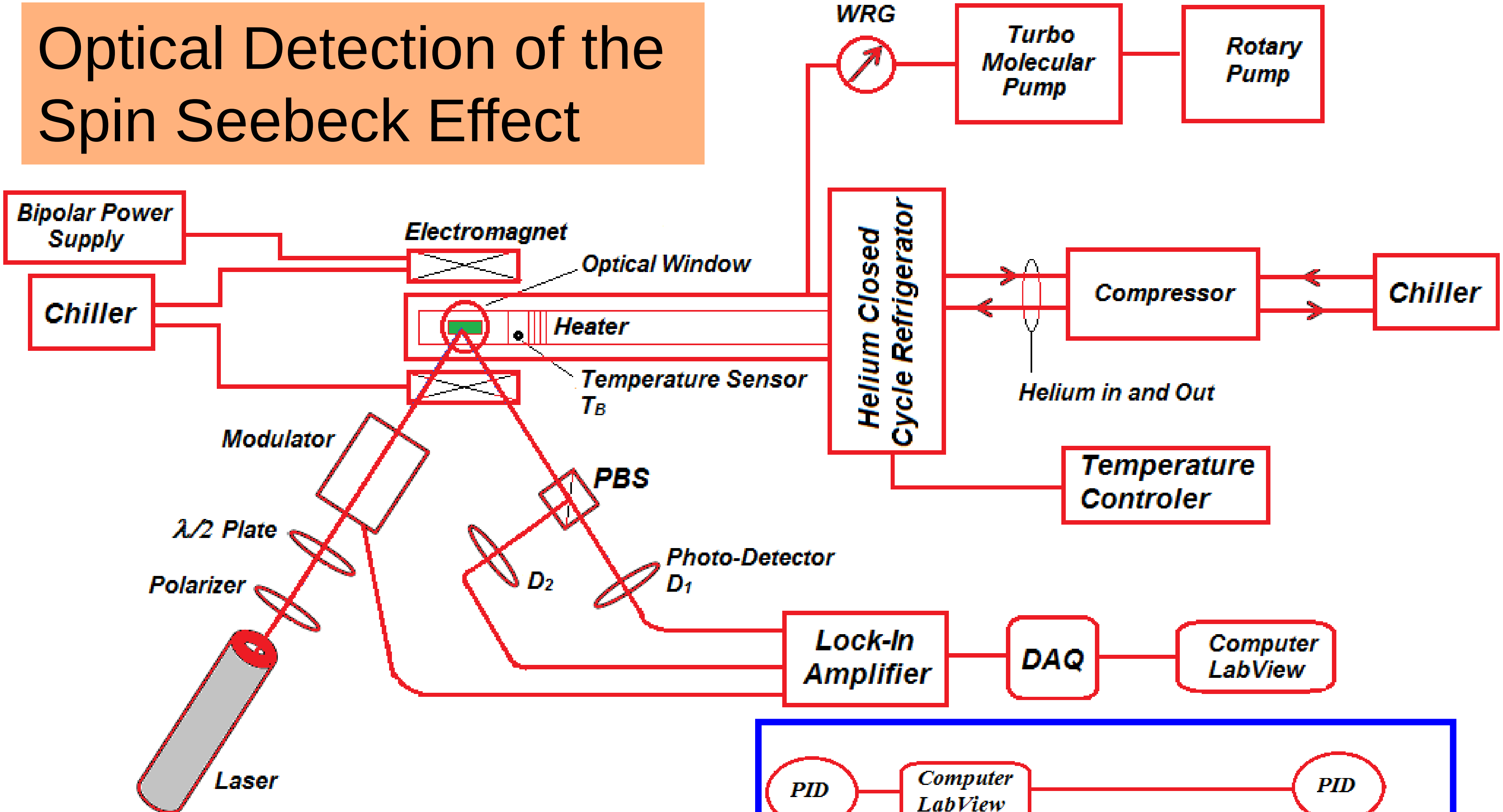


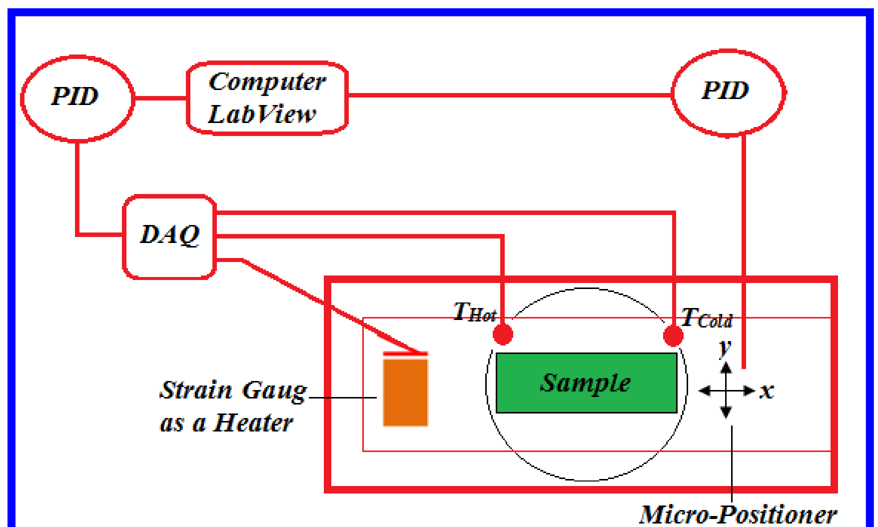
CoFeB, longitudinal, second harmonic

0.8 nm



Optical Detection of the Spin Seebeck Effect





Experiment under progress.