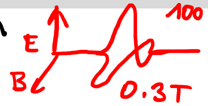
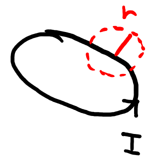
Table 10.1. Production of high magnetic fields

Method	Duration	Maximum field (T)
Air-core solenoid ~ 1kE	Steady	0.2
Permanent magnet ~0,1 - 10E	Steady	0.1–2
Electromagnet ~ 10 - 25kE	Steady	0.5–2.5
Superconducting solenoid ~30kE	Steady	2–23
Bitter magnet > 1ME	Steady	15–35 - 37T (24MW, 30kA, ϕ 5cm)
Hybrid magnet > ∞	Steady	40–45
Discharge coil	100 ms	25–80
Discharge coil	10 μs	50–100
Expendible coil	1 μs	>100
Implosive flux compression	< 1 μs	1000
THz Waveform	~ 1ps	0.3T

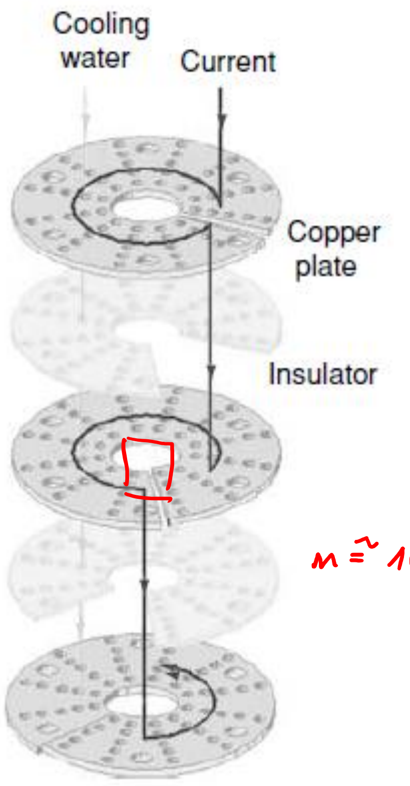


$$E = \frac{1}{c} B \qquad E \sim 1 MV/cm \sim 10^8 V/m$$
$$c \sim 3 \cdot 10^8 m/s$$



$$\oint \vec{H} d\vec{l} = I$$
$$2\pi r H = I$$
$$H = \frac{I}{2\pi r}$$ ← od jedné smyčky × n

GRENOBLE LCHMI



$n \cong 1000/m$

Coey, Magnetism and Magnetic Materials

GENERACE B

Table 10.1. Production of high magnetic fields

Method	Duration	Maximum field (T)
Air-core solenoid	Steady	0.2
Permanent magnet	Steady	0.1–2
Electromagnet	Steady	0.5–2.5
Superconducting solenoid	Steady	2–23
Bitter magnet	Steady	15–35
Hybrid magnet	Steady	40–45
Discharge coil	100 ms	25–80
Discharge coil	10 μs	50–100
Expendible coil	1 μs	>100
Implosive flux compression	< 1 μs	1000
THz Waveform	~1ps	0.3T

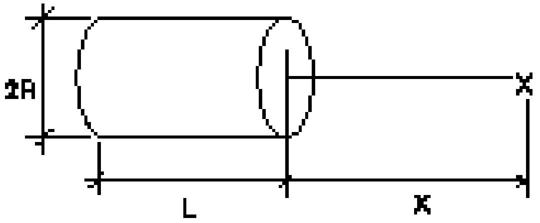
$Nd_2Fe_{14}B$: $M_S \sim 1.3$ MA/m $\rightarrow \mu_0 \sim 10^6 \simeq 1T$

→ $B < 0.5T$ perm. mg lepší volba

- N35 – N55

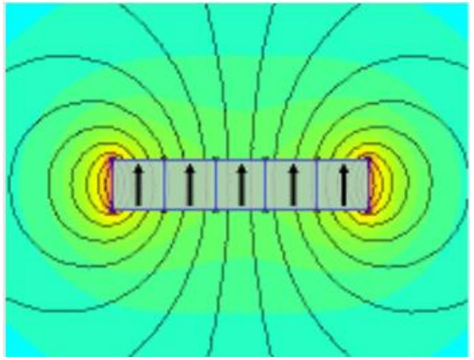
https://silnemagnety.cz/kalkulacka/

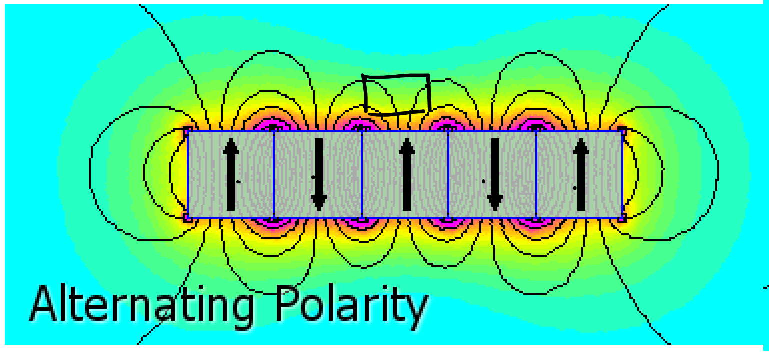
- ~1,5T @ 300 $

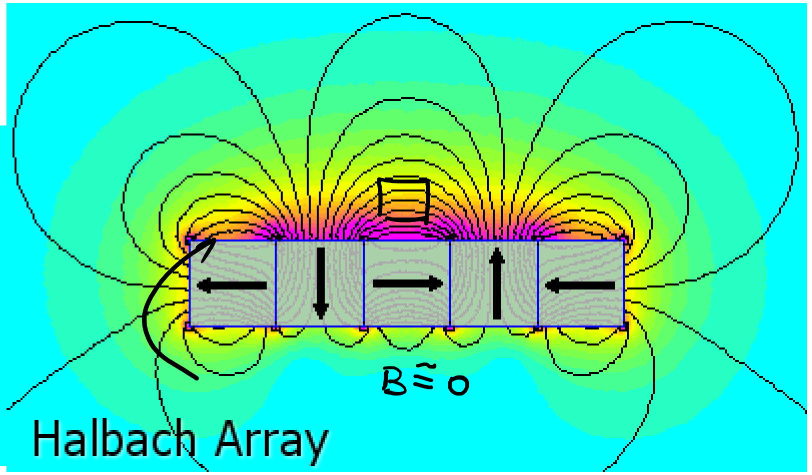


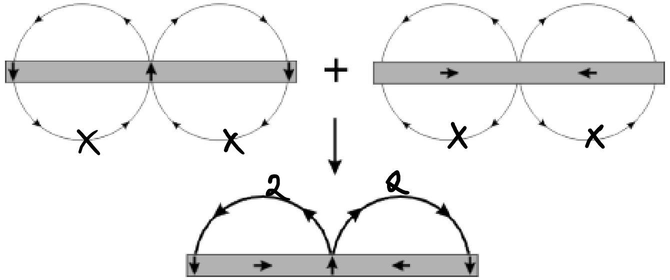
$$B_x = \frac{B_r}{2}\left(\frac{(L+X)}{\sqrt{R^2+(L+X)^2}} - \frac{X}{\sqrt{R^2+X^2}}\right)$$

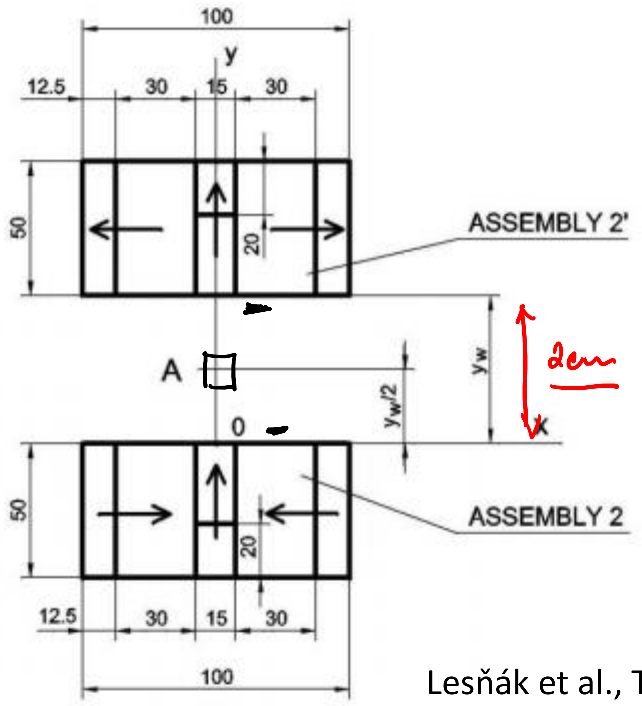
HALBACHOVO USPOŘÁDÁNÍ











$M_S \sim 1{,}3\,T$

↓

$\boxed{B \sim 2T}$

Lesňák et al., Technical University of Ostrava

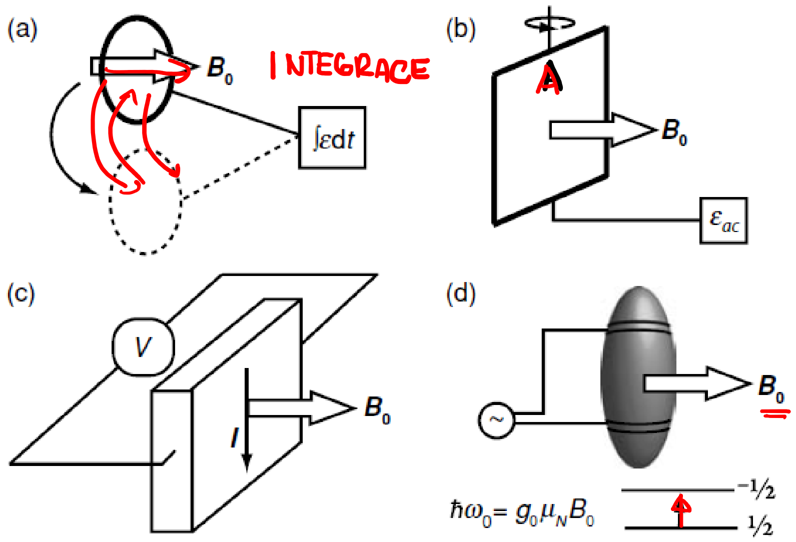
DETEKCE B

Pohybující se cívka

Rotující cívka

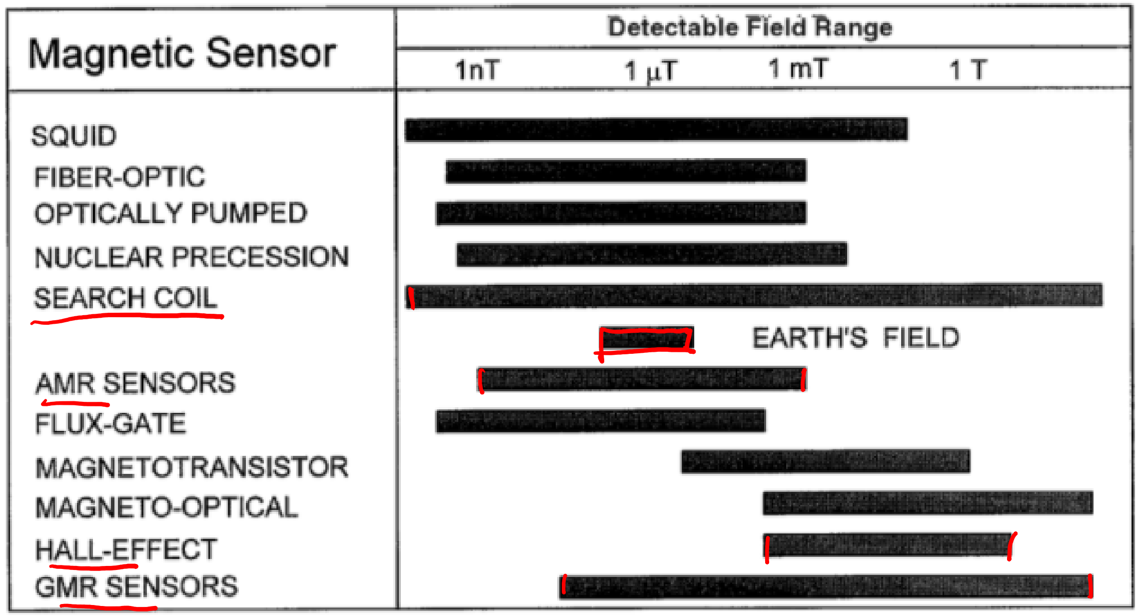
$$\varepsilon = -N \frac{\partial \Phi}{\partial t} \qquad \Phi = \vec{B} \cdot \vec{A}$$

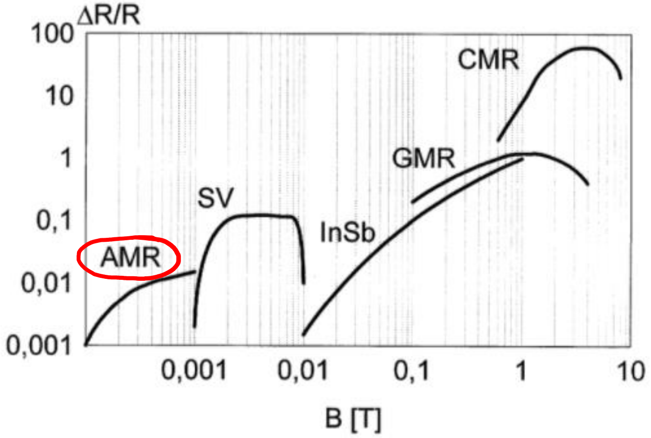
plocha



Hallovské a magnetorezistenční senzory

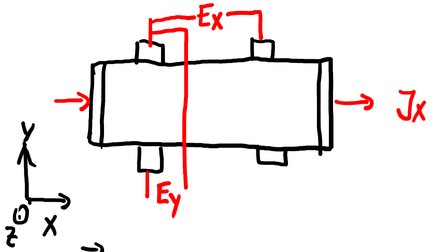
NMR senzory





S. Tumanski, Thin Film Magnetoresistive Sensors

DETEKCE B – MAGNETOREZISTENCE



$\vec{B} = (0,0,B)$

$j_x(B)$
$\rho(B)$
$\sigma(B)$

pohyb. rce: $m\left(\dot{v} + \frac{v}{\tau}\right) = e(\vec{E} + \vec{v} \times \vec{B})$

steady state: $\dot{v} = 0$

$$\underline{\underline{\vec{v}}} = \frac{e\tau}{m}(\vec{E} + \vec{v} \times \vec{B})$$

$\mu \qquad j = ne\vec{v}$

$$\boxed{\mu B = \frac{eB}{m}\tau = \omega_c \tau \equiv \alpha}$$

rozptyl. čas

- Longitudinální MR? $B \parallel \hat{x} \Rightarrow j_x \neq j_x(B) \neq f(B)$
- Transverzální MR? $B \perp \hat{x}$, $B \parallel \hat{z}$, $\vec{v} = ?$

$$v_x = \frac{j_x}{ne} = \mu E_x + \alpha v_y$$
$$v_y = \mu E_y - \alpha v_x$$
$$v_z = \mu E_z$$

$$v_x = \mu E_x + \mu\alpha E_y - \alpha^2 v_x = \frac{\mu}{1+\alpha^2}(E_x + \alpha E_y)$$

$$v_y = \dots = \frac{\mu}{1+\alpha^2}(E_y - \alpha E_x)$$

$\Rightarrow$ je to tenzor $\quad \vec{j} = ne\vec{v} = \bar{\bar{\sigma}}\vec{E}$

$$\boxed{\bar{\bar{\sigma}} = \frac{\overbrace{ne\mu}^{\sigma_0}}{1+\alpha^2}\begin{pmatrix} 1 & \alpha & 0 \\ -\alpha & 1 & 0 \\ 0 & 0 & 1+\alpha^2 \end{pmatrix}}$$

$\Rightarrow \vec{j} \nparallel \vec{E}$, stáčí se

$\rightarrow \qquad \alpha \gg 1$

$\rightarrow$ takže pro $B \to \infty$, $\sigma_{xx} \propto B^{-2}$ – tj. kvadratická MR ⌣ ? Ne tak rychle, okraj. podm.

DETEKCE B – MAGNETOREZISTENCE

tenzor jen pro x, y ! $\bar{\bar{\sigma}} = \frac{\sigma_0}{1+\alpha^2}\begin{pmatrix}1 & \alpha\\ -\alpha & 1\end{pmatrix}$

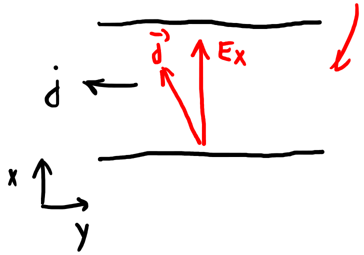
chceme-li spočítat $\vec{j}$: $\vec{j} = \bar{\bar{\sigma}}\vec{E} = \bar{\bar{\sigma}}\nabla\varphi$ ← elstat. potenciál

⊕ $\Delta\varphi = 0$ ⊕ okraj. podm. : fyzické okraje vzorku

→ „Jaký je proud kolmý na E_x?"

ve směru y

① žádné okraje!

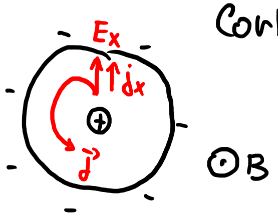


nic nebrání proudu téct v y ⇒ žádné dodatečné E_y

$E = (E_x, 0, 0)$

okraj podm. $E_y = 0$

Corbino disk



$\vec{j} = \bar{\bar{\sigma}}\vec{E}$

$$j_x = \frac{\sigma_0}{1+\alpha^2}E_x$$

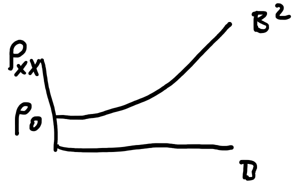
$$j_y = -\frac{\sigma_0}{1+\alpha^2}\alpha E_x$$

$\vec{j} \nparallel \vec{E}$

$\alpha = \mu B$

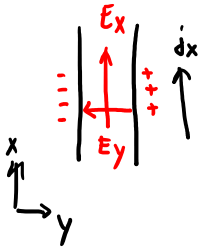
$$\Rightarrow \rho_{xx} = \frac{1}{\sigma_{xx}} = \frac{1+\alpha^2}{\sigma_0} \propto B^2$$

MR kvadrat.



DETEKCE B – MAGNETOREZISTENCE

② Hall bar :



okraj. podm. $\underline{j_y = 0}$

nelze držet $E=(E_x,0,0)$, máme vždy $(\underline{E_x}, \underline{E_y})$ $\neq 0$

naopak víme, že vždy $\underbrace{\vec{j} = (j_x, \underline{0}, 0)}$ → přejít k $\bar{\bar{\rho}}$, protože $\vec{j}$ je známé:

a) $\underline{j_y = 0}$

$$j_y = \frac{\sigma_0}{1+\alpha^2}\left(-\alpha E_x + E_y\right) \overset{!}{=} 0 \quad \Rightarrow \quad E_y = \alpha E_x \quad \text{Hall voltage}$$

$$j_x = \frac{\sigma_0}{1+\alpha^2}\left(E_x + \alpha E_y\right) = \frac{\sigma_0}{1+\alpha^2} E_x \left(1+\alpha^2\right) = \sigma_0 E_x \neq f(B)!$$

b) nebo pomocí přechodu k $\bar{\bar{\rho}} = \bar{\bar{\sigma}}^{-1}$ $\qquad \vec{E} = \bar{\bar{\rho}}\,\vec{j}$

$$\begin{bmatrix} a & b \\ -b & a \end{bmatrix}^{-1} = \frac{1}{a^2+b^2}\begin{bmatrix} a & -b \\ b & a \end{bmatrix} \qquad \bar{\bar{\rho}} = \frac{1}{\sigma_0}\begin{pmatrix} 1 & -\alpha \\ \alpha & 1 \end{pmatrix}$$

$a = 1$
$b = \alpha$

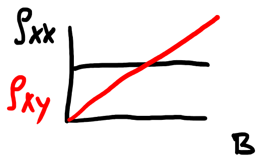
náš případ : $j = (j_x, 0, 0)$

$$E_x = \frac{1}{\sigma_0} j_x = \rho_0 j_x \qquad \rho_{xx} \neq f(B)$$

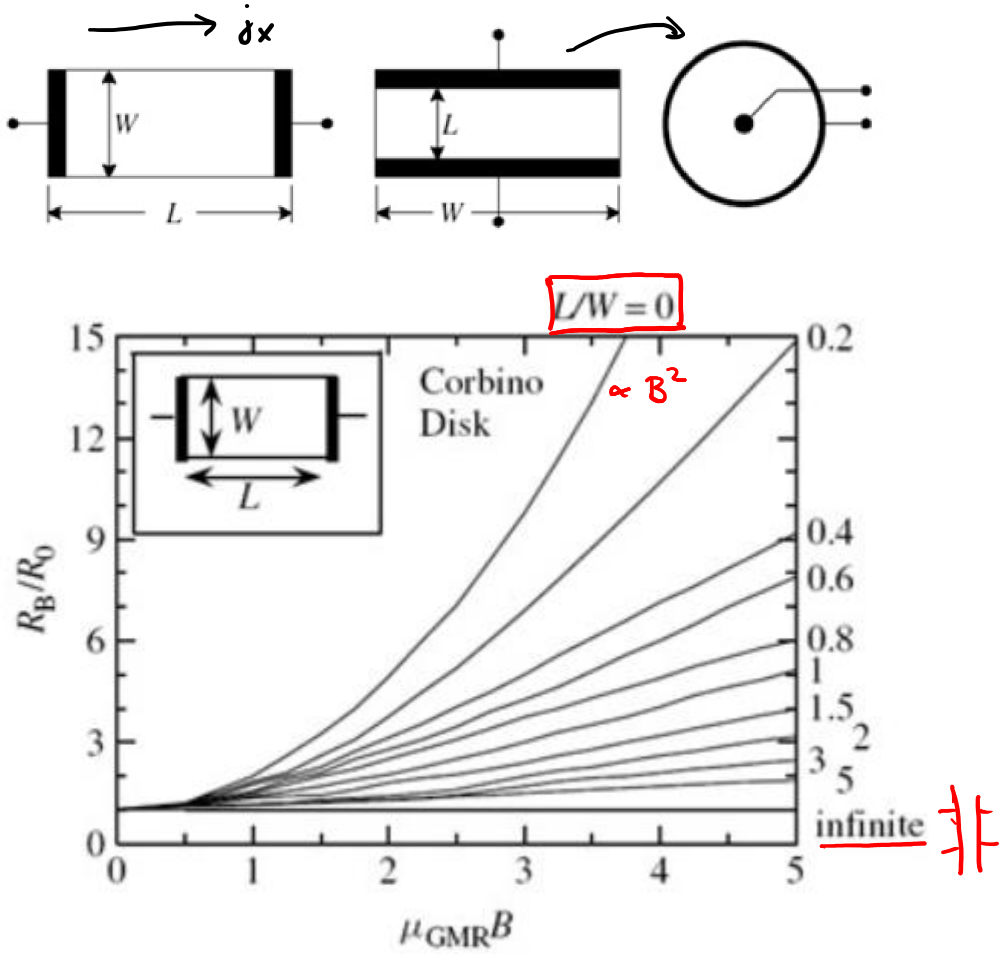
$$E_y = \rho_0 \alpha j_x = \frac{\mu B}{ne\mu} j_x = R B j_x$$

Hallova konst.

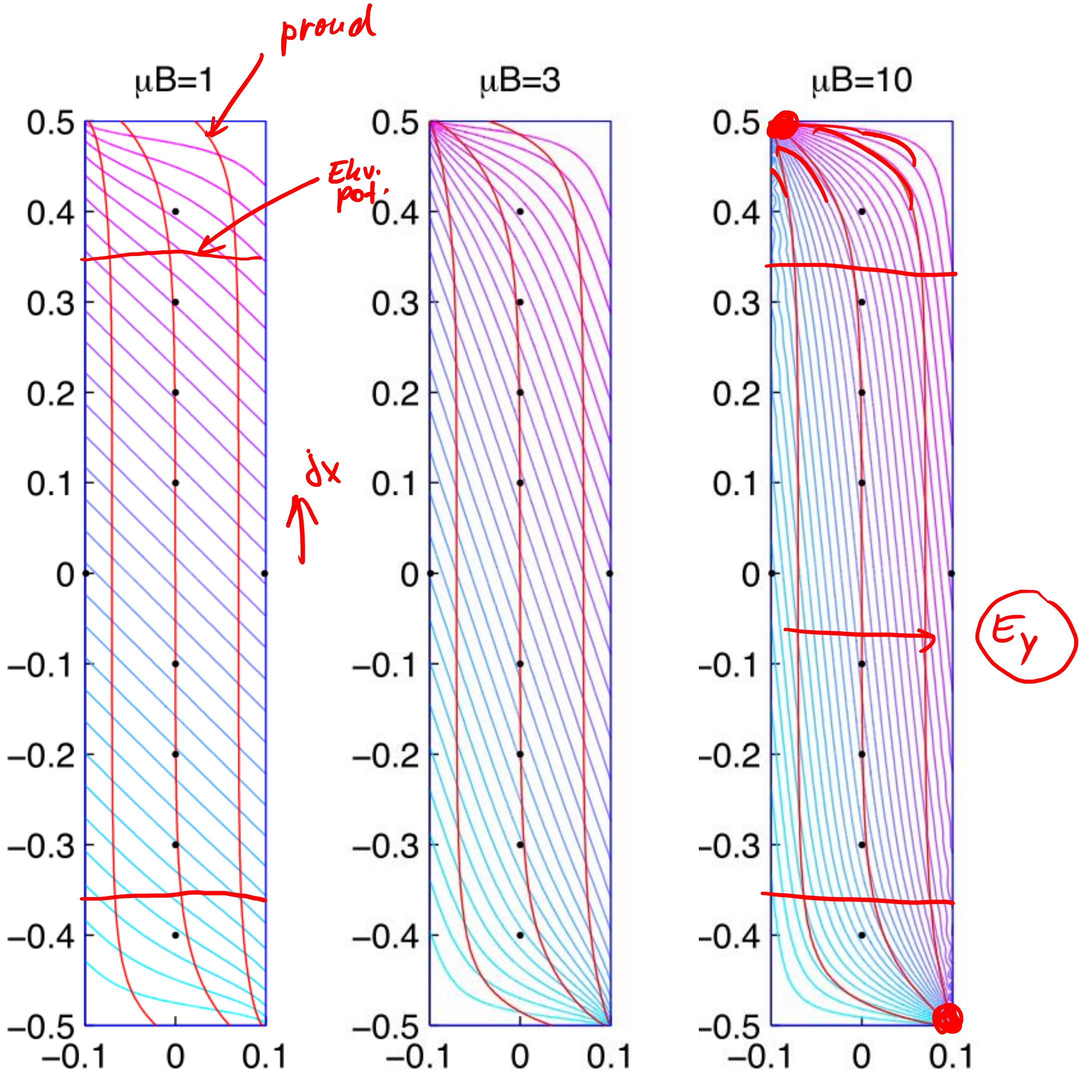
⇒ žádná MR



DETEKCE B – MAGNETOREZISTENCE



Lippmann, Kuhrt (1958)



Shurt, Solid-state Electronics 20, 389 (1977)

Vít Novák, AVČR

DETEKCE B – MAGNETOREZISTENCE

→ v realitě je MR přítomná skoro vždy :
(i v Hall bar geom.)

a) ρ roste s B, ale pak se saturuje

b) ρ roste stále jako B^2

c) v jednom směru B platí a), v druhém b)

→ doteď jen $1m$, 1τ, 1μ → vícepásová realita transportu

• VÍCEPÁSOVÁ MR :

$$\overline{\overline{\sigma}} = \overline{\overline{\sigma}}_1 + \overline{\overline{\sigma}}_2 = \frac{\sigma_{01}}{1+\alpha_1^2}\begin{pmatrix} 1 & \alpha_1 \\ -\alpha_1 & 1 \end{pmatrix} + \frac{\sigma_{02}}{1+\alpha_2^2}\begin{pmatrix} 1 & \alpha_2 \\ -\alpha_2 & 1 \end{pmatrix} = \begin{bmatrix} a & b \\ -b & a \end{bmatrix}$$

v Hall bar → $\vec{\rho}$

$\alpha_i = \mu_i B$

$\mu_i = \frac{e\tau_i}{m_i}$

$\sigma_{0i} = e M_i \mu_i$

$i = 1, 2, \dots$

$$a = \frac{\sigma_{01}}{1+\alpha_1^2} + \frac{\sigma_{02}}{1+\alpha_2^2}$$

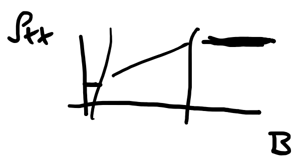
$$b = \frac{\sigma_{01}\alpha_1}{1+\alpha_1^2} + \frac{\sigma_{02}\alpha_2}{1+\alpha_2^2}$$

$$\overline{\overline{\rho}} = \frac{1}{a^2+b^2}\begin{bmatrix} a & -b \\ b & a \end{bmatrix}$$

$$\Rightarrow \quad \rho_{xx} = \frac{a}{a^2+b^2}$$

Matlab

$$\rho_{xx} = \frac{\sigma_{01}(1+\alpha_2^2) + \sigma_{02}(1+\alpha_1^2)}{\sigma_{01}^2(1+\alpha_2^2) + \sigma_{02}^2(1+\alpha_1^2) + 2\sigma_{01}\sigma_{02}(1+\alpha_1\alpha_2)}$$



případy : (1) $B=0$ $\alpha_i = 0$

$$\rho_{xx}(0) = \frac{\sigma_{01}+\sigma_{02}}{(\sigma_{01}+\sigma_{02})^2} = \frac{1}{\sigma_{01}+\sigma_{02}} = \frac{1}{\sigma_0} \neq f(B).$$

(2.) $B \neq 0$, $\mu_1 = \mu_2$ $(\alpha_1 = \alpha_2)$

$$\rho_{xx} = \frac{(1+\alpha^2)}{(1+\alpha^2)}\rho_{xx}(0) = \frac{1}{\sigma_0} \neq f(B)$$

(3.) $B \to \infty$ $\mu_1 \neq \mu_2$ $\alpha_i \gg 1$

$$\rho_{xx} = \frac{\cancel{B^2}}{\cancel{B^2}}\,\frac{\sigma_{01}\mu_2^2 + \sigma_{02}\mu_1^2}{\sigma_{01}^2\mu_2^2 + \dots} \neq f(B)$$

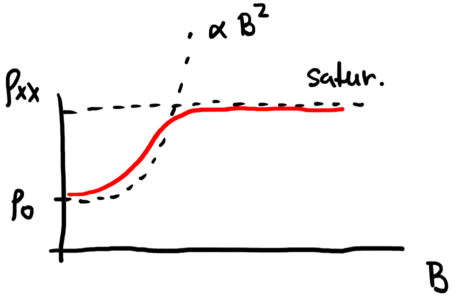
$$\neq \frac{1}{\sigma_0} = \frac{1}{\sigma_{01}+\sigma_{02}}$$

DETEKCE B – MAGNETOREZISTENCE

① Taylorův rozvoj: $f(x)|_{x\sim 0} \sim f(0) + f'(0)x$ $\quad x \to B^2$ $\quad \rho_0 = \frac{1}{\sigma_0}$

Matlab: $\rho_{xx} \sim \rho_0 \left[1 + \frac{\sigma_{01}\sigma_{02}\,(\mu_1-\mu_2)^2}{(\sigma_{01}+\sigma_{02})^2} B^2 \right]$ $\quad \mu_1 \neq \mu_2$

kvadratická MR i v Hallbar geom. pro malé B

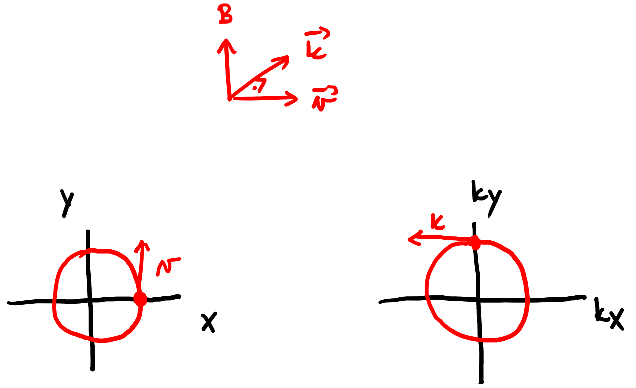


• fyzikální význam saturace?

$F = \hbar\dot{k} = m\dot{v} = -e(\vec{E} + \vec{v}\times\vec{B})$

"$\dot{k} \propto \dot{r} \times B$" $\quad \int dt$

"$k \propto r \times B$"

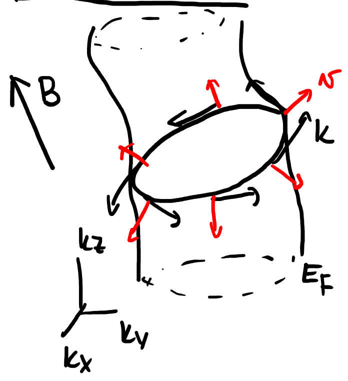


→ cyklotron. orb. v r-prostor ↔ orbita v k-prost.

$\varepsilon = \frac{\hbar^2 k^2}{2m}$ $\quad \varepsilon_{konst} = $ sféra $\quad \perp B$

→ pro nás: $\mu B \gg 1$, mnoho orbit v r-prostoru, než se rozptýlí ⇒ mnoho orbit v k-prostoru

UZAVŘENÉ ORBITY:



→ E_x přidá rychlost v_x, ale orbitování na místě, žádný dopředný pohyb až do rozptylu

$\langle v \rangle_t = 0$. Proto také $\underbrace{\sigma_{xx} \propto B^{-2}}$ $\sigma_{yy} \propto B^{-2}$ klesají k 0 pro velké B

→ $\sigma_{xx} \propto B^{-2}$ ⊕ jsme v Hallbar geom ⇒ $\rho_{xx} = \frac{a}{a^2 + b^2}$

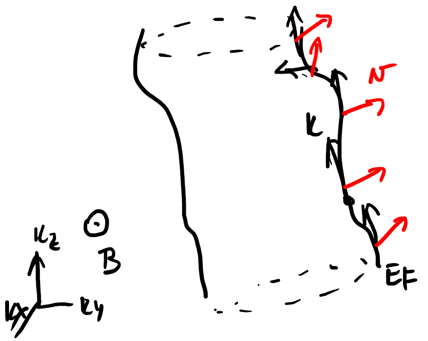
$a = \sigma_{01}\alpha_1^{-2} + \sigma_{02}\alpha_2^{-2}$

$b = \sigma_{01}\alpha_1^{-1} + \sigma_{02}\alpha_2^{-1}$

vytknout B & $\alpha = \mu B$

$$\rho_{xx} = \frac{B^{-2}}{B^{-2}} \; \frac{k_1 \cancel{f(B)}}{\underbrace{k_2 B^{-2}}_{\to 0} + k_3} \to \text{konst.}$$

OTEVŘENÉ ORBITY:



→ neuzavř. orbita se nepodílí na snížení σ v $\hat{y}$

$v_y \neq f(B) \to \sigma_{yy} = c$ (ne $\propto B^{-2}$)

σ_{yy}

$\overline{\overline{\sigma}}_1 = \sigma_{01}\begin{pmatrix} \alpha_1^{-2} & \alpha_1^{-1} \\ -\alpha_1^{-1} & c \end{pmatrix}$

$\overline{\overline{\sigma}} = \overline{\overline{\sigma}}_1 + \overline{\overline{\sigma}}_2$

$\begin{bmatrix} a & b \\ -b & c \end{bmatrix}^{-1} = \frac{1}{ac + b^2}\begin{bmatrix} c & -b \\ b & a \end{bmatrix}$

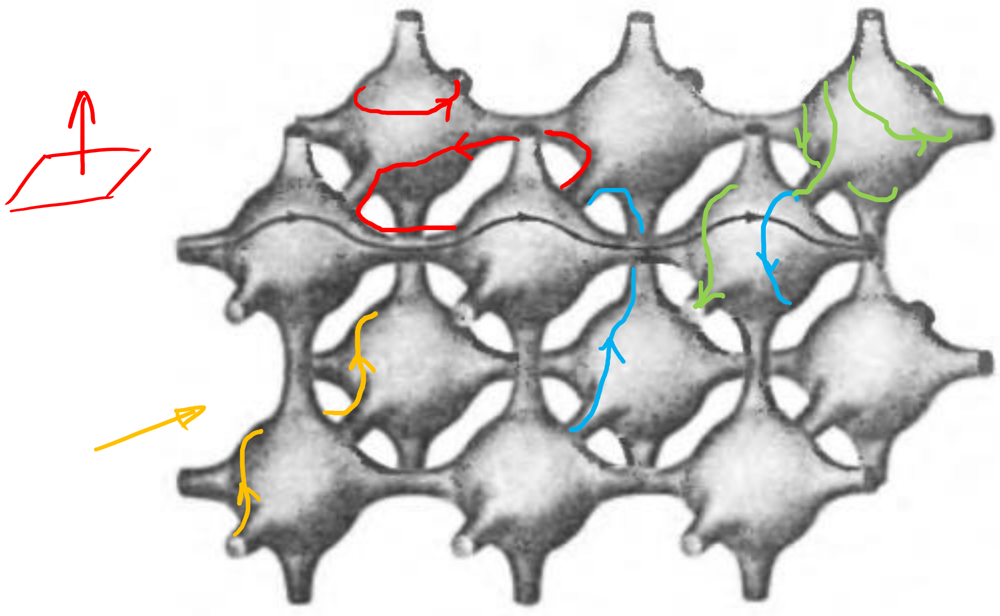
$$\rho_{xx} = \frac{\overset{\text{konst. v B}}{c}}{\underset{\propto B^{-2}}{a}c + \underset{\propto B^{-2}}{b^2}} \doteq \text{kons. } B^2$$

→ žádná saturace

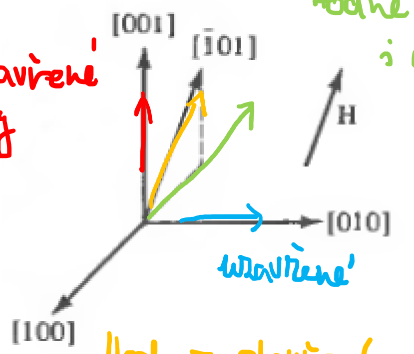
DETEKCE B – MAGNETOREZISTENCE

Co

FERMIHO PLOCHA



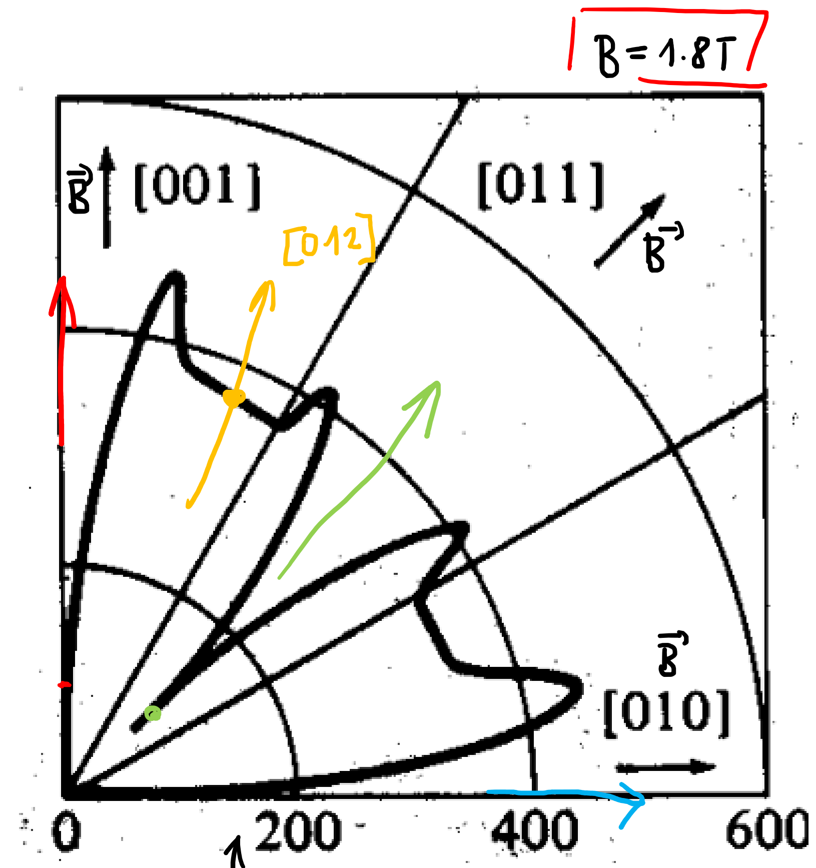
pouze uzavřené orbity



Hodně uzavřených, ale i otevřené

uzavřené

Hodně otevřené

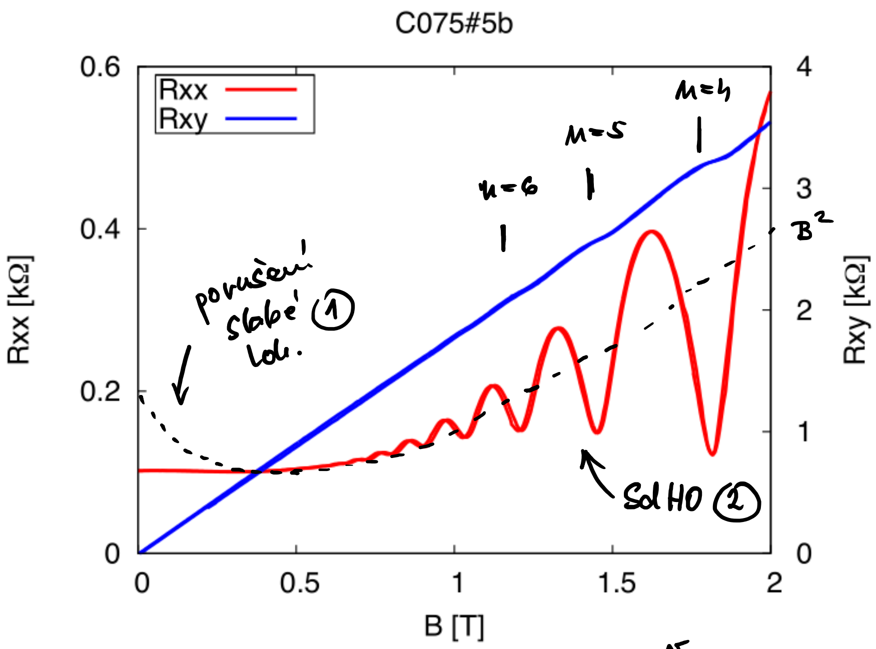


$\odot j$ $\quad \Delta\rho = [\rho(B) - \rho(0)]/\rho(0)$

Ashcroft, Mermin

J.R. Klauder and J.E. Kunzler,´The Fermi Surface, Wiley, New York, 1960.

DETEKCE B – MAGNETOREZISTENCE KVANTOVÁ



(1) WL: $e^{i\vec{k}\vec{r}}$ (ϕ) $\quad \hbar\vec{k} = \vec{p} \to \vec{p} - e\vec{A}$

$$\phi = \int \left(\vec{k} - \frac{e}{\hbar}A\right) d\vec{l}$$

(2) SdHO:

$$\phi = 2\pi(n + 1/2) = \int \vec{k}\cdot d\vec{r} - \frac{e}{\hbar}\oint \vec{A}\, d\vec{r}$$

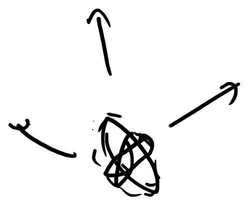
$$\frac{1}{\hbar}\oint m\vec{v}\cdot d\vec{r} = \frac{R_c}{\hbar} eB \underbrace{\oint \hat{n}\cdot d\vec{r}}_{2\pi R_c} = \frac{2}{\hbar}\underbrace{\pi R_c^2}_{S} eB$$

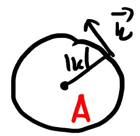
$$-\frac{e}{\hbar}\int_S \overbrace{\nabla\times\vec{A}}^{B}\, d\vec{r} = -\frac{e}{\hbar} SB$$

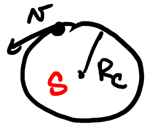
$$\cancel{2\pi}\,\frac{SB}{\hbar/e} = \frac{\phi}{\phi_0} = \cancel{2\pi}(n + 1/2)$$

$$\boxed{\frac{1}{B} = \frac{2\pi e}{\hbar A}(n + 1/2)}$$

$n = 1, 2, 3 \ldots$







$$k = \frac{vm}{\hbar} \qquad R_c = \frac{v}{eB}m$$

$$A = \pi k^2 = \underbrace{\pi R_c^2}_{S}\left(\frac{\hbar}{eB}\right)^2$$

nezávislé na B

závisí na B

$$\boxed{\Delta\left(\frac{1}{B}\right) = \frac{1}{B_n} - \frac{1}{B_{n+1}} = \frac{2\pi e}{\hbar A}}$$

plocha řezu E_F

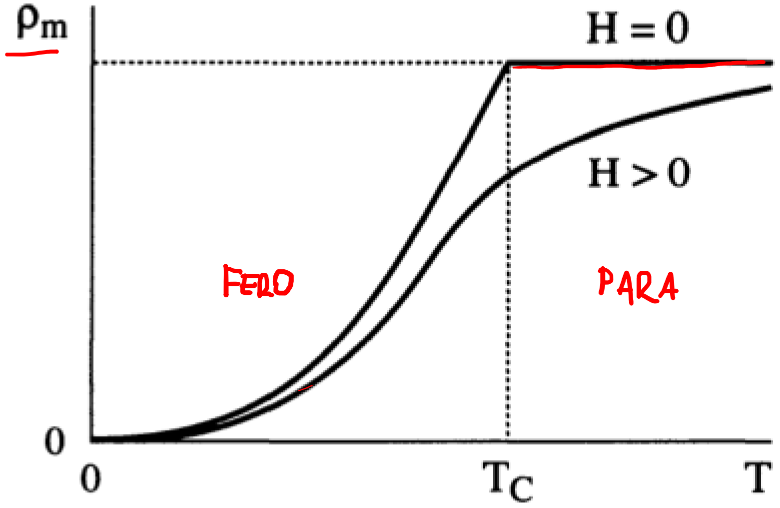
DETEKCE B a M – MAGNETOREZISTENCE V MAGN. LÁTKÁCH

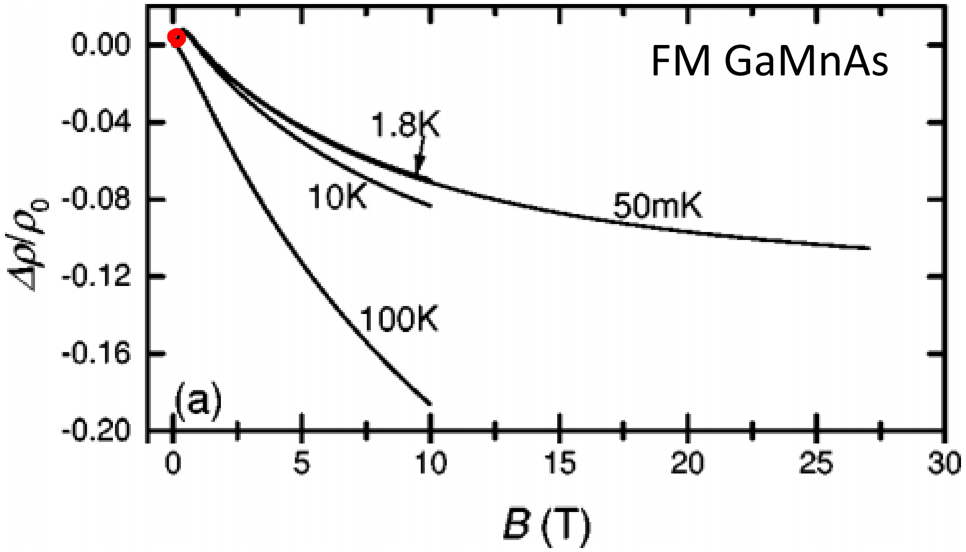
$$\sigma = ne\mu = ne^2 \frac{\tau}{m^*}$$ ← rozptyl. času ↔ neuspořádanost v syst.

$$\rho(B,T) \cong \rho_0 - \langle S_i, S_j \rangle_{B,T} \sim M^2(T=0) - M_s^2(T)$$

$T \nearrow$ větší neuspoř. $\nearrow \rho$

$B \nearrow$ menší neusp. $\searrow \rho$

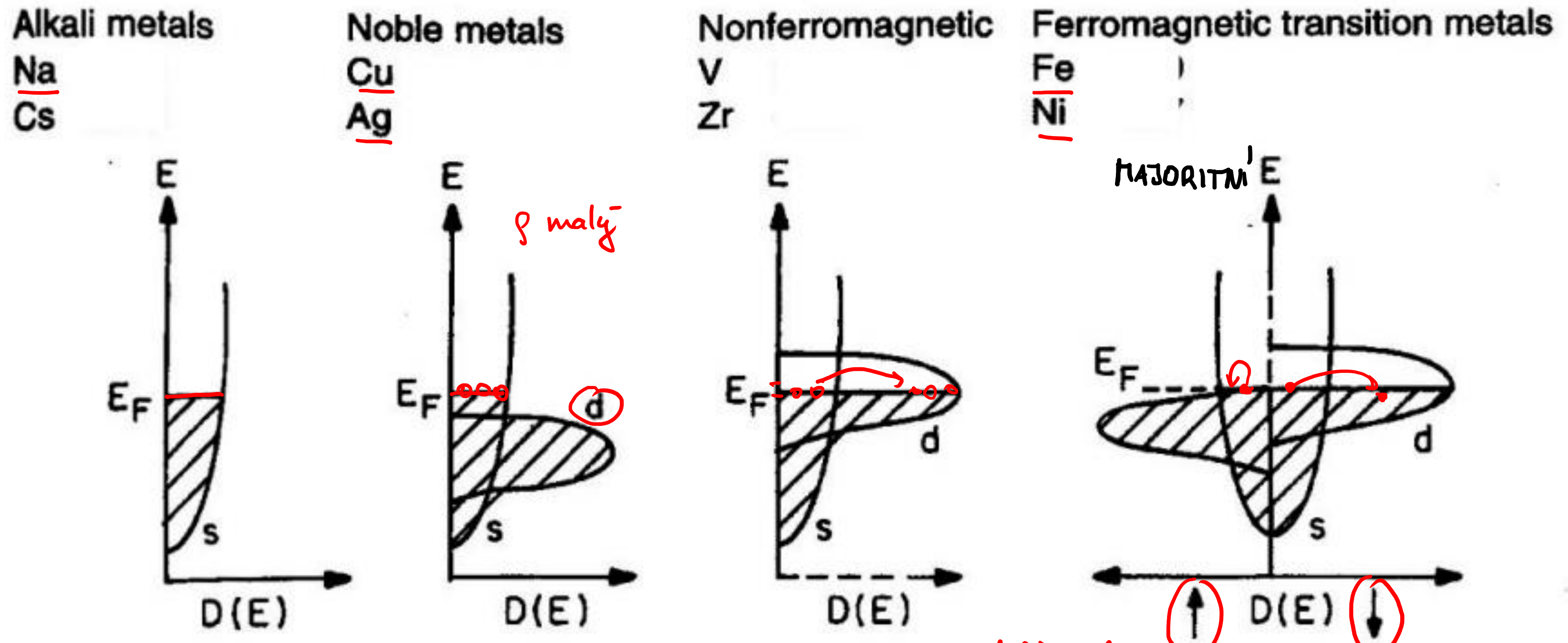




H. Ohno et al., J. Appl. Phys. 85, 4277 (1999).

DETEKCE B a M – MAGNETOREZISTENCE V MAGN. LÁTKÁCH

ODBOČKA: Vodivost v kovech $\boxed{\sigma = ne\mu}$ $v = E\mu$



Mottův two-current model:

s stavy: $n\downarrow$ $\mu\uparrow$ ($m \propto [\partial_k E(k)]^{-1}$) dobře vodí

d stavy: $n\uparrow$ $\mu\downarrow$

dobře se do nich rozptyluje

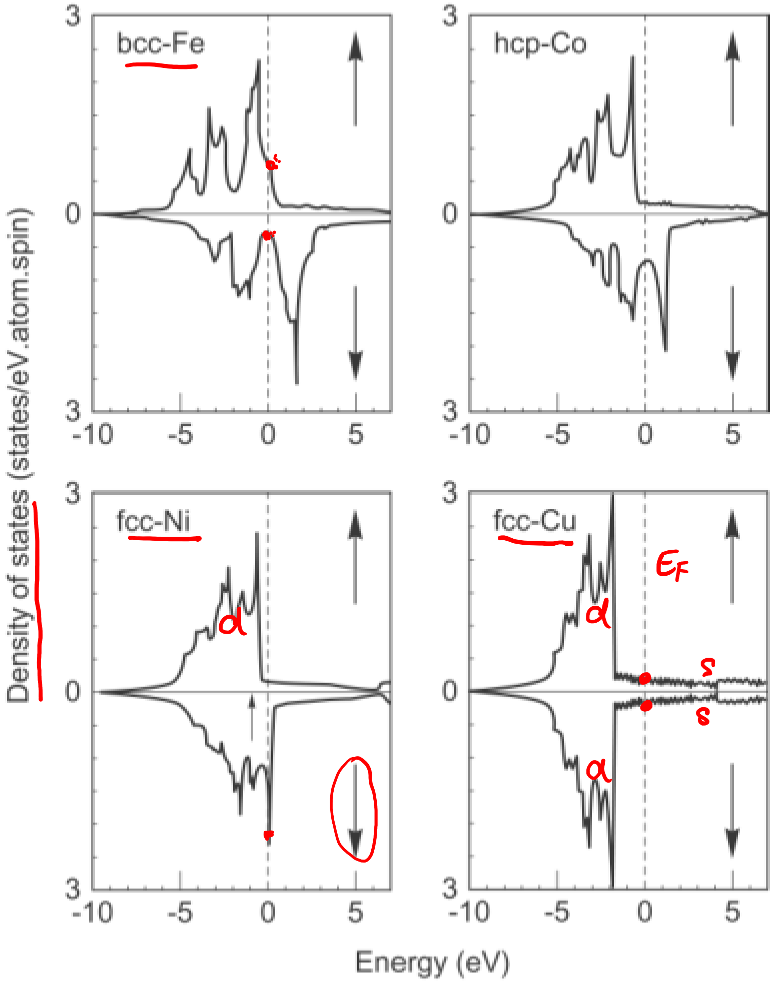
$$\sigma = \underset{\text{velká}}{\sigma_\uparrow} + \underset{\text{malá}}{\sigma_\downarrow} \rightarrow \rho = \frac{\rho_\uparrow \rho_\downarrow}{\rho_\uparrow + \rho_\downarrow}$$

DETEKCE B a M – MAGNETOREZISTENCE V MAGN. LÁTKÁCH

$\alpha = \frac{\sigma\uparrow}{\sigma\downarrow}$

Table 5.11. Room-temperature resistivity of metals (10^{-8} Ω m)

Metal	Orbitals	Magnetization	$\varrho\uparrow$	$\varrho\downarrow$	ϱ	α
Cu	*s*-band	Paramagnet	4	4	2	1
Ni	*d*-band	Strong ferromagnet	13	65	11	5
Co	*d*-band	Strong ferromagnet	8	120	7	15
Fe	*d*-band	Weak ferromagnet	32	28	15	0.9

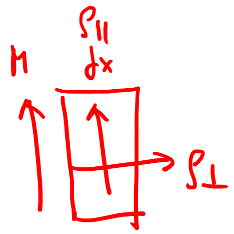


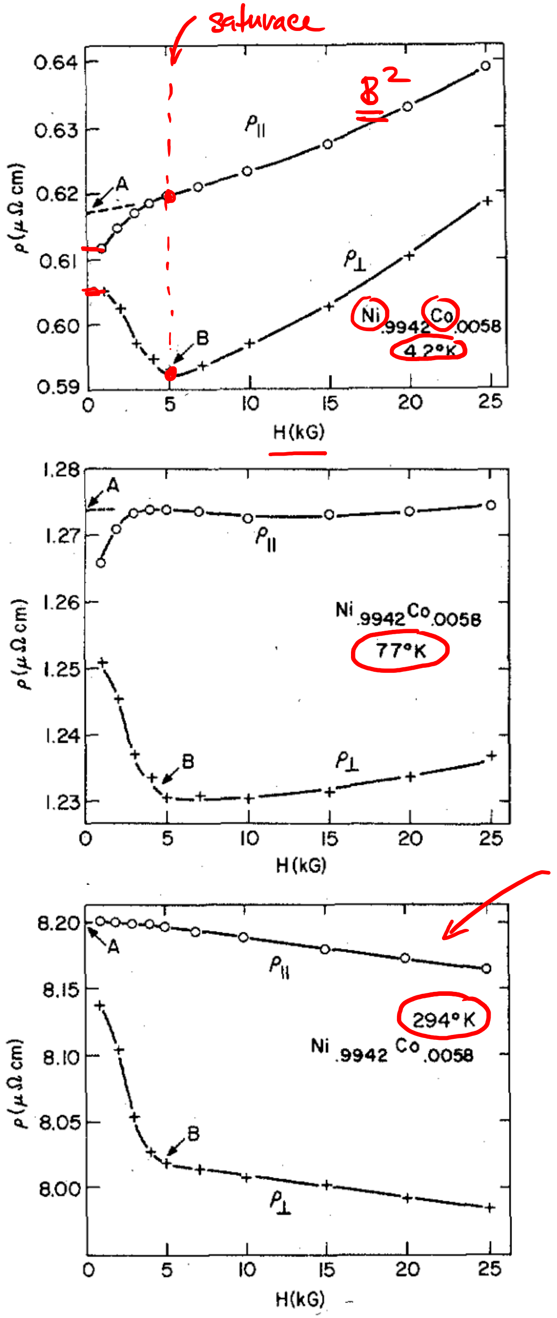
DOBŘE VYSVĚTLUJE ρ :)

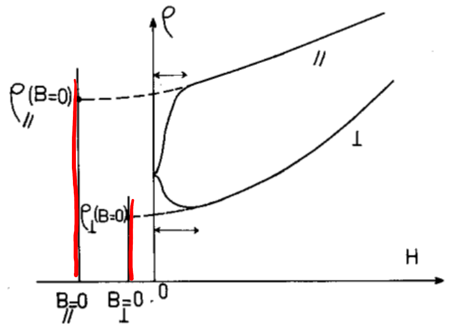
ALE JE IZOTROPNÍ :(

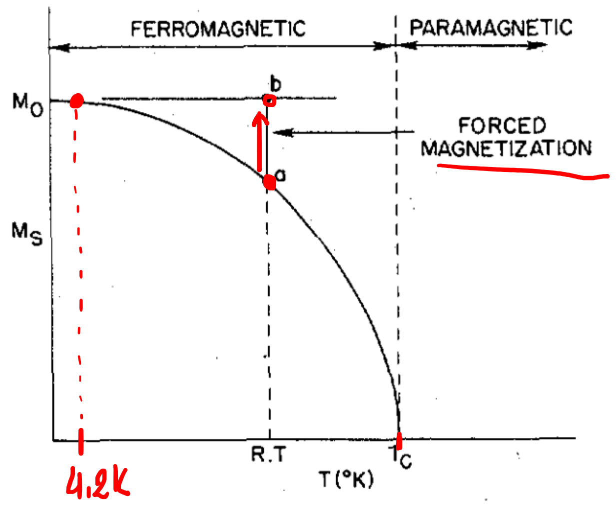
→ EXISTUJE ANIZOTROPNÍ MR

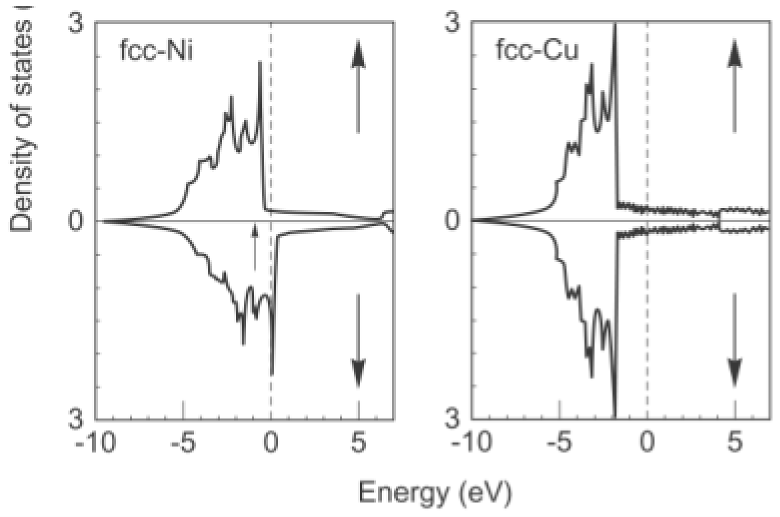
DETEKCE B a M – MAGNETOREZISTENCE V MAGN. LÁTKÁCH









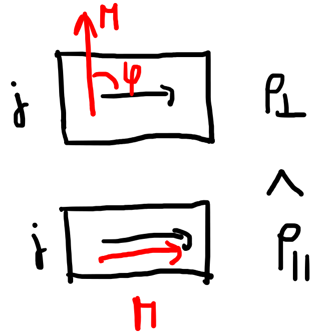


T. McGuire and R. Potter, IEEE Trans. Magn. **11**, 1018 (1975).

DETEKCE B a M – MAGNETOREZISTENCE V MAGN. LÁTKÁCH

"AMR" "MLD"

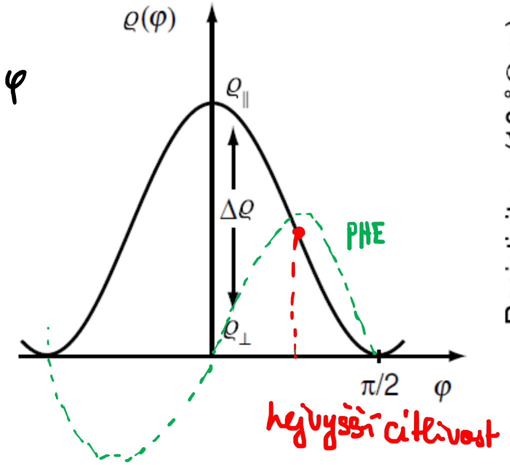
ANIZOTROPNÍ MR: $\propto M^2$

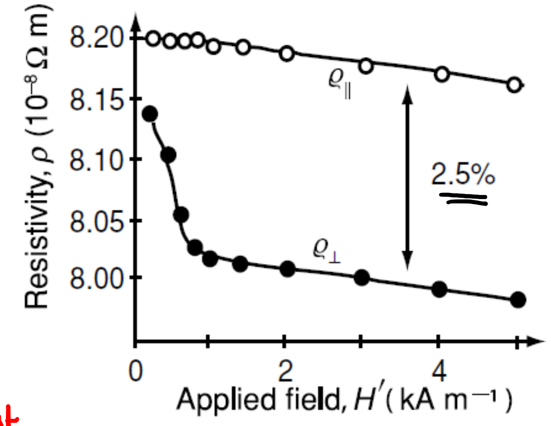


$$\rho(\varphi) = \rho_\perp + \Delta\rho \cos^2\varphi$$

$\uparrow$

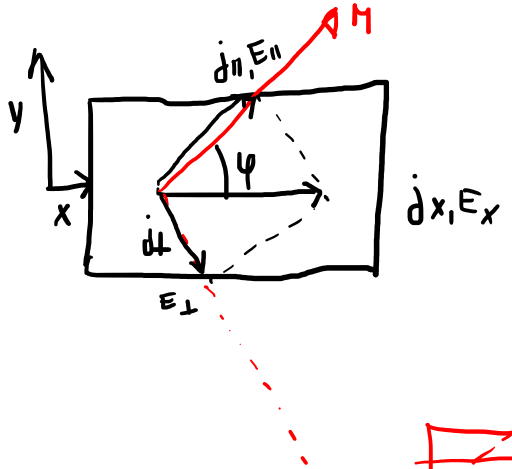
$\rho_\parallel - \rho_\perp$

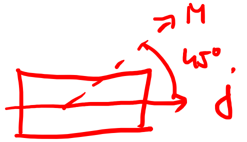




~~AHE~~

PLANAR HALL EFFECT: $\propto M^2$





$$E_\parallel = \rho_\parallel j_x \cos\varphi$$
$$E_\perp = \rho_\perp j_x \sin\varphi$$

$\Rightarrow$

$$\underline{\underline{E_y}} = E_\parallel \sin\varphi + E_\perp \cos\varphi = \rho_\parallel j_x \cos\varphi \sin\varphi + \rho_\perp j_x \sin\varphi \cos\varphi =$$

$$= \Delta\rho \tfrac{1}{2} \sin 2\varphi \, j_x \longleftarrow \text{PLANAR HE}$$

posunuté o π/4 oproti AMR

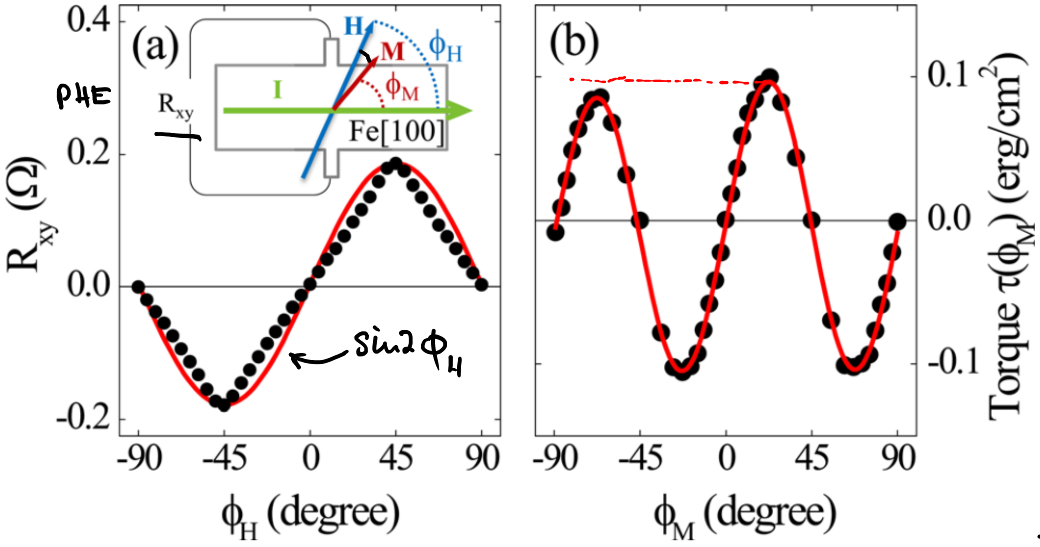
AMR

kvadrat ~ M 2φ-period.

$$\underline{\underline{E_x}} = E_\parallel \cos\varphi + E_\perp \sin\varphi = \rho_\parallel j_x \cos^2\varphi - \rho_\perp j_x \cos^2\varphi =$$

$$= (\rho_\perp + \Delta\rho \cos^2\varphi) j_x$$

AMR



URČENÍ MG. ANISOTROPIÍ

$$R_{xy} \overset{!}{=} \Delta R \sin 2\phi_M$$

$$= \underbrace{\Delta R \sin 2\phi_H}$$

$$\phi_M \neq \phi_H$$

$$\Rightarrow \phi_M(\phi_H)$$

známe

známe

$$E = -M_s d H \cos(\phi_H - \phi_M) + K_U \sin^2\phi_M + K_4 \cos^2\phi_M \sin^2\phi_M$$

$$\frac{\partial E}{\partial \phi_M} = 0$$

$$M_s d H \sin(\phi_H - \phi_M) = K_U \sin 2\phi_M + \frac{1}{2} K_4 \sin 4\phi_M$$

W. Cao, APL 98, 262506 (2011)

DETEKCE B a M – MAGNETOREZISTENCE V MAGN. LÁTKÁCH

PŮVOD ? SOI (ale nejasný)

SMITŮV MODEL:

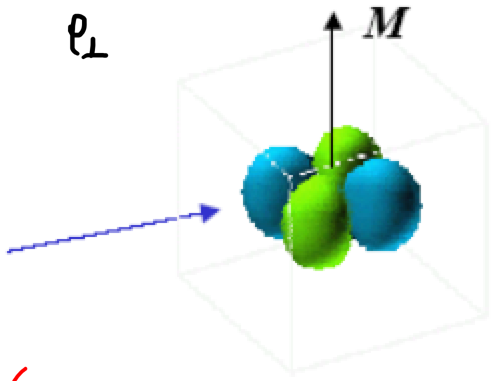
$H_{SO} = \lambda \vec{S}\cdot\vec{L}$

SPIN (∥ magnetizace)

ORBITAL

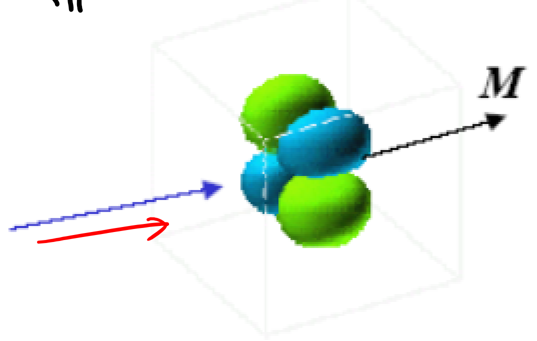
$\tau_\perp$

$\rho_\perp$



$\tau_\parallel$

$\rho_\parallel$



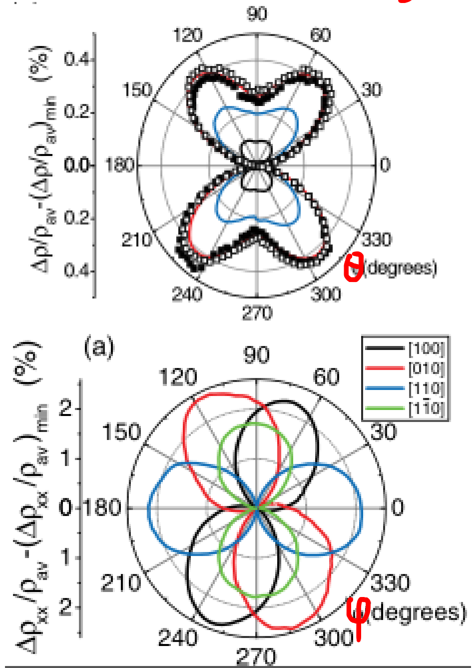
=> $\boxed{\psi_d}$ snížená symetrie => τ_{s-d} se změní a je neizotropní => j_x a j_y nesymetrii zobrazí

=> d-orbitaly jsou také nacouplované na krystalické pole => magnetokrystal. anizotropie

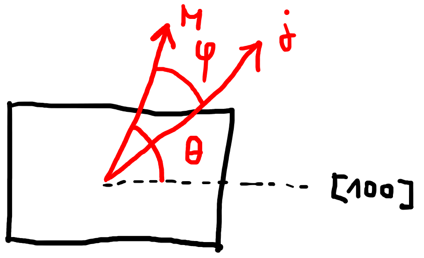
↳ ⊕ změna τ_{s-d}

GaMnAs

T. McGuire and R. Potter, *Anisotropic Magnetoresistance in Ferromagnetic 3d Alloys*, IEEE Trans. Magn. **11**, 1018 (1975).



RŮZNÉ AMR:



NON-CRYSTALLINE CRYSTALLINE CROSSED TERM

$$\rho_{xx}/\rho_{av} = C_1\cos 2\varphi + \underbrace{C_u\cos 2\theta + C_c\cos 4\theta}_{} + \underbrace{C_{1,c}\cos(4\theta - 2\varphi)}_{}$$

$$\rho_{xy}/\rho_{av} = C_1\sin 2\varphi + C_{1,c}\cos(4\theta - 2\varphi)$$

Rushforth et al., PRL 99, 147207 (2007).

DETEKCE B a M – HALLOVY JEVY

ORDINARY HALL EFFECT: (1 částice)

$$\bar{\bar{\rho}} = \rho_0 \begin{pmatrix} 1 & -\alpha \\ \alpha & 1 \end{pmatrix} \qquad \alpha = \mu B$$

$$\rho_{xy} = \frac{\mu B}{ne\mu} = \frac{1}{ne} B$$

R_H měření n

detekce B

Hall 1879 (nemag.)

Hall 1881 (Fe, R_H 10x větší...)

$$\rho_{xy} = \mu_0 (R_H H + R_S M_S)$$

$$R_S(\rho_{xx}) \propto \rho_{xx}^{1.9}$$

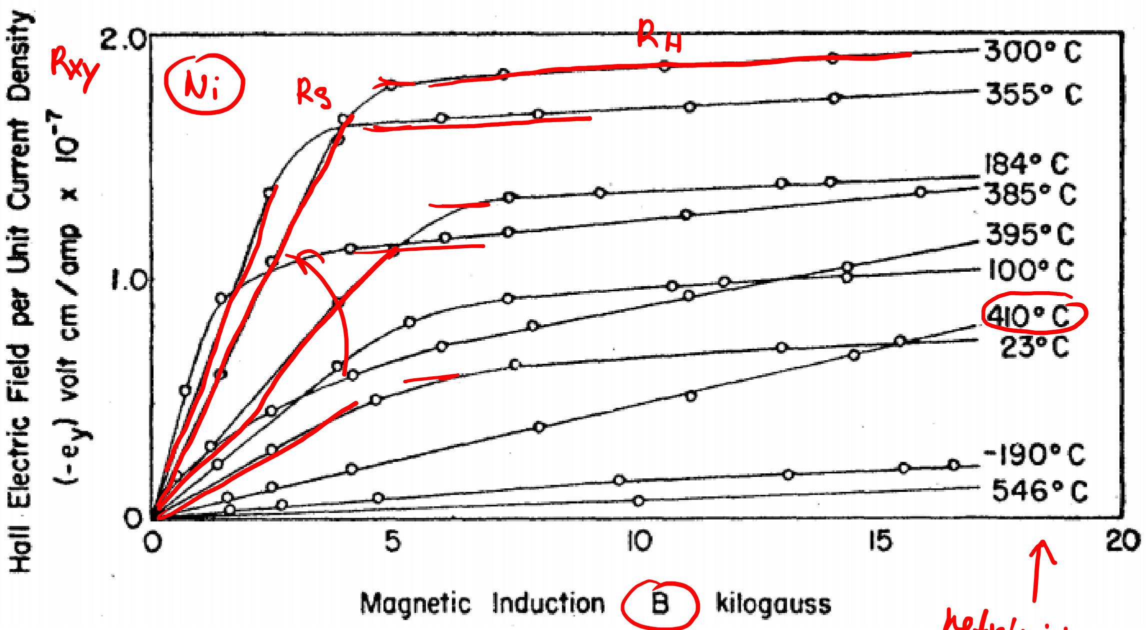
senzory

skvělé sensory (jsou všude)

"queen of solid-state transport experiments"

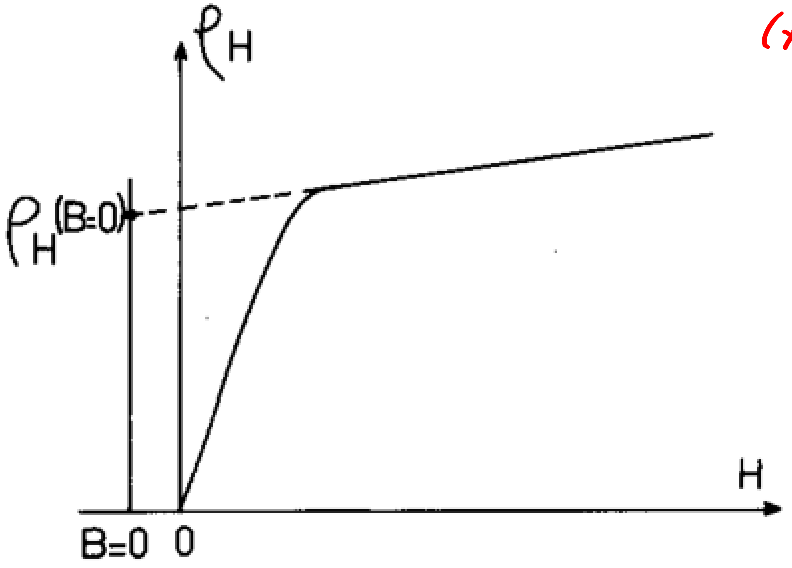
velké trápení

(až do 50. let 20. stol.)



Ni $T_c \sim 353°C$

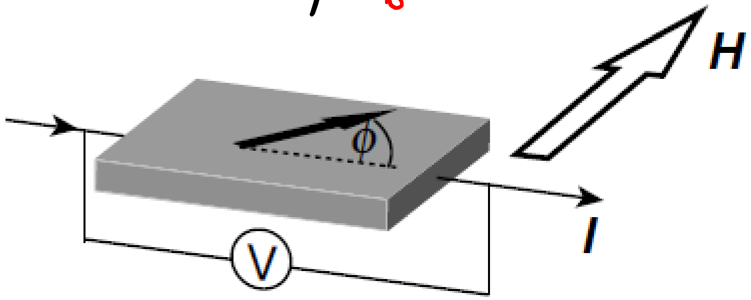
netriviální vývoj R_S s T (tedy ρ_{xx})



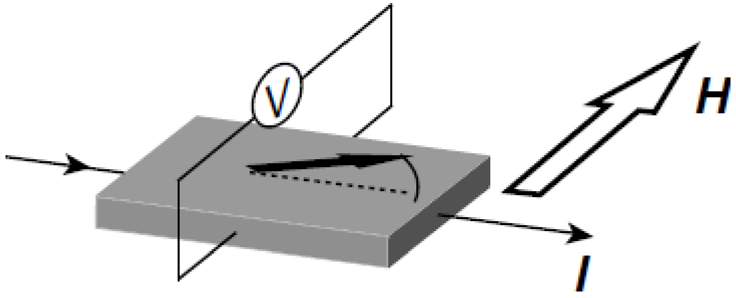
DETEKCE B a M – SENZORY NA BÁZI MAGNETOTRANSPORTU

AMR $\propto M^2$

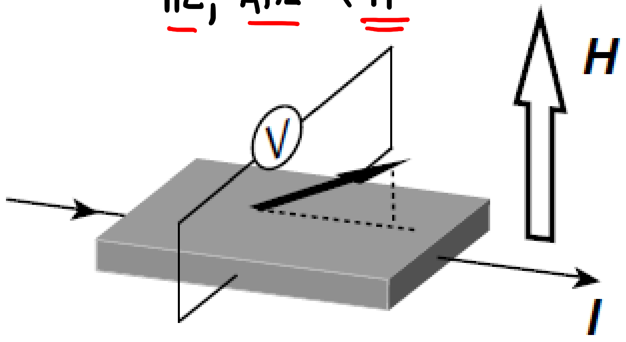
(OMR) $\propto B^2$



PHE $\propto M^2$



HE, AHE $\propto M$

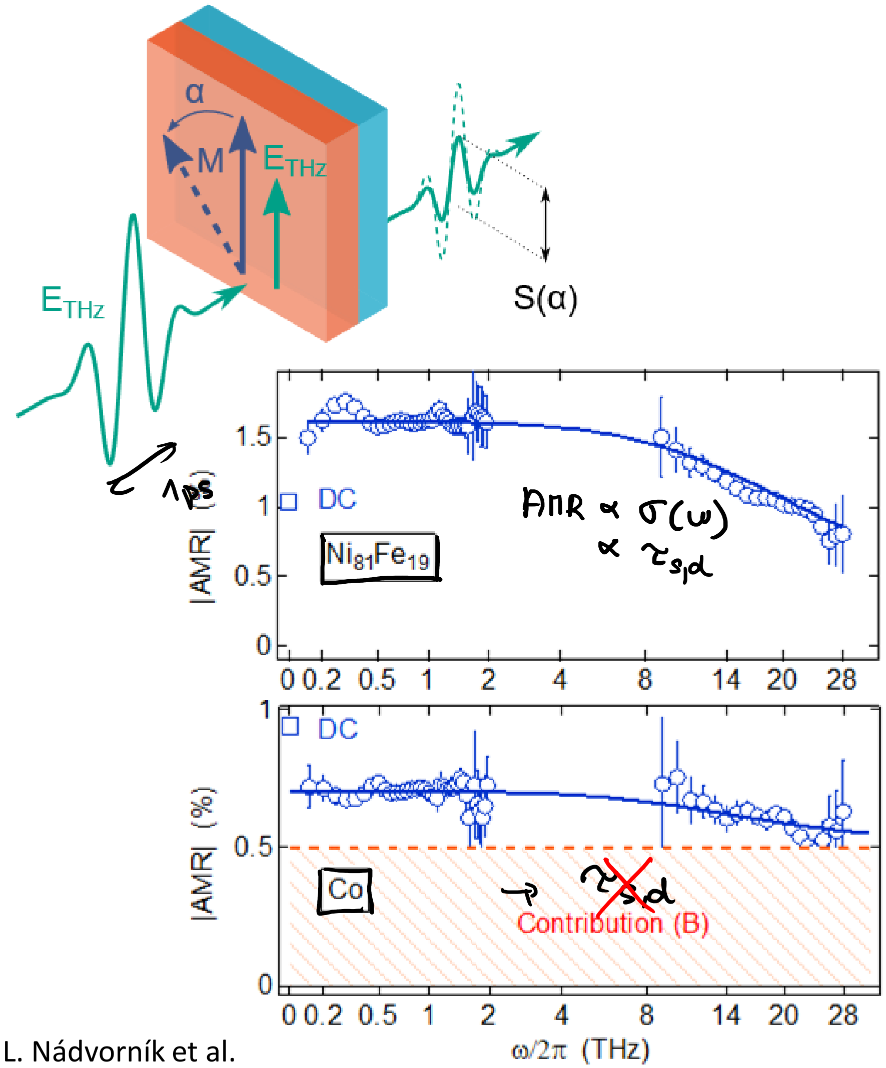


DETEKCE B a M – MAGNETOTRANSPORT NA VYŠŠÍCH FREKVENCÍCH

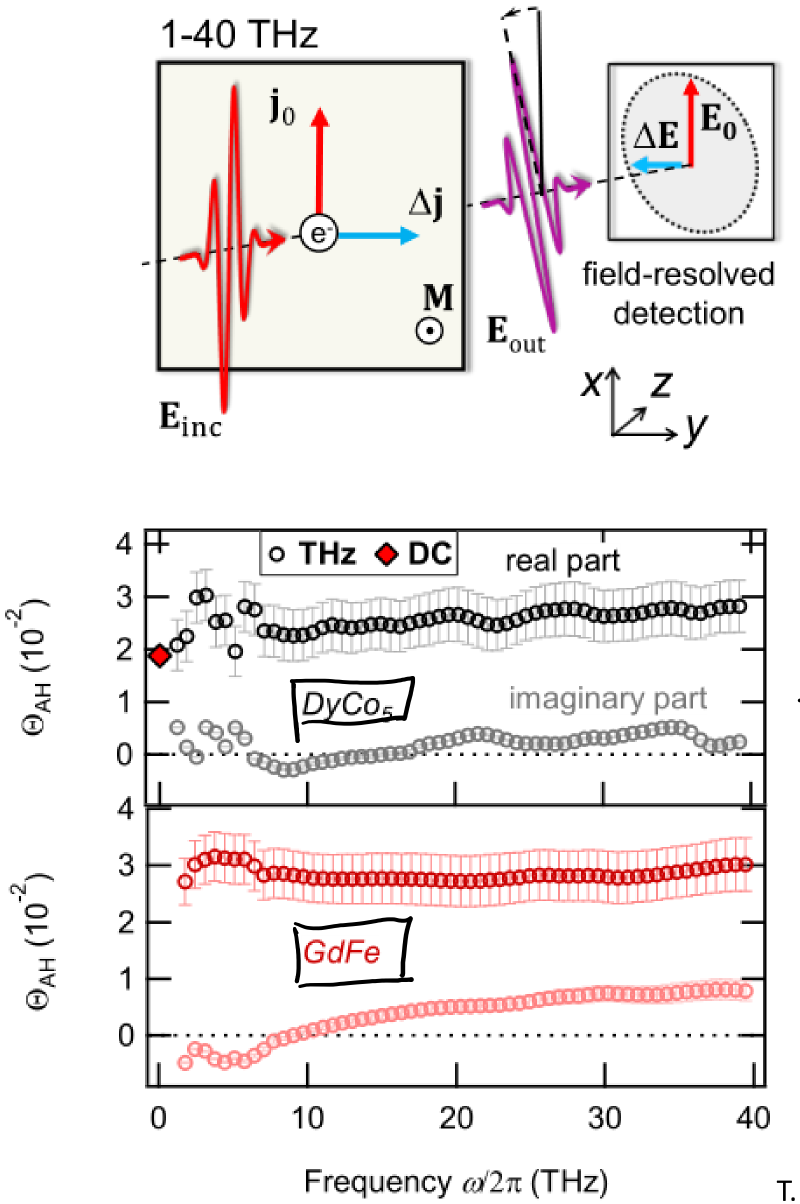
@ AC (GHz) : Magnetoimpedance

@ THz AMR

} stále intraband transport



L. Nádvorník et al.

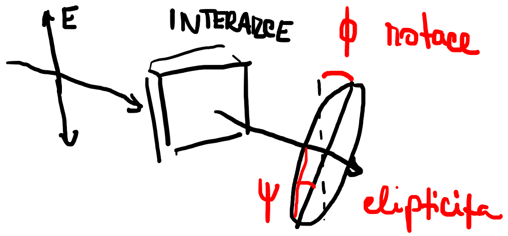


⇒ AHE intrinsic

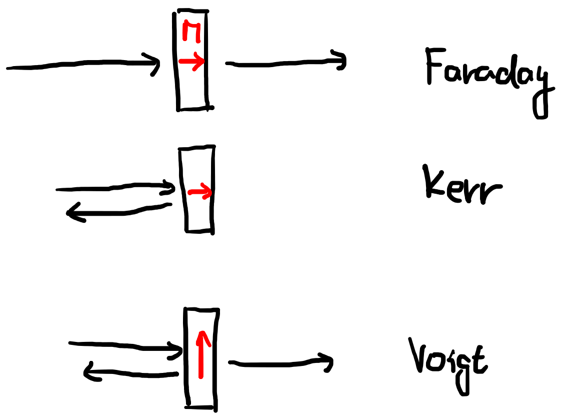
T. Seifert et al.

DETEKCE POVRCHOVÉ MAGNETIZACE – MAGNETOOPTIKA

Magneto-optika :



Geom :



Z Maxwellek : $-\nabla^2 E + \nabla(\nabla \cdot E) = \frac{1}{c^2}\frac{\partial^2 D}{\partial t^2}$ $D = \bar{\bar{\varepsilon}} E$

$E = E_0 e^{ikr - i\omega t}$ $\bar{\bar{\varepsilon}} = \bar{\bar{\varepsilon}}(\omega, M)$

$n^2 E - \vec{n}(\vec{n} \cdot E) = \bar{\bar{\varepsilon}} E$ $\vec{n} = \frac{\omega}{c}\vec{k}$

řešení v závislosti na sym. $\bar{\bar{\varepsilon}}$ → vlastní polarizační módy s vlastními $n_\pm = n'_\pm + i n''_\pm$

pro $n'_+ \neq n'_-$ BIREFRINGENCE (CIRCULAR OR LINEAR)

$n''_+ \neq n''_-$ DICHROISMUS

MCB : Faraday or Polar kerr

MCD

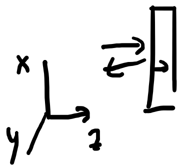
MLB Voigt or Cotton-Mouton

MLD

DETEKCE POVRCHOVÉ MAGNETIZACE – MAGNETOOPTIKA

Jednoduchý příklad: $\boxed{\text{P-MOKE:}}$

$\vec k \cdot \vec E = 0$



$$n^2\vec E - \vec n(\vec n\cdot\vec E) = \bar{\bar\varepsilon}\,\vec E$$

$$\boxed{\begin{aligned}(n^2-\varepsilon_{xx})E_x - \varepsilon_{xy}E_y &= 0\\ (n^2-\varepsilon_{xx})E_y + \varepsilon_{xy}E_x &= 0\end{aligned}}$$

řeš. $n_\pm^2 = \varepsilon_{xx} \pm i\varepsilon_{xy}$

(+) $+i\varepsilon_{xy}E_x - \varepsilon_{xy}E_y = 0 \quad / \frac{1}{\varepsilon_{xy}}$

$+i\varepsilon_{xy}E_y + \varepsilon_{xy}E_x = 0$

$$\boxed{\begin{aligned}iE_x &= E_y\\ iE_y &= -E_x\end{aligned}} \qquad i = e^{i\pi/2}$$

E_x a E_y jsou posunuté o $\pi/2$ → kruh. pol.

dále doplněním ověřeno, že $E_y = E_y$ → je řešení

→ Vlastní módy: $E_\pm \propto (E_x \pm iE_y)\,e^{-i\omega t}\,e^{i\omega n_\pm z/c}$ $\qquad k = \frac{\omega n}{c}$

fáze (i lin. pol. se dá rozložit do LCP a RCP)

rozdíl n pro módy → rotace a elipticita

$$\bar{\bar\varepsilon} = \begin{pmatrix}\varepsilon_{xx} & \varepsilon_{xy} & 0\\ -\varepsilon_{xy} & \varepsilon_{yy} & 0\\ 0 & 0 & \varepsilon_{zz}\end{pmatrix} \qquad \varepsilon_{yy} = \varepsilon_{xx}$$

$\hat\varepsilon = \hat\varepsilon_0 + i\frac{\hat\sigma}{\omega}$ ← kompl. vodivost

ve vakuu

ε_{xy} jsou analogie k AHE

pozn.

$n_\pm^2 = \varepsilon_{xx} \underbrace{\pm i\varepsilon_{xy}}_{\propto \pm\sigma_{xy}}$ ← $\varepsilon_{xy} = \varepsilon_{0,xy} + i\frac{\sigma_{xy}}{\omega}$ ← HE, AHE

→ pro reálné σ_{xy} → $n_+ \neq n_-$ → rotace.

Voigt coeff.

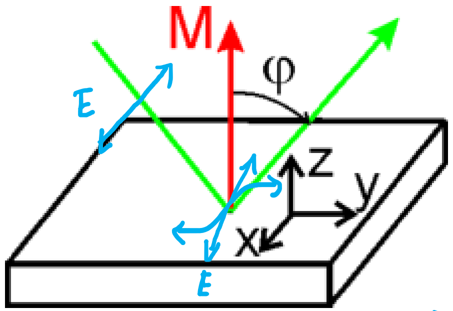
$\varepsilon_{xy} \equiv iQm_z$ ← přímo m

$j_H = j_x \times B_M$

$$r^\pm = \frac{n_\pm - 1}{n_\pm + 1}$$

Polar MOKE

$M \perp$ sample surface



příspěvek od Ey do Ex

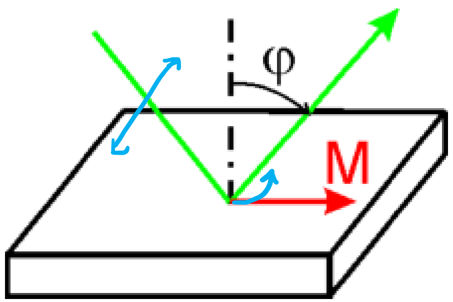
$E_y \to E_x$

$E_x \to E_y$

$$\begin{bmatrix} \varepsilon_0 & -\varepsilon_1 m_z & 0 \\ \varepsilon_1 m_z & \varepsilon_0 & 0 \\ 0 & 0 & \varepsilon_0 \end{bmatrix}$$

Longitudinal MOKE

$M \parallel$ plane of incidence



musí tu být komp. v z

$E_z \to E_x$

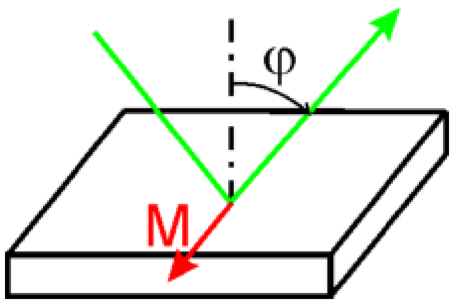
$$\begin{bmatrix} \varepsilon_0 & 0 & \varepsilon_1 m_y \\ 0 & \varepsilon_0 & 0 \\ -\varepsilon_1 m_y & 0 & \varepsilon_0 \end{bmatrix}$$

$E_x \to E_z$

⇒ nekolmý dopad

Transversal MOKE

$M \perp$ plane of incidence



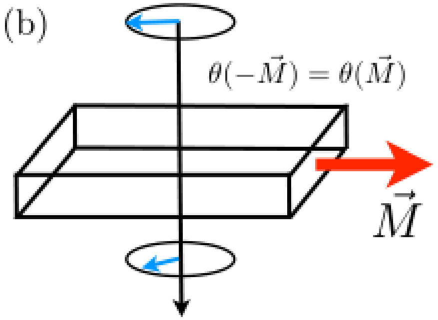
$E_z \to E_y$

$$\begin{bmatrix} \varepsilon_0 & 0 & 0 \\ 0 & \varepsilon_0 & -\varepsilon_1 m_x \\ 0 & \varepsilon_1 m_x & \varepsilon_0 \end{bmatrix}$$

J. Hamrle, slides on MOKE

MLD ($\propto M^2$, AMR)

Stejný postup



pro nekolmý dopad

$\hat{\varepsilon} = \hat{\varepsilon}_0 + i\frac{\hat{\sigma}}{\omega}$

$\sigma_{xx} = (1+(\mu B)^2)^{-1} \sim 1-(\mu B)^2$

$M_\parallel^2 = \varepsilon_{xx}$ $\quad M_\perp^2 = \varepsilon_{zz}\left(1+\left(\frac{\varepsilon_{yz}}{\varepsilon_{zz}}\right)^2\right)$

$$\bar{\bar{\varepsilon}} = \begin{pmatrix} \varepsilon_{xx} & 0 & 0 \\ 0 & \varepsilon_{zz} & \varepsilon_{yz} \\ 0 & -\varepsilon_{yz} & \varepsilon_{zz} \end{pmatrix} \quad \begin{pmatrix} E_x \\ E_y \\ 0 \end{pmatrix}$$

$\propto (B)^2$

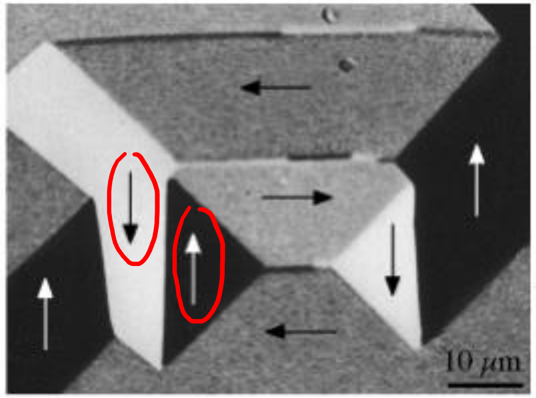
$$\underbrace{n_\parallel - n_\perp}_{\text{"MLB + iMLD"}} \approx \frac{1}{2} n_0 \underbrace{\left(\varepsilon_{xx} - \varepsilon_{zz} - \frac{\varepsilon_{yz}^2}{\varepsilon_{zz}}\right)}_{\propto M_x^2}$$

"$\frac{B^2}{1-B^2} \sim B^2$"

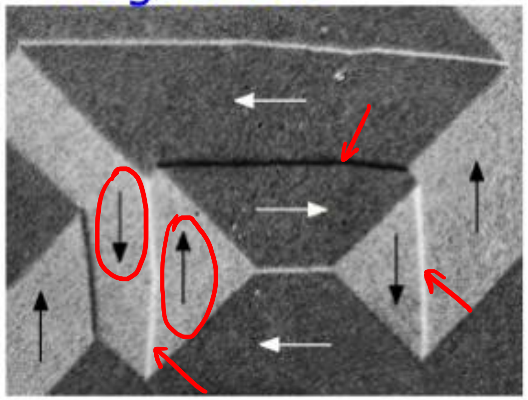
$1-(\mu B)^2$

AMR → MLD

Kerr effect



Voigt effect



N. Tesařová et al. PRB 89, 085203 (2014)