Giant Magneto Impedance and Applications

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a) **Introduction.-** What is Magnetoimpedance?, its origin? *General Definitions*

b) **GMI and Magnetization Process.-** *Materials; Magnetic Anisotropy; "Single Peak" and "Double Peak" behavior, Stress-impedance*

c) **Advances in GMI**: New soft materials; Developping sensors based in GMI

References

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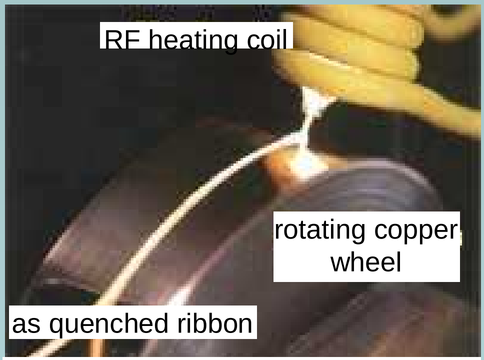
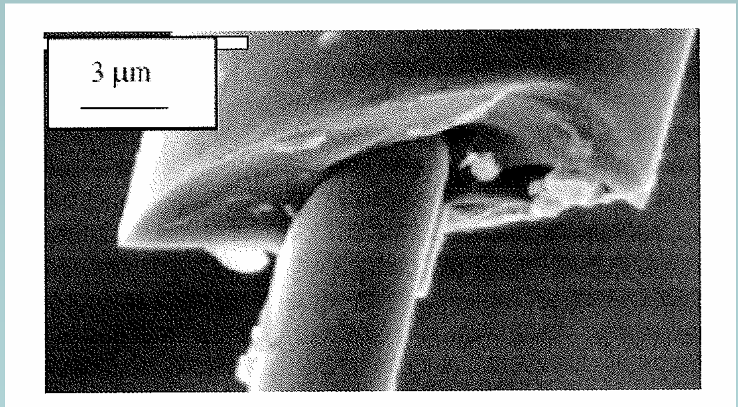
- M. Knobel and K. Pirota, J. Magn. Magn. Mater 242-245 (2002) 33

Soft Materials : ***Ribbons, Wires and Microwires for sensors***



melt spinning Process
≈ 1 mm

Amorphous wire 20-100 μm (Unitika)



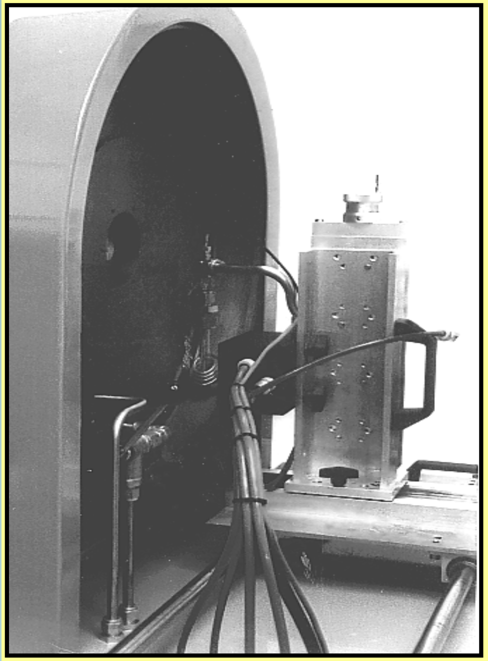
Microwire CoFeNi(SiB) glass coated

Rotating wheel :
Amorphous (Fe or Co based), Nanocristalline

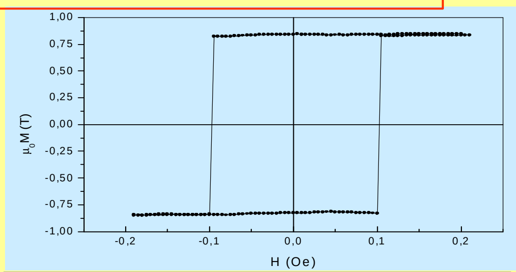
Water Cooled Microwires :
Amorphous (Fe or Co based)

Classical Wire drawing :
Cristalline NiFe mumetal

Soft amorphopus wires obtined by rapid solidification techniques



Amorphous wire obtained by rapid solidification into rotating water: ~ 100 µm diameter



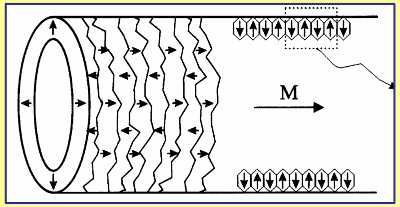
Amorfo wire, FeSiB, 10 cm in length
120 µm diámeter

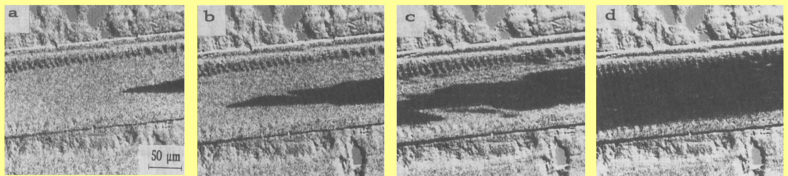
Composition:
FeSiB ($\lambda_s \approx +3x10^{-5}$),
CoFeSiB ($\lambda_s \approx -1x10^{-7}$)
CoSiB ($\lambda_s \approx -2x10^{-6}$)

Glass-coated microwires:
Fabrication by rapid solidificatio (10^6 K/s) Metallic ferromagnetic nucleus (0.6-30 micron diameter)
Pyrex coating(2-20 micron thick)
Continuous Production (400 m/min, 1 kg-40.000 km)

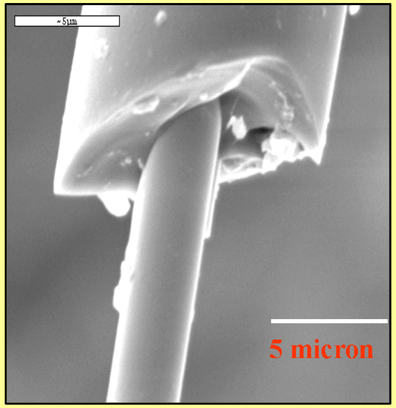
Amorphous wire FeSiB

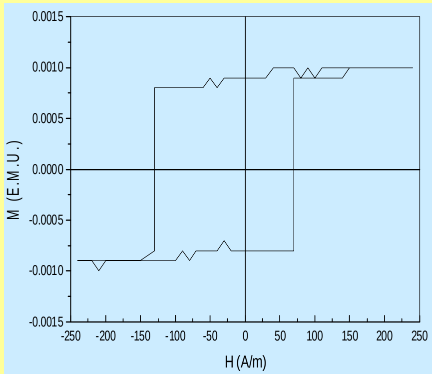
(positive and large magnetostriction)





Magnetization process by a single Barkhausen jump





Glass-coated microwire FeSiBC, coated by Pyrex, 2 mm in length
10 µm diameter

Under which conditions a wire is magnetically ultrasoft?

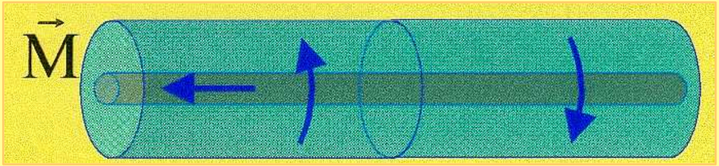
Easy to remagnetize ⟺ *Low magnetic anisotropies*

Minimum Magnetocrystalline anisotropy ⟺ *Amorphous or nanocrystalline structure*

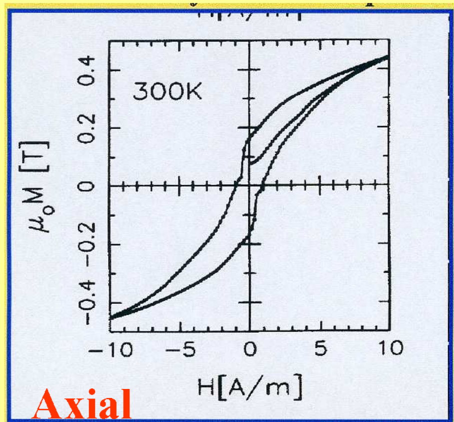
Mínimum Magnetoelastic Anisotropy, $E_{melas} \approx (\lambda_s \sigma)$ ⟺ *Non-magnetostrictive, Mínimum stresses*

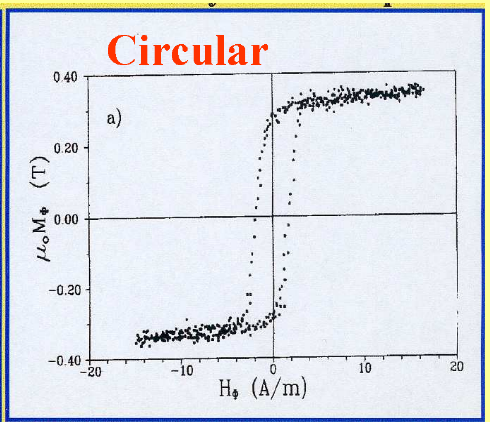
Non-magnetostrictive Amorphous Wire

Alloy Composition: $(Co_{94}Fe_6)_{75}Si_{15}B_{10}$ Magnetostriction: $-1x10^{-7}$



Domain structure

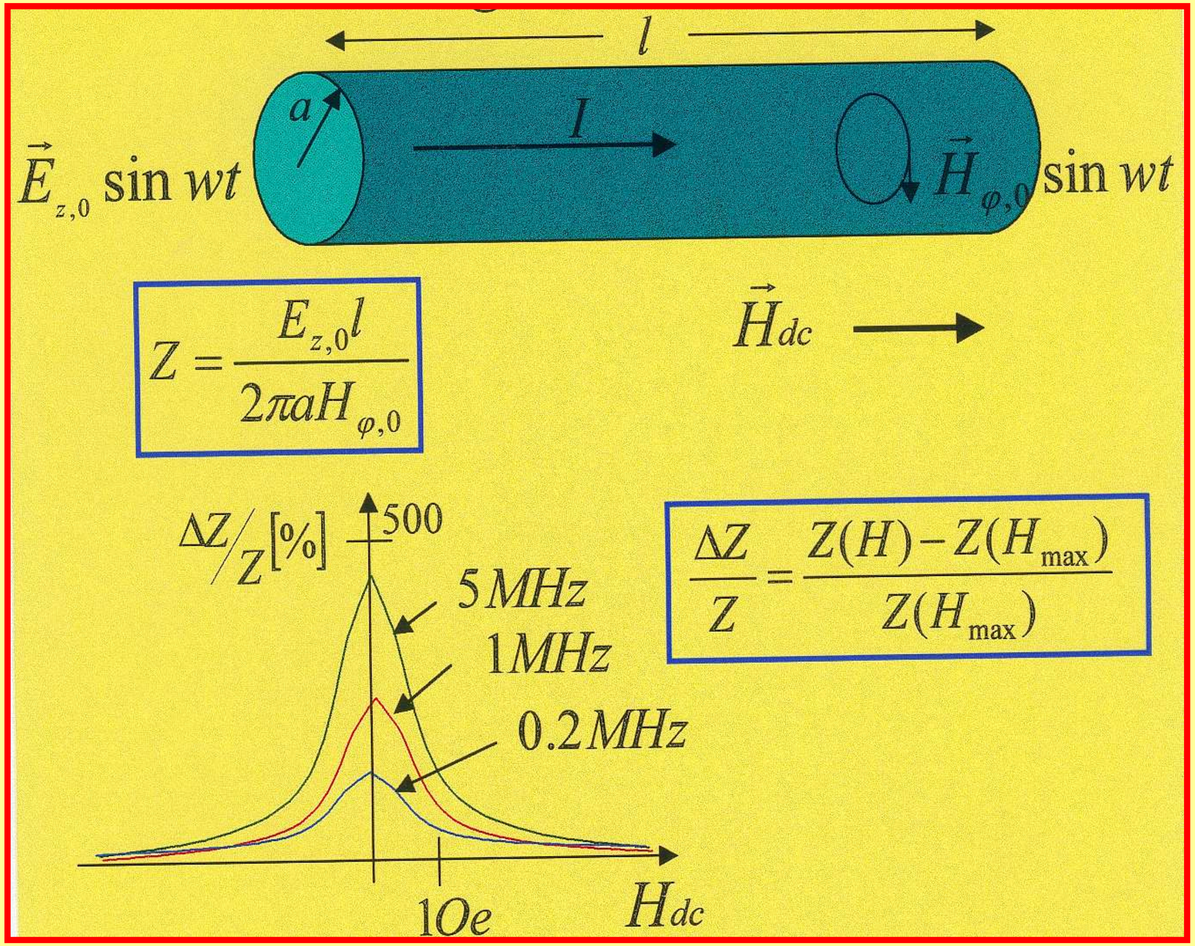




Hysteresis Loops: Coercivity ~ mOe !!

What is Magnetoimpedance?

It consists of the large modificatio of Impedance (real and imaginary components) of a magnetic conductor magnético at the presence of changing static magnetic field

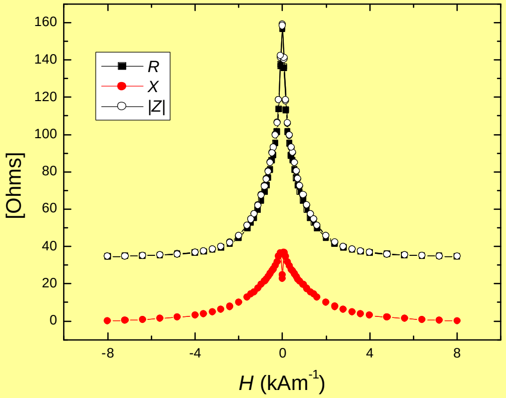


High field Sensitivity
≈ 500% /Oe

Low static magnetic field
H_{max} ≈ 1-10 Oe

Observed in soft Magnetic Materials

GMI phenomenology

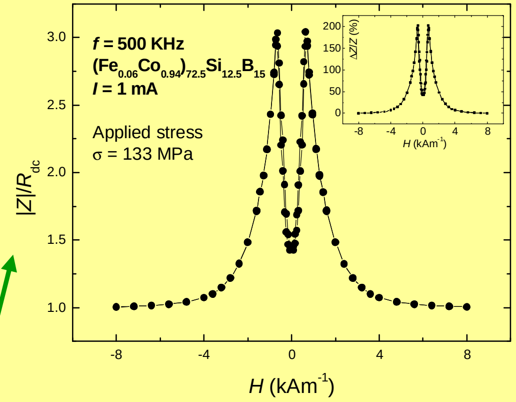


Variation of real and imaginary Components of Impedance $Z=R+i\omega X$

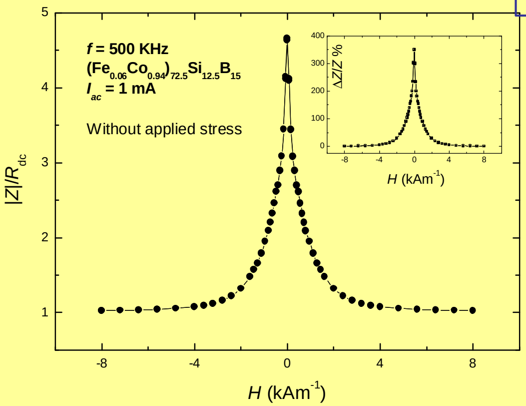
GMI definition

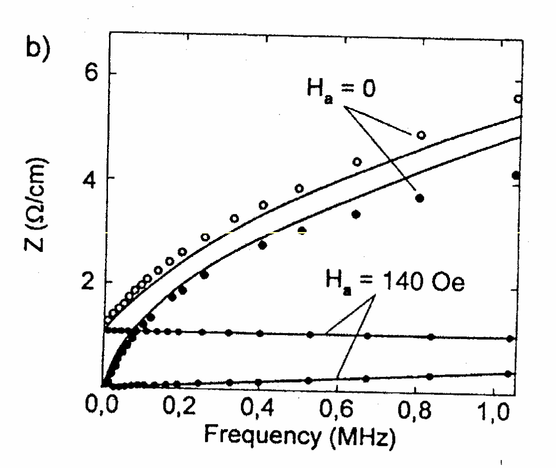
$Z(H)\ /R_{dc}$

$\Delta Z/Z(\%)=[Z(H)-Z(H_{max})]/Z(H_{max})$



Different Behavior:
"Single Peak" y "Double Peak"





Dependence on exciting frequency

Amorphous CoFeSiB wire

Families of Materials exhibiting GMI

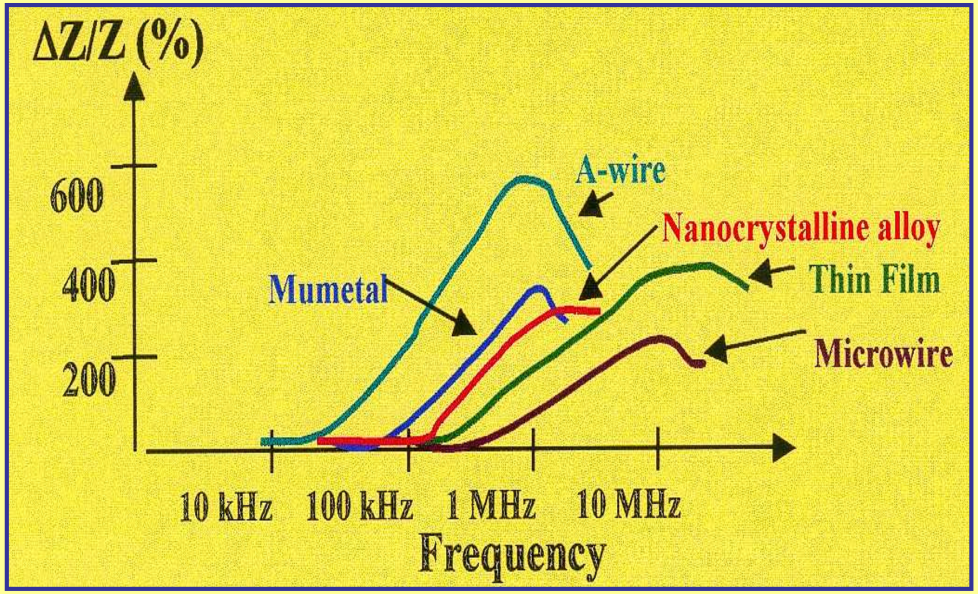
First Publications:

Harrison et al. Nature (1935), Makhotin et al. Sensors and Actuators (1991), Mohri et al. IEEE Trans. Magn. (1993), Machado et al. J. Appl. Phys. (1993), Mandal & Ghatak Phys. Rev.B (1993), Velázquez et al. Phys. Rev. B (1994)

Rediscovering GMI in Amorphous Wires:
Panina & Mohri, Appl. Phys. Letter (1994), Beach & Berkowitz, Appl. Phys. Letter (1994)

Large number of initial publications in other materials during the 90's:

Amorphous ribbons (Machado et al., Sommer & Chien, Tejedor et al.) Nanocrystalline alloys (Knobel et al., Chen et al.) Thin films (Panina & Mohri, Sommer & Chien) Sandwichs Metal/Insulating (Morikawa et al., Antonov et al.) FeSi (Carara& Sommer) Permalloy fibers (Ciureanu et al., Vázquez et al.) Mumetal (Nie et al.) Electroplated microtubes (Beach & Berkowitz, Sinnecker et al.) Amorphous microwires (Vázquez et al., Chiriac et al., Zhukov et al.)

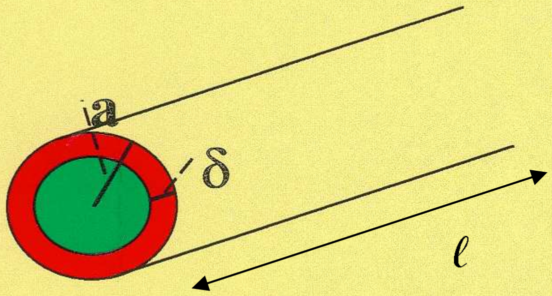


Impedance and skin effect

$$rot\vec{E} = -\partial\vec{B}/\partial t$$
$$rot\vec{H} = -\sigma\vec{E} + \partial\vec{D}/\partial t$$
$$div\vec{E} = div\vec{B} = 0$$

$$\nabla^2\vec{E} + k^2\vec{E} = 0 \qquad k = \frac{1-i}{\delta}$$

$$\delta = \frac{1}{\sqrt{\pi\sigma f\mu}}$$

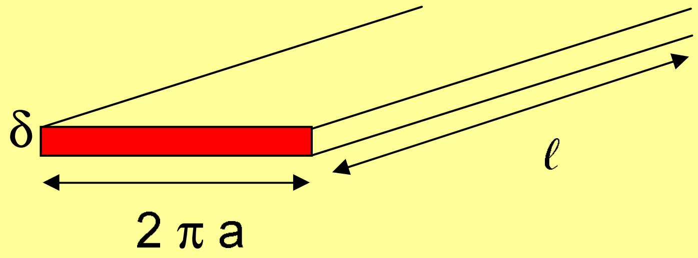


$$E_z = CJ_0(kr)$$
$$H_\phi = C\frac{\sigma}{k}J_1(kr)$$

$$Z = (R + iX) = R_{dc}\frac{ka}{2}\frac{J_0(ka)}{J_1(ka)}$$

Conductor	σ (10^7Mhos/m)	μ_r	δ at 1 kHz (mm)	δ at 1 MHz (mm)	δ at 3 GHz (μm)
H_2O (salt)	5	1	7000	200	
Al	3.54	1	2.7	0.08	1.6
Zn	1.86	1	3.7	0.12	2.1
Cu	5.80	1	2.1	0.07	1.2
Cr	3.80	1	2.6	0.08	1.5
Ag	6.15	1	2.0	0.06	1.2
Au	4.50	1	2.4	0.08	1.4
Ni	1.30	100	4.4	0.014	0.26
Fe	1.00	200	0.35	0.011	0.2
a-alloy	0.08	10000	0.17	0.005	0.1

δ << a

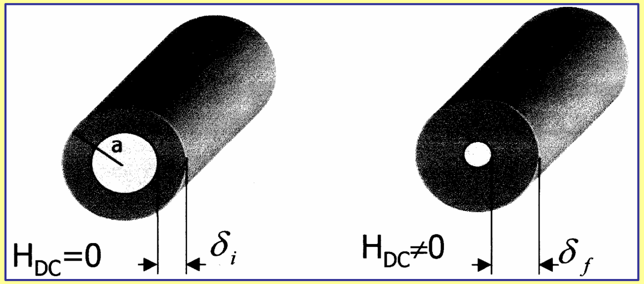


$Z \approx R \approx \rho\,\ell / (2\pi a\delta) \approx f^{1/2}\,\mu^{1/2}$

The skin effect is very intense in amorphous alloys owing to their high permeability and resistivity

→ $\phi_{min} \approx 0.5\ \mu m$

Origin of GMI: the skin effect
(a problem: the non-linearity of permeability)



The static field, H_{dc}, reduces the circular permeability, μ_ϕ, and increases the skin effect penetration depth, δ, so reducing the impedance, Z

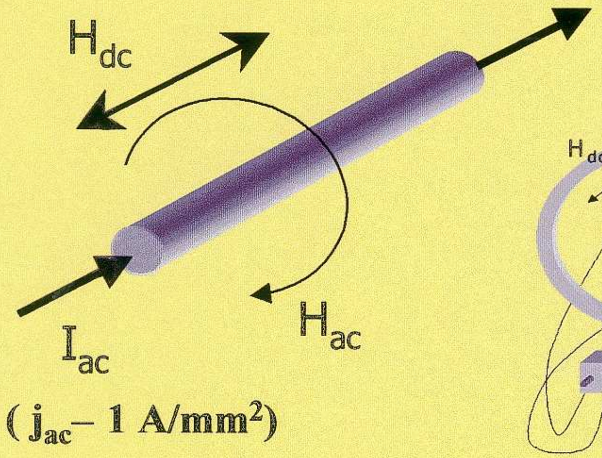
Dificulties for quantitative estimation of δ :
in ferromagnetic materials permeability, μ_ϕ, is not linear function

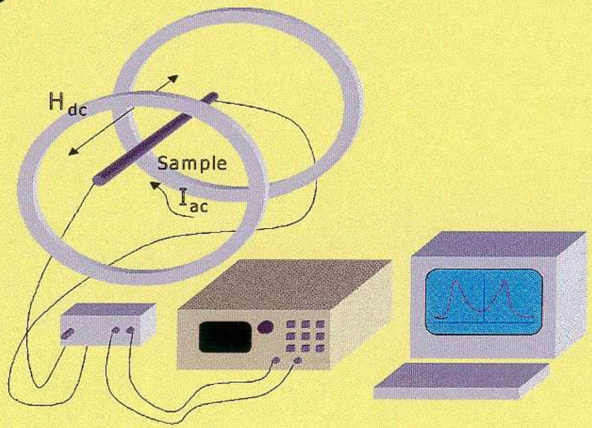
First approximation: taking $<\mu_\phi>$

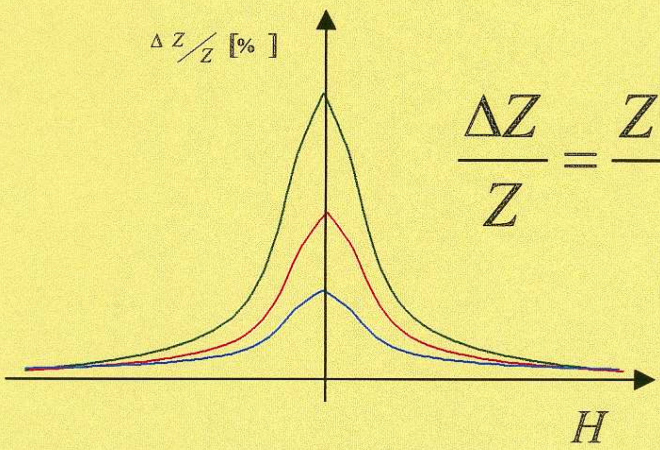
Introducing the magnetization process in the skin effect:
i) Radial profile of internal stresses ($K_{m.elást}$) and magnetic hystory (K_{ind})
ii) Influence of the amplitude (I_{ac}) and frequency (f) of current or circular field (H_ϕ)

Determining experimentally GMI

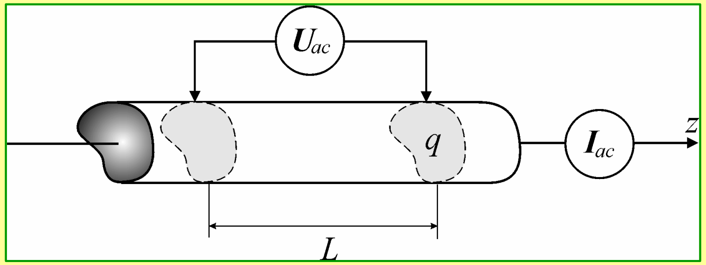
f - 10 kHz to 10 MHz







$$\frac{\Delta Z}{Z} = \frac{Z(H) - Z(H_{\max})}{Z(H_{\max})}$$



$$U_{ac} = U_R + iU_L = R_{dc} I_{ac} + i\omega L_i I_{ac}$$

f<< (no skin effect)

$$Z = \frac{U_{ac}}{I_{ac}} = R_{dc} + i\omega L_i$$

Magnetoinductive effect

$$Z = \frac{U_{ac}}{I_{ac}} = \frac{\int_L e_z(S)\, dz}{\iint_q j_z\, dq} = \rho \frac{\int_L j_z(S)\, dz}{\iint_q j_z\, dq}$$

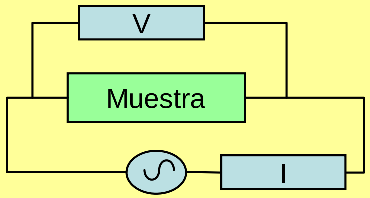
$$\boldsymbol{e}_t(S) = \hat{\zeta}\, \boldsymbol{n} \times \boldsymbol{h}_t(S)$$

Impedance tensor

$$Z = \frac{L}{l}\left(\zeta_{zz} - \zeta_{z\phi}\frac{h_z}{h_\phi}\right)$$

Careful with the measuring process!:
Is there too many cables?

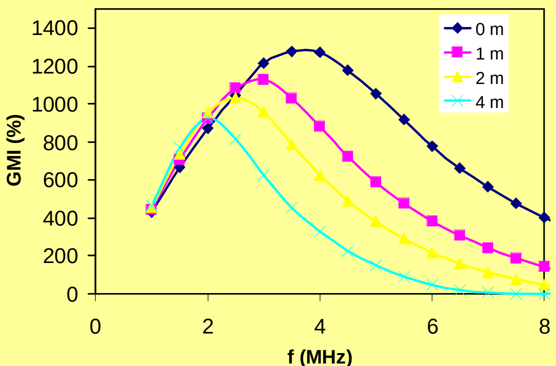
Measuring through the four points technique



$$Z = \frac{V}{I}$$

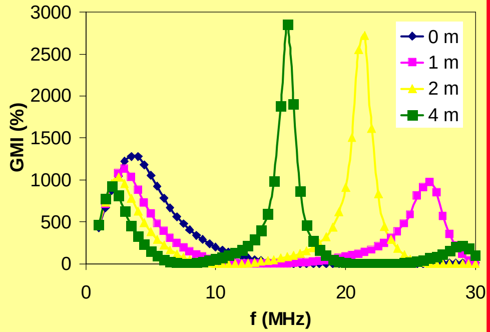
Eliminating parasitic resistence but not capacities/autoinduction of cables

Low frequency:
resonance with parasitic capacitance

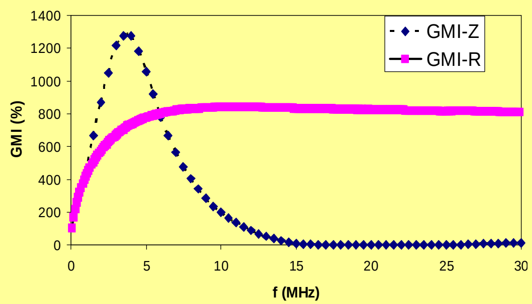


C (pF) (line length)	Experimental Frequency (MHz)	Theoretical Frequency (MHz)
100 (0 m)	4	5.0
200 (1 m)	3	3.5
300 (2 m)	2.5	2.9
500 (4 m)	2	2.2
1600 (15 m)	1	1.2

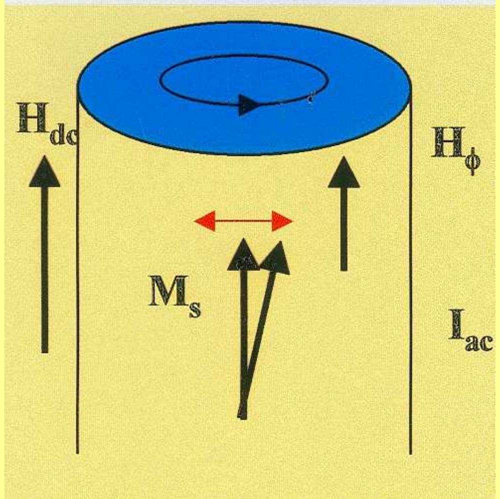
High frequency: analysis though transmission lines: stationary waves (maxima and mínima in voltage)



Impedance network analyser: authomatic cancelling of parasitic impedances



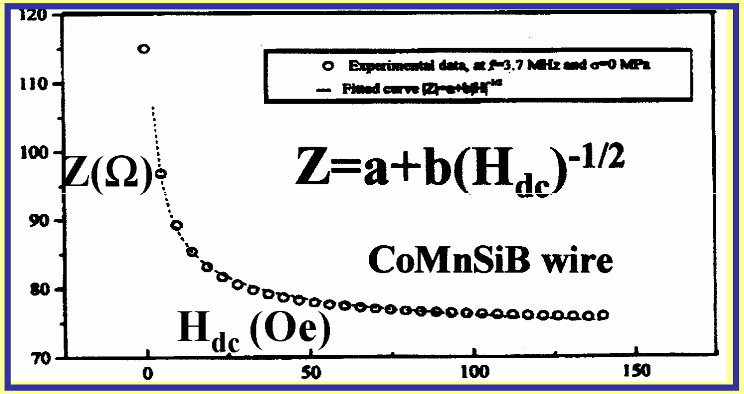
Longitudinal Magnetic Anisotropy: "Single-Peak" like GMI



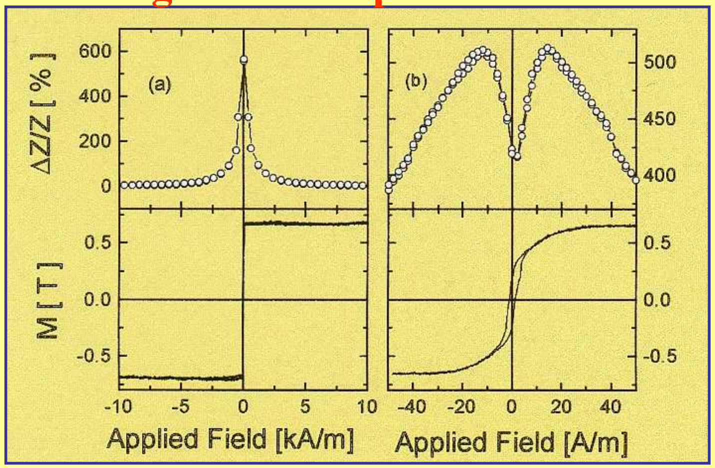
Magnetization process by rotation

Under the circular alternating field magnetization rotates around the axial direction

$\mu^{ac}_{\phi} = \mu_{\phi,rot}$ & $1/H_{dc}$



Correlatio between GMI and magnetization process



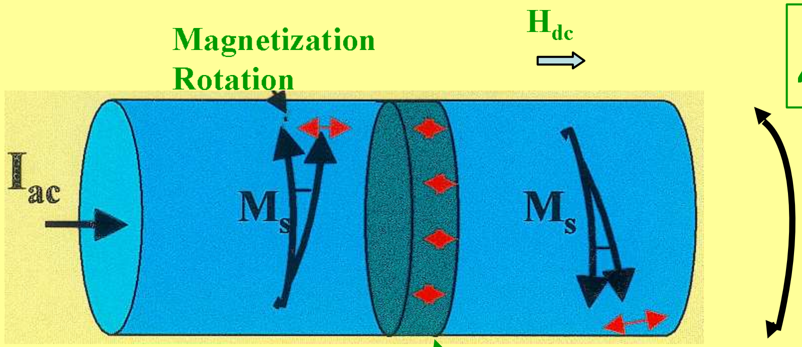
$\delta \ll a$

$$Z = R_{dc} a \sqrt{\pi}(1+i)\sqrt{\sigma f \mu_{\varphi}}$$

$f = 3.7$ MHz

Fine structure of double peak: irreversible magnetization process

Circular Magnetic Anisotropy: “Double Peak” like GMI

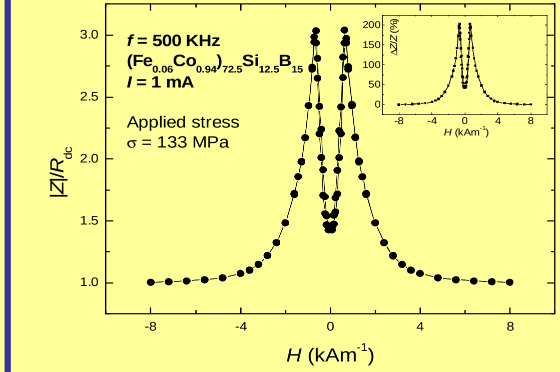


$$\mu_\phi = \mu_{\phi\, rot} + \mu_{\phi\, dw}$$

Circular Anisotropy, H_k

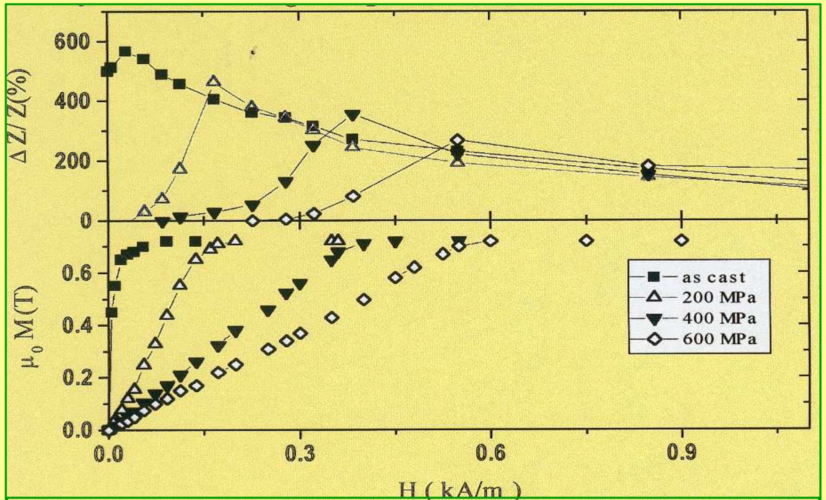
$H_{ac}(circ) < H_k < H_{dc}(long)$

Wall bending

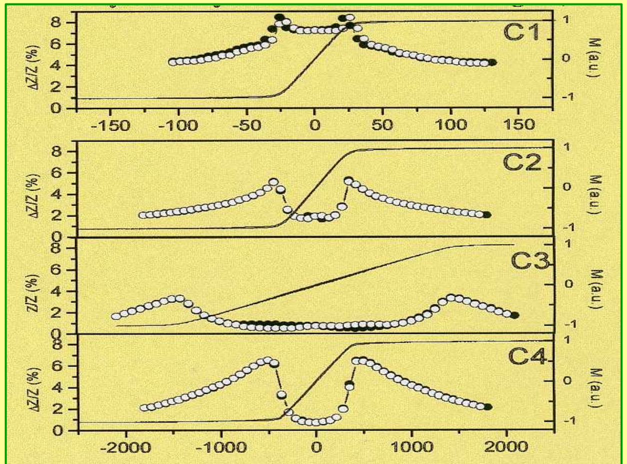


Applied static field, H_{dc}, tries to overcome intrinsic circular anisotropy, H_k

μ_t and GMI maxima at $H_{dc}=H_k$



CoFeSiB amorphous wire after thermal stress-annealing inducing circular anisotropy (correlation GMI & Magnetization Curves)



Transverse anisotropy induced by thermal field-annealing (C1,C4) and stress-annealing (C2,C3) (FeSiBCuNb Nanocrystalline)

Theoritical description :

$\boldsymbol{H}_0$ *perpendicular* to the easy axis ($\boldsymbol{H}_0 \parallel x$).

$$\chi_{t\,dw} = \frac{2u}{dh} M_s \sin\theta_0 = \frac{4\mu_0 M_s^2}{\beta}\left(1 - \frac{H_0^2}{H_K^2}\right). \quad \text{(a)}$$

$$\chi_{t\,rot} = \frac{M_s \cos^2\theta_0}{H_0\cos\theta_0 - H_K\cos 2\theta_0} \qquad \cos\theta_0 = H_0/H_K \quad \text{(b)}$$

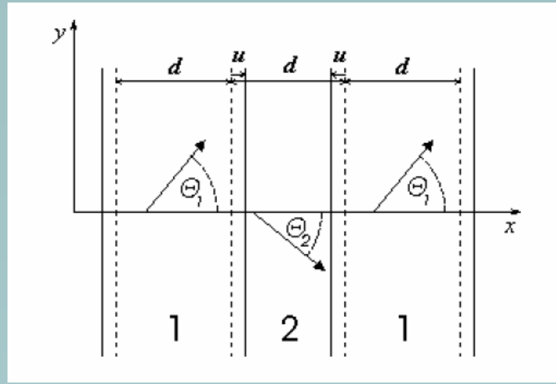
$\boldsymbol{H}_0$ *parallel* to the easy axis ($\boldsymbol{H}_0 \parallel y$).

$$\chi_{t\,rot} = \frac{M_s}{H_K}\left(1 - \frac{M_0}{M_s}\frac{H_0}{H_K}\right)\Big/\left(1 - \frac{H_0^2}{H_K^2}\right) \quad \text{(c)}$$

$M_0 = 2M_s u/d$ = *dc magnetization*

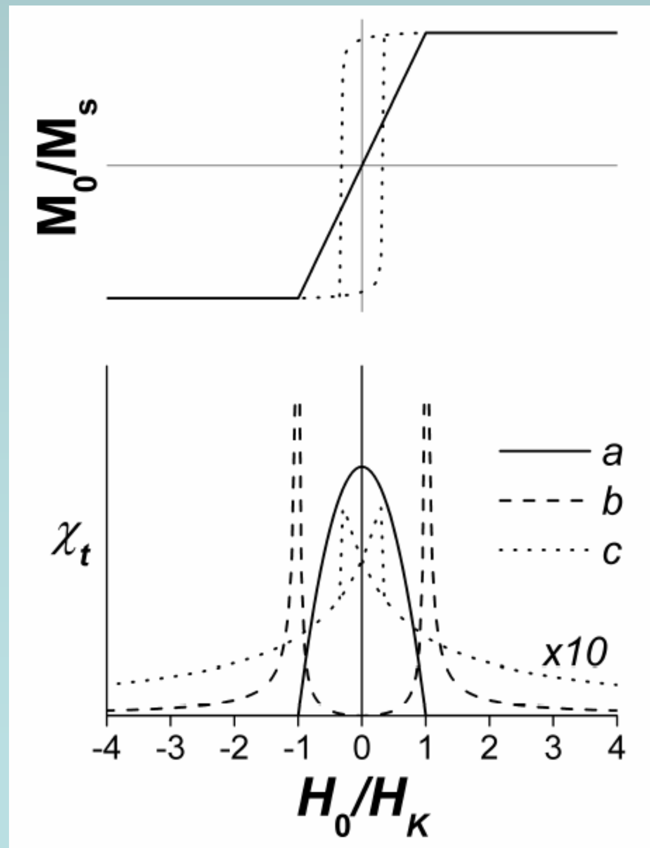
$H_0 > H_C$: $M_0 = M_S$ ➡ $\chi_{t\,rot} = 2M_s/(H_0+H_K)$.

$H_0 \gg H_K$: ➡ $\chi_{t\,rot} = 2\,M_S/H_0$



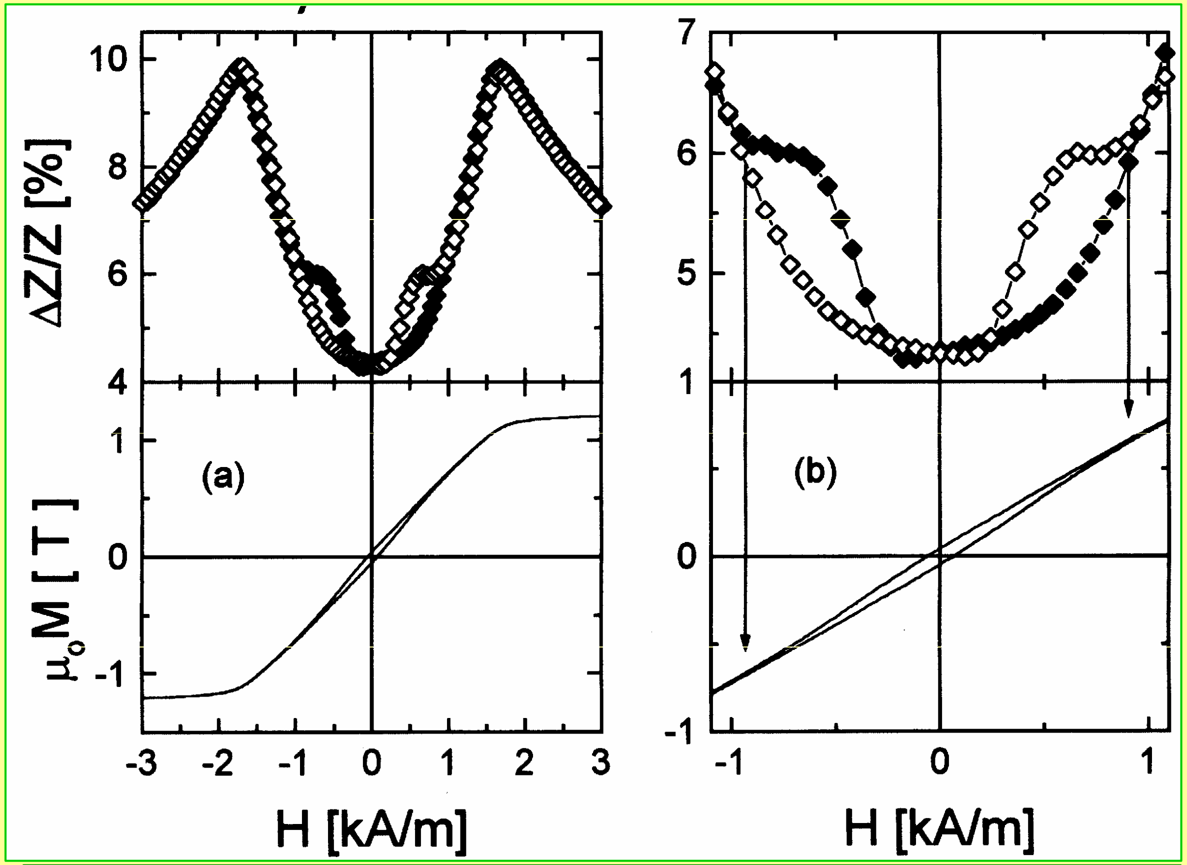
Easy axis

$H_K = 2K/J_S$



GMI hysteresis

Nanocrystalline FeSiBCuNb wire after stress annealing



Correlation between hysteresis of magnetization process and GMI

$H_k \neq H_{irrev}$

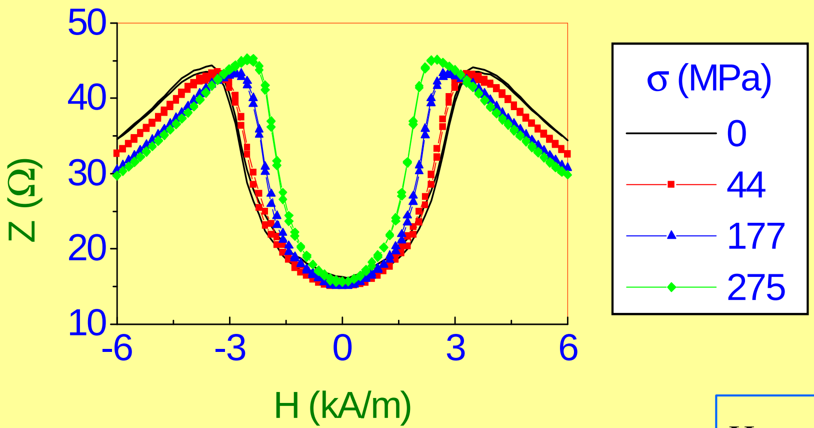
Hysteresis extends to region of irreversibilities of magnetization process

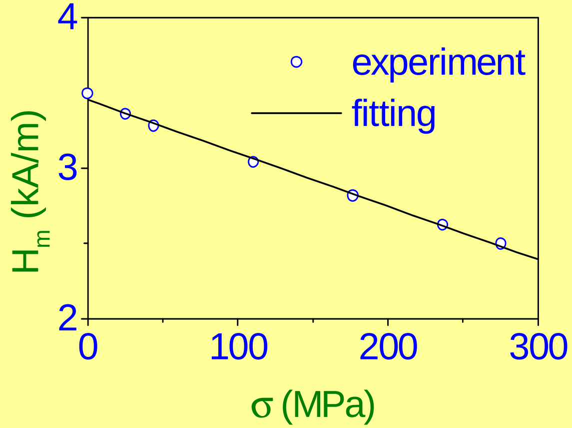
Magnetoelastic effects and their applications

$$H_k = H_{int} + H_{melas} = (H_{k0} + H_{ind}) + 3\lambda_s\sigma/\mu_0 M_s$$

Nanocrystalline wire $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$
After treatment under dc current and tensile stress (30 s, 50 A/mm², 135 MPa)

Determination of induced anisotropy H_{ind}, and of magnetostriction λ_s by applying mechanical stress

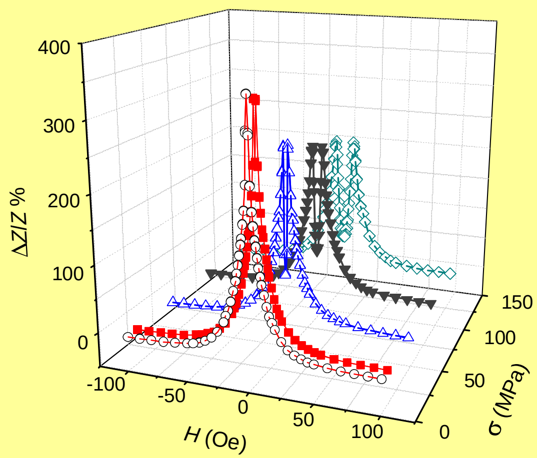




$$H_m = H_{ind} + \frac{3\lambda_s\sigma}{\mu_0 M_s}$$

H_{ind} = 3.46 kA/m,
$\lambda_s = 1.42 \times 10^{-6}$

Amorphous wire de FeCoSiB ($\lambda_s \approx -1 \times 10^{-7}$)

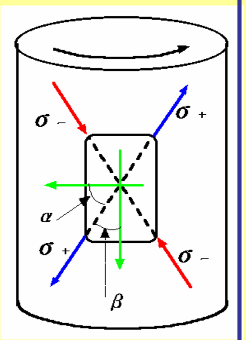


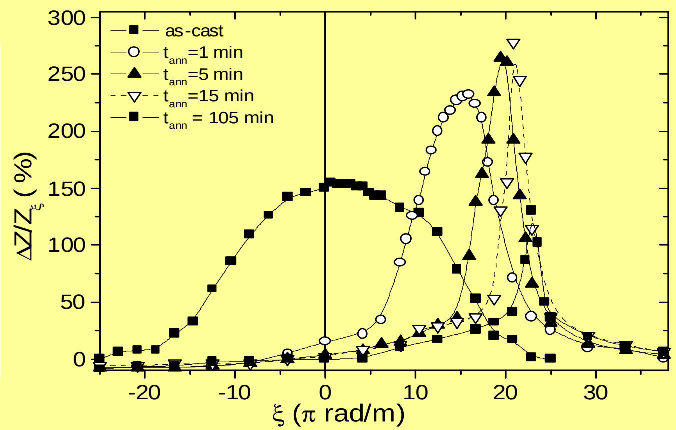
Transition from "Single Peak" to "Double Peak" by applying tensile stress (Inducing circular anisotropy)

Stress impedance: Variation of impedance with applied stress

$\Delta Z/Z(\%)=[Z(t)-Z(t_{max})]/Z(t_{max})$

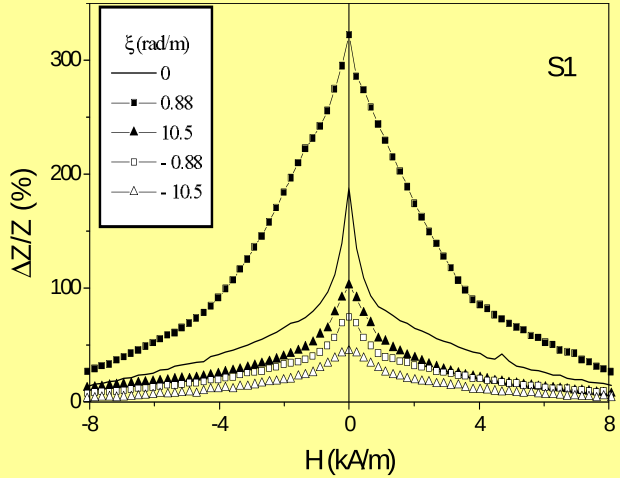
t = tensile stress (σ), torsion (τ)



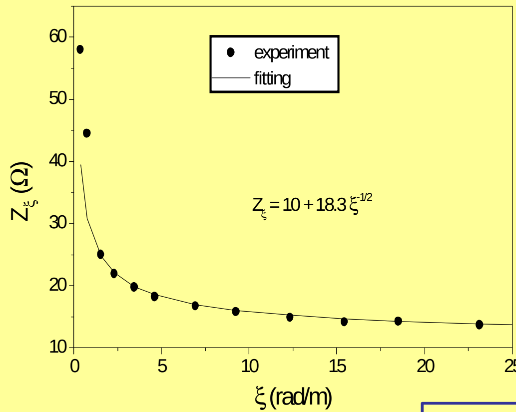


Example: Torsion impedance

Helicoidal anisotropy induced in a microwire, CoFeSiB, by torsion annealing



Dependence on torsion of GMI in a nanocrystalline wire $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$



Torsion-Impedance: its fitting to a model

$$Z_\xi = p + q\xi^{-1/2}$$

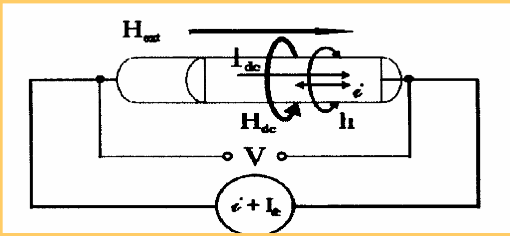
Can GMI behavior be asymmetric?

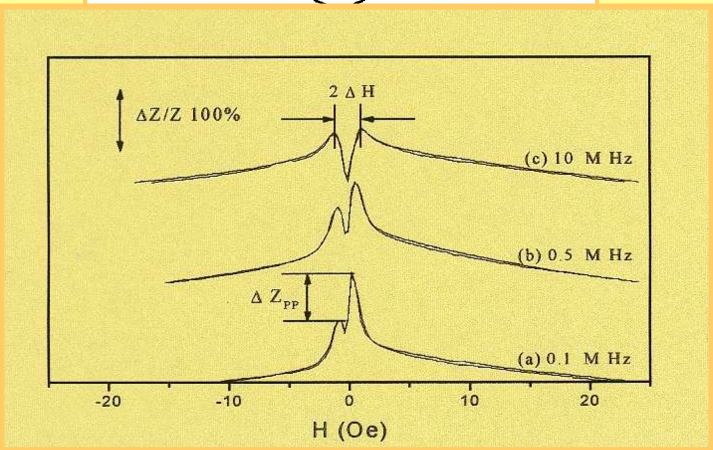
Asymmetry appears when there is a preferred sense to the excitation of the dc axial field

That can be induced by:

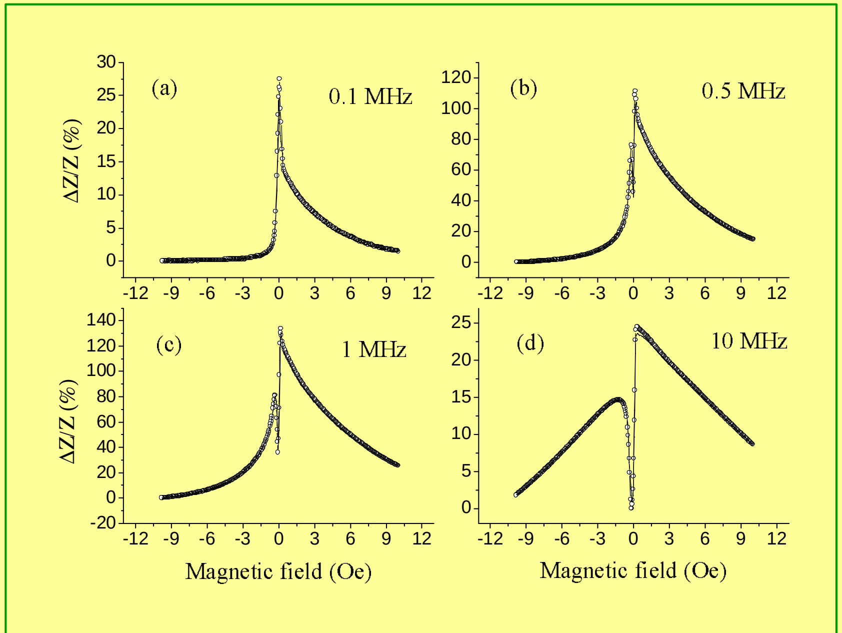
a) Polarization under additional DC current + Intrinsic Anisotropy (helicoidal)

b) Unidirectional Exchange Anisotropy (oxidation produced at the surface during thermal treatment at the presence of H)





Asimmetry induced by biasing current



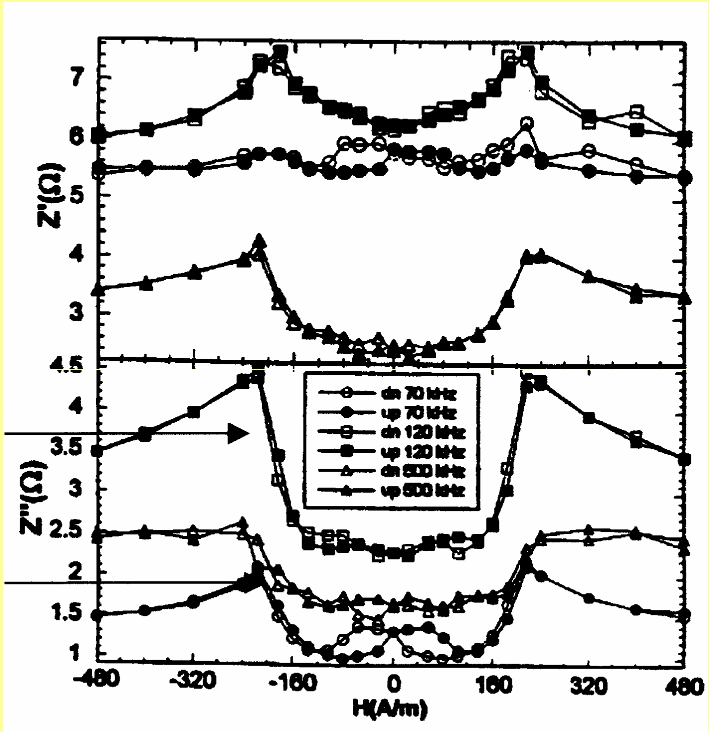
Asimmetry induced by Unidirectional exchange (Annealing under axial field)

Damping of domain walls with high frequency of exciting field

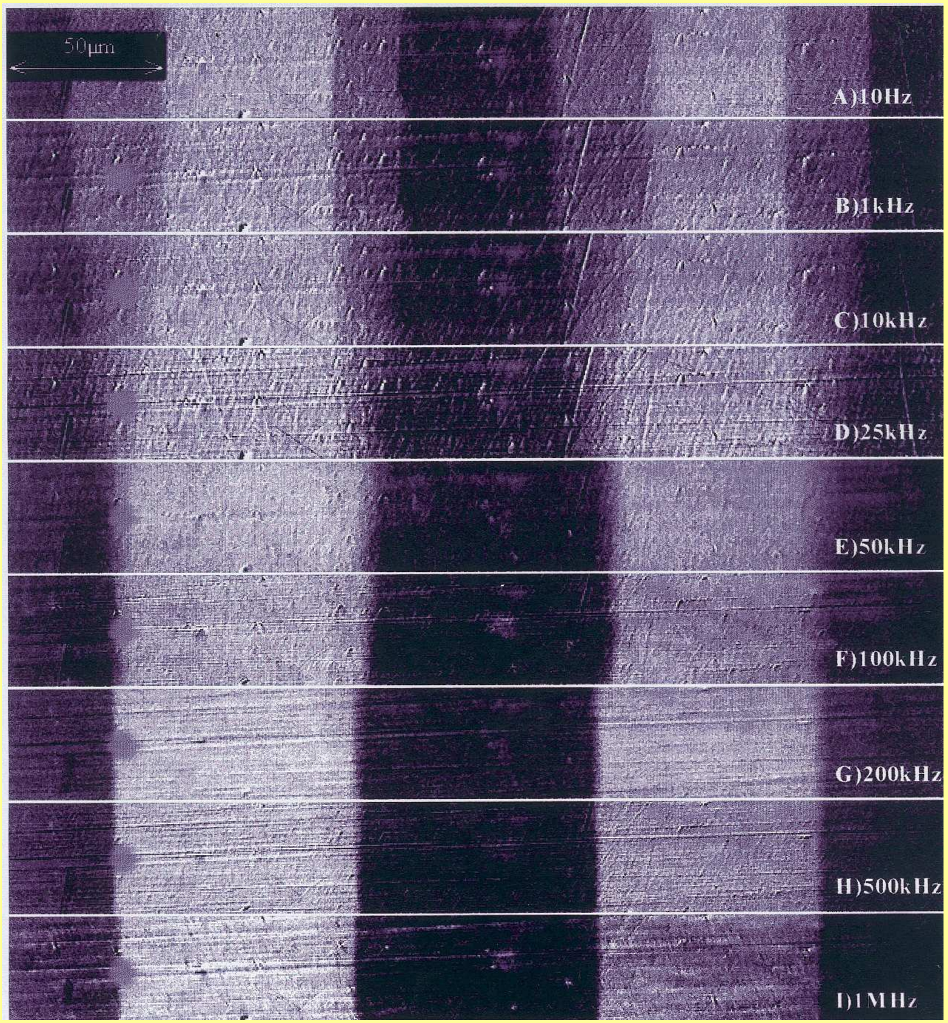
FeCoSiB amorphous ribbons thermally treated to induce transverse anisotropy

500 kHz

70 kHz

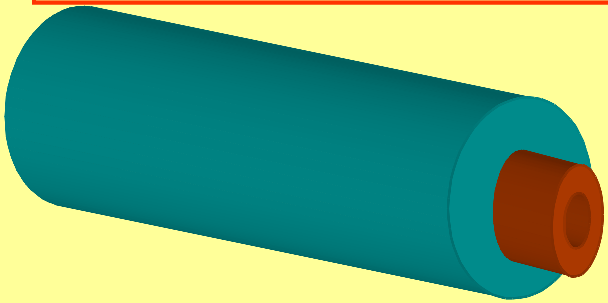


Hysteresis reduced by increasing the frequency that reduces movility of walls

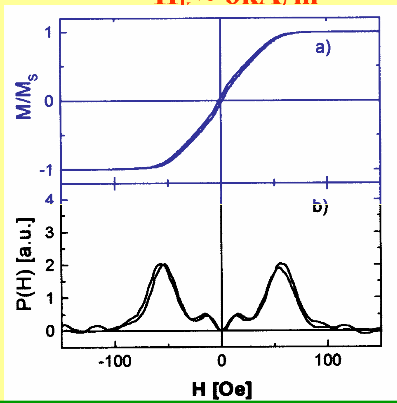


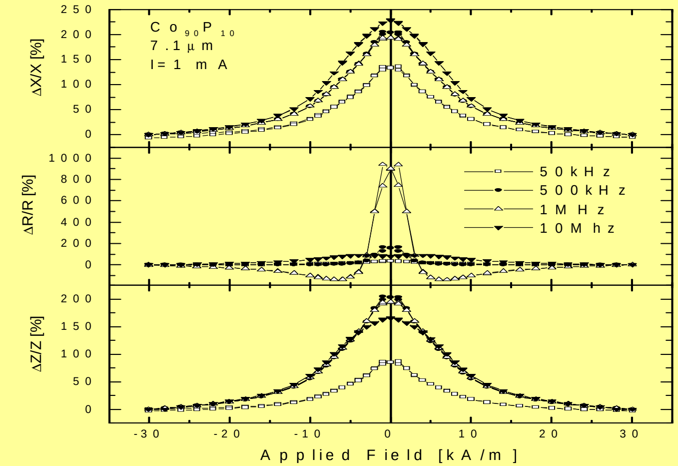
GMI in novel materials: magnetic coatings

Coating of $Co_{90}P_{10}$ (2 to 22 μm thick on a Cu wire 200 μm diameter



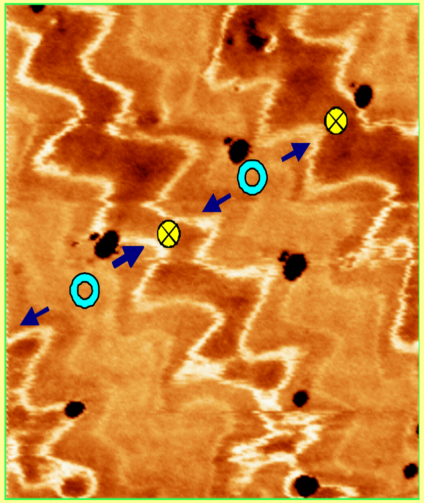
Anisotropía Transversal
$H_L \approx$ 6kA/m



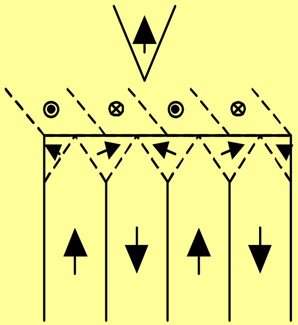


High GMI response

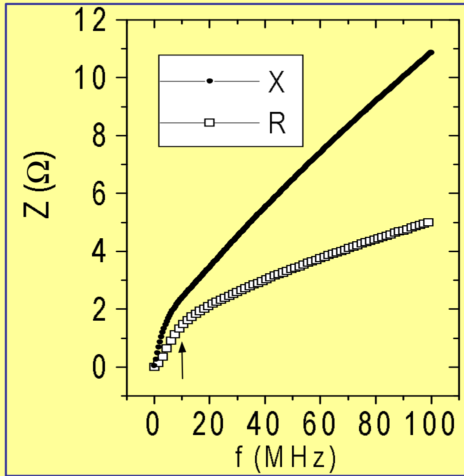
Image MFM: 12.5 μm x 12.5 μm
distance tip-surface: 25 nm



Determinating domain structure through Impedance & MFM



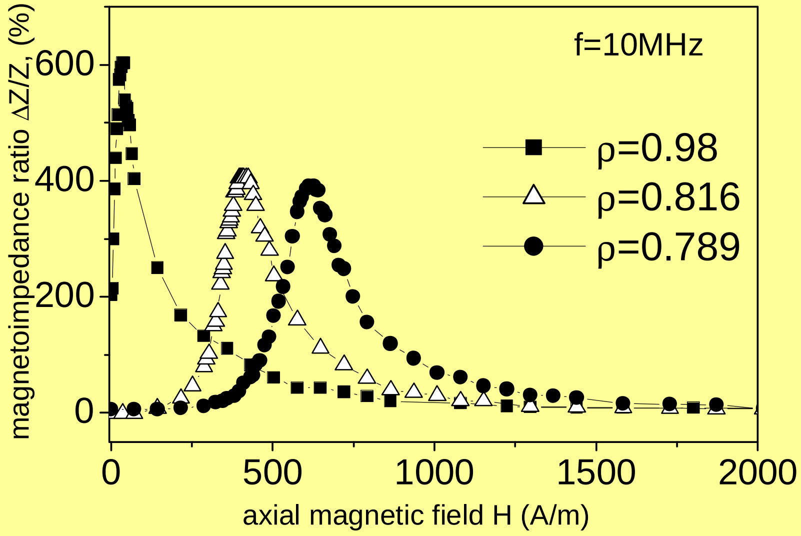
Scheme of domain structure observed by MFM



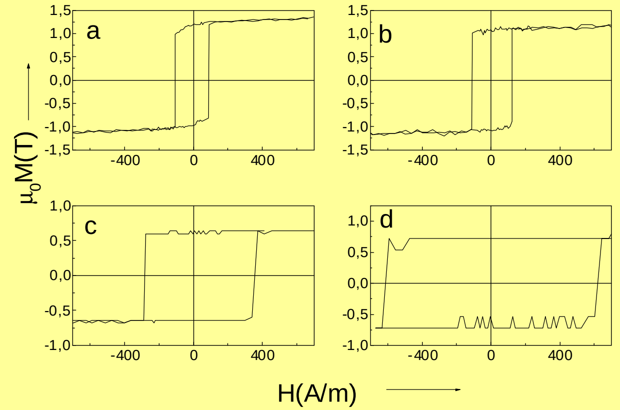
Skin effect reaches the closure domains at $\delta \approx 2.4$mm

GMI novel materials: microwires coated by glassy cover

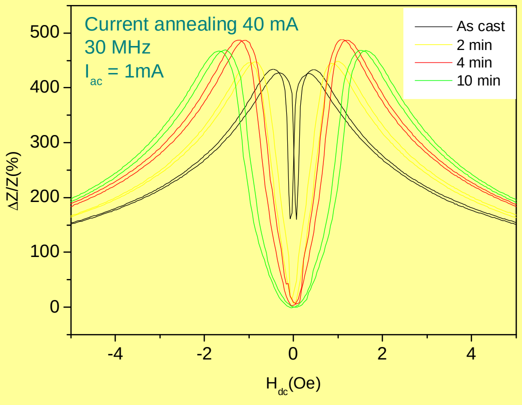
Importance of specific geometry



$\rho = R_{met}/R_{tot}$



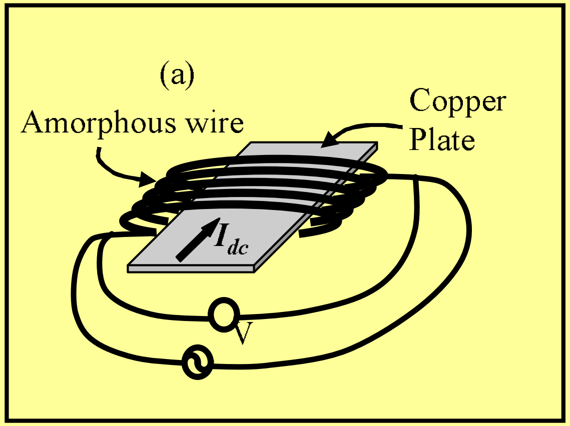
Histeresis loops



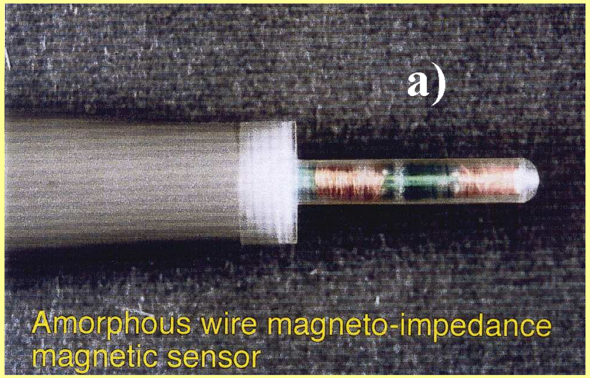
GMI in treated microwires

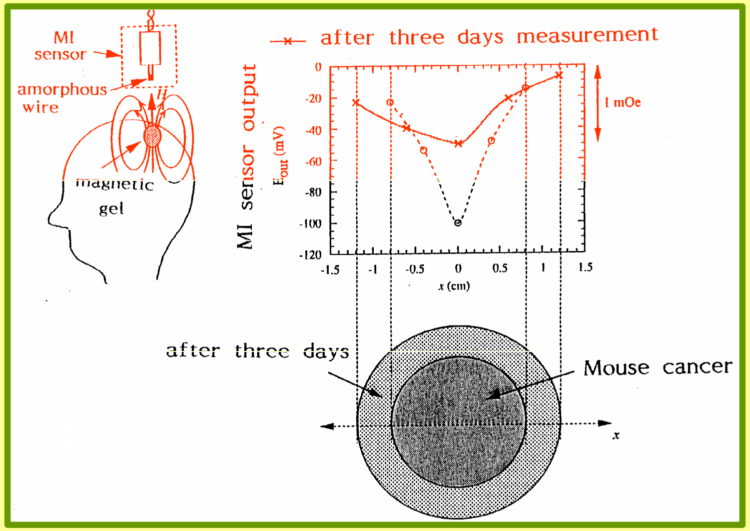
Static field Sensors based on GMI

DC current sensor (Power Electronics)



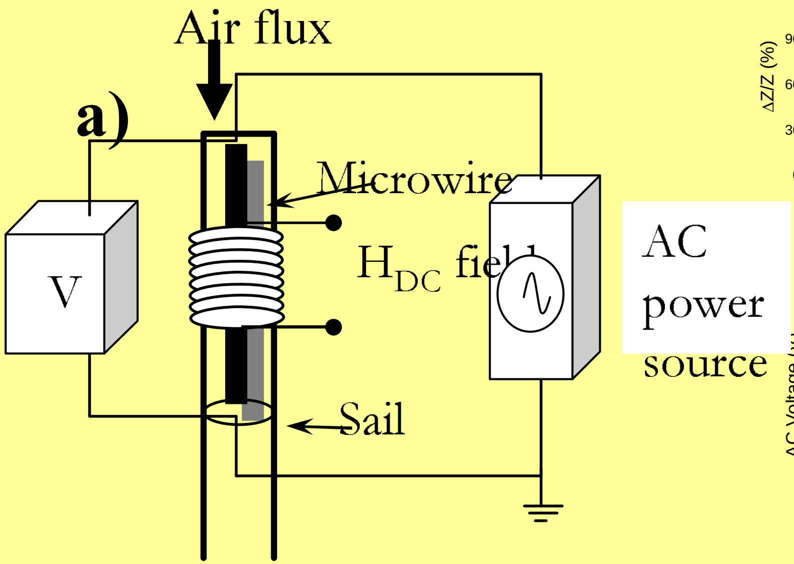
DC magnetic field Sensor (Biomedicine)

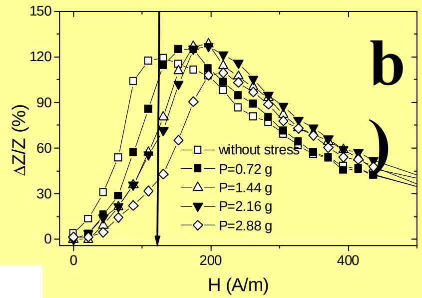


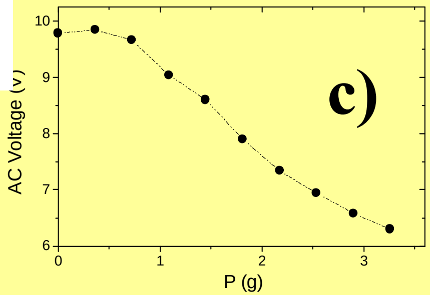


Sensors based on en GMI and stress

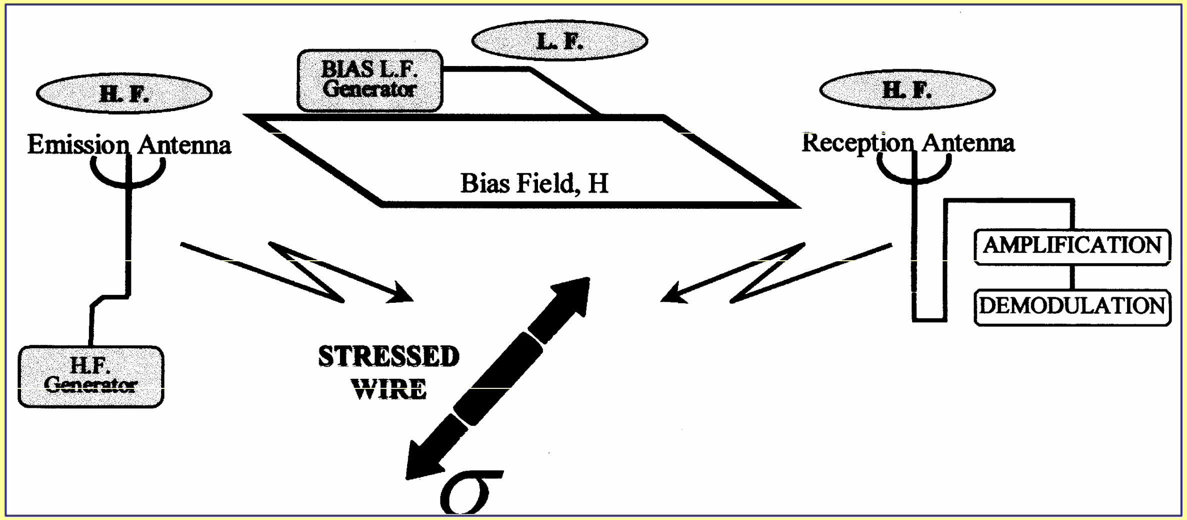
Sensor de flujo/presión (Electrodomésticos)





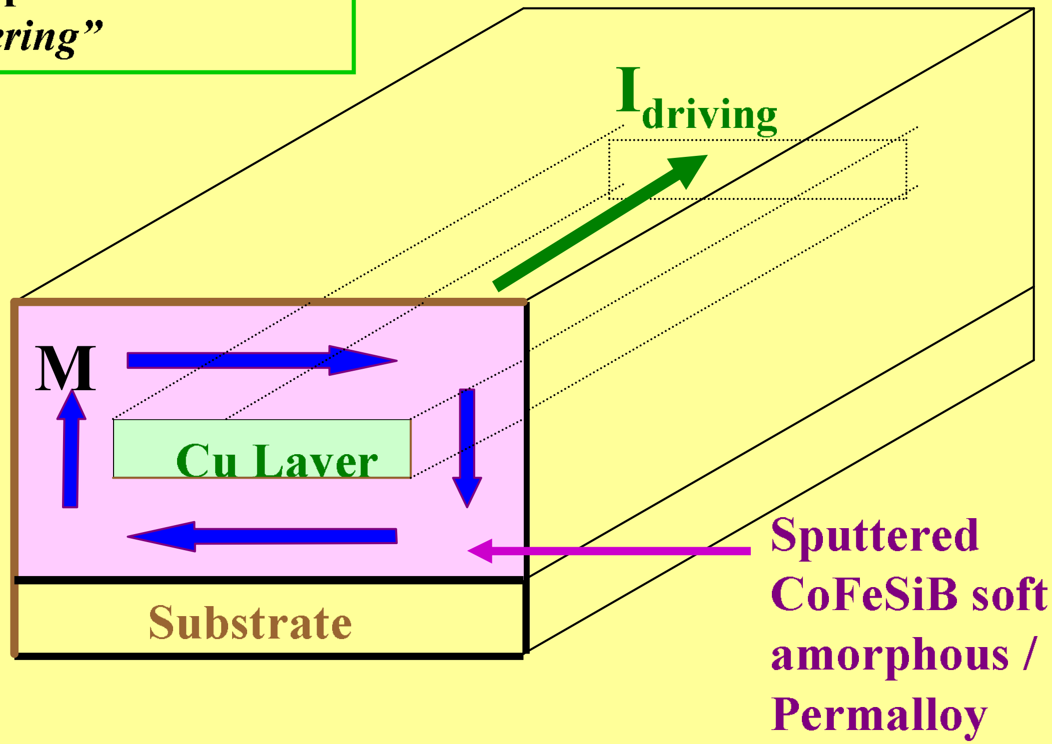


Radiodetector de tensiones mecánicas (Automoción)



Sensors for Thin Film technology

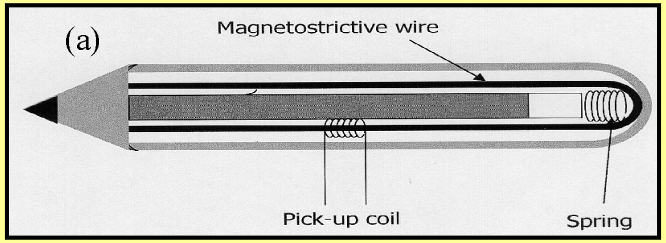
Scheme of sensor type "sandwich" prepared by *"sputtering"*

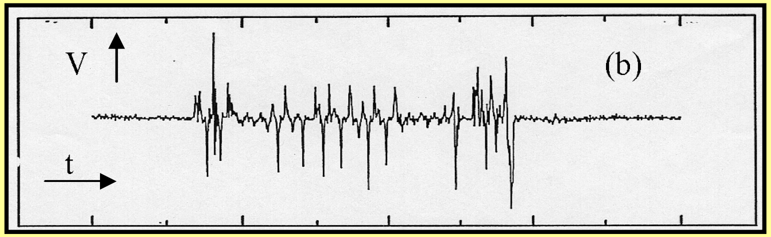


"Single Layer" film, or "Sandwich" F/M/F like structure: i) Suitable for integration in microtechnology ii) Reduced size (few micron)
iii) Magnetically harder of sensing element

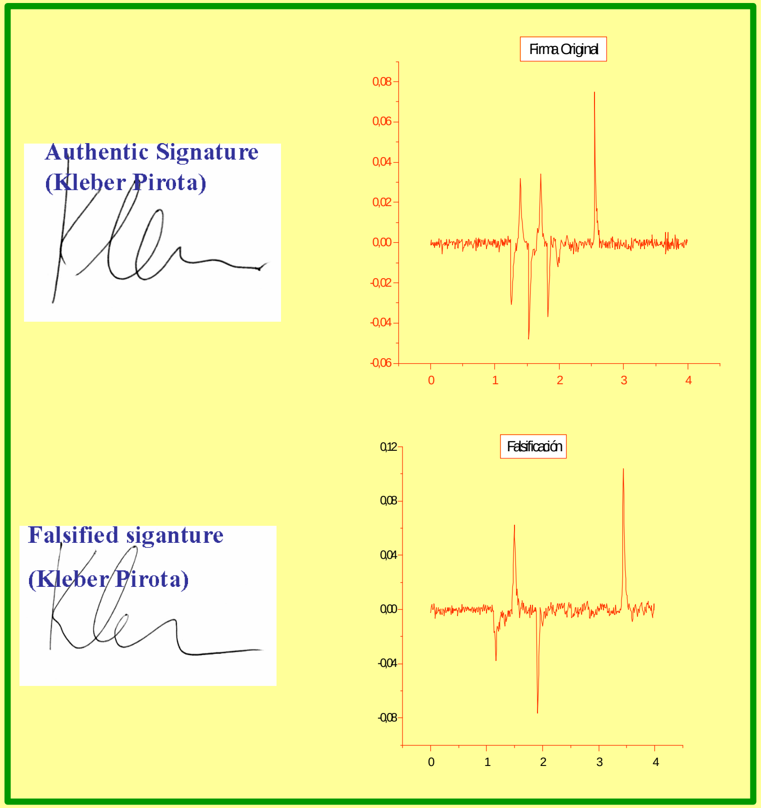
Sensors based in Stress Impedance

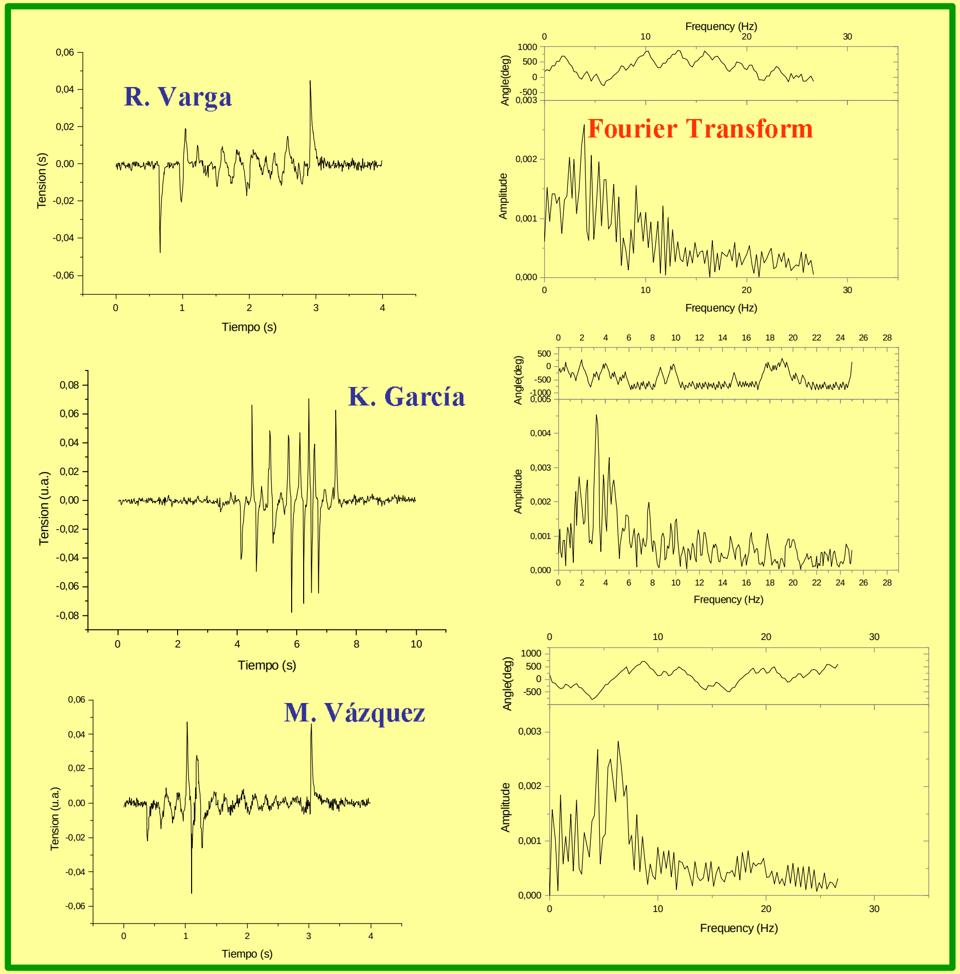
Magnetoelastic signature pen (Secutity)





Change of Impedancia with applied stress when signing





Families of Sensors

Principle of work	Head length (m)	Resolution full scale (Am^{-1})	Response speed (Hz)	Power Consumption (W)
Hall	$10 \sim 100 \times 10^{-6}$	$40 / \pm 8 \times 10^{4}$	10^{6}	10^{-2}
Magnetoresistence (MR)	$10 \sim 100 \times 10^{-6}$	$8 / \pm 8 \times 10^{3}$	10^{6}	10^{-2}
Giant Magnetoresistence (GMR)	$10 \sim 100 \times 10^{-6}$	$0.8 / \pm 1.6 \times 10^{3}$	10^{6}	10^{-2}
Fluxgate	$10 \sim 20 \times 10^{-3}$	$8 \times 10^{-5} / \pm 2.4 \times 10^{2}$	5×10^{3}	1
SQUID	$10 \sim 20 \times 10^{-3}$	$50 \times 10^{-12} / \pm 1 \times 10^{-6}$	5×10^{3}	-
Magnetoimpedance	$1 \sim 2 \times 10^{-3}$	$8 \times 10^{-5} / \pm 2.4 \times 10^{2}$	10^{6}	5×10^{-3}
Stressimpedancia	$1 \sim 2 \times 10^{-3}$	0.1 / 30	10^{4}	5×10^{-3}

Giant Magneto-Impedancia: Summary

Origin:
Skin effect
(tecnologically not wished in general)

Materials:
Magnetically Ultrasoft
(advanced fabrication, processing techniques)

Tendencies:

Materials: Magnetic coatings, Integrated microelements
Frequency Range: Radio to Microwave
Micromagnetism: Non-linear, GMI tensor
Applications: Optimized Sensors, Integrated Technology

Classical Electrodinamics

Micromagnetism

GMI
New branch of research

Processing of materials

Thecnología of Sensors and Integration