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Department of Polymers and Advanced Materials
Magnetism Research Group

Magneto-Impedance effect for magnetic sensors: challenges, advances and perspectives

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Outline

1. INTRODUCTION
1.1. STATE OF THE ART ON GMI
   1. 2.MOTIVATION :
2. MEASUREMENTS METHODS
   3.FACTORS AFFECTING GMI
3.1. MAGNETOELASTIC ANSITROPY
4. LINEARITY OF GMI
5. GMI HYSTERESIS
6. INTERFACE LAYER
7. CONCLUSIONS

Advances in Giant Magnetoimpedance of Materials

A. Zhukov,[1,2,3,*] M. Ipatov[1,2] and V. Zhukova[1,2]

November 2015

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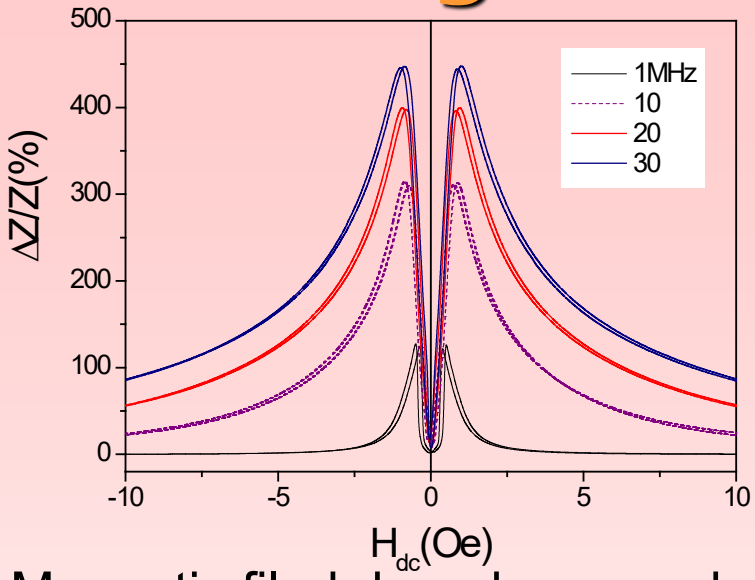
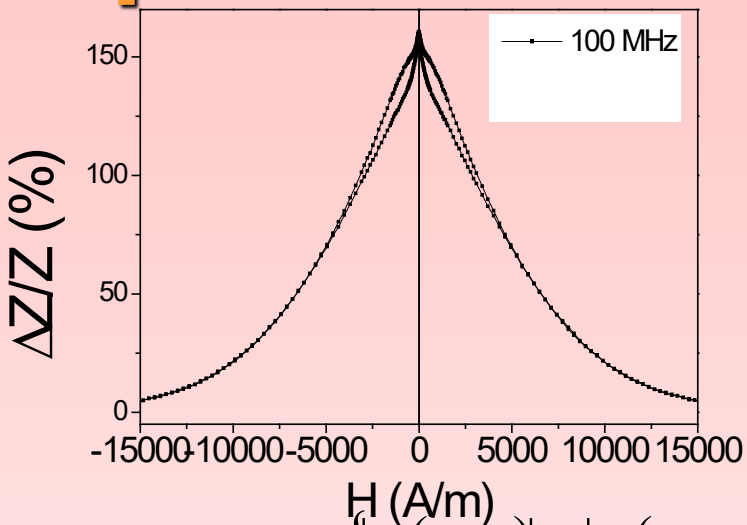
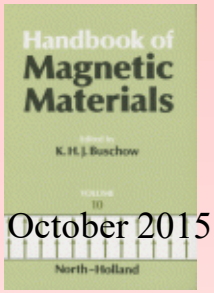
Giant Magneto-impedance effect





Advances in Giant Magnetoimpedance of Materials

A. Zhukov, M. Ipatov and V. Zhukova



October 2015

$$\Delta Z / Z = \{|Z(H_{ex})| - |Z(H_{max})|\} / |Z(H_{max})|$$

Magnetic filed depedence and value are affected by magnetic anisotropy

- Skin Effect of the Magnetic Conductor

AC current frequency

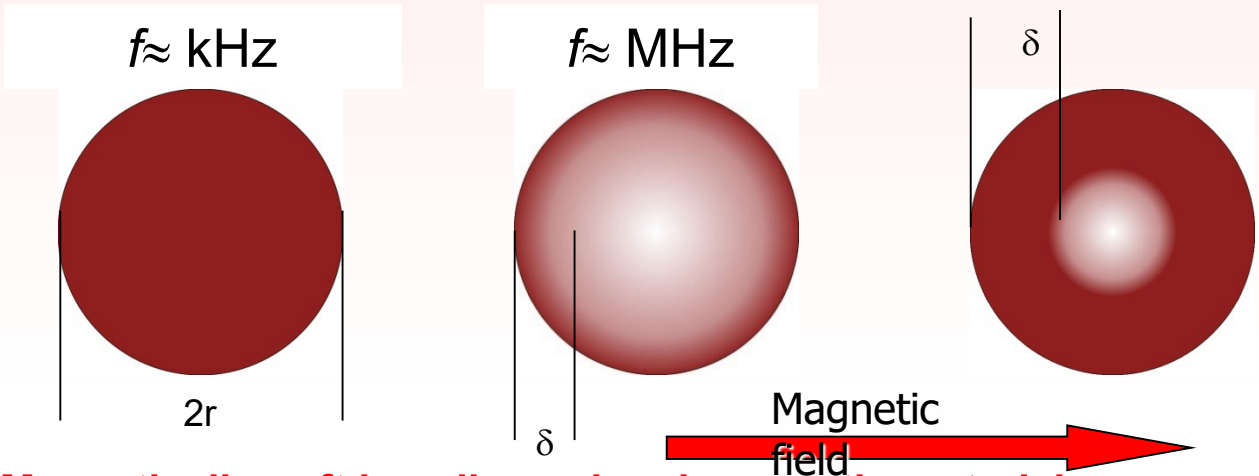
$$\mu_\phi \Downarrow \quad \rightarrow \quad \delta \Uparrow$$

$$\delta = \sqrt{\frac{\rho}{\pi \mu_\phi f}}$$

$\mu_\phi(H,f)$

$\delta < r$

(at high enough f)



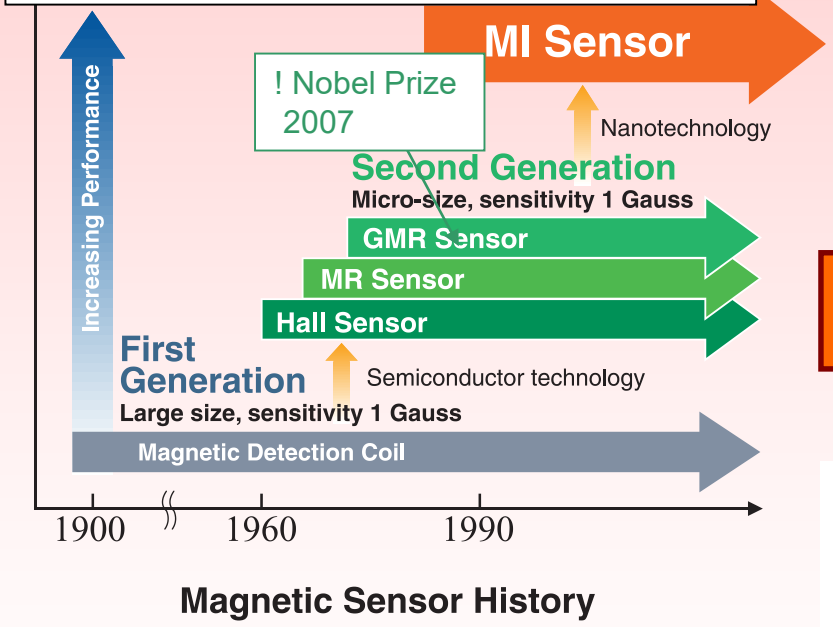
Z(H)

Magnetically soft low dimensional magnetic materials

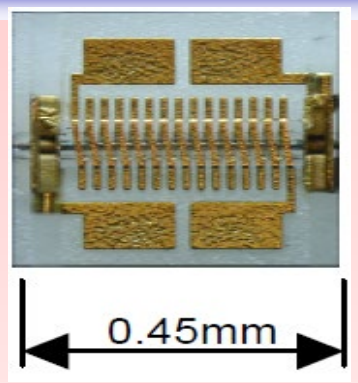
Promising GMI applications: 1. Magnetic sensors and smart composites

Third Generation of Magnetic Sensors — Smart composites

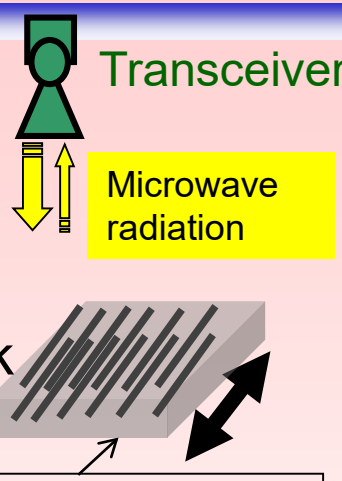
MI Sensors with excellent performance!



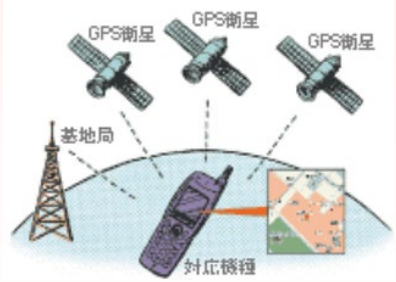
Magnetic Sensor History



Based on Amorphous Wwire since 2010



External stimuli: strain, compression, magnetic field, or heating



CASIO 2013.June 68250yen

Amorphous wire: (glass-coated wire)
Metal dia. : 11.3 μm
Total wire : 14.5 μm
Wire length: 520 μm

Amorphous Wire 3-axis Electronic Compass chip: *A MI 306*

Resolution	0.16 μT (160 nT)
Dynamic range	± 1.2 mT (±12 Oe)
Power voltage Vdd	1.7 V
Power current Idd	150 μA
Power consumption	255 μW
Operating temperature	−45 ~ 80 ℃
Chip dimension	2.04 × 2.04 × 1.0 mm
Reversibility for big disturbance magnetic field shock	∞

Advantageous of MI sensor :

1) Micro size and small power consumption (sub-mW)
2) High sensitivity with resolution of 0.01 % for dynamic range (Pico-Tesla resolution)
3) Quick response with GHz
4) High reversibility for big magnetic field disturbance shock
5) High temperature stability

Advanced 3−axis MI sensor chip installed in watch

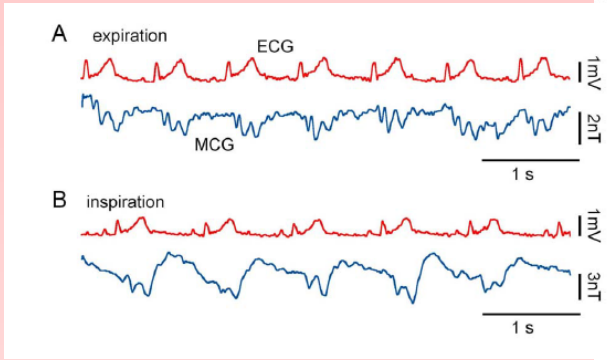
Industrial application in Smart phone using MI sensor

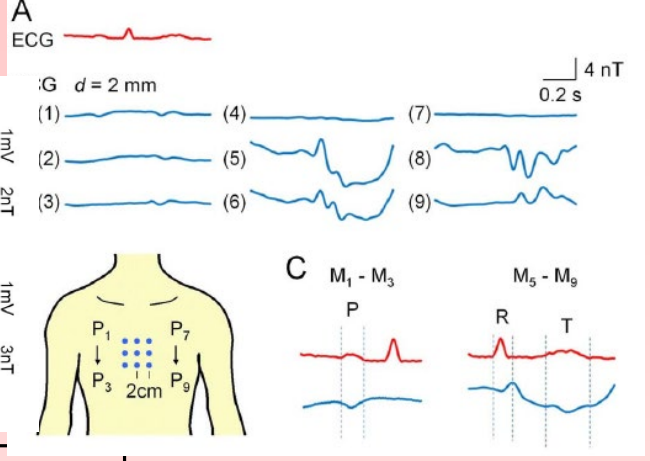
Last tendencies: Size reduction, frequency increasing Soft magnets are needed

Source: Aichi Micro Intelligent Corporation

Magnetic Field and Magnetic Sensors

Magnetic wires (up to 730%), up to 10%/A/m pico-Tesla sensitivity !





Bio magnetic field

Nature magnetic field

Geo-magnetisms

Industrial magnetic field

Storage and magnet

SC-magnet

Space magnetic field

Tesla (T)

pT nT μT mT T kT

10^{-10} 10^{-8} 10^{-6} 10^{-4} 10^{-2} 1 10^{2} 10^{4} 10^{6}

Gauss (G)

nG μG mG G kG MG

Intrinsic noise level at room temperature.

Hall sensor (0 ~ 1 MHz)

MR, GMR sensor (0 ~ 10 MHz)

Fluxgate sensor (0 ~ 10 kHz)

Amorphous wire MI sensor (0 ~ 10 MHz)

SQUID

Proton magnetometer (0 ~ 0.01Hz)

Source: Prof. K. Mohri

OPEN ACCESS Freely available online PLOS one

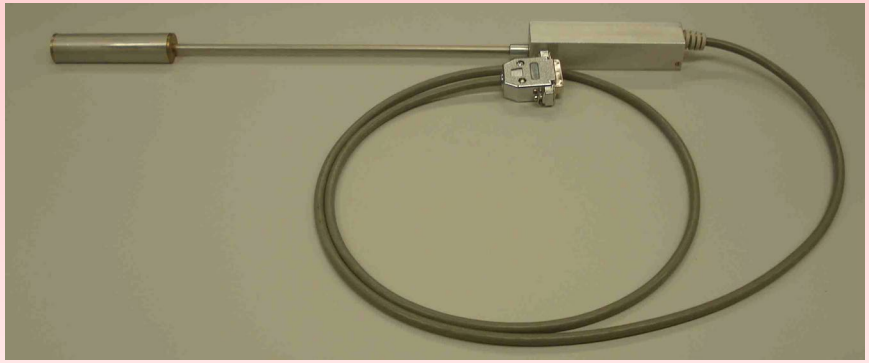
Pulse-Driven Magnetoimpedance Sensor Detection of Cardiac Magnetic Activity

Shinsuke Nakayama[1], Kenta Sawamura[1], Kaneo Mohri[2], Tsuyoshi Uchiyama[2]*

1 Department of Cell Physiology, Nagoya University Graduate School of Medicine, Nagoya, Japan, 2 Department of Electronics, Nagoya University of Graduate School of Engineering, Nagoya, Japan

GMI magnetometer versus SQUID and fluxgate

Advantages:
Lower cost
Smaller size



SQUID (superconducting quantum interference device)

All the GMI magnetometer prototypes are made with magnetic wires where the highest GMI ratio is achieved!

Main features and definitions of the GMI effect

The widely used GMI ratio definition [1,2]:

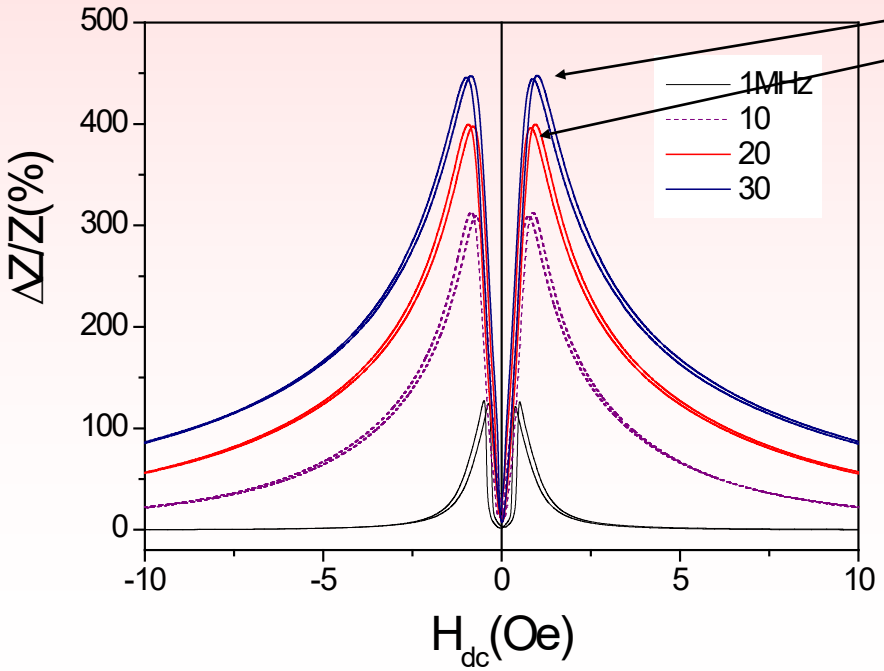
$$\Delta Z / Z = \left\{ \left| Z\left(H_{ex}\right) \right| - \left| Z\left(H_{\max}\right) \right| \right\} / \left| Z\left(H_{\max}\right) \right| \qquad (1)$$

where Z is the impedance modulus and H_{max} is the maximum measured field

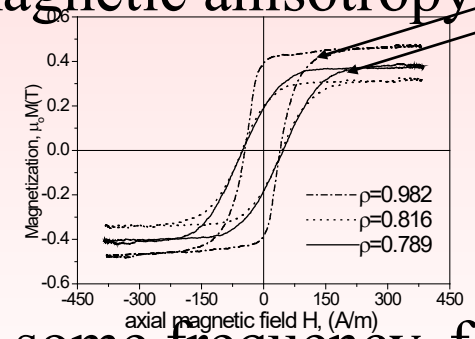
[1] R. S. Beach, A. E. Berkowitz, *Appl.Phys.Lett.*, **64**, 3652 (1994).

[2] L. V. Panina, K. Mohri, *Appl.Phys. Lett.*, **65**, 1185 (1994).

Typical GMI ratio curve



The maximum (if there is) corresponds to the transverse magnetic anisotropy field [2]

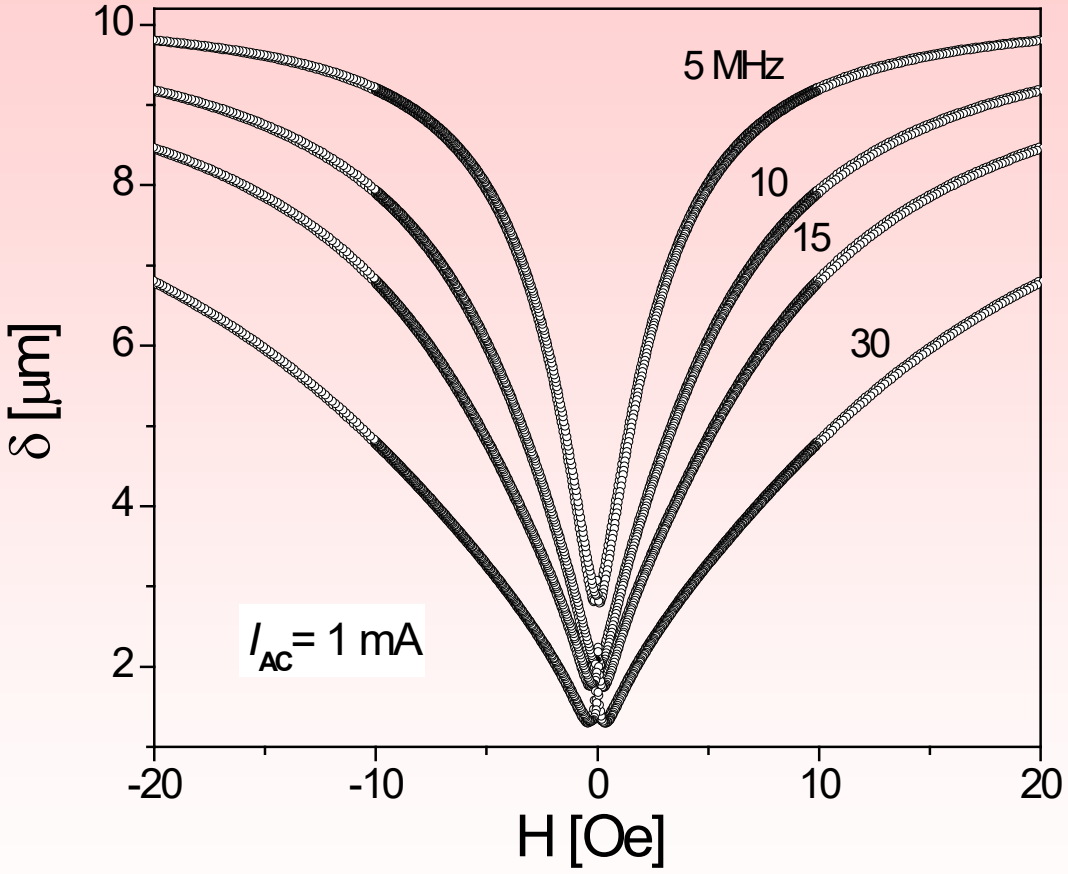


Until some frequency, f, the GMI ratio increases with f

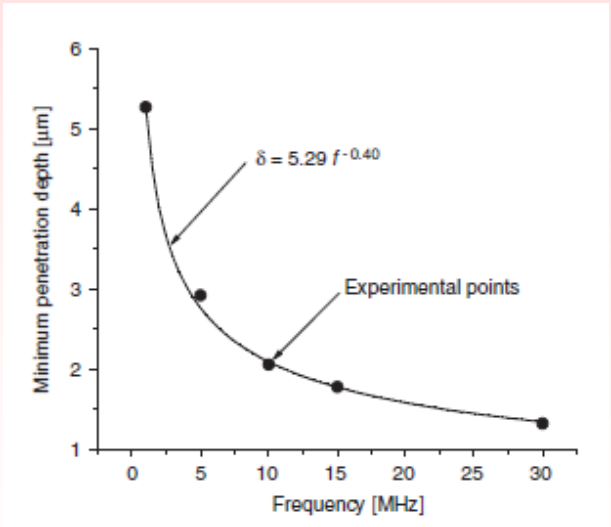
Changing the hysteretic properties we can modify the GMI effect

GMI effect

Calculated penetration depth vs. axial dc-field at various frequencies of ac-current in $Co_{67}Fe_{3.85}Ni_{1.45}Mo_{1.7}Si_{14.5}B_{11.5}$ microwire with metallic nucleus diameter 22.4 μm



Essentially surface effect. Thin surface layers are involved in the GMI process

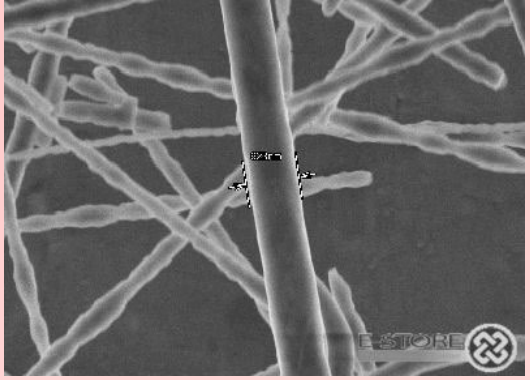


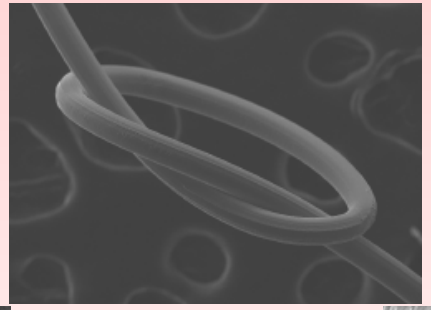
H. Lachowicz, M. Kuzminski, K.L. García, A. Zhukov and M. Vázquez, A. Krzyzevski, "Influence of Alternative circular magnetic field strength on magnetoimpedance of glass-coated micro-wire", J. Magn. Magn. Mater. 300 (2006), e88-e-92

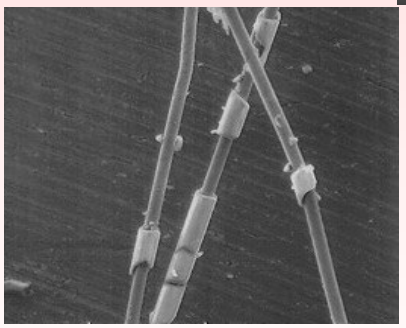
Magnetic wires:

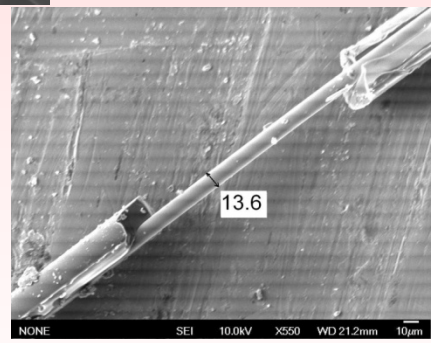
-Iron whiskers
-Wiegan magnetic wires
(CoVFe,1970-th)

Amorphous: milli
(since 80-th) micro } wires
nano









Properties

Fast domain walls propagation (after Sixtus-Tonks, 1936)

GMI effect (after E.P. Harrison, et.al *Nature*, 1935, vol. 135, p. 961

and later resurrected by Beach R and Berkowitz A (1994), *APL,* 64, 3652.
Panina L V and Mohri K (1994), *APL,* 65, 1189.)

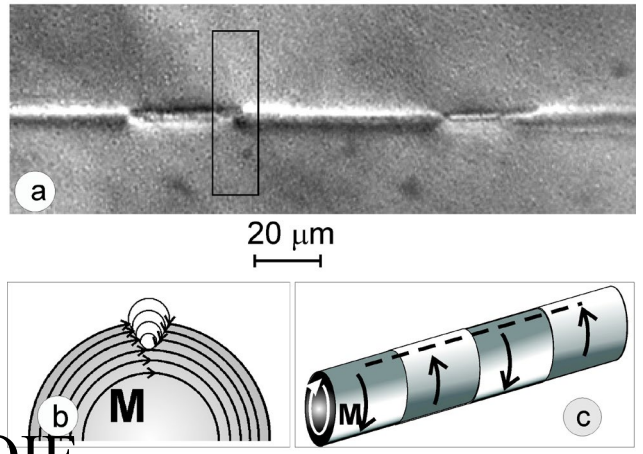
GMI effect

The ***Magneto-Impedance*** (MI) effect:
- extremely high sensitivity to external stimulus (magnetic field, stresses, temperature etc)
- relatively low-cost implementation
- suitable for integration into current technological process
- RT effect (not cryogenic)

Conditions of high GMI effect:
- high transversal magnetic permeability μ and magnetic softness
- high saturation magnetization M_s
- low resistivity ρ

Amorphous μ-wires with vanishing λ_s

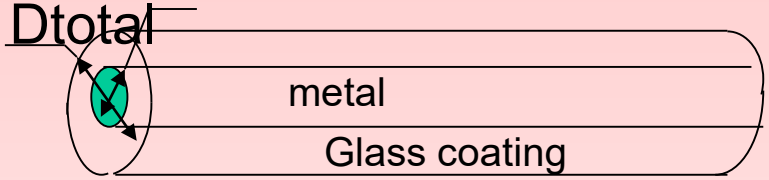
- **Reduced dimensions** (metallic nucleus diameter 0.2–100 μm, glass-coating 1–10 μm).
- **High homogeneity low cost** and almost continuous process (1 gram of the alloy allows to obtain about Km of the wire).
- **Excellent soft magnetic properties**

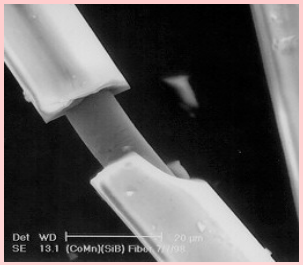


MOIF, Yu. Kabanov, A. Zhukov, et al APL. 87 (2005) p142507

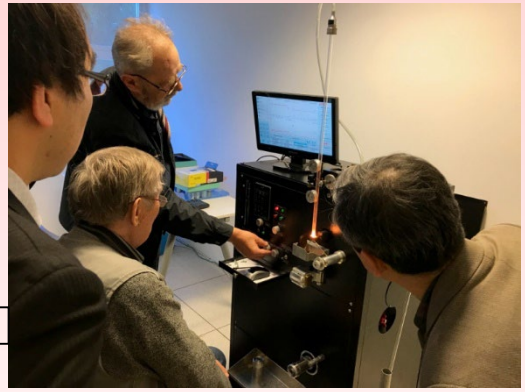
Glass coated amorphous magnetic microwires

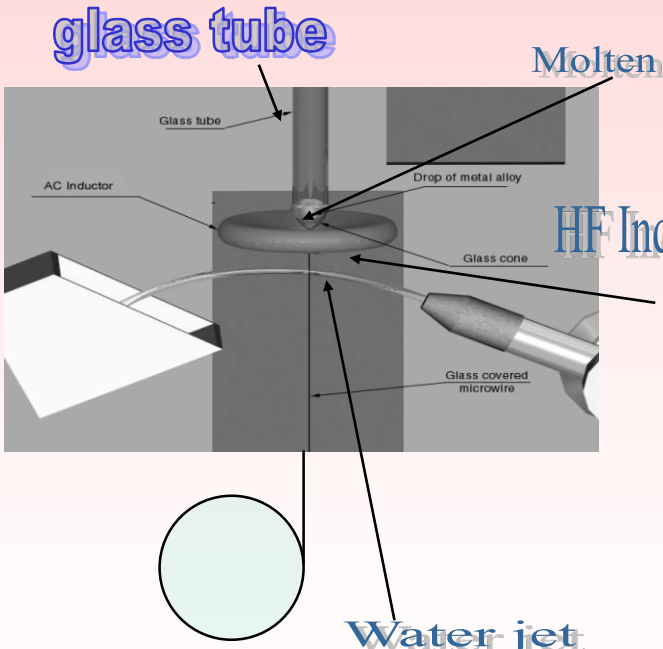
- Co, Ni , Fe and Cu rich compositions

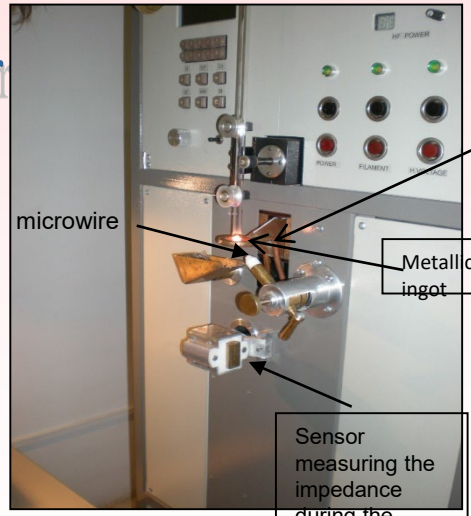




Typical dimensions:
Total diameter 1-120 μm
Metallic nucleus diameter 0.2-100 μm
Glass coating thickness 1-10 μm
Length - few km (up to 10 in 1 bobbin)



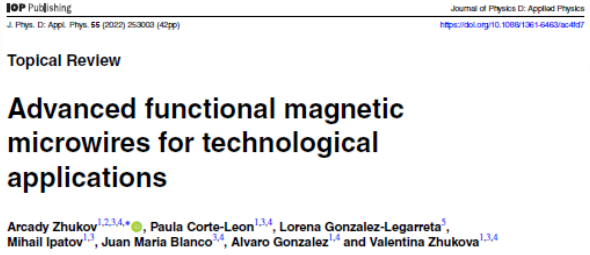




HF induct or

Advantages: (functionalities)

1. *Unexpensive and simple fabrication method*
2. *Excellent soft magnetic properties (if amorphous)*
3. *Magnetic bistability (DW propagation)*
4. *Thin dimensions (Raw materials saving)*
5. *Biocompatibility (glass-coating)*
6. *Better corrosion resistance (glass-coating)*
7. *Robust properties*


IOP Publishing Journal of Physics D: Applied Physics
J. Phys. D: Appl. Phys. 55 (2022) 253003 (42pp) https://doi.org/10.1088/1361-6463/ac4fd7

Topical Review

Advanced functional magnetic microwires for technological applications

Arcady Zhukov[1,2,3,4,•], Paula Corte-Leon[1,3,4], Lorena Gonzalez-Legarreta[5], Mihail Ipatov[1,3], Juan Maria Blanco[3,4], Alvaro Gonzalez[1,4] and Valentina Zhukova[1,3,4]

Experimental Facilities at UPV/EHU and Tamag

GMI features relevant for applications

1. Value of the effect
2. Linearity
3. Hysteresis
4. Time/temperature stability
5. Low dimensions (high frequency)

Magnetically soft low dimensional magnetic materials are needed

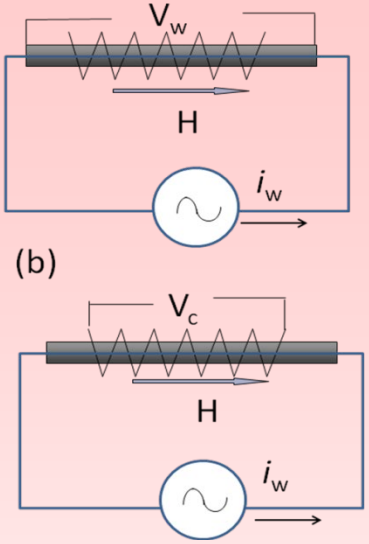
GMI effect (after E.P. Harrison, et.al *Nature*, 1935, vol. 135, p. 961 and later resurrected by Beach R and Berkowitz A (1994), *APL,* 64, 3652. Panina L V and Mohri K (1994), *APL,* 65, 1189.)

Measurements of GMI

Low-f impedance can be measured by the four-point method.

ΔZ/Z, is defined as:

ΔZ/Z = [(Z (H) - Z (H_{max})] / Z (H_{max})



$$V_w = \xi_{zz} i_w$$

$$i_Z \rightarrow h_\varphi \rightarrow [\hat{\mu}]$$

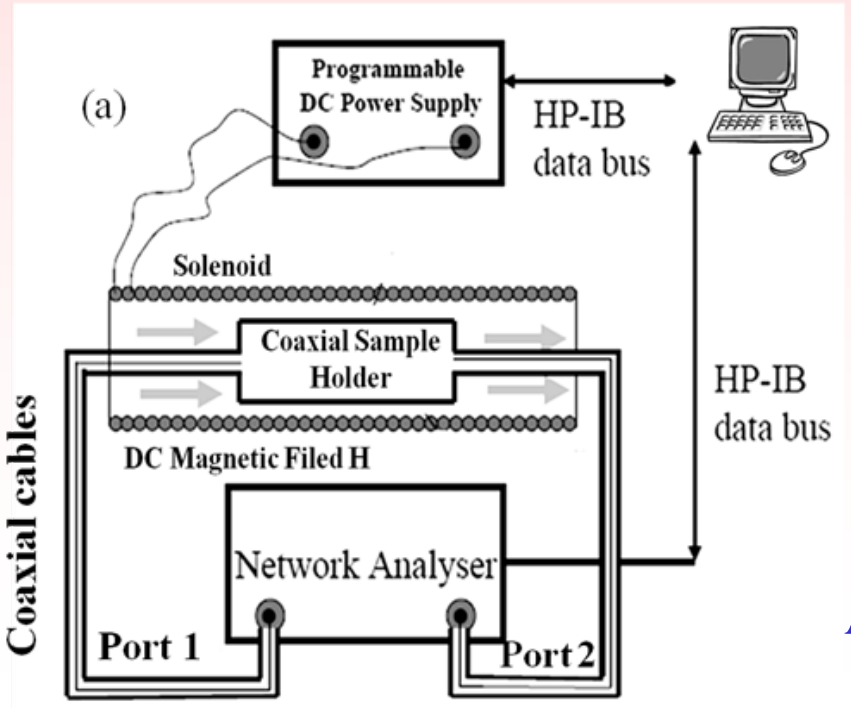
$$[1]: m_\varphi, m_r$$

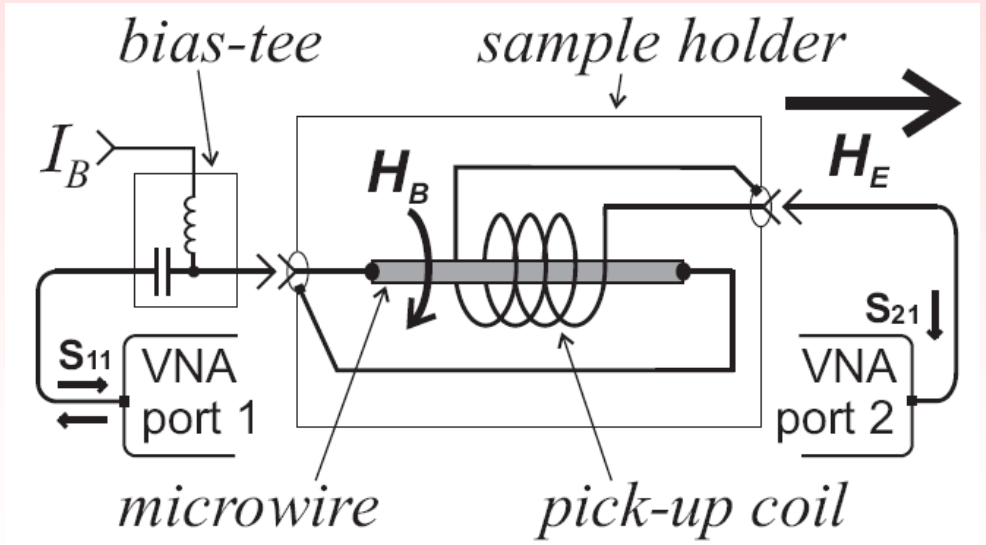
$$[2]: m_Z \rightarrow V_C$$

$$Z_{zz} \propto Z = \frac{1+S_{11}}{1-S_{11}} Z_0$$

$$V_c = \xi_{\phi z} i_w$$

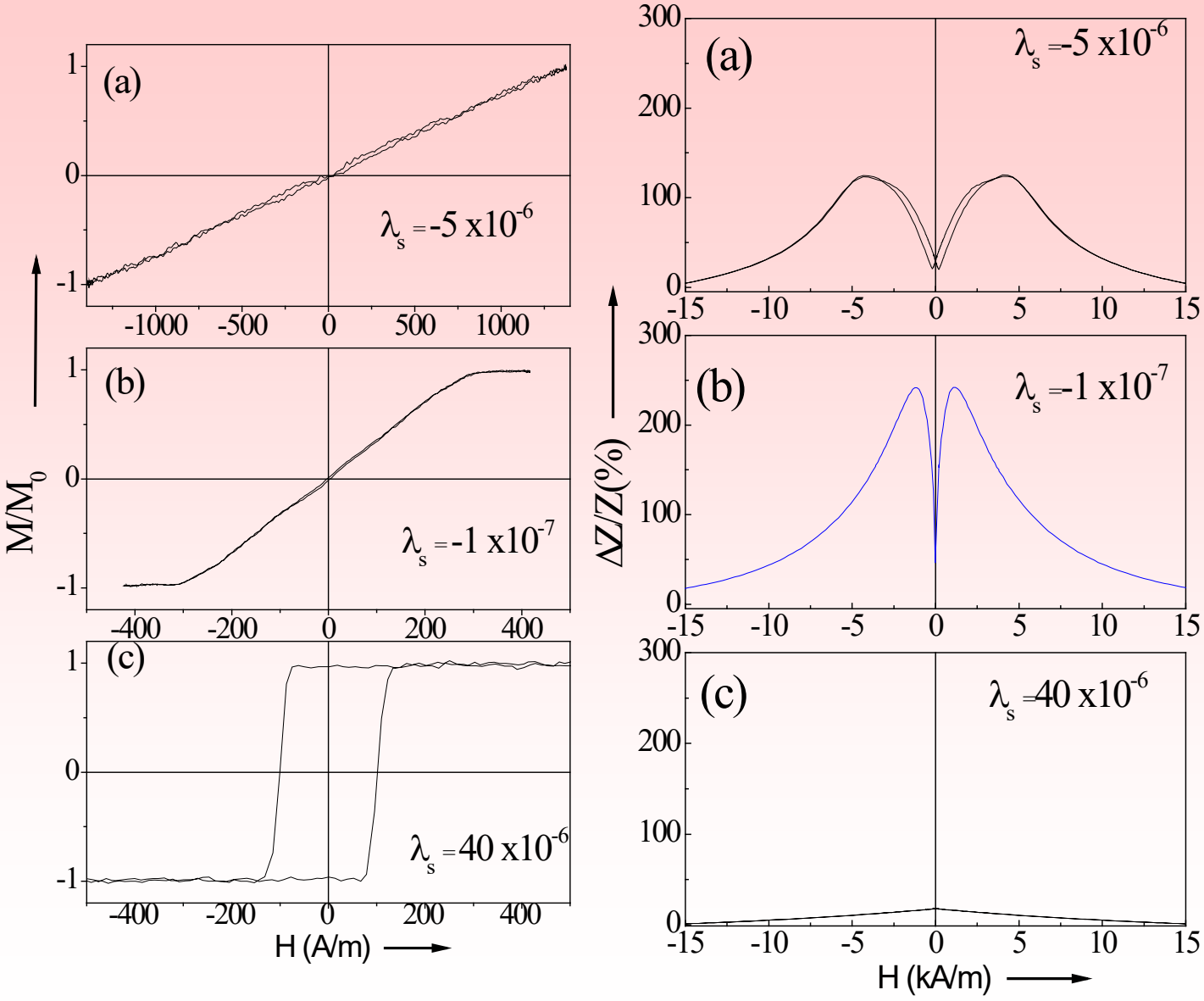
$$Z_{\varphi z} \propto V_c = S_{21}$$





The impedance was evaluated using Network Analyzer HP8753 at frequency between 10MHz -3GHz .

Magnetic properties and GMI effect of magnetic microwires



$\lambda s \approx -5 \times 10^{-6}$ $Co_{77.5}Si_{15}B_{7.5}$ (a),

$\lambda s \approx -1 \times 10^{-7}$ $Co_{67}Fe_4Ni_{1.4}Si_{14.5}B_{11.5}Mo_{1.7}$ (b)

$\mu = \Delta M / \Delta H$

High μ, low Hc

Good candidate for GMI

and

$\lambda s \approx 40 \times 10^{-6}$ $Fe_{75}B_9Si_{12}C_4$ (c) microwires

Hysteresis loops, shape and value of GMI ratio are different

Factors affecting soft magnetic propeties of amorphous alloys

Amorphous materials do not have defects typical for crystalline materials (dislocations, point defects...)

H. Kronmüller (1981) contributions in coercivity of amorphous materials:
Local anisotropy fluctuations (10^{-3}–1 me), $H_c(i)$
Clusters and chemical inhomogeneities (< 1 me), $H_c(SO)$
Surface defects and iregularities (< 5 Me), $H_c(surf)$
Local srtuctural defects (0.1-10 me), $H_c(rel)$
Pinning of DW on defects in magnetostrictive alloys (10-100 Me), $H_c(s)$

$$H_c(total)=[\ H_c(s)^2 + H_c(surf)^2 + H_c(SO)^2 + H_c(i)^2\ ]^{1/2} + H_c(rel)$$

или

$$H_c(total)= H_c(s) + H_c(surf) + H_c(SO) + H_c(i) + H_c(rel)$$

Magnetostriction
Anisotropy (stresses)
Clusters and chemical inhomogeneities (nanocrystallization)
Defects (surface)

Magnetoelastic energy

$K_{me} \approx 3/2\ \lambda_s \sigma_i$, :

Magnetostriction λ_s -determines by the chemical composition

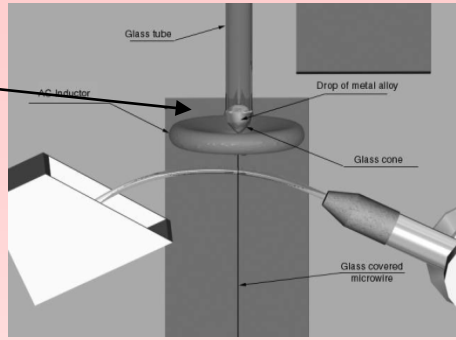
$\sigma = \sigma_{i} + \sigma_a$

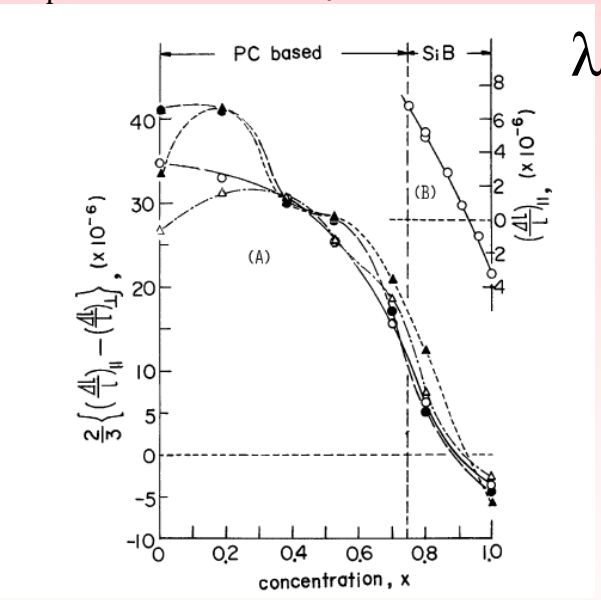
σ_a - applied stresses

σ_i -determines by the ratio $\rho = d/D$

Internal stresses in composite microwires

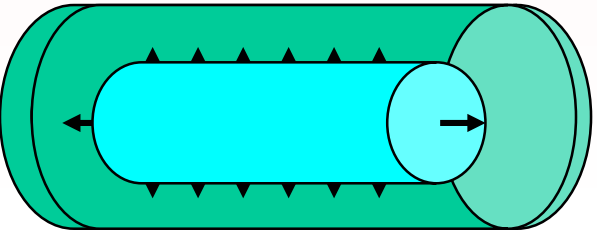
Stress appears at simultaneous solidification of metallic alloy inside the glass coating





λ_s

$\sigma = f(\rho)$, $\rho = d/D$



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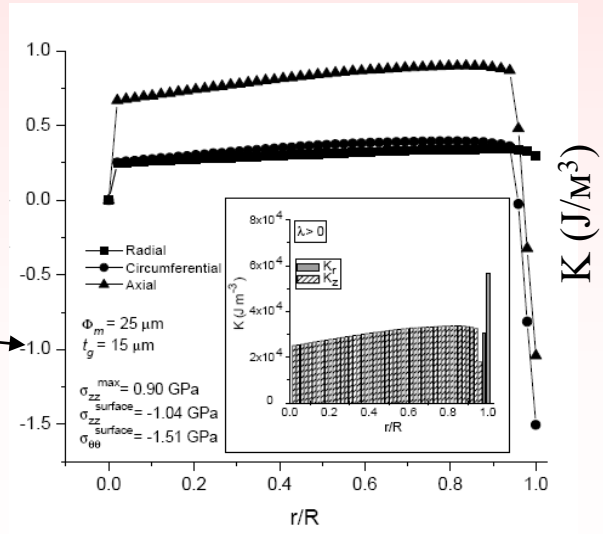
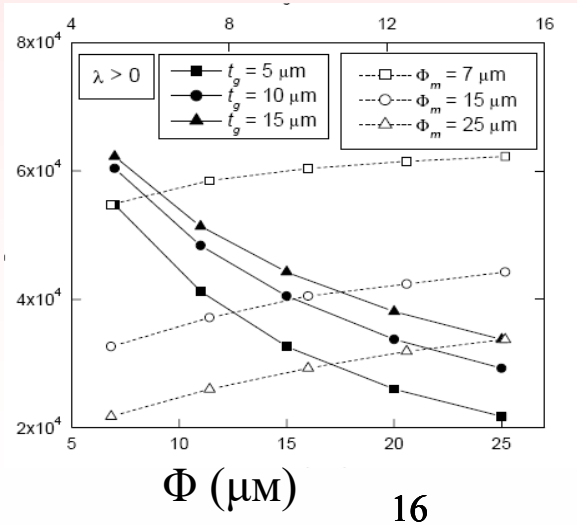
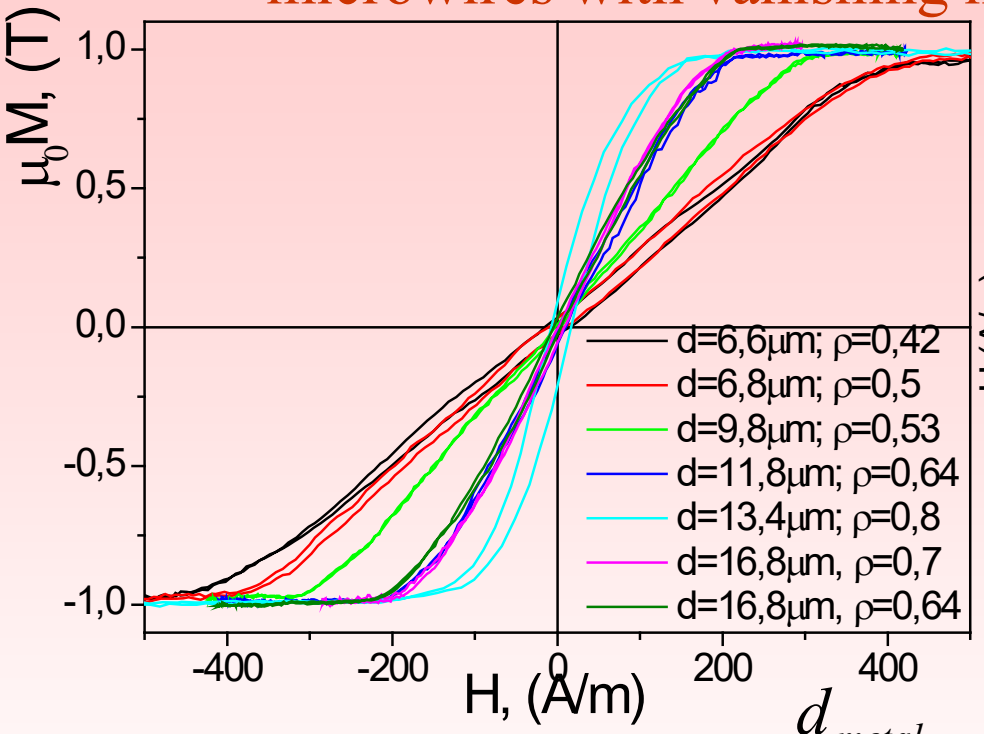


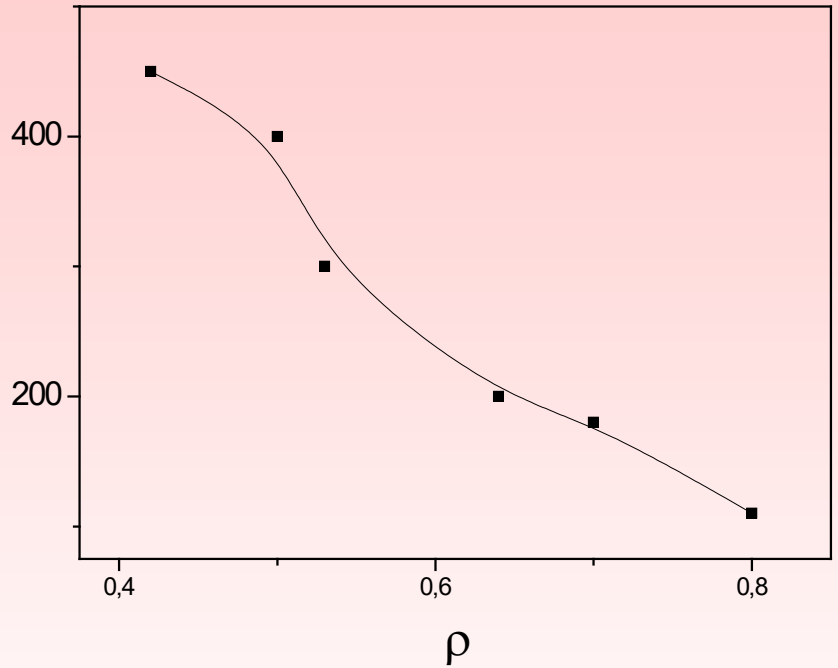


H. Chiriac, T.-A. Ovari, A. Zhukov, J. Magn. Magn. Mater. 254–255 (2003) 469–471

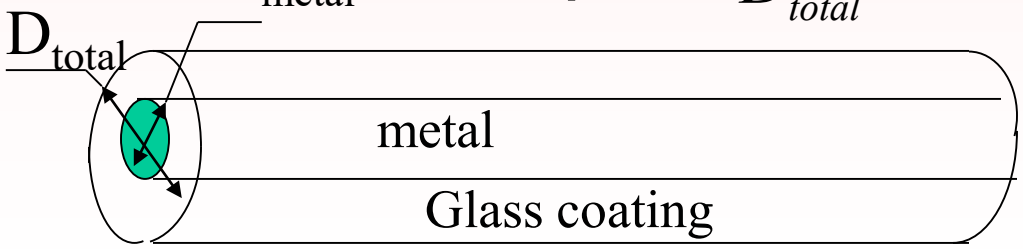
TAILORING OF GMI EFFECT AND MAGNETIC PROPERTIES

Effect of the samples geometry on the hysteresis loops of Co-rich microwires with vanishing magnetostriction constant.





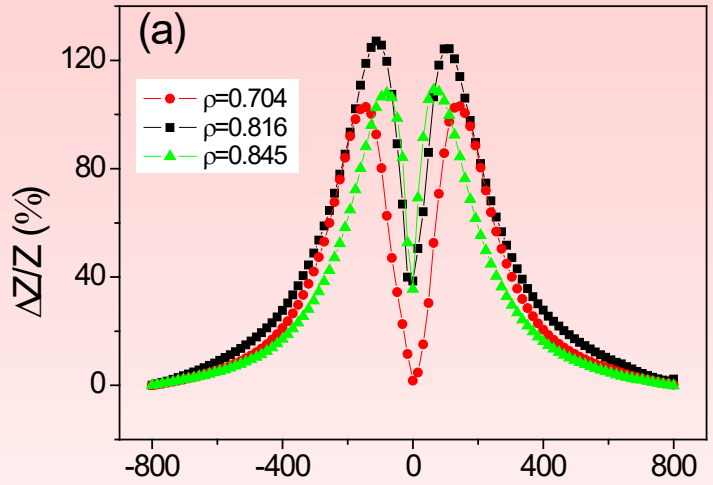
$$\rho = \frac{d_{metal}}{D_{total}}$$

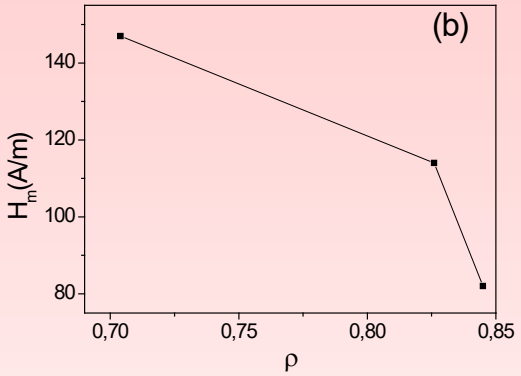


Correlation with magnetic anisotropy

Effect of internal stresses through the geometry

Effect of ρ–ratio on GMI effect in $Co_{67,05}Fe_{3.85}Ni_{1.4}B_{11.33}Si_{14.47}Mo_{1.69}$ microwire samples with different ρ–ratios (a) and dependence of field of maximums on ρ–ratio (b).



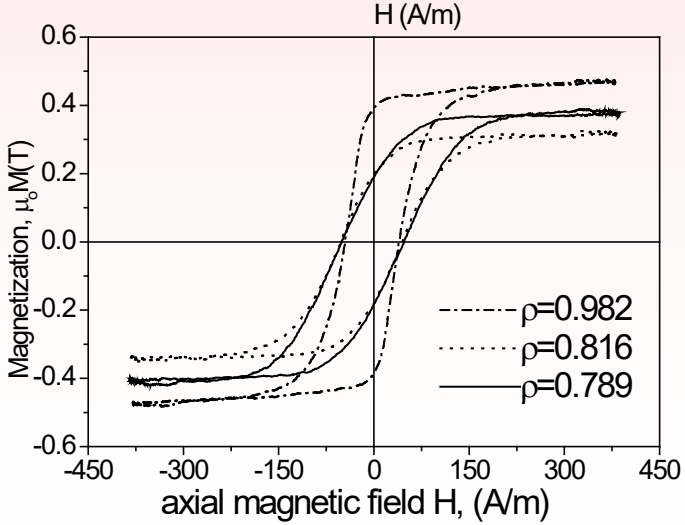


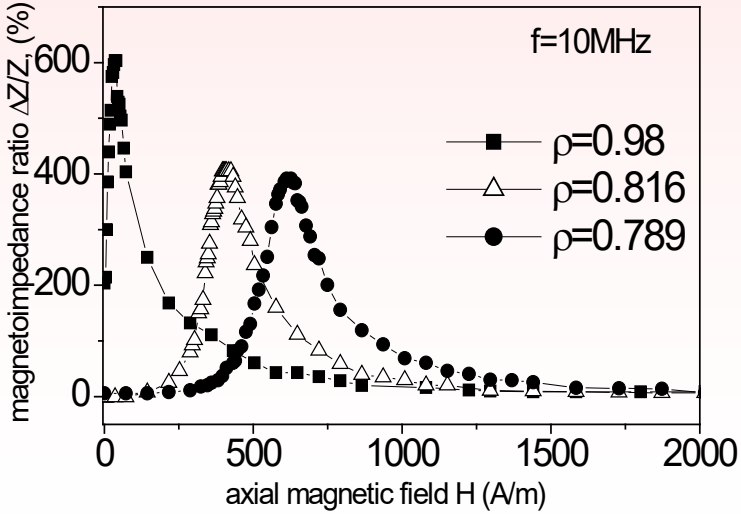
Possibilities:

tailoring of GMI effect in Co-rich glass coated microwires by

-Joule heating.

-Choosing adequate geometry





Magnetoelastic energy

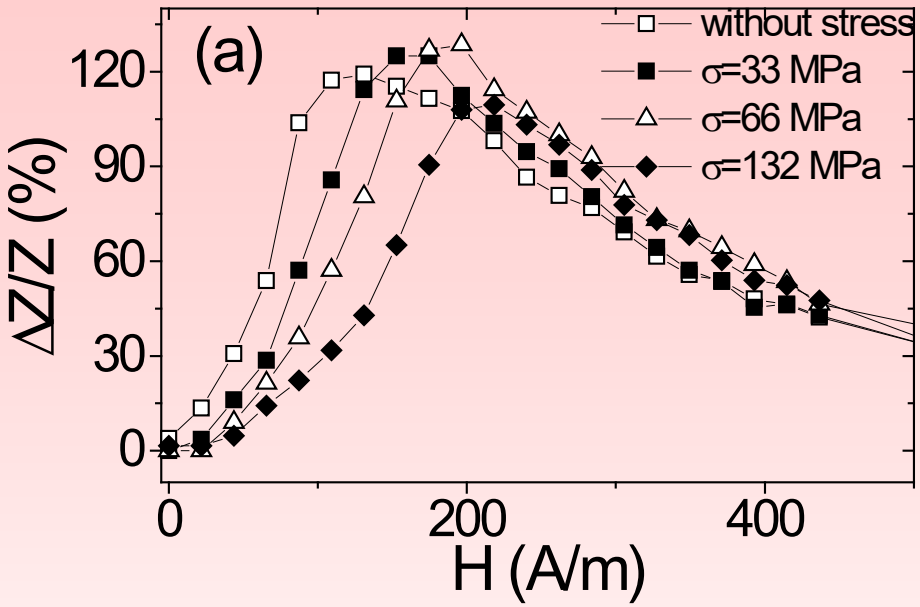
$K_{me} \approx 3/2\ \lambda_s \sigma$,

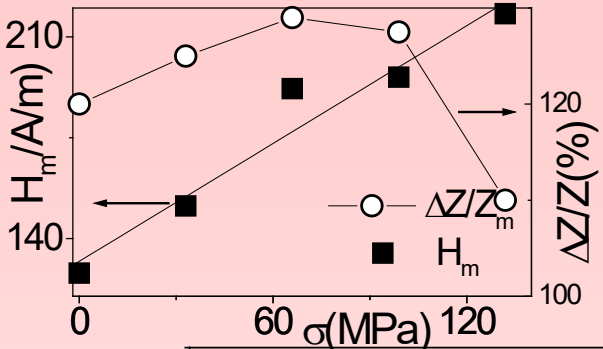
λ_s – f (chemical composition)

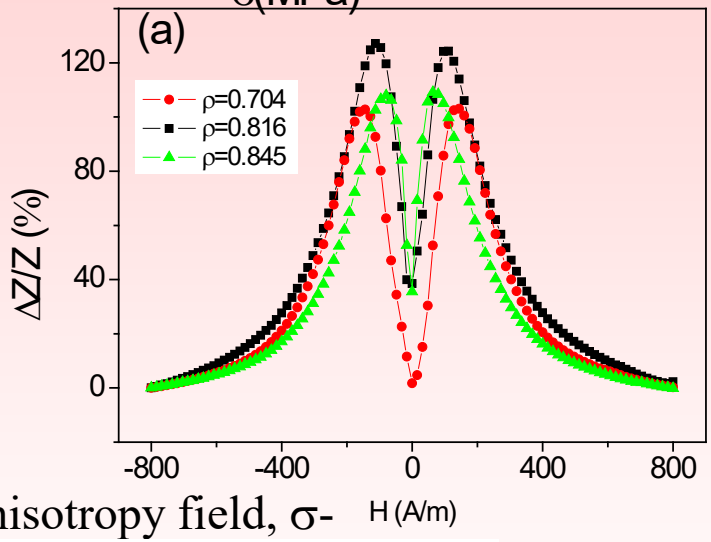
$\sigma = \sigma_a + \sigma_i$

$Co_{67}Fe_{3.85}Ni_{1.45}B_{11.5}Si_{14.5}Mo_{1.7}$

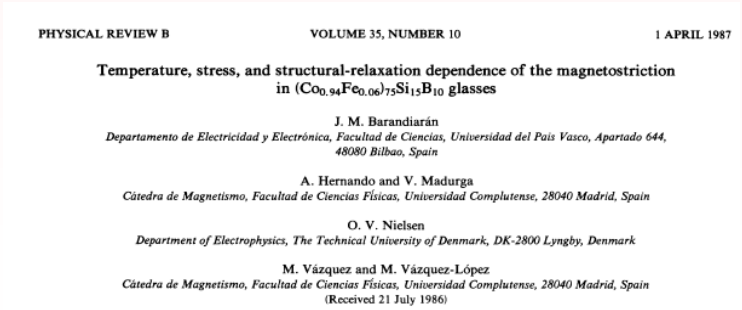
Are stresses always reduce GMI?







The magnetostriction constant changes with the stress:
$\lambda s = (\mu oMs/3)(dHk/d\sigma)$,
where μoM is the saturation magnetization, Hk- magnetic anisotropy field, σ- stresses.



PHYSICAL REVIEW B VOLUME 35, NUMBER 10 1 APRIL 1987

Temperature, stress, and structural-relaxation dependence of the magnetostriction in $(Co_{0.94}Fe_{0.06})_{75}Si_{15}B_{10}$ glasses

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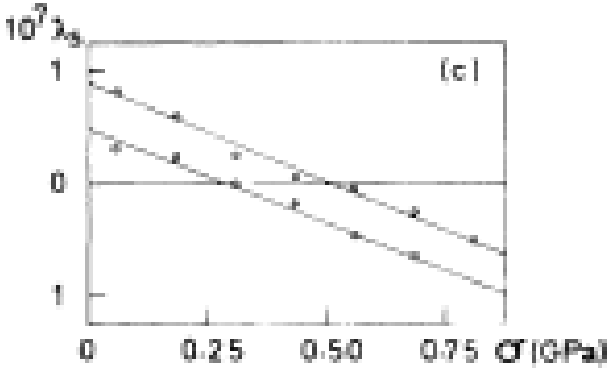
(Received 21 July 1986)

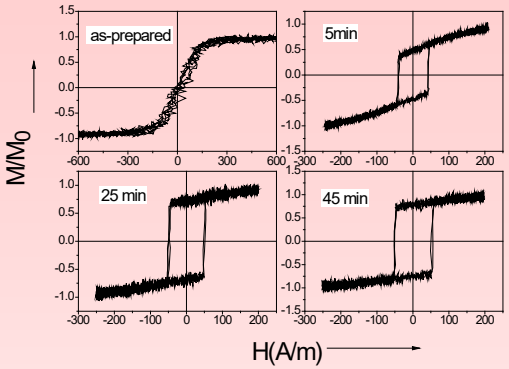


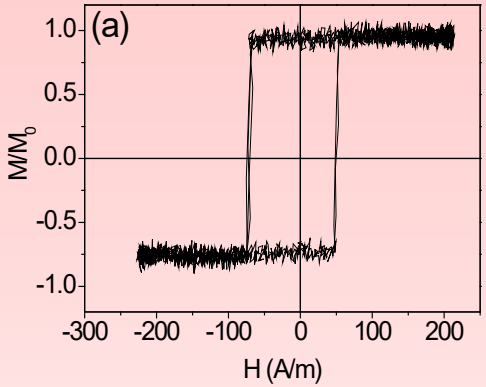
Stress relaxation?

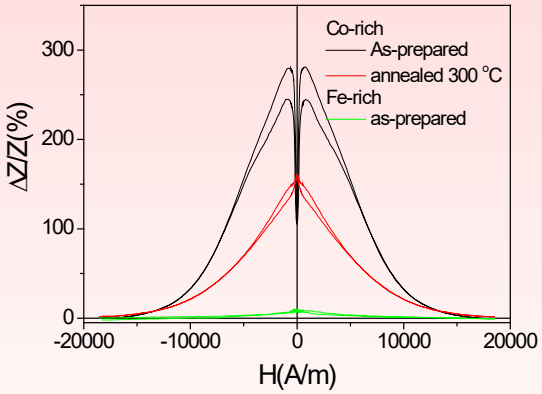
Annealing

Annealing:
Hysteresis loops and DW dyamics
-Fe-rich- enhancement of DW velocity
-Co-rich –induced magnetic bistability

Co-based (λs<0)

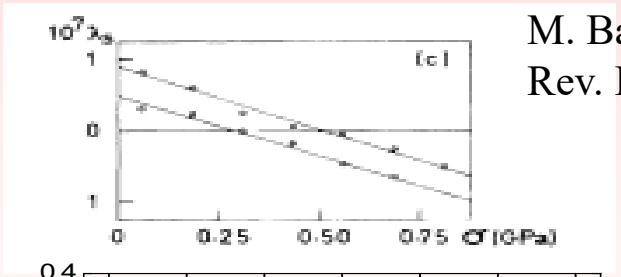




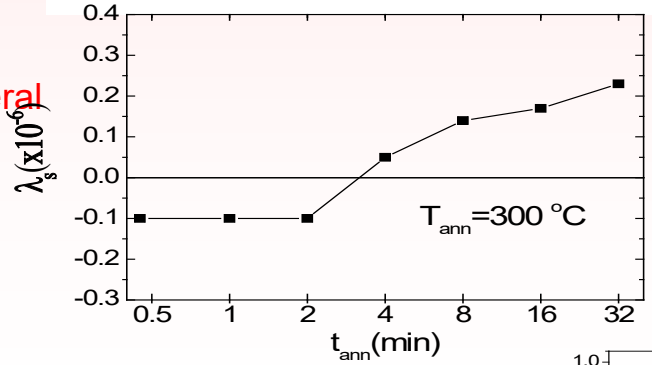


Origin of annealling induced changes in Co-rich microwires

M. Barandiaran, et.all, Phys. Rev. B 35 (1987) 5066-5071.

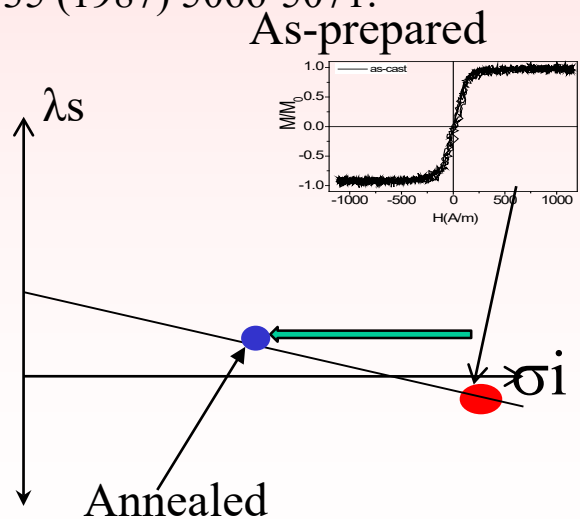


Such hardedning was observed in several Co-rich microwires



GMI: For GMI is not a solution!

Co-rich – decrease



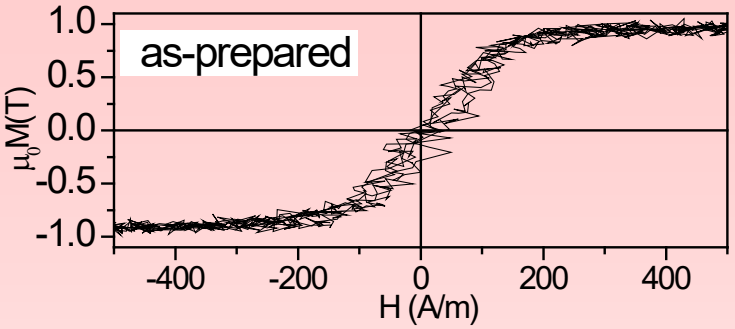
A. ZHUKOV, et.al J. ELECTRONIC MATERIALS (2015)
DOI: 10.1007/s11664-015-4011-2

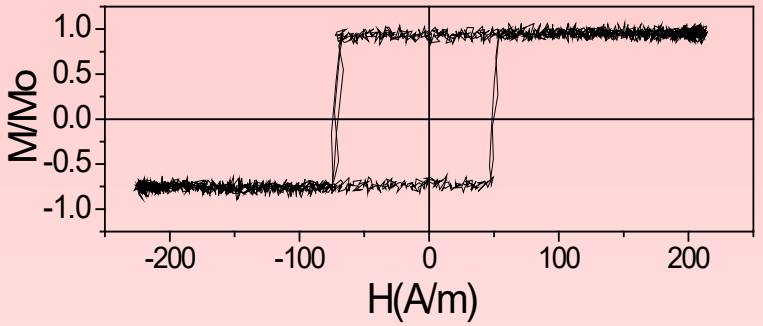
Magnetostriction

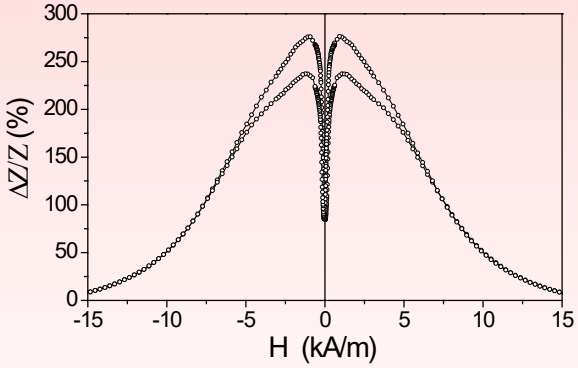
$\lambda \leq 0$

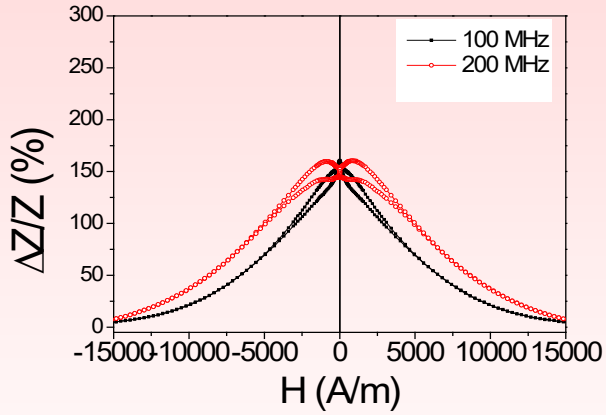
$\Lambda \geq 0$

$Co_{69.2}Fe_{4.1}B_{11.8}Si_{13.8}C_{1.1}$ microwire









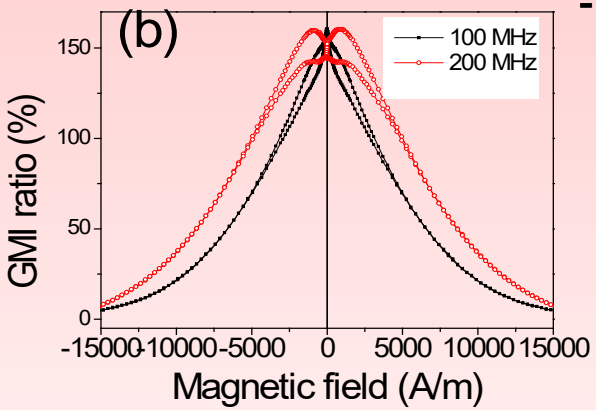
Composition	treatment	ρ=d/D	$\lambda_s \times 10^6$
$Co_{68.7}Fe_4Ni_1B_{13}Si_{11}Mo_{2.3}$	As-prepared	0.72	-1.05
$Co_{68.7}Fe_4Ni_1B_{13}Si_{11}Mo_{2.3}$	Annealed (300 °C, 30 min)	0.72	0.42

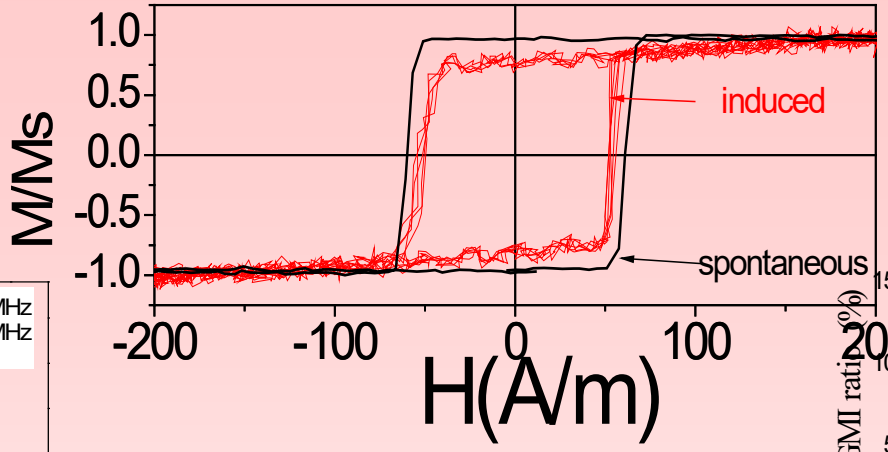
Recent SAMR Measurements

A.Zhukov, et.al. J.Magn. Magn. Mater., 383 (2015) 232–236

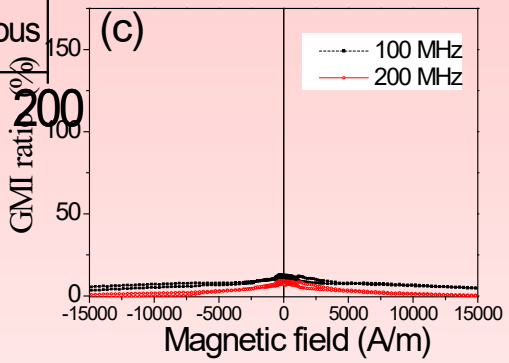
Comparison of hysteresis loops and GMI effect in Co and Fe rich microwires

Co-rich



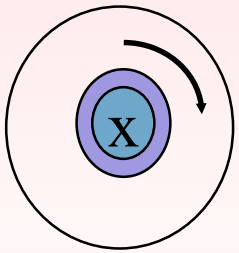


Fe-rich



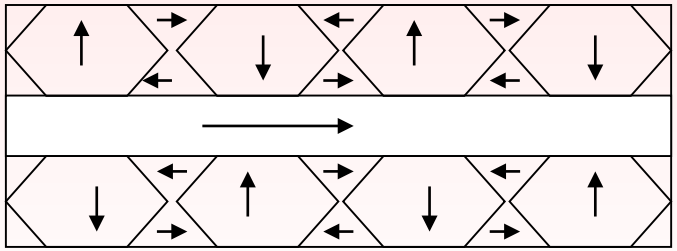
$\lambda \approx o$

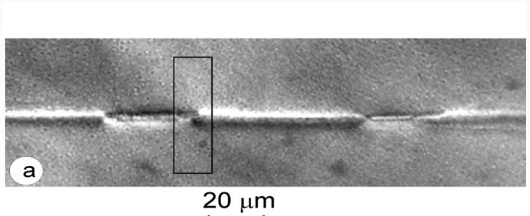
$\lambda > o$

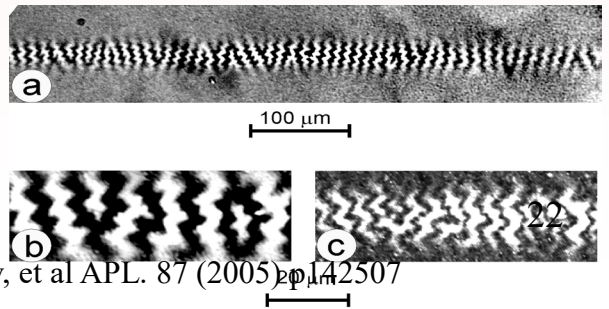


High GMI and magnetic bistability be relaized in thes same sample!

We can also assume that outer domain shall of the annealed Co-rich microwire exhibiting both fast DW propagation and GMI effect has high circumferential magnetic permeability. This assumption is deduced by much higher GMI ratio of anneled Co-rich microwires as-compared with Fe-rich amorphous microwires.







MOIF, Yu. Kabanov, A. Zhukov, et al APL. 87 (2005) p.142507

22

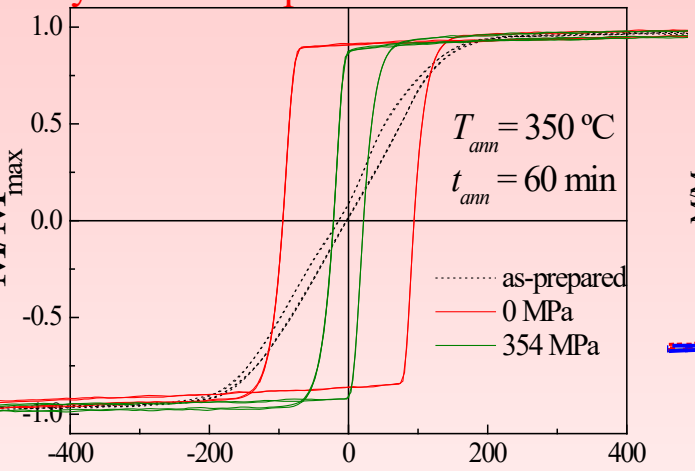
Induced anisotropy

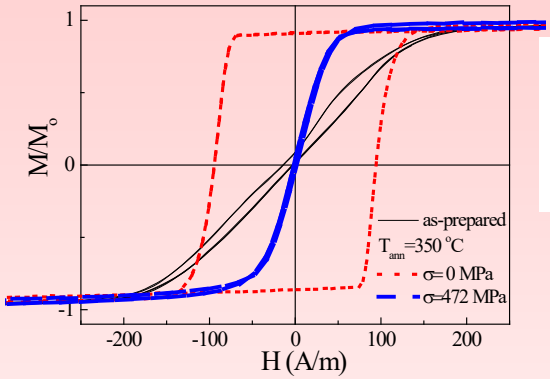
Stress-annealing

$Fe_{3.6}Co_{69.2}Ni_1B_{12.5}Si_{11}Mo_{1.5}C_{1.2}$

Co-rich microwires

Hysteresis loops of studied Co-rich microwires stress-annealed at different conditions.

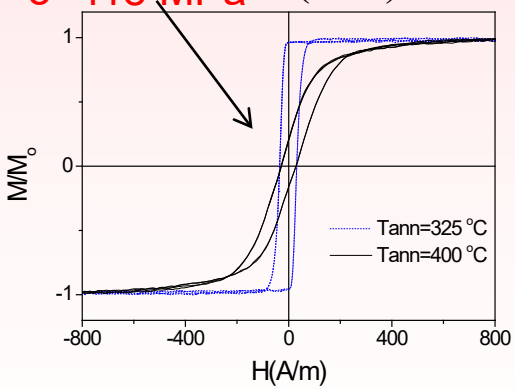


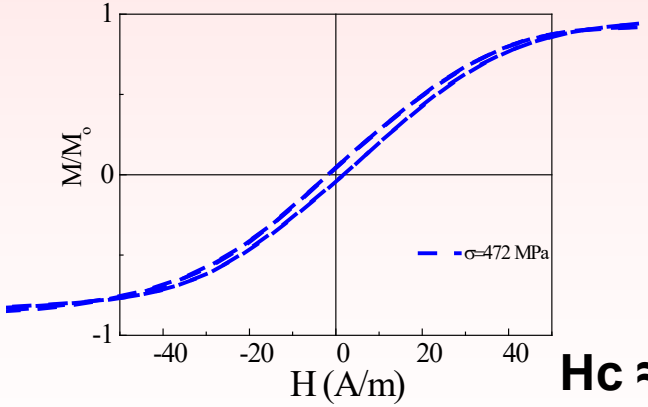


comparison of hysteresis loops of as-prepared, annealed at T_{ann}=350 ºC and stress-annealed at T_{ann}=350 ºC and σ =472 MPa microwires.

Better magnetic softness

σ=118 MPa





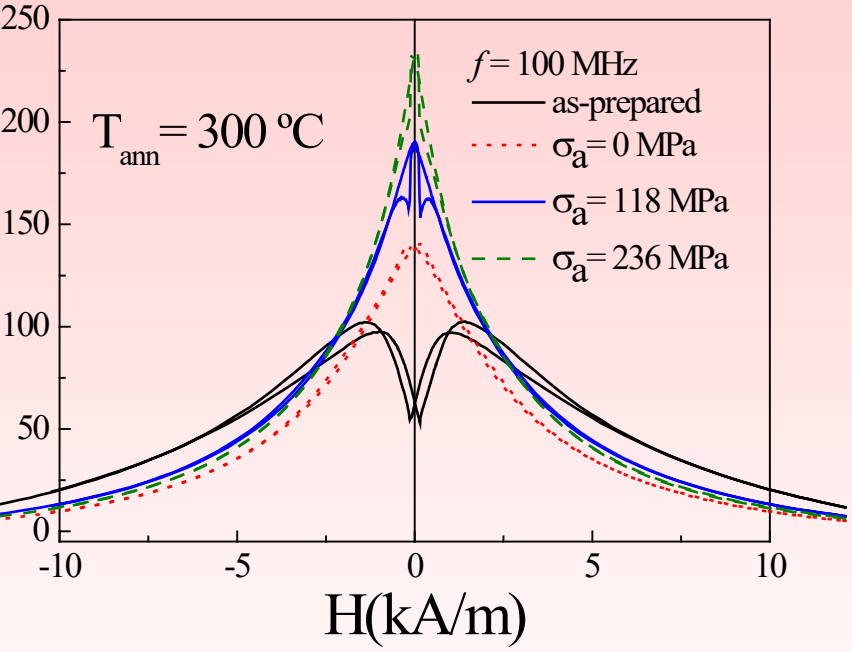
Hc ≈2A/m

At high enough Tann or σ a transverese anisotropy can be induced

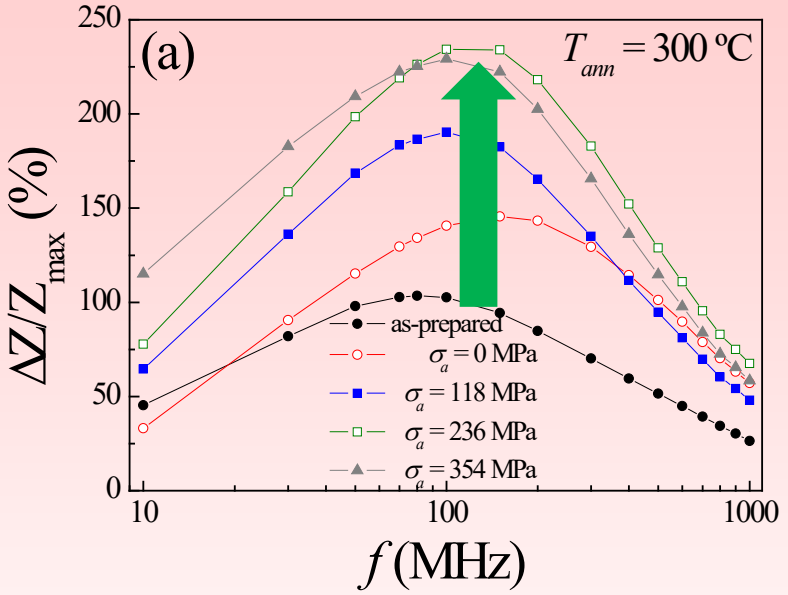
L. Gonzalez-Legarreta, P. Corte-León, V. Zhukova, M. Ipatov, J.M. Blanco, M. Churyukanova, S. Taskaev, A. Zhukov, Route of magnetoimpedance and domain walls dynamics optimization in Co-based microwires, J. Alloys Compound. Vol. 830 (2020) 154576, doi: https:// doi.org/10.1016/j.jallcom.2020.154576

Stress-annealing Co-rich microwires

$\Delta Z/Z(H)$ dependences of as-prepared and stress-annealed at T_{ann} = 300 ºC samples at different σ_a measured at 100 MHz.



$\Delta Z/Z_{max}(f)$ evaluated for different σ_a –values for the samples annealed at T_{ann} = 300 ºC

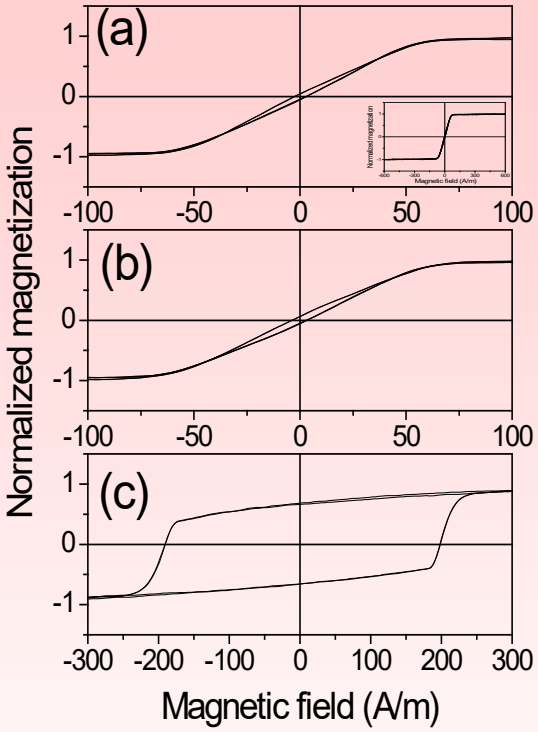


SA allows more remarkable GMI improvement

Origin of MI rising: Right magnetic anisotropy in thin surface layer?

L. Gonzalez-Legarreta, P. Corte-León, V. Zhukova, M. Ipatov, J.M. Blanco, M. Churyukanova, S. Taskaev, A. Zhukov, Route of magnetoimpedance and domain walls dynamics optimization in Co-based microwires, J. Alloys Compound. Vol. 830 (2020) 154576, doi: https:// doi.org/10.1016/j.jallcom.2020.154576

Tailoring by Joule heating



Hysteresis loops of as-prepared (a), Joule heated at 30 mA for 40 min (b) and annealed at conventional furnace at 300° C for 60 min studied microwire.

Looks that Joule heating prevents magnetic hardening reported for Co-based microwires after conventional annealing

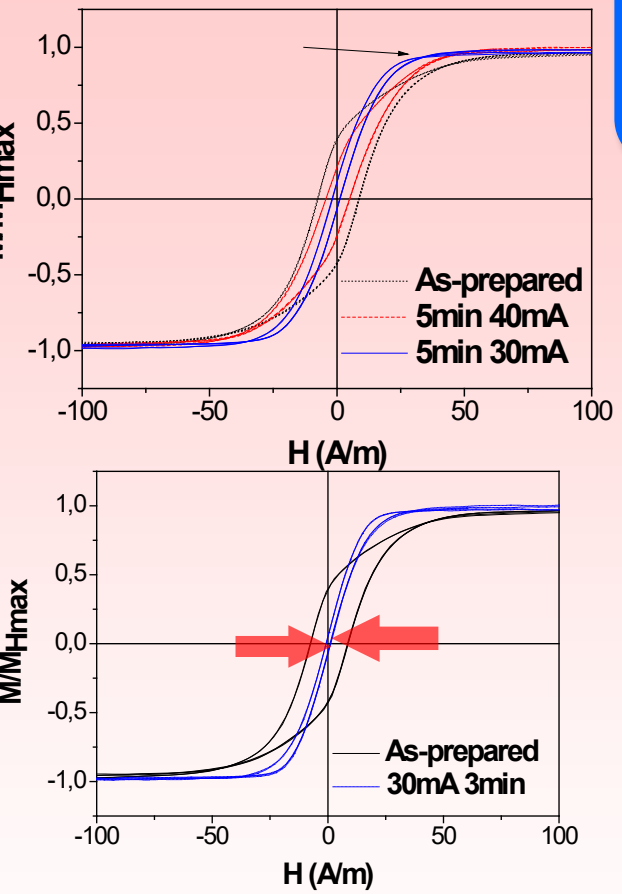
V. Zhukova, J.M. Blanco, M. Ipatov, M. Churyukanova, J. Oliver, S. Taskaev, A. Zhukov, Optimization of high frequency magnetoimpedance effect of Fe-rich microwires by stress-annealing, Intermetallics, 94 (2018) 92-98

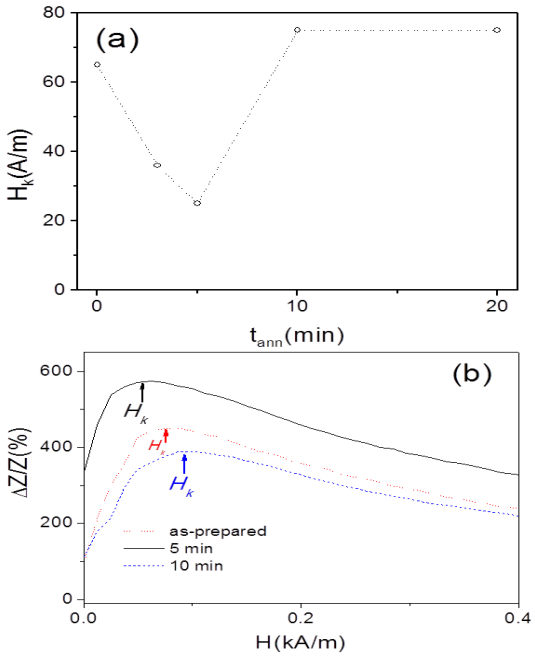
Induced anisotropy Tailoring by Joule heating

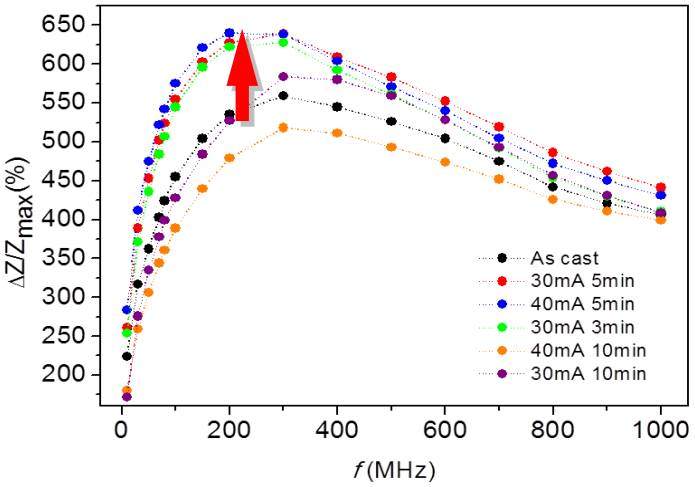
- Internal stresses relaxation
- Induced magnetic anisotropy

GMI ratio up to 650%

Hk=25A/m

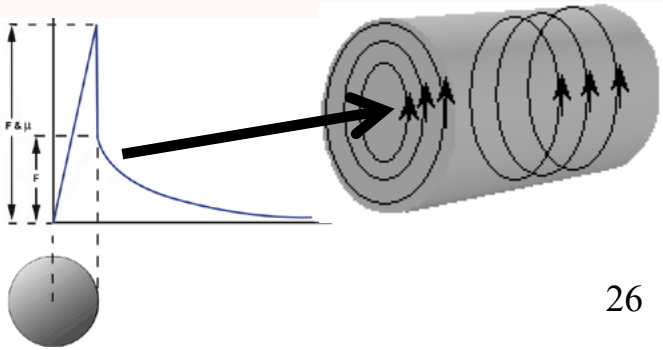






Hc=2 A/m

Circular magnetic field by current:



V. Zhukova, et.al, Optimization of high frequency magnetoimpedance effect of Fe-rich microwires by stress-annealing, Intermetallics, 94 (2018) 92-98

Looking for the highest GMI effect

Hysteresis loops of as-prepared (a) and annealed at Tann= 275 °C (b), Tann= 300 °C (c) and Tann= 350 °C (d) Co72Fe4B13Si11 sample (40 μm).

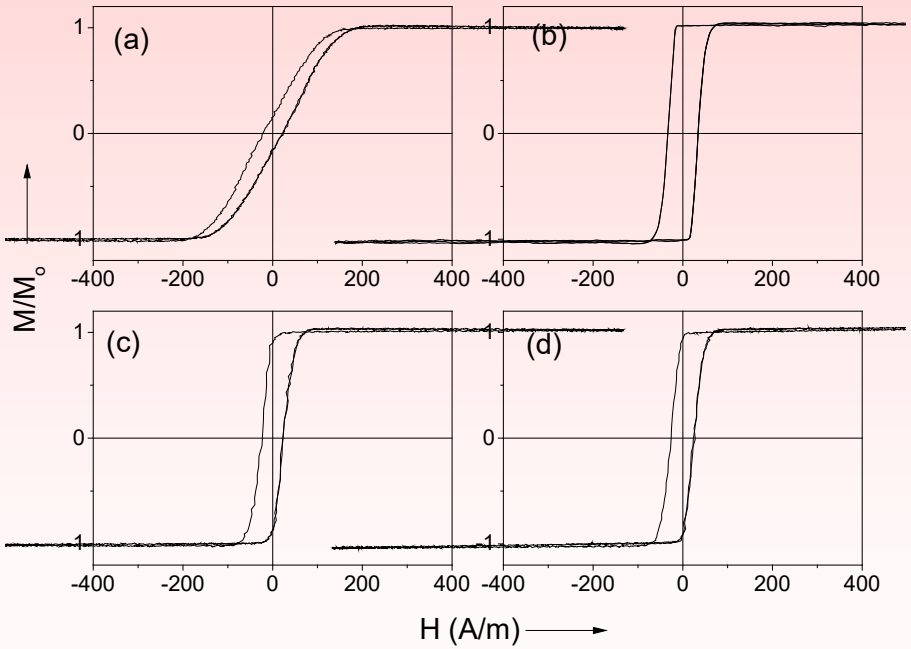
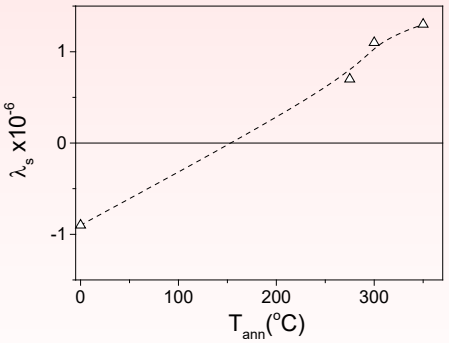


Table 1. The magnetostriction coefficient of as-prepared and annealed $Co_{72}Fe_4B_{13}Si_{11}$ microwires.

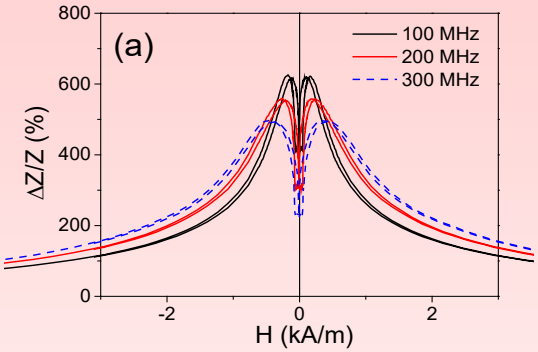
Sample	l_s (x10^{-7})
As-prepared	-9
Annealed at 275 °C	+7
Annealed at 300 °C	+11
Annealed at 350 °C	+13

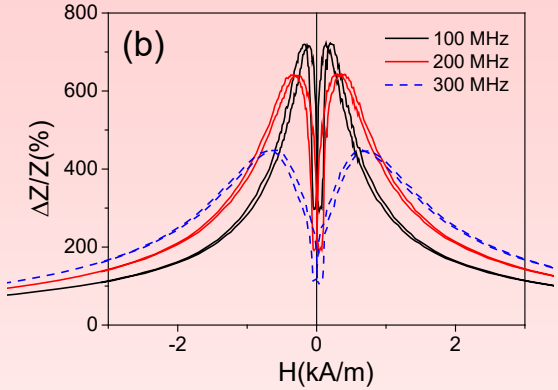


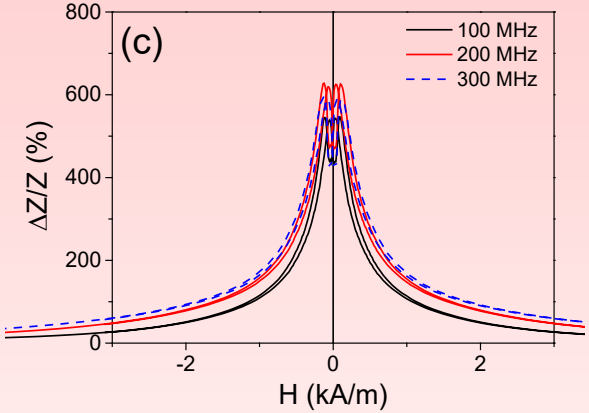
Corte –León P, Gonzalez A, Zhukova V, Ipatov M, Blanco J M, Zhukov A, Optimization of giant magnetoimpedance effect in Co-rich glass-coated microwires by annealing, J. Alloys Compound, Vol. 999 (2024) p. 175023

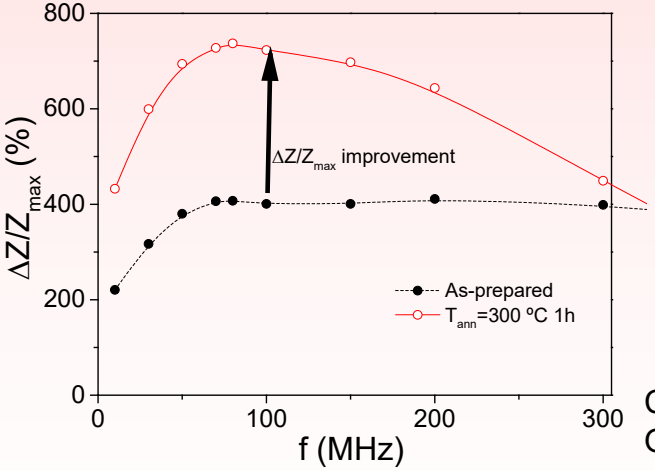
Looking for the highest GMI effect

GMI of annealed at Tann= 350 ºC (a); Tann= 300 ºC (b) Tann= 275 ºC (c) Co72Fe4B13Si11 sample (40 μm).



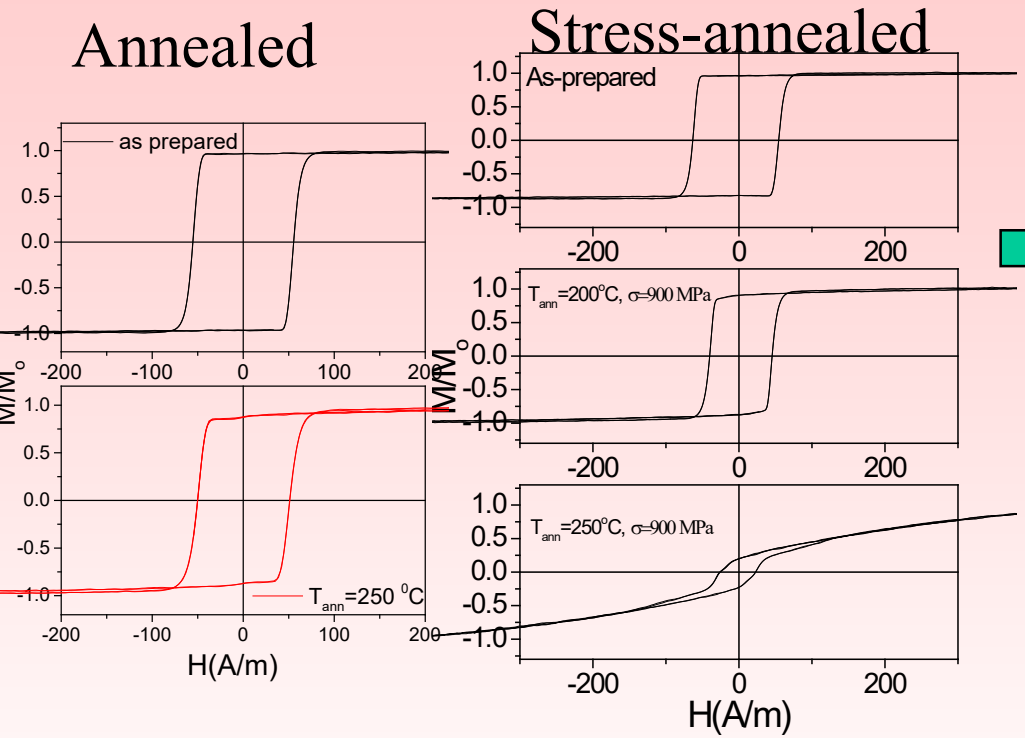


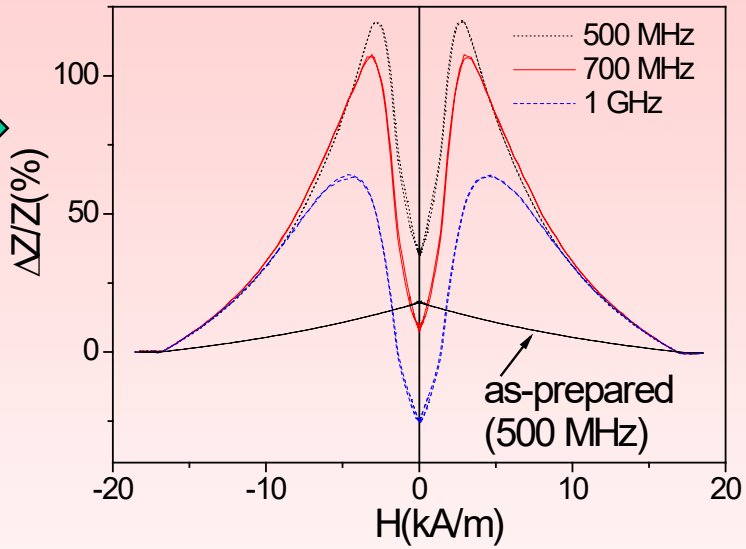


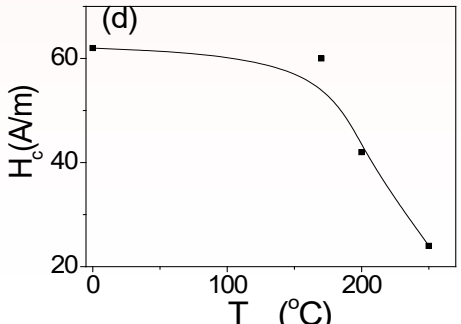


Corte –León P, Gonzalez A, Zhukova V, Ipatov M, Blanco J M, Zhukov A, 2024, Optimization of giant magnetoimpedance effect in Co-rich glass-coated microwires by annealing, J. Alloys Compound, Volume 999, p. 175023

Stress-annealing induced Anisotropy and GMI in Fe-rich microwires





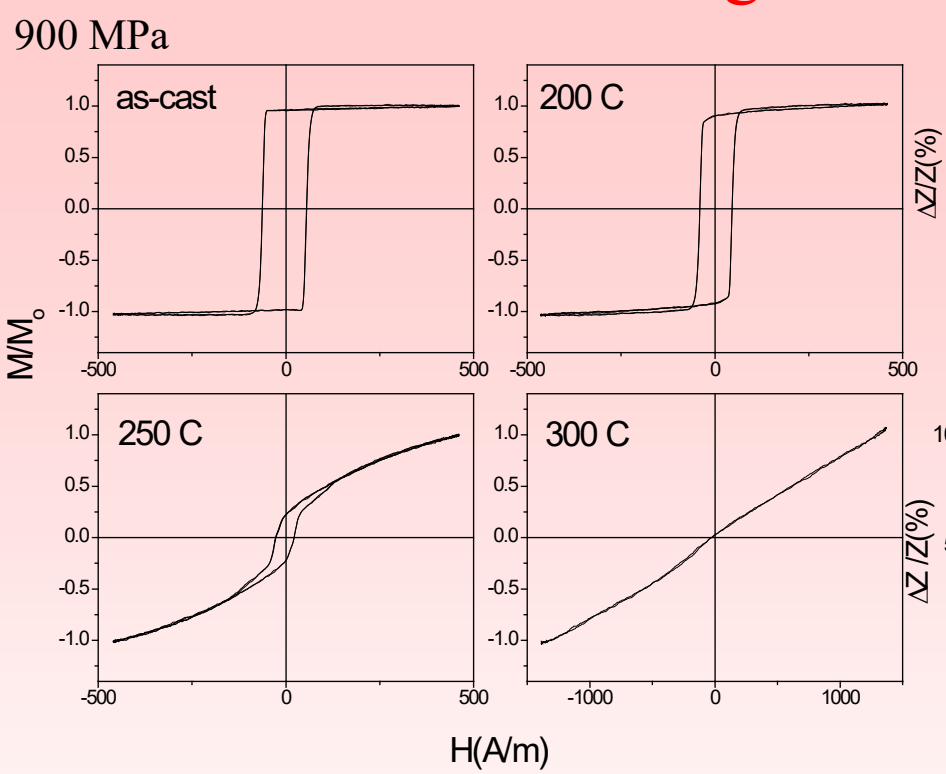


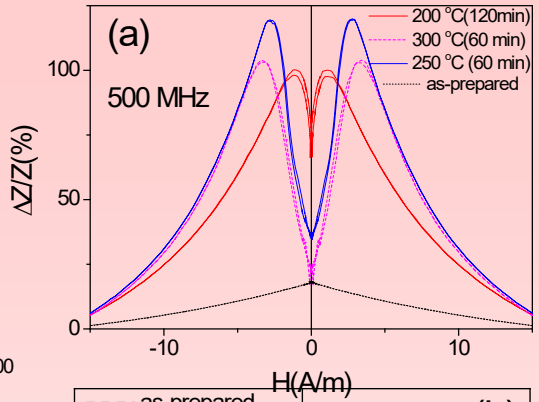
i)considerable transversal magnetic anisotropy and magnetic softening
ii) existence of maximum on *ΔZ/Z (H)* dependences reflects transversal magnetic anisotropy of stress-annealed

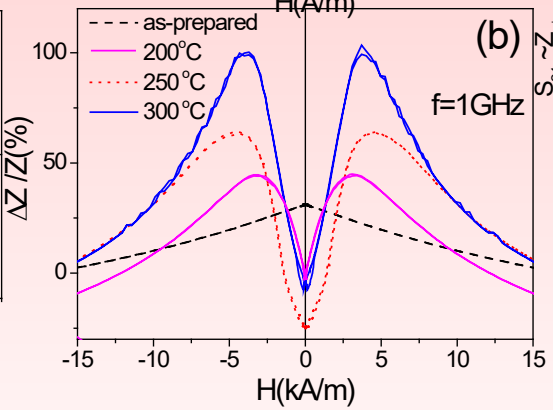
V. Zhukova, M. Ipatov, A. Talaat, J. M. Blanco, M. Churyukanova and A. Zhukov, *J. Alloys Compound (accepted , 2016)*http://dx.doi.org/10.1016/j.jallcom.2016.10.178;
V. Zhukova, J.M. Blanco, M. Ipatov, J. Gonzalez, M. Churyukanova A., Zhukov, Scripta Materialia Vol. 142, 1 January 2018, 10–14, doi: 0.1016/j.scriptamat.2017.08.014

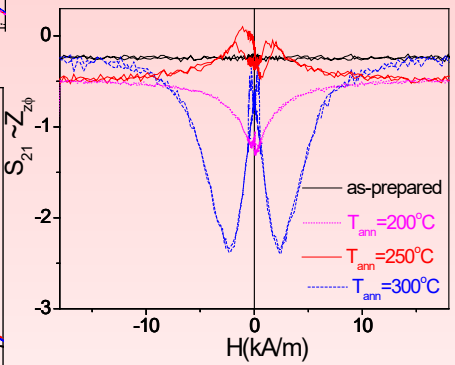
Ways to improve GMI in Fe-rich microwires

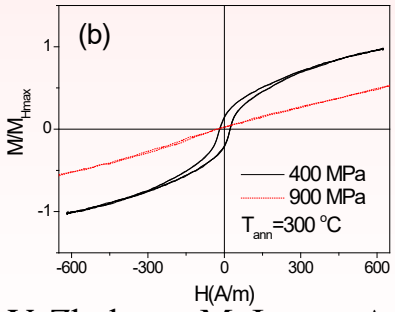
Effect of stress annealing on GMI of Fe -rich microwires

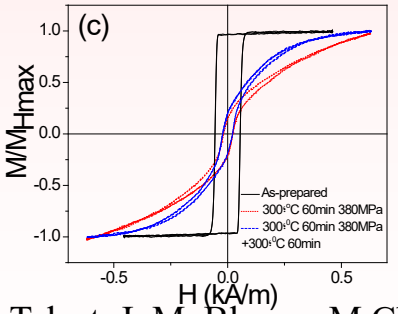












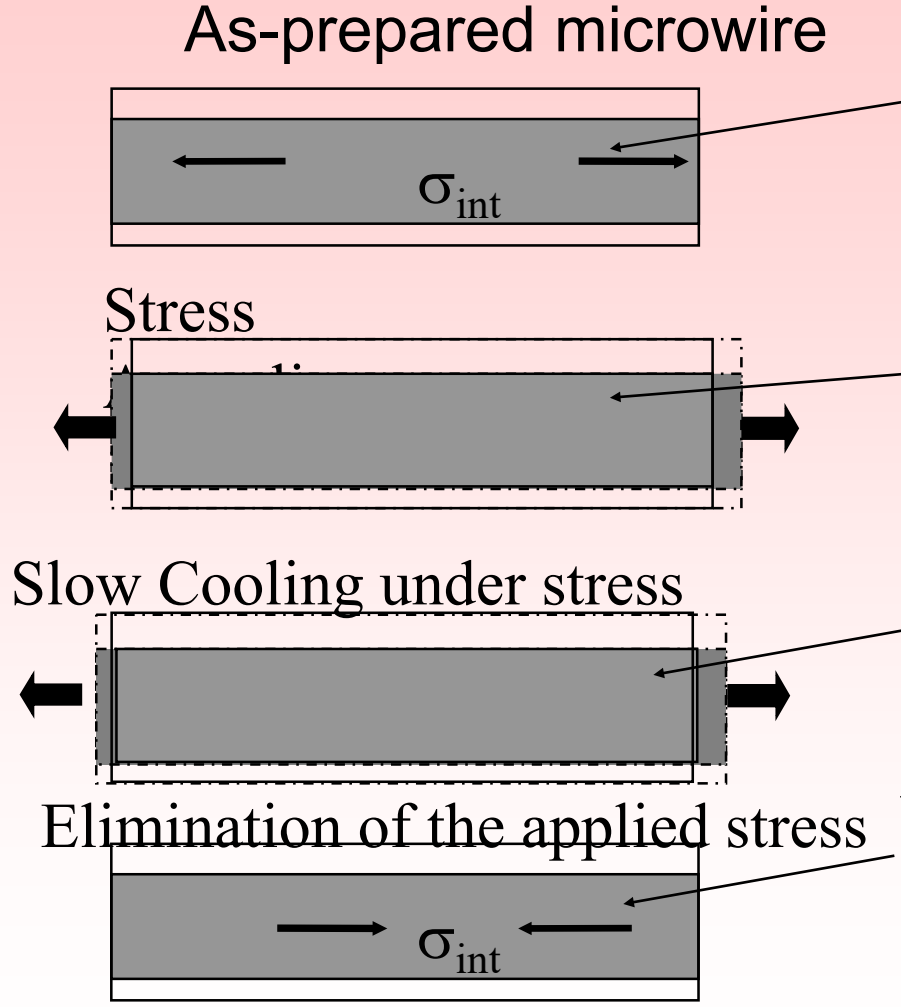
1. Depend on T, σ
2. Only partially reversible
3. SA is a promisng method

for MI optimization in Fe-rich MWs

V. Zhukova, M. Ipatov, A. Talaat, J. M. Blanco, M.Churyukanova, S. Taskaev and A. Zhukov, "Effect of stress-induced anisotropy on high frequency magnetoimpedance effect of Fe and Co-rich glass-coated microwires" J. Alloys Compound. 735 (2018) 1818-1825

V. Zhukova, J. M. Blanco, M. Ipatov, M.Churyukanova, S. Taskaev and A. Zhukov, Tailoring of magnetoimpedance effect and magnetic softness of Fe-rich glass-coated microwires by stress- annealing, Sci. Reports 8 (2018) 3202

Origin of stress-induced anisotropy



Internal stresses with mainly axial component

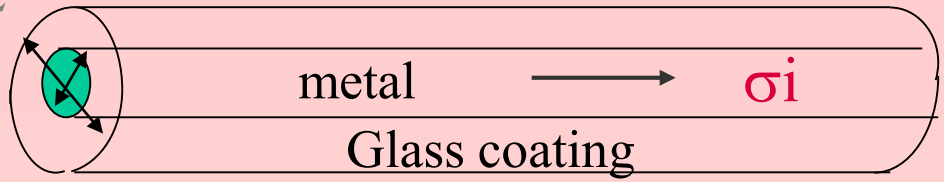
Induction of magnetic anisotropy during stress annealing

Stress relaxation in the stressed state at room temperature

Induction of the compressive stresses at room-temperature (so-called “Back stresses”)

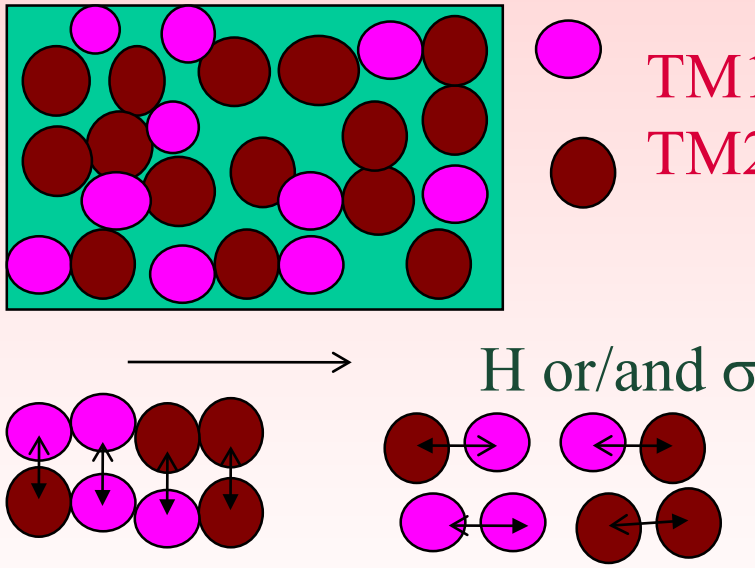
A. Zhukov, Advanced Funcional Materials Volume 16, Issue 5, 2006, pp.675-680

Origin of induced anisotropy 2



Possilbe origin:
-Stress induced anisotropy (stress from glass coating)?

Origin: Pair ordering usually considered



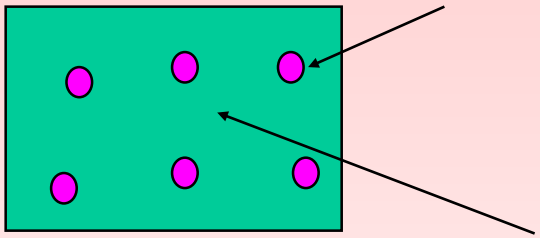
Pair reorientation under field and/or stress annealing (after Neel)

Possible origin 3:
The topological short range ordering (also known as structural anisotropy) can play an important role. This involves the angular distribution of the atomic bonds and small anisotropic structural rearrangements at temperature near the glass transition temperature

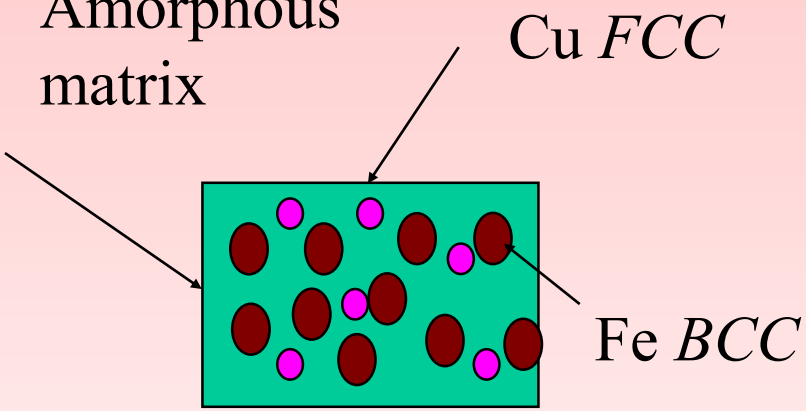
[1] F. E. Luborsky and J. L. Walter, "Magnetic Anneal Anisotropy in Amorphous Alloys", *IEEE Trans.Magn.* Vol.13 (2), pp.953-956, 1977.
[2] J. Haimovich, T. Jagielinski, and T. Egami, "Magnetic and structural effects of anelastic deformation of an amorphous alloy", *J. Appl. Phys*. Vol. 57, pp. 3581-3583, 1985.

Nanocrystallization. Method of improvement of magnetic softness and GMI

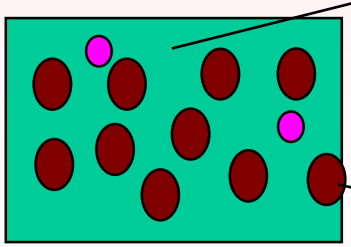
Structure evolution after annealing



Tann<Tx



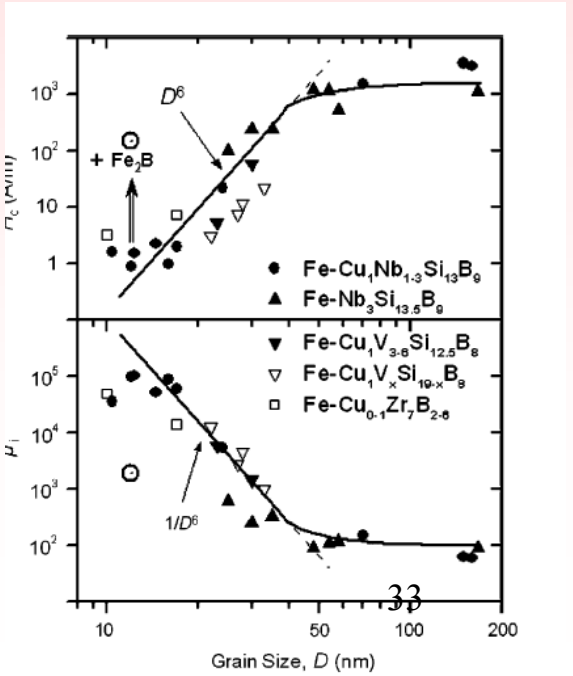
1. λ_s Amorphous matrix with $\lambda_s>0$



$$\lambda_{s,eff} = V_{cr}\,\lambda_{s,cr} + (1 - V_{cr})\,\lambda_{s,am}$$

Nanocrystals with $\lambda_s<0$

2. Grain size



G. Herzer / J. Magn. Magn. Mater. 294 (2005) 99–106

Magnetostriction

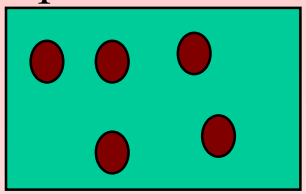
Effect of nanocrystallization on magnetic softness of $Fe_{71.8}Cu_1Nb_{3.1}Si_{15}B_{9.1}$ microwires

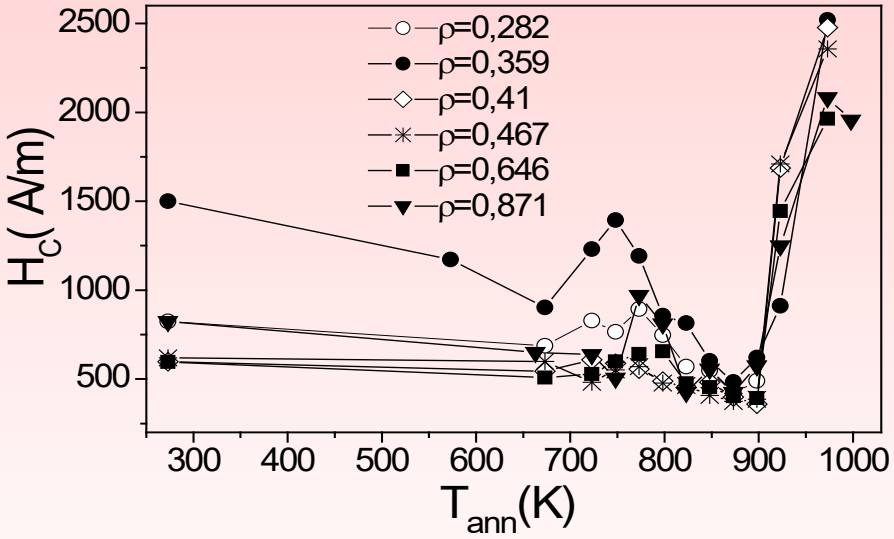
Cu and Nb additions result in nanocrystalites precipitation after annealing :

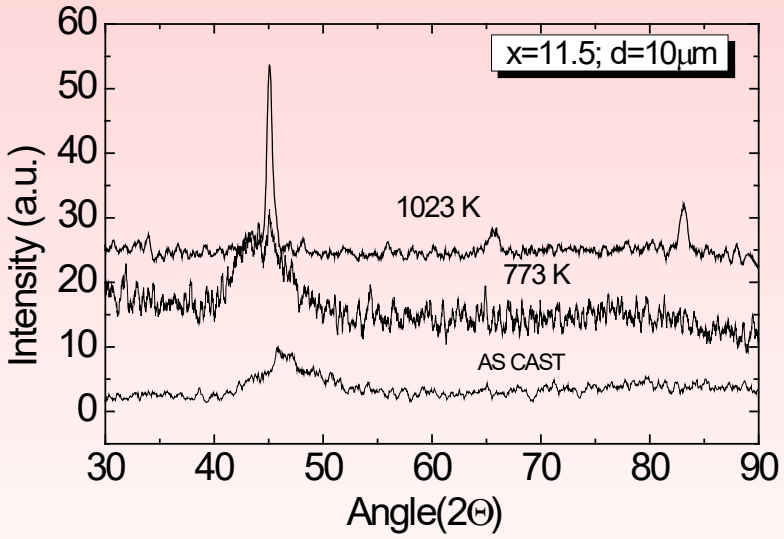
-High concentration of small grains

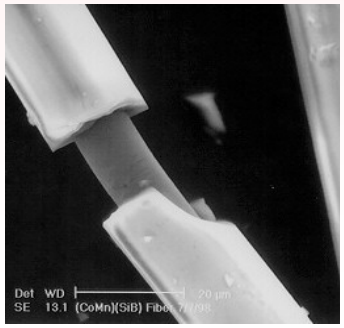
-Nanosize of crytsalites 10-20 nm

-Amorphous matrix







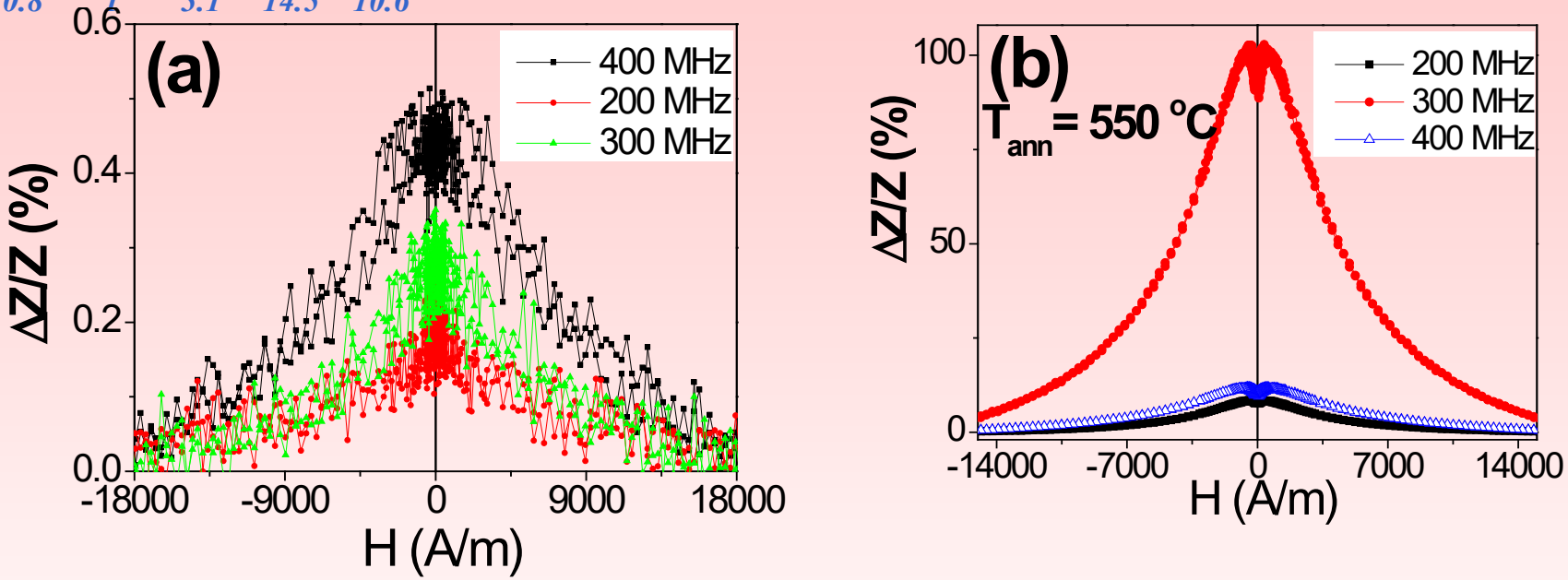


ρ=*d/D*; *d* – metallic nucleus diameter and *D –total diameter*

Magnetostriction

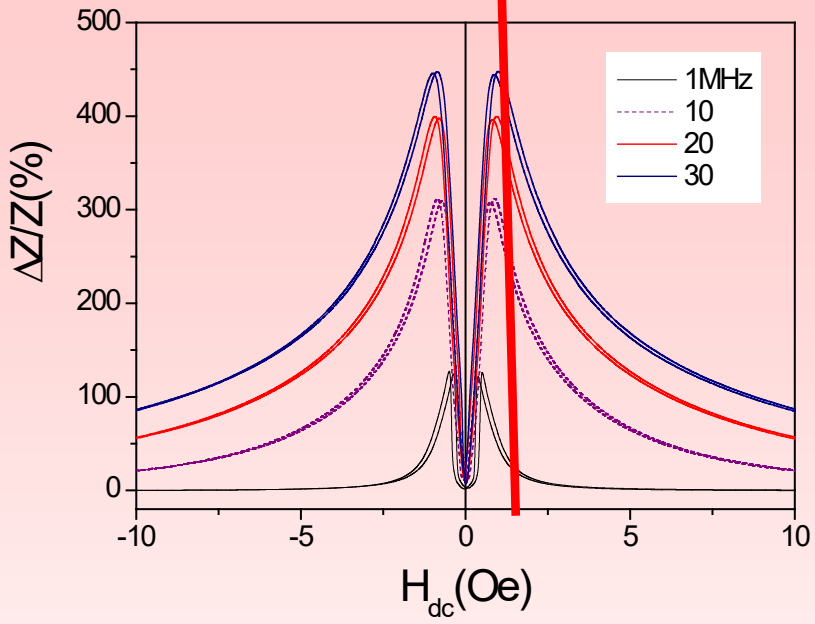
Effect of nanocrystallization on GMI of $Fe_{71.8}Cu_1Nb_{3.1}Si_{15}B_{9.1}$ microwires

ΔZ/Z (H) dependences in amorphous and annocrystalline $Fe_{70.8}Cu_1Nb_{3.1}Si_{14.5}B_{10.6}$ microwires



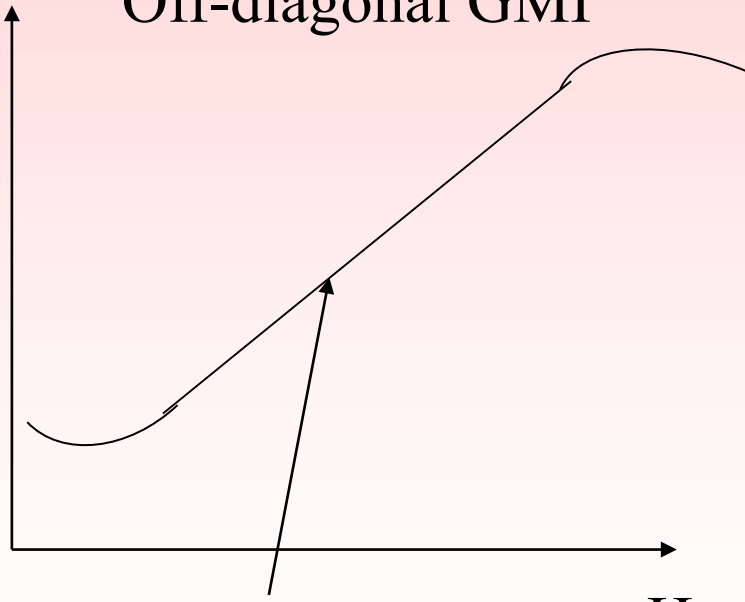
ΔZ/Z (H) in as-prepared (a), and annealed at 550°C (b) $Fe_{70.8}Cu_1Nb_{3.1}Si_{14.5}B_{10.6}$ microwire with ρ = 0.65.

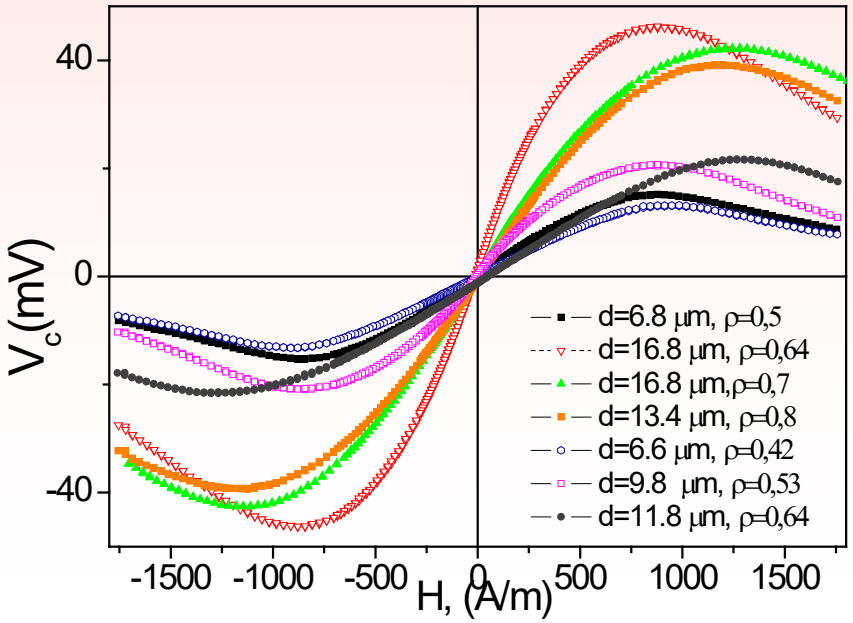
Requests for applications - linearity



GMI effect, high sensitivity
450%/Oe: 1 Oe = 0,1 mT)
1% MI change ≈0,0002 mT
But non-linear

Off-diagonal GMI

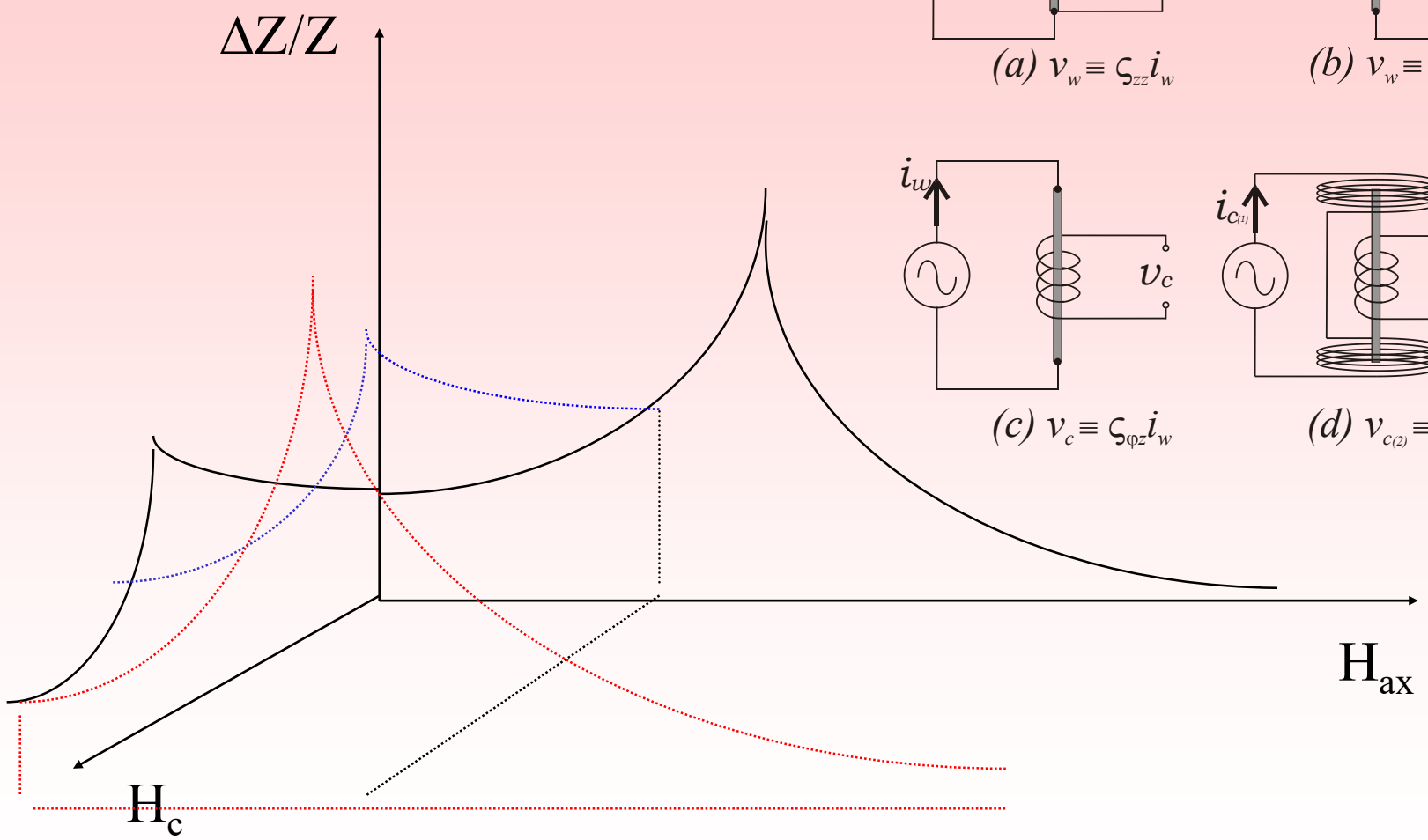




Good linearity on V(H),
Extended range of linear behaviou
absence of hysteresis

Tensor character of GMI

Schematic representation

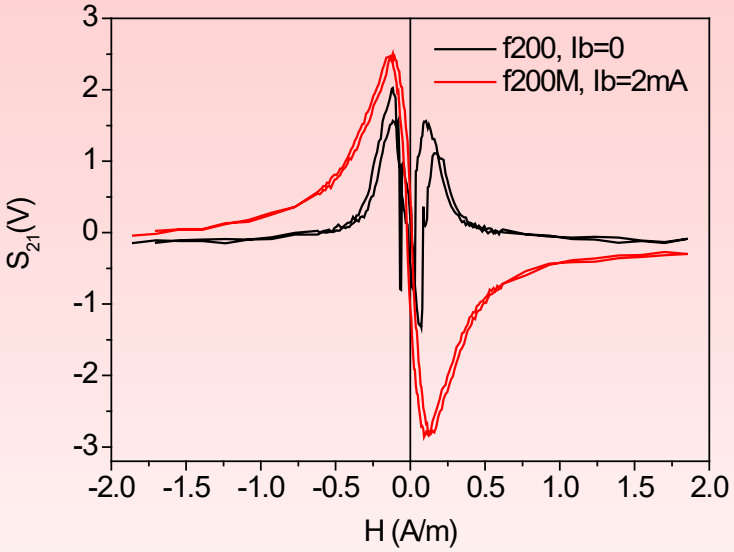


N. A. Usov, A. S. Antonov and A. N. Lagar`kovJ Magn Magn Mat **185**, 159 **(**1998).

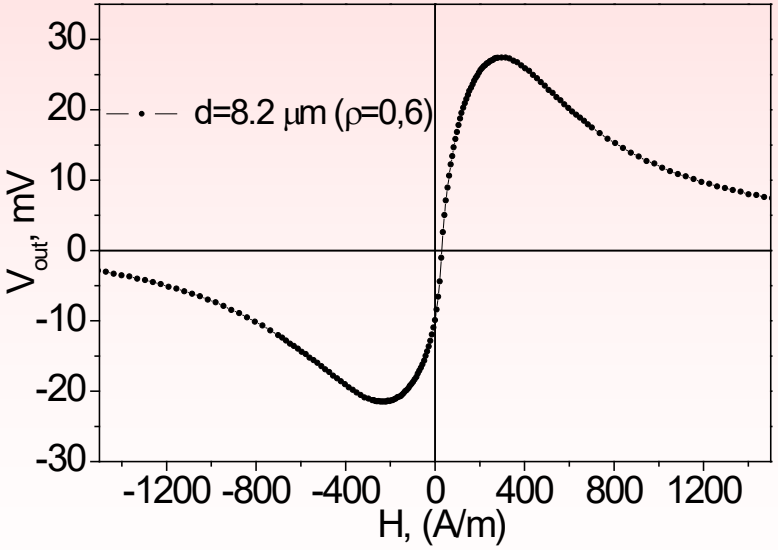
P. Aragoneses, A. Zhukov, J. Gonzalez, J.M. Blanco and L. Dominguez**,** Sensors and Actuators A, 81/1-3 (2000) 86-90

Off-diagonal GMI effect

Effect of bias current on magnetic field dependence of S_{21} parameter measured at 200 MHz in $Co_{67.71}Fe_{4.28}Ni_{1.57}Si_{11.24}B_{12.4}Mo_{1.25}C_{1.55}$ microwires



$V_{out}(H)$ response of $Co_{67,1}Fe_{3,8}Ni_{1,4}Si_{14,5}B_{11,5}Mo_{1,7}$ microwires measured in pulsed excitation



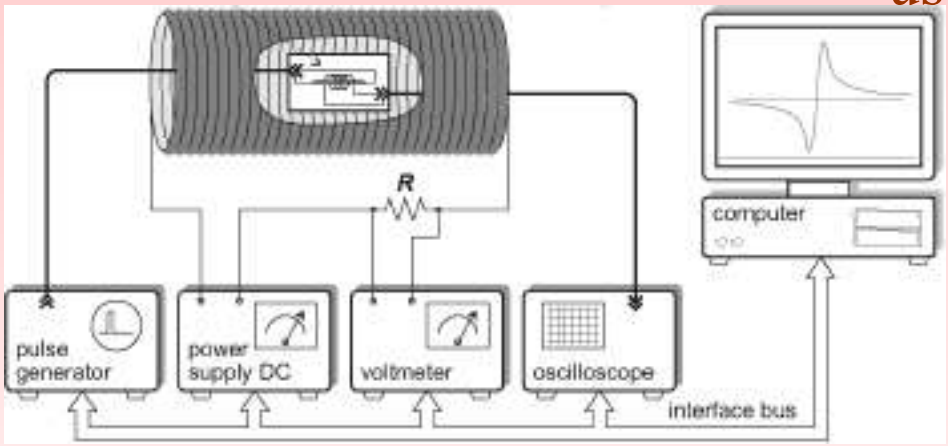
M. Ipatov, V. Zhukova, A. Zhukov, J. Gonzalez, and A. Zvezdin, "Low-field hysteresis in the magnetoimpedance of amorphous microwires", Phys. Rev.B vol. 81, p. 134421, 2010

M. Ipatov, V. Zhukova, J. Gonzalez and A. Zhukov, "Magnetoimpedance sensitive to DC bias current in amorphous microwires" Appl. Phys. Lett vol. 97, p. 252507, 2010.

GMI effect

Linearity: Pulsed GMI

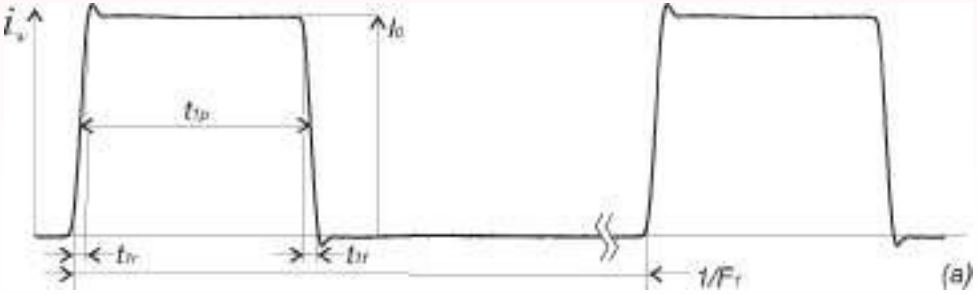
Pulsed GMI: linear field dependence, useful for cicruitry, low noise

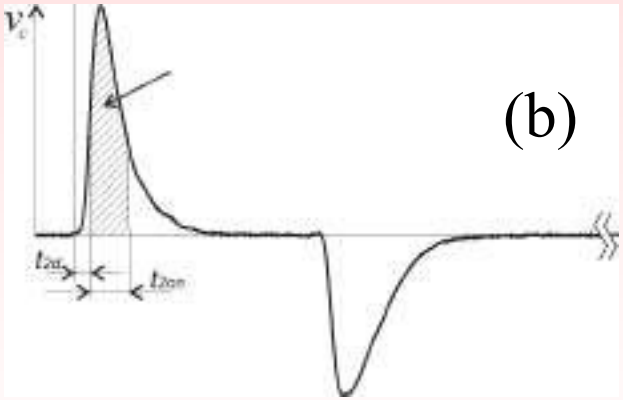


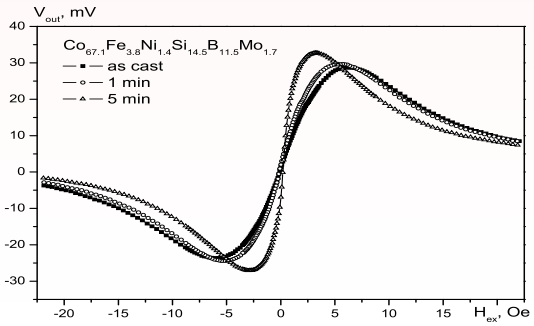
Experimental setup for MI investigation with pulse excitation

Excitation current pulse in the wire (a) and voltage induced in the pickup coil (b)

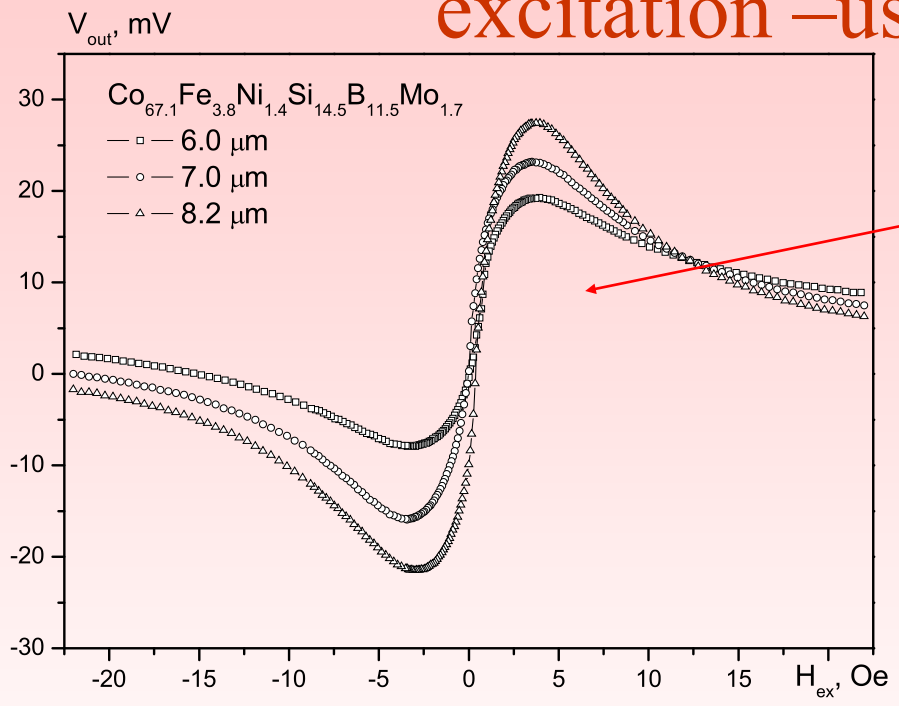
(a)







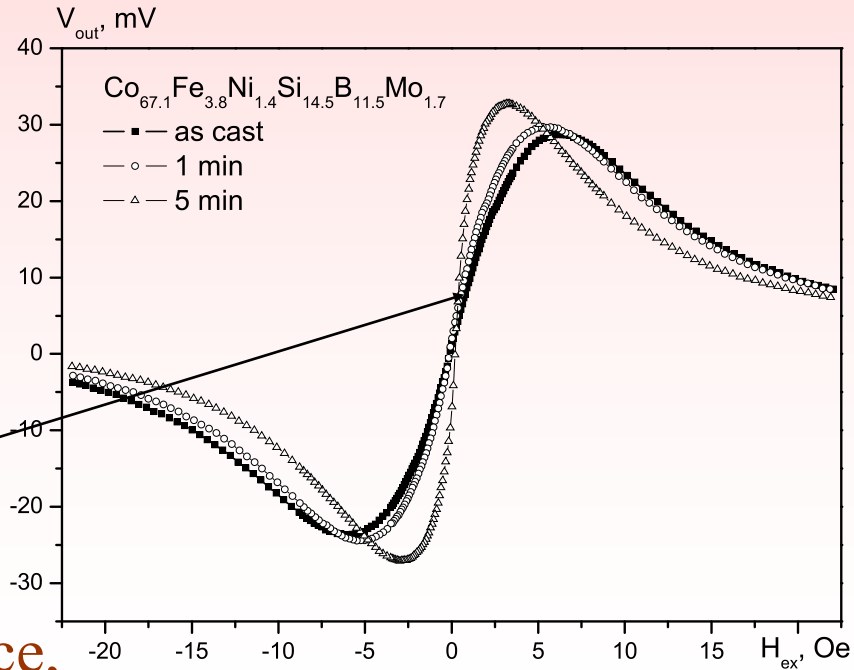
Off-diagonal GMI of nearly zero magnetostriction $Co_{67,1}Fe_{3,8}Ni_{1,4}Si_{14,5}B_{11,5}Mo_{1,7}$ microwires (pulsed excitation –used in practice)



Asymmetrical shape,
Almost linear region

Linear region and maximum
Position depends on geometry

Tailoring of GMI by heat treatment

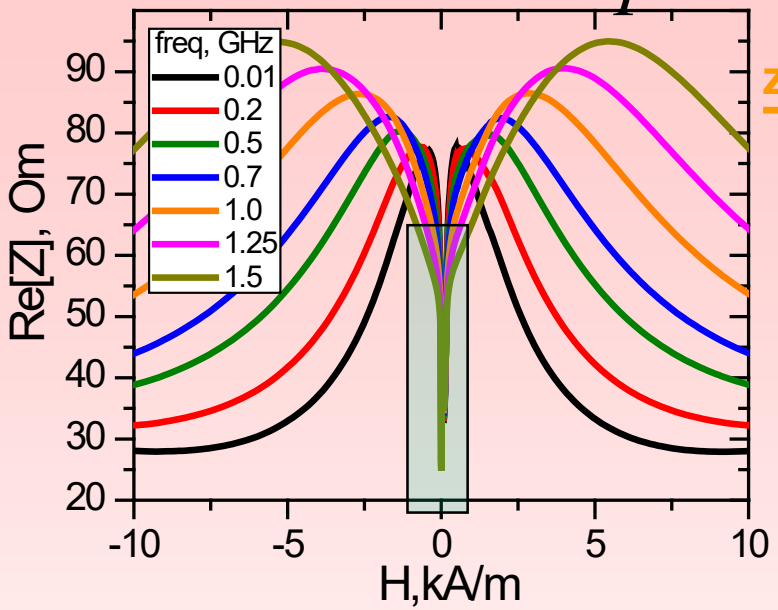


Pulsed GMI: linear field dependence, useful for cicruitry, low noise

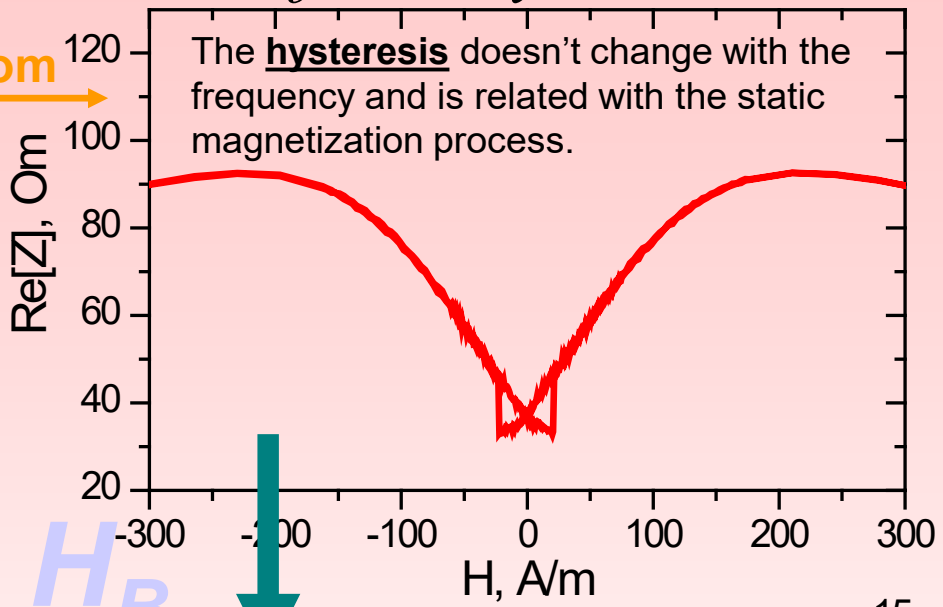
GMI effect

High frequency GMI effect

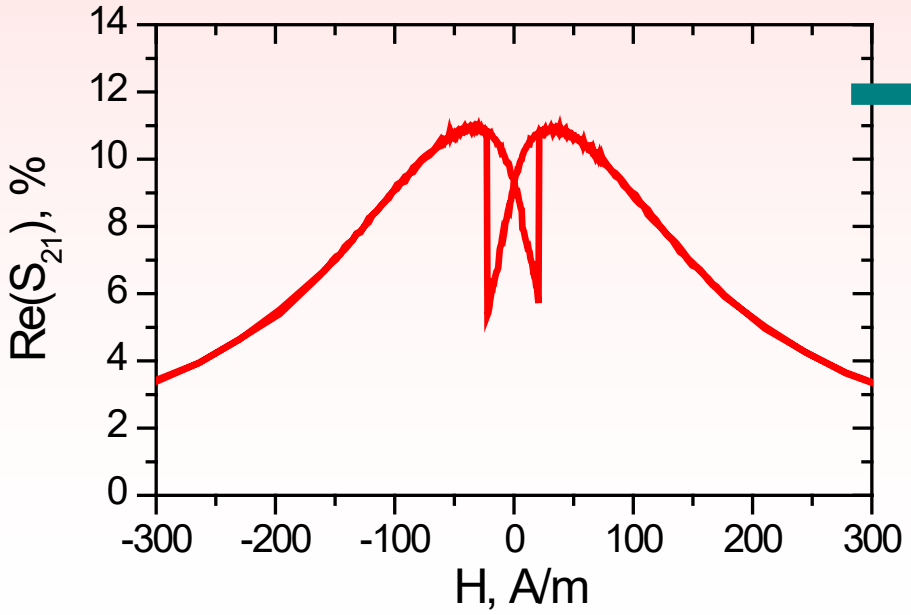
Considerable problem – low field hysteresis

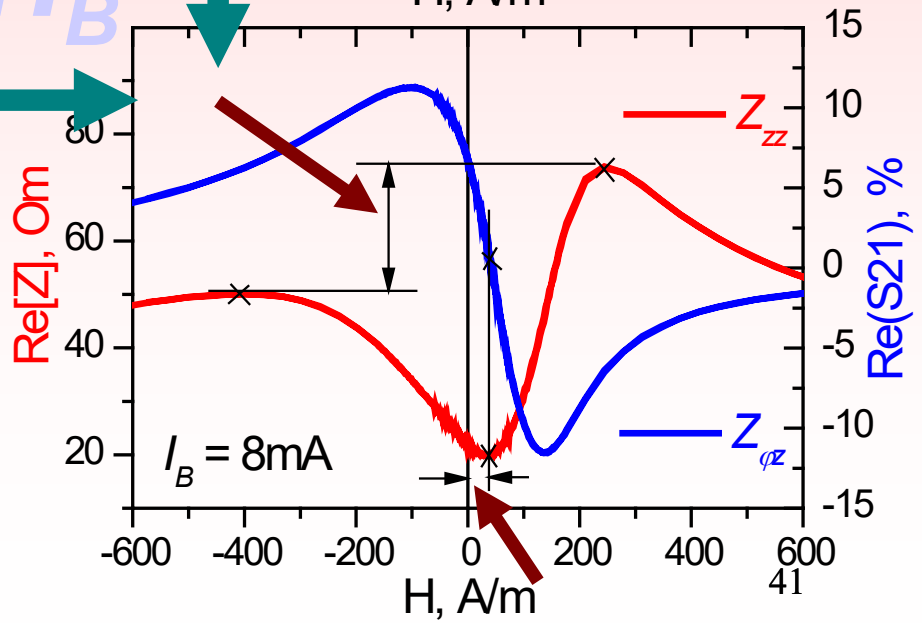


zoom



H_B

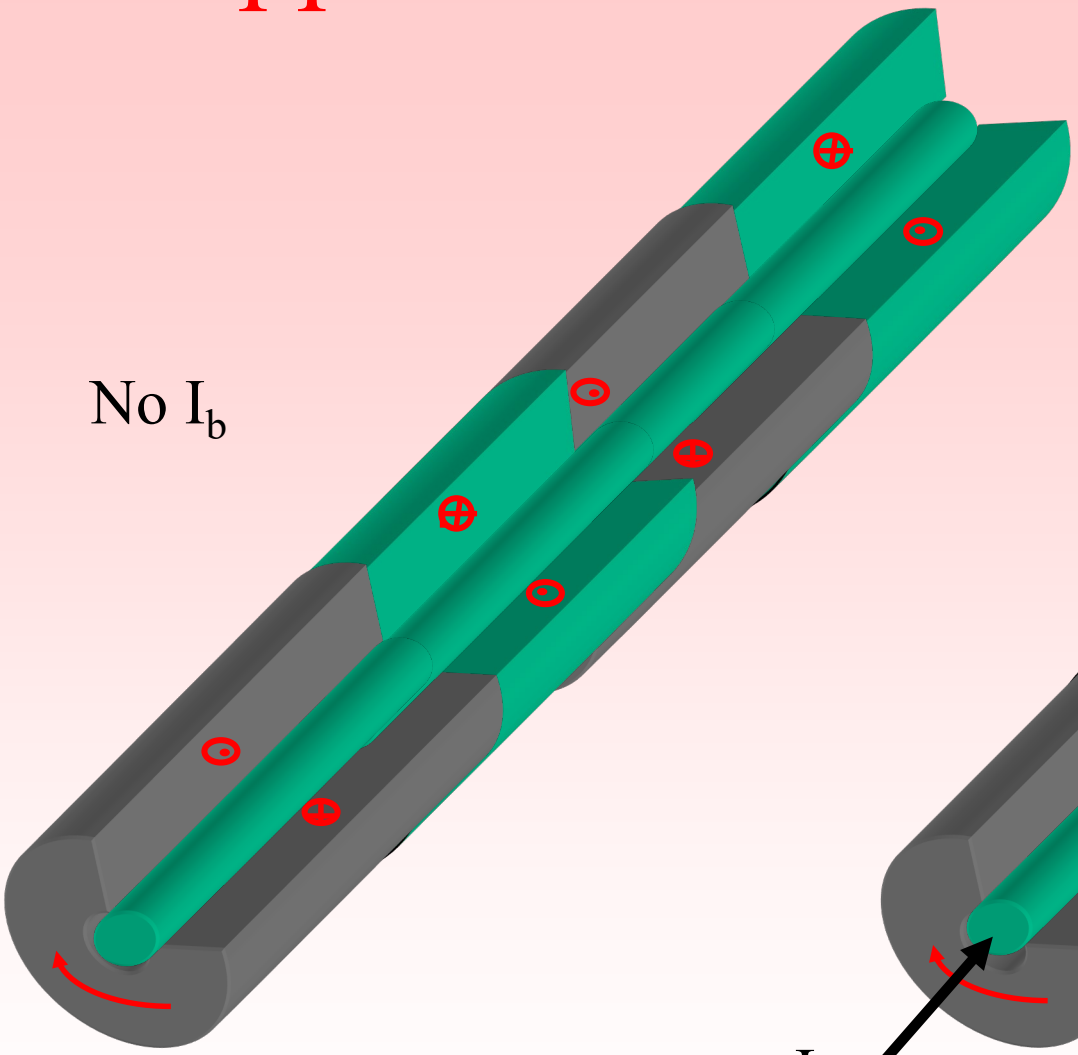


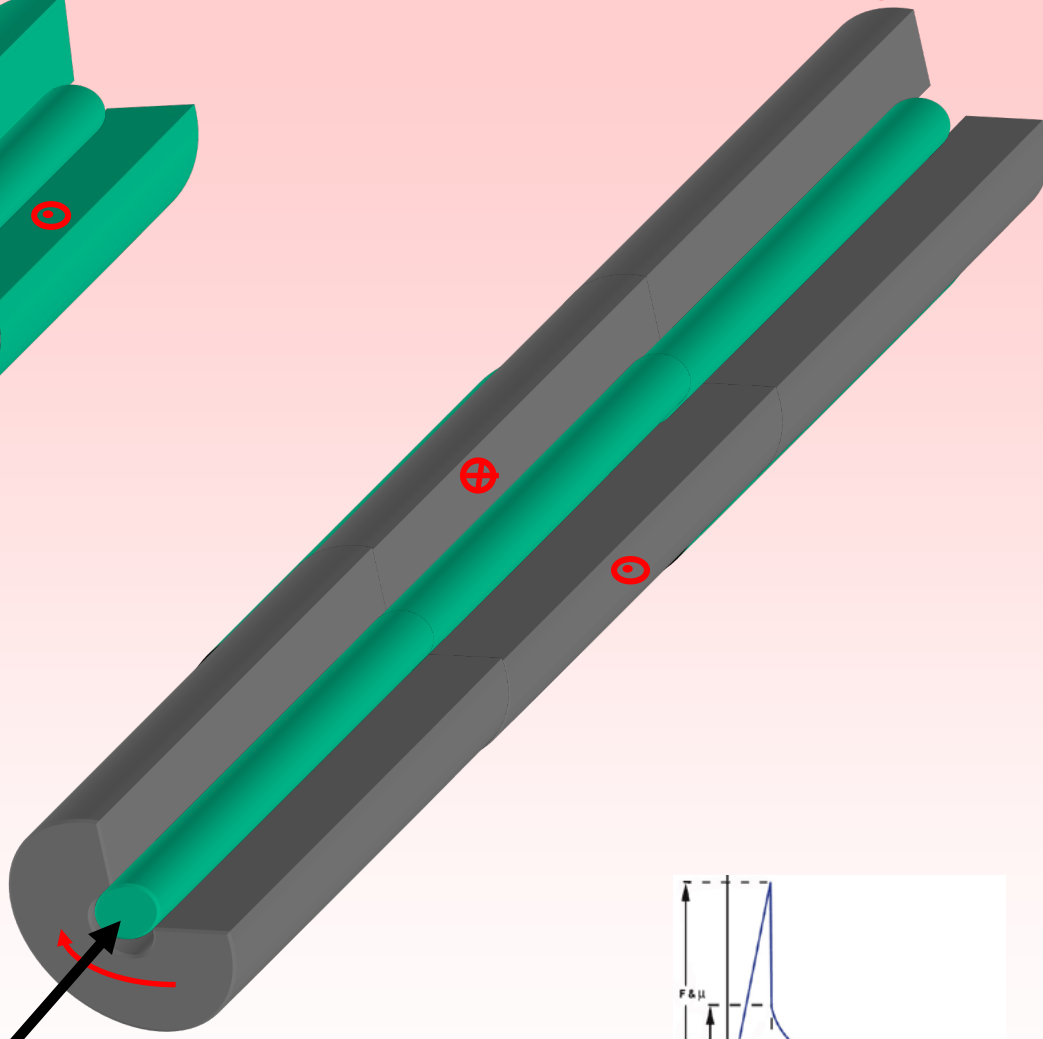


M. Ipatov, V. Zhukova, A. Zhukov, J. Gonzalez, and A. Zvezdin, PHYS. REV. B **81**, (2010), 134421.

Suppresion of GMI hysteresis by I_b

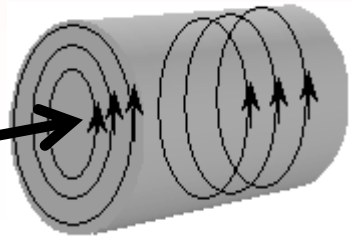
No I_b

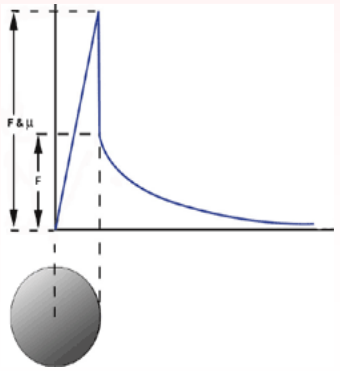




I_b

Circular magnetic field by current suppresses bamboo-like domain structure responsable for MI hysteresis

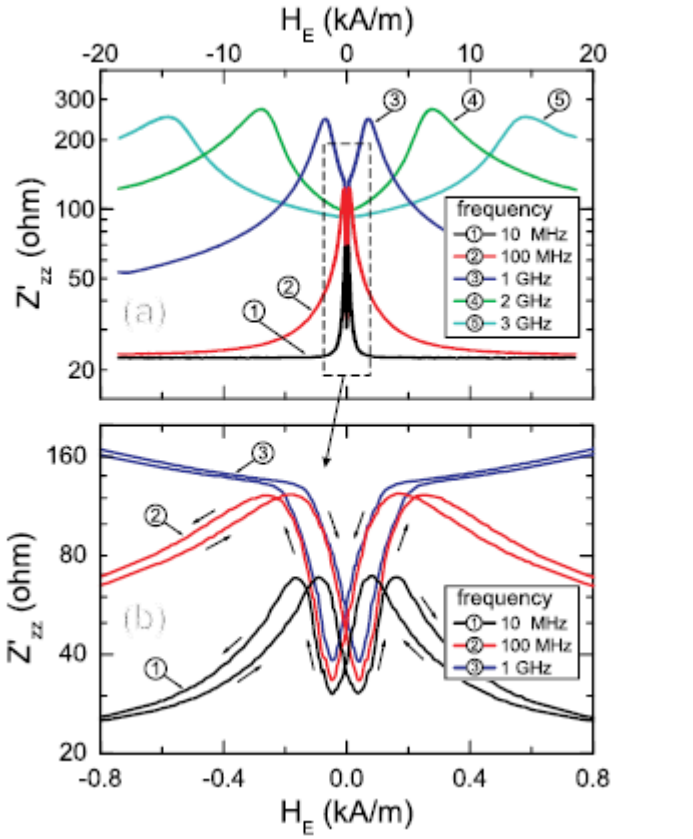




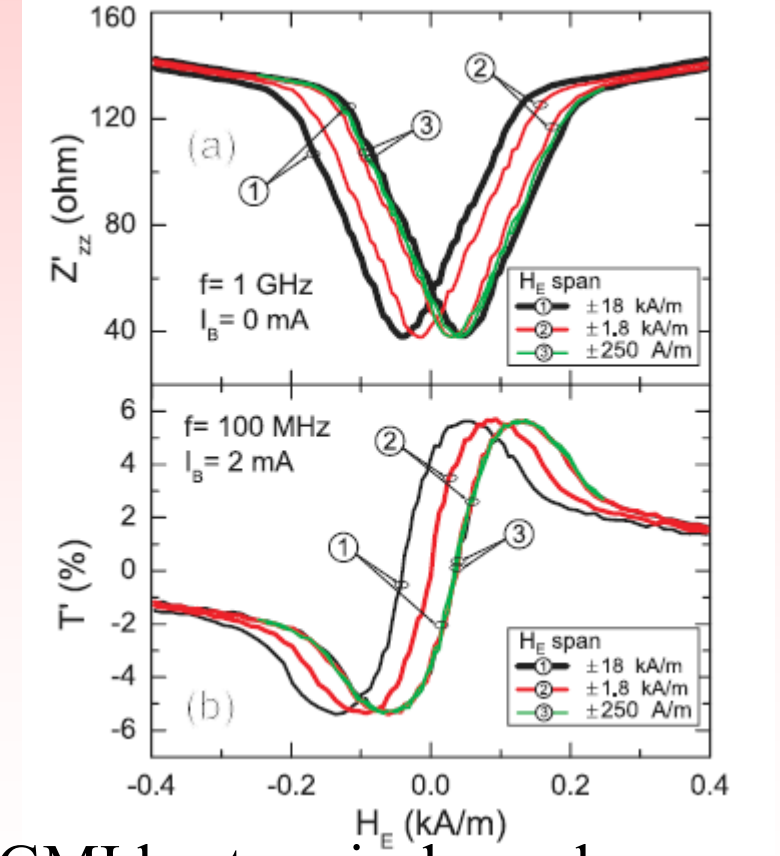
Magnetoimpedance hysteresis in amorphous microwires induced by core–shell interaction

Longitudinal MI measured at different frequencies.

Longitudinal Zzz (a) and off-diagonal Z ϕz (b) MI measured for 3 different magnetic field spans.



GMI hysteresis persists at all *f*



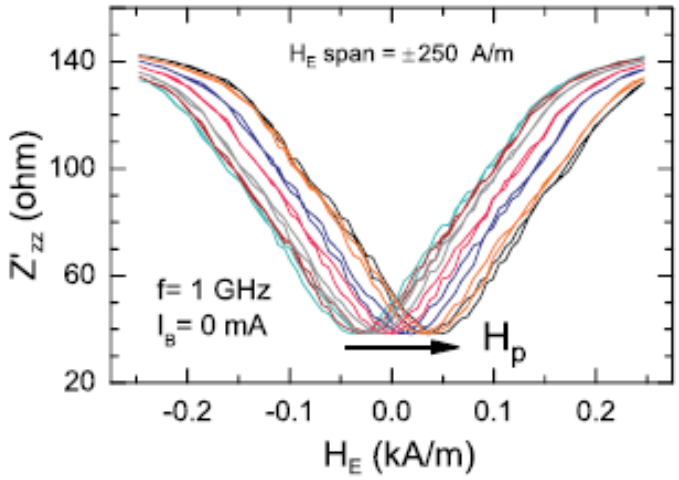
GMI hysteresis depends on magnetic history

M. Ipatov, V. Zhukova, J. Gonzalez, and A. Zhukov, Appl. Phys. Lett. 105, 122401 (2014)

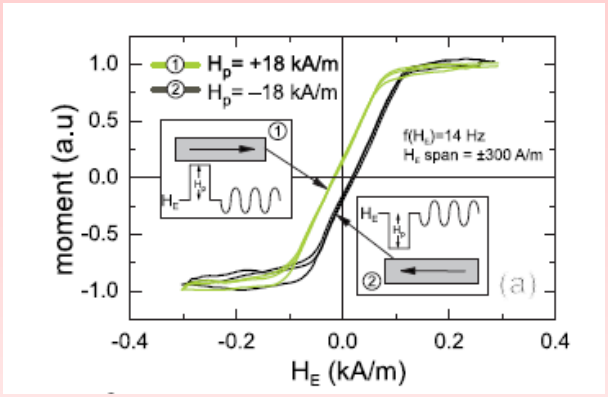
Magnetoimpedance hysteresis in amorphous microwires induced by core–shell interaction

Effect of Hp pulse applied before measurements on shift of the longitudinal MI.

First, pulses Hp of the axial magnetic field HE with positive or negative amplitudes between 18 and 0.3 kA/m were applied. After each pulse, the MI dependence was measured within a HE span of +- 250A/m.

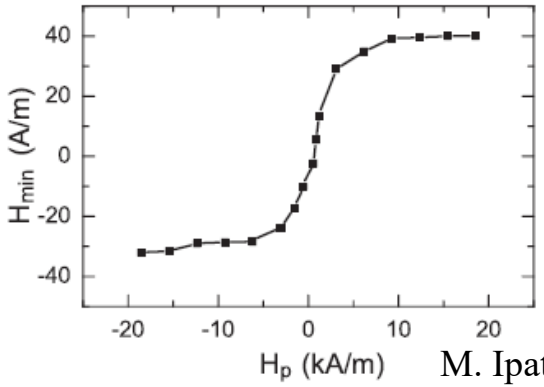


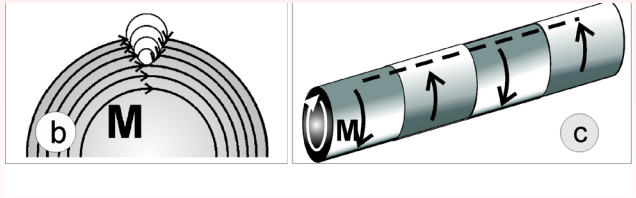
Hyst. loop also depends on Hp!

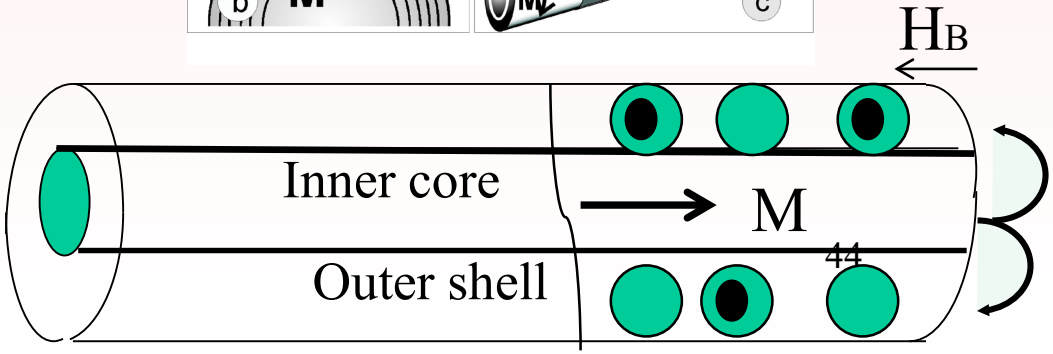


Considering domain structure consisting of an inner core and an outer shells, we supposed that the observed effect of magnetic history of the microwire on the MI arises from the interaction between them (core-shell interation).

Dependence Hmin as a function of the applied pulse of magnetic field Hp. Field Hmin corresponding to the field at which the MI dependence Zzz(HE) exhibits a minimum







M. Ipatov, V. Zhukova, J. Gonzalez, and A. Zhukov, Appl. Phys. Lett. 105, 122401 (2014)

Giant Magneto-impedance effect

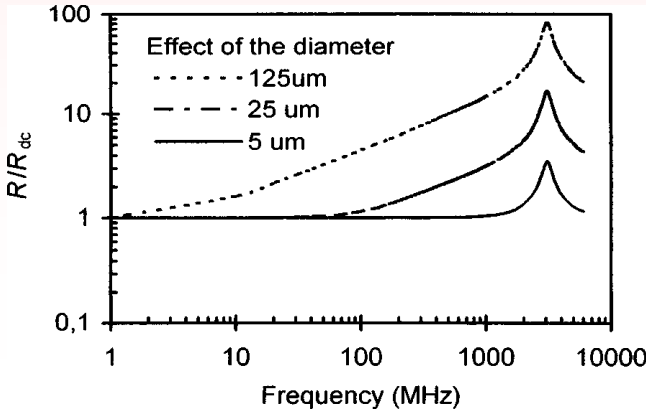
At high frequencies, of the order of GHz, the magnetization rotation is strongly influenced by the gyromagnetic effect. With increasing the frequency the GMI peaks are shifted to static fields where **sample is magnetically saturated**. At this frequency range strong changes of the sample's impedance have been attributed to the ferromagnetic resonance (FMR).

The criteria for determining the frequency regions is probably the ratio of skin depth to transversal dimensions of the sample (δ/a):

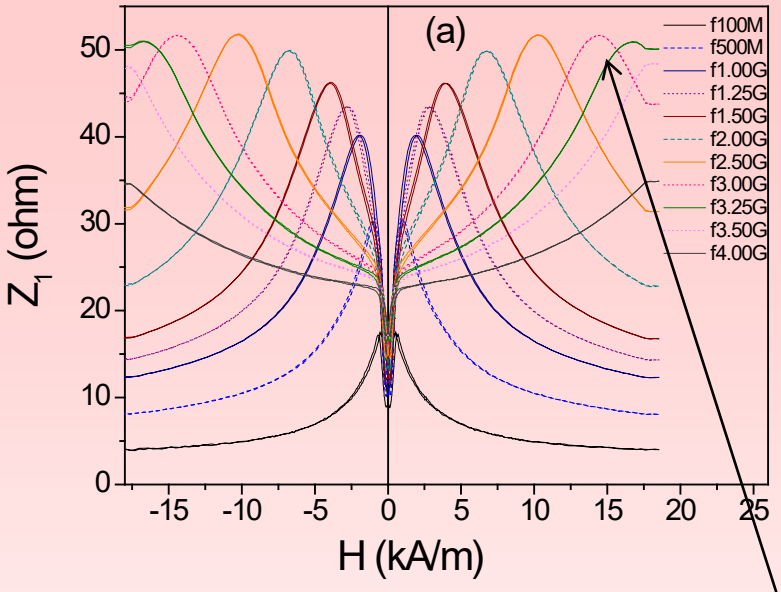
$\delta/a >> 1$ indicates a **weak skin effect** regime, while $\delta/a << 1$ indicate a **strong skin effect**.

δ/a ratio also depends on many other parameters, such as sample dimensions, material properties, magnetic field, etc.

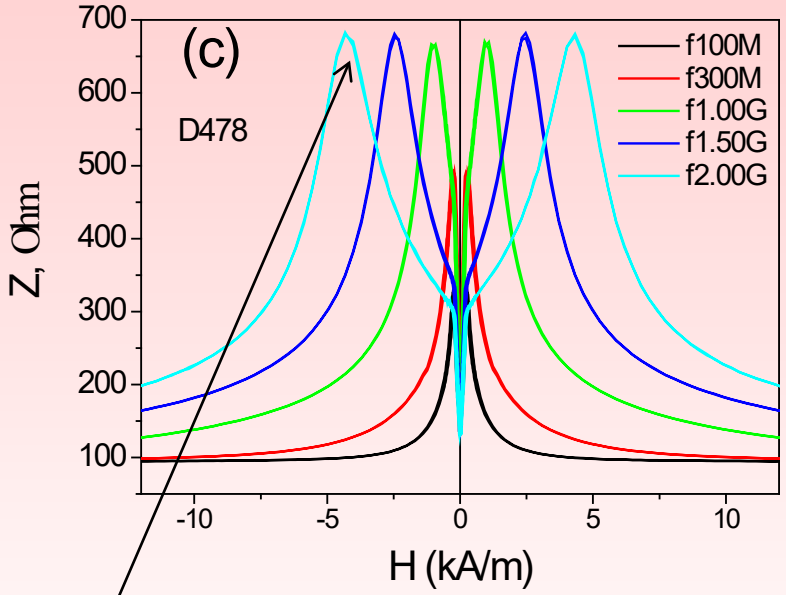
As thinner wire as higher GMI frequency !

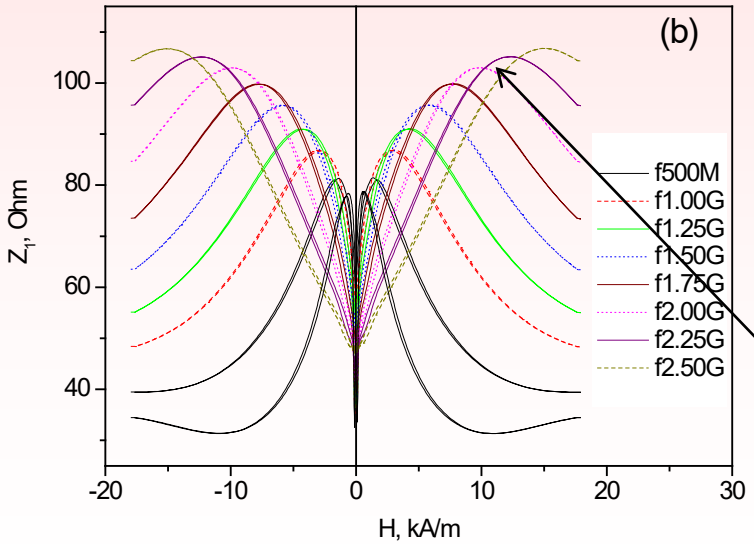


Experiments: Frequency dependence of GMI effect



$Z_1(H)$ dependence of $Co_{66}Cr_{3.5}Fe_{3.5}B_{16}Si_{11}$ (a) and $Co_{67}Fe_{3.85}Ni_{1.45}B_{11.5}Si_{14.5}Mo_{1.7}$ (b) and $Co_{67.71}Fe_{4.28}Ni_{1.57}Si_{11.24}B_{12.4}Mo_{1.25}C_{1.55}$ microwires measured at different frequencies

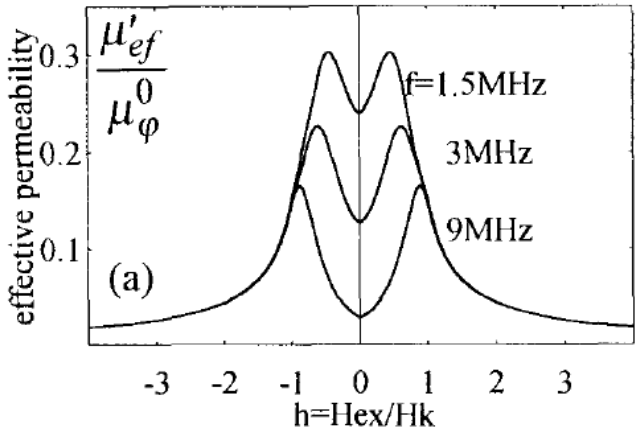




V. Zhukova, M. Ipatov and A Zhukov, "Thin Magnetically Soft Wires for Magnetic Microsensors", *Sensors* 9: 9216-9240, 2009.

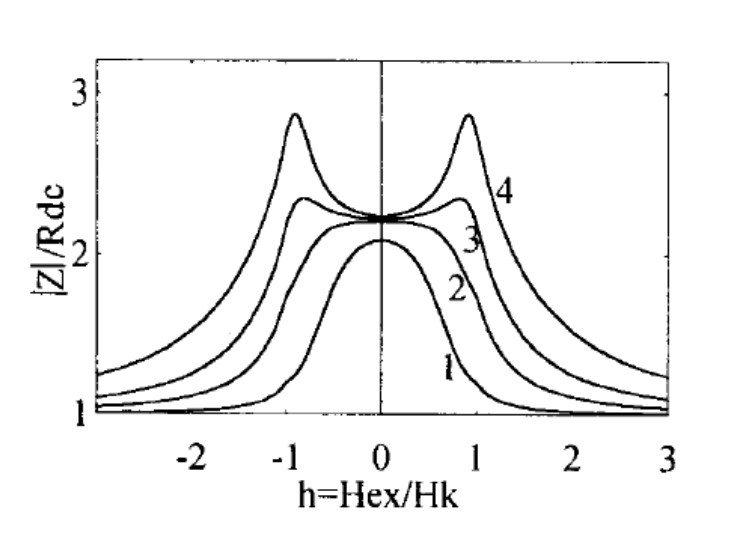
High enough magnetic fields

Frequency dependence of GMI effect: interpretation

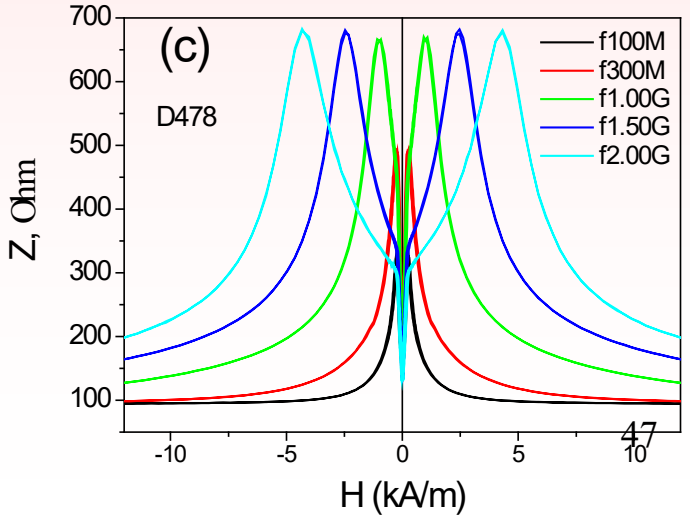


L. V. Panina, K. Mohri, T. Uchyama, and M. Noda, IEEE TRANS. MAGN. VOL. 31, (1995), 1249

position of μ and Z maximums becomes closer to $h(H_{ex}/H_k)$= 1 with increasing frequency

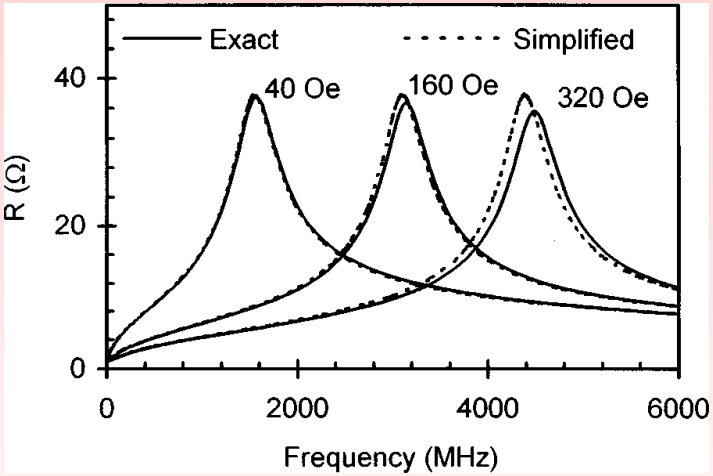


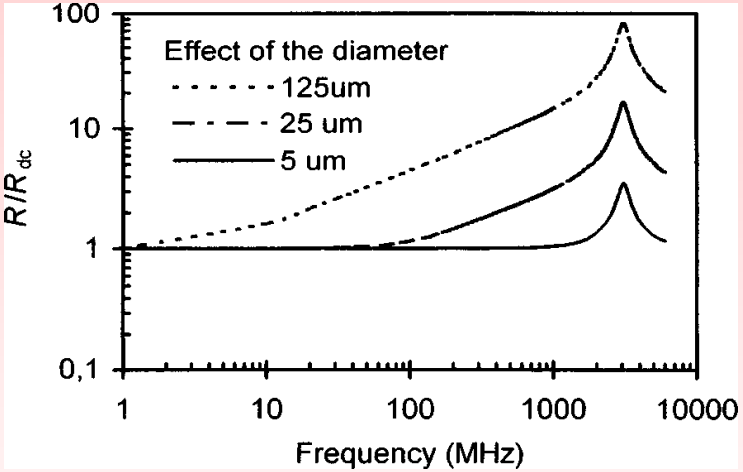
Experimental data (above presented) – Hk is too high (kA/m) ?
FMR?

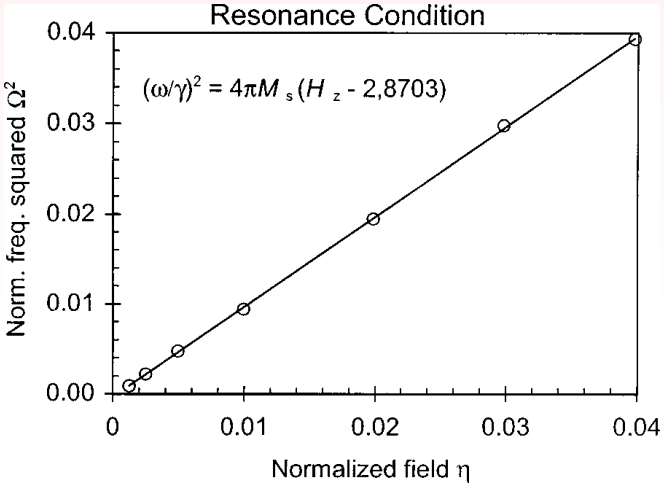


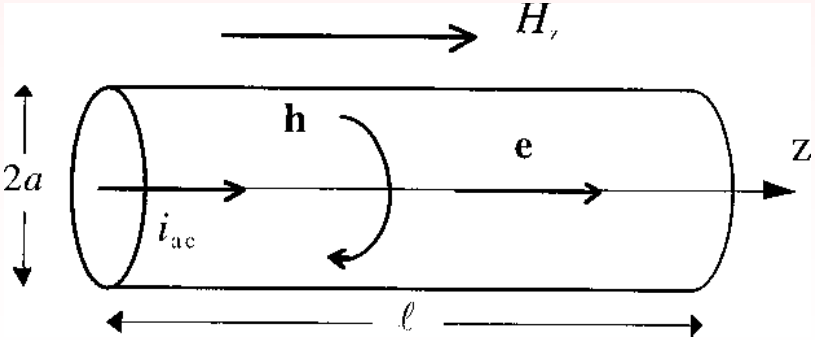
Frequency dependence of GMI effect: interpretation

D. Ménard, M. Britel, P. Ciureanu, and A. Yelon, JAP, 84, 5 (1998), 2805:
high field, or linear GMI, for which the cylindrical magnetic conductor is nearly saturated along its axis (*H>10 Oe) in* absence of domain structure or wall motion,
Similar approach L. Kraus & M. Vazquez









*Application for MI effect - **Sensors***

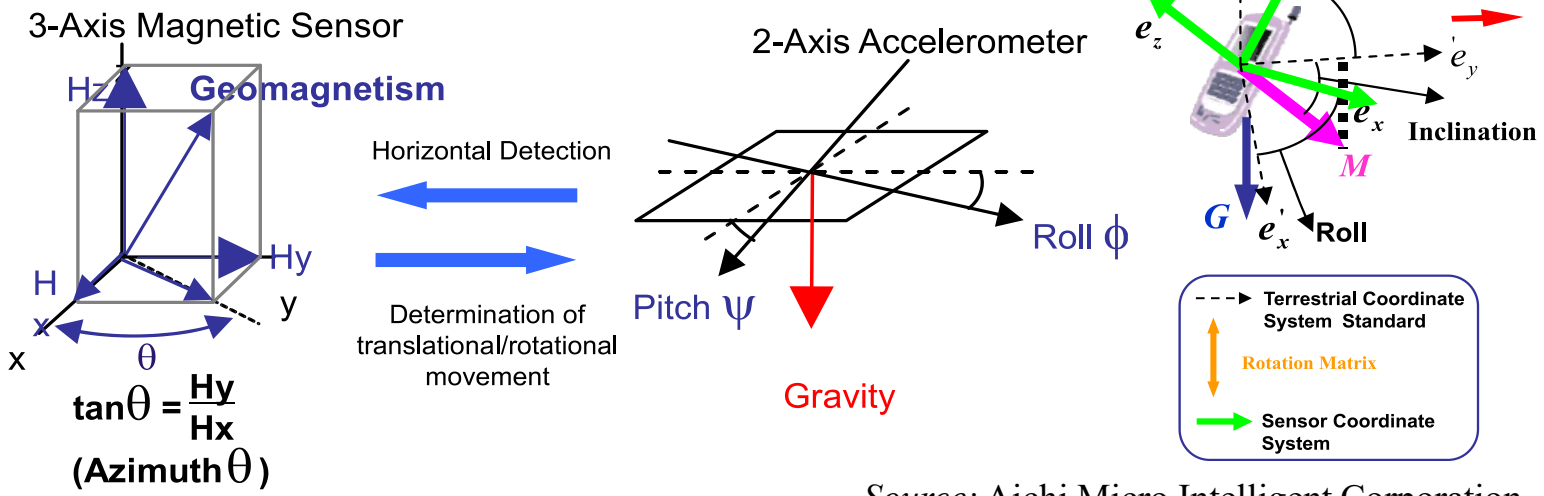
❖ *High sensitive electronic compass*

❖ **Positional sensor** ❖ Motion-sensing controllers ❖ Operating attitude automated control.

Motion Sensor = 3D magnetic sensor + 2/3D accelerometer

It determines the **attitude** of mobile devices relative to **geomagnetism** and **gravity**, and by analyzing the attitude and speed, other aspects of movement such as **acceleration**, **translational speed** and **rotational speed** can be calculated.

Attitude Detection Principles

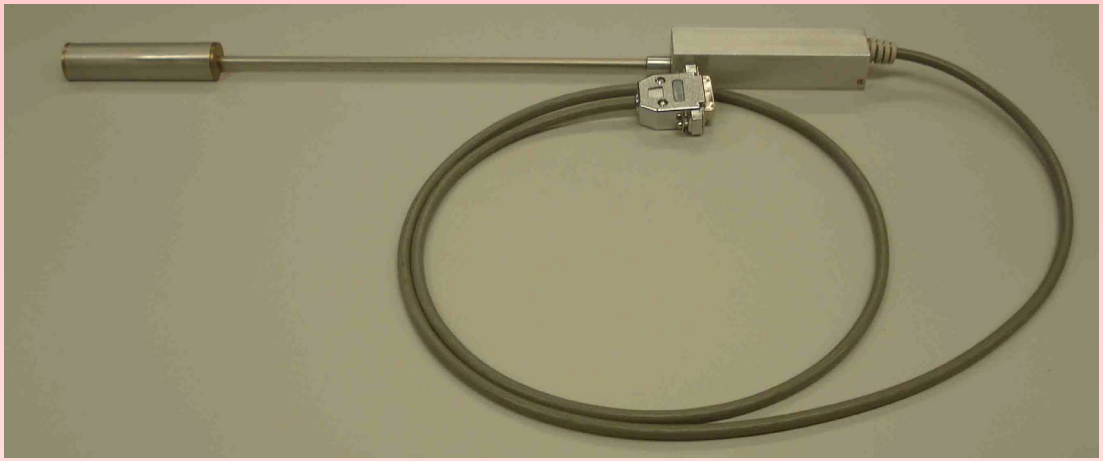


Source: Aichi Micro Intelligent Corporation

❖ **Navigation** functions combining the motion sensor with a GPS:
Intelligent Transportation System,
Control of operating attitude in unmanned helicopters, robots, automobiles, etc.

Requirements: high sensitivty at low H (up to few Oe)

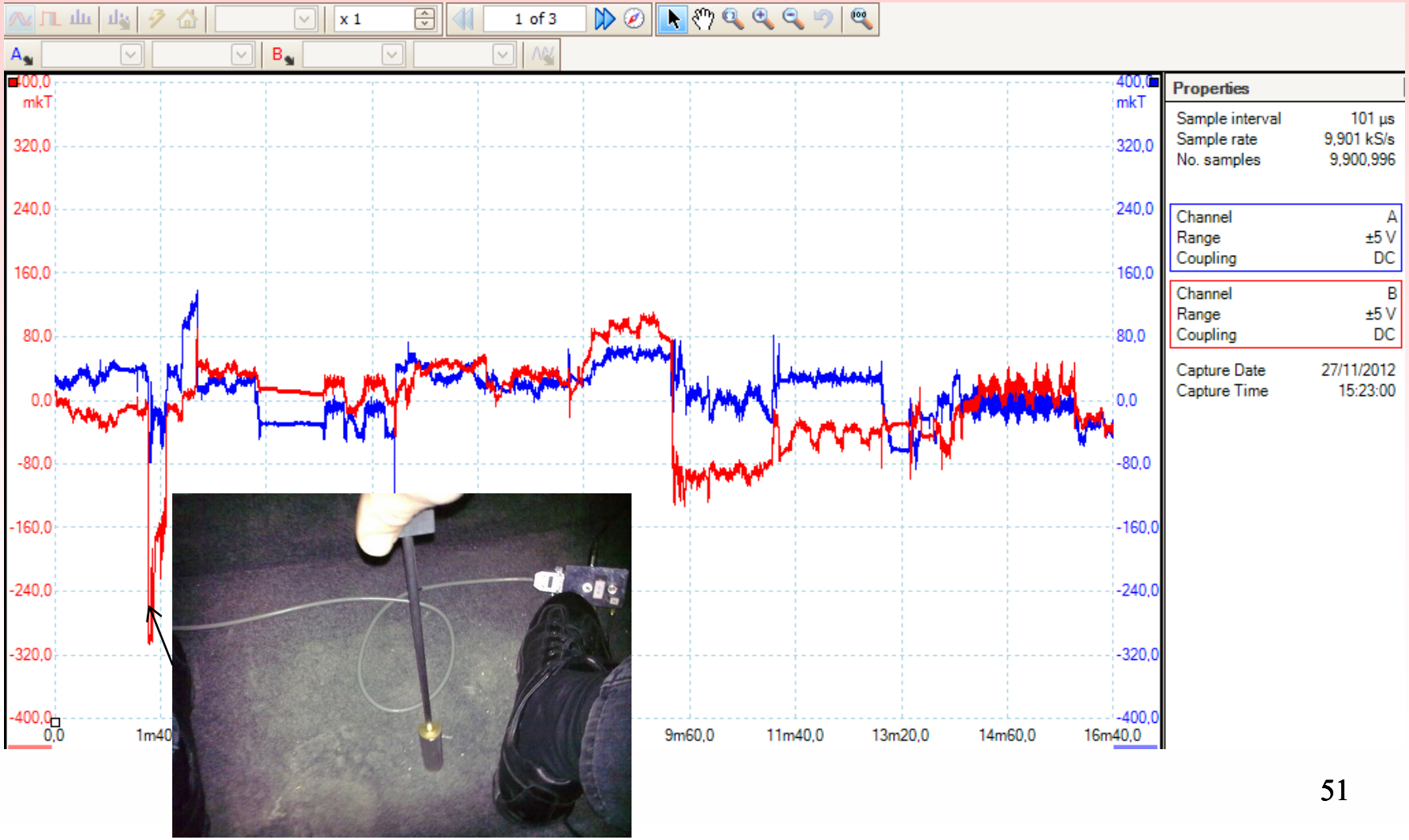
Designed by us magnetometer



Technical characteristics

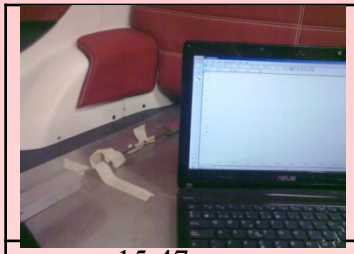
Channel number	3 (X, Y, Z components);
Size of the 3-component sensing element	cube with 14 mm edge;
Input voltage of the channel, not less	± 4.5 V;
Dynamic range, not less	± 2.5 Oe;
Frequency range, not less	1 kHz;
Power voltage	0 + 5.5V;
Consuming current	~ 250 mA;
Transmission coefficient of the channels	
Channel X	1.58V per 1Oe;
Channel Y	1.57V per 1Oe;
Channel Z	1.69V per 1Oe.
Noise level (resolution)	≈10 nT

MAGNETIC FIELD MEASUREMENTS WITH GMI MAGNETOMETER inside the electric car (FIAT Turin Nov. 2012) (FP7 project)



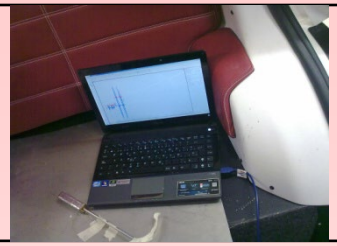
MAGNETIC FIELD MEASUREMENTS WITH GMI MAGNETOMETER (Turin Nov. 2012), (FP7 project)

Frame 4, Start time 15:45:55

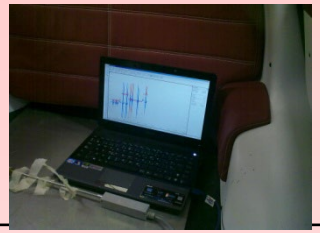


15:47

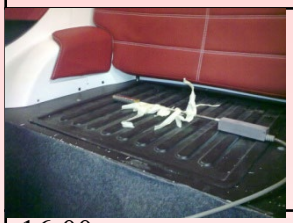
15:49



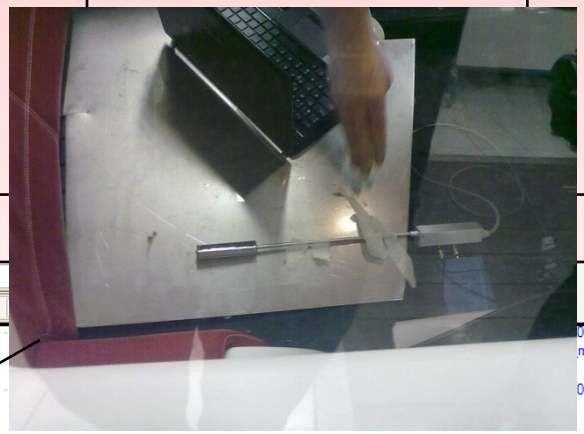
15:51

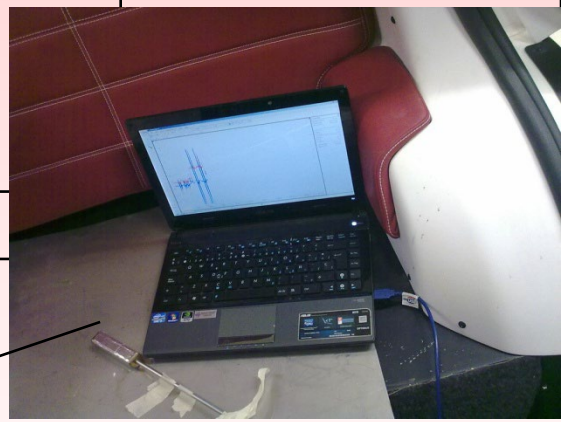


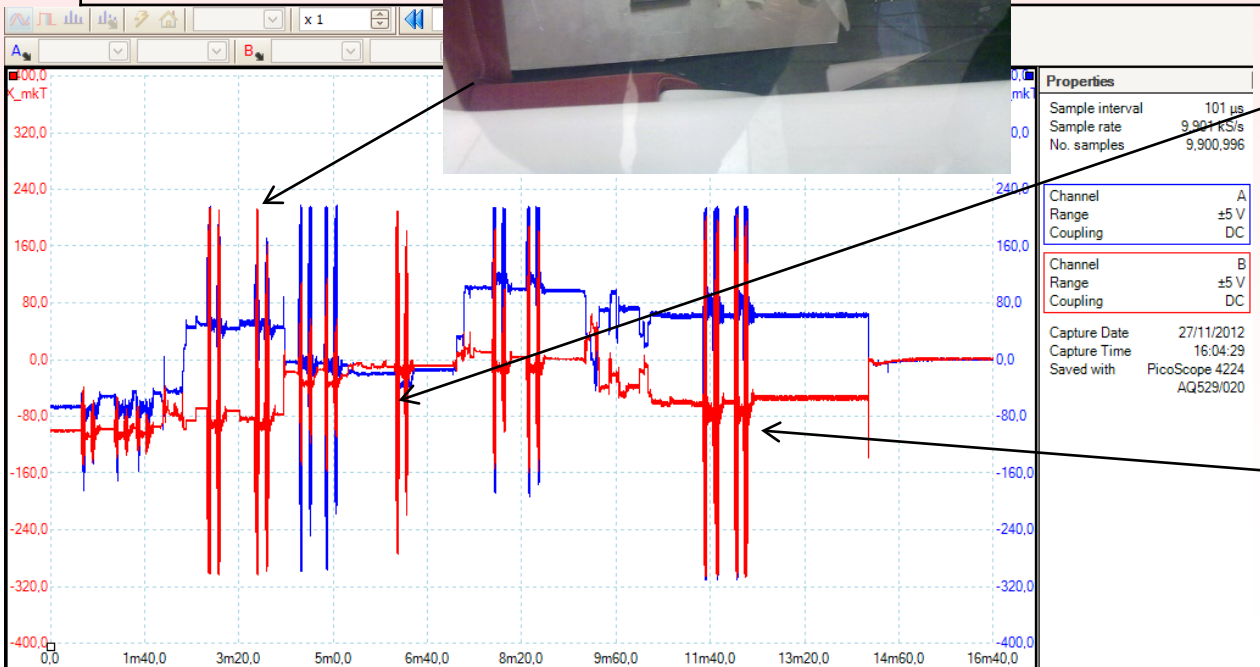
15:55



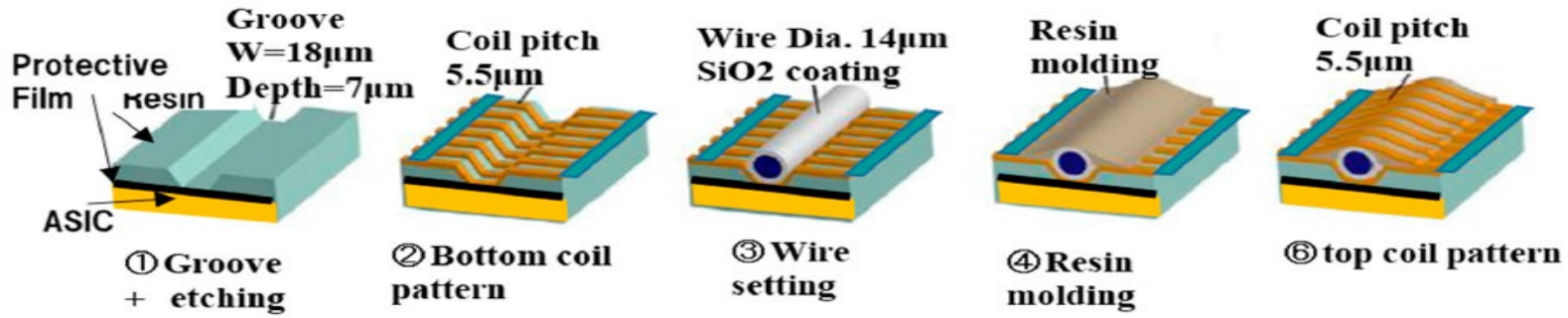
16:00

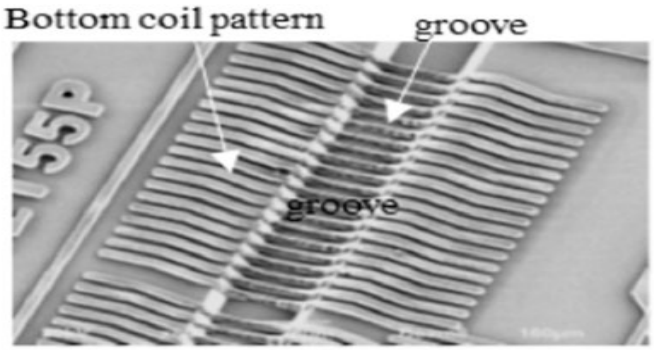


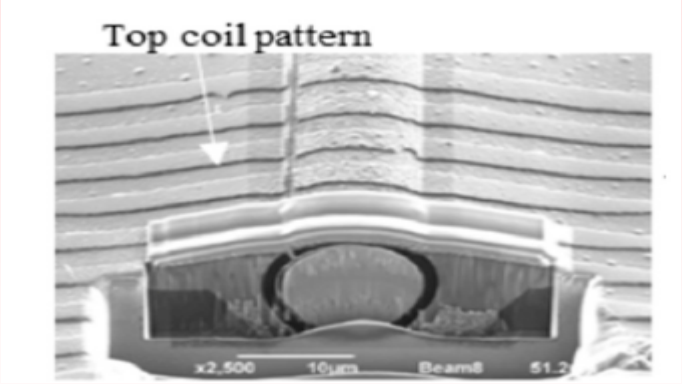




Microwires and compatibility with integrated circuits







sensors

MDPI

Article

The Development of ASIC Type GSR Sensor Driven by GHz Pulse Current †

Yoshinobu Honkura [1,*] and Shinpei Honkura [2,*]

Sensors **2020**, *20*, 1023; doi:10.3390/s20041023

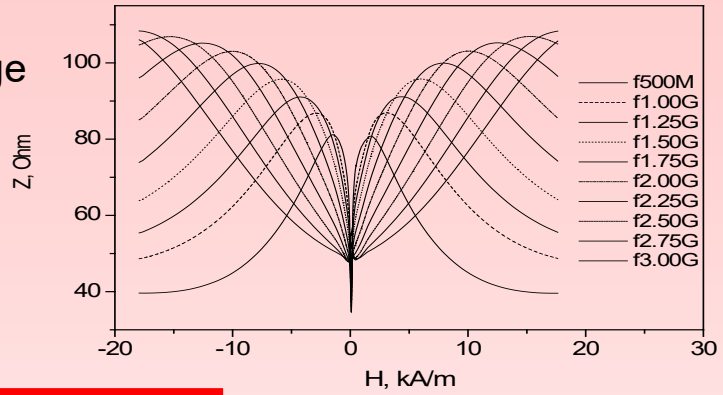
Smart composites: contactless sensor technilogy

The components of tuneable composite metamaterial:

(1) strong dispersion of the effective permittivity in microwave range of composite containing metallic wires

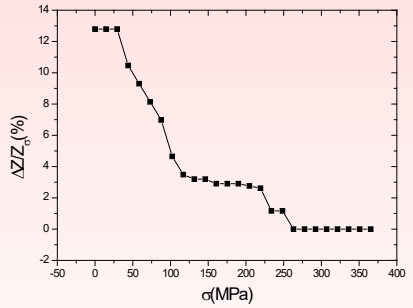
(2) Magneto-Impedance (MI) in Magnetically Soft Microwires.

HF GMI

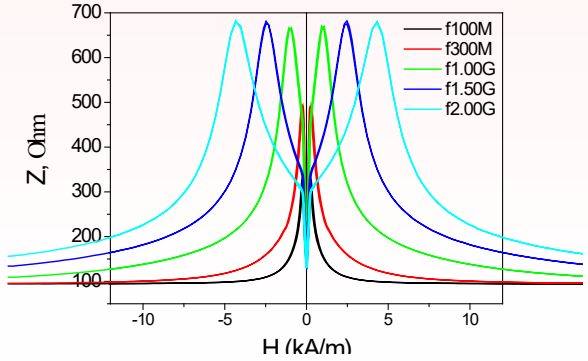


Microwave MI effect

Dispersion of the effective permittivity

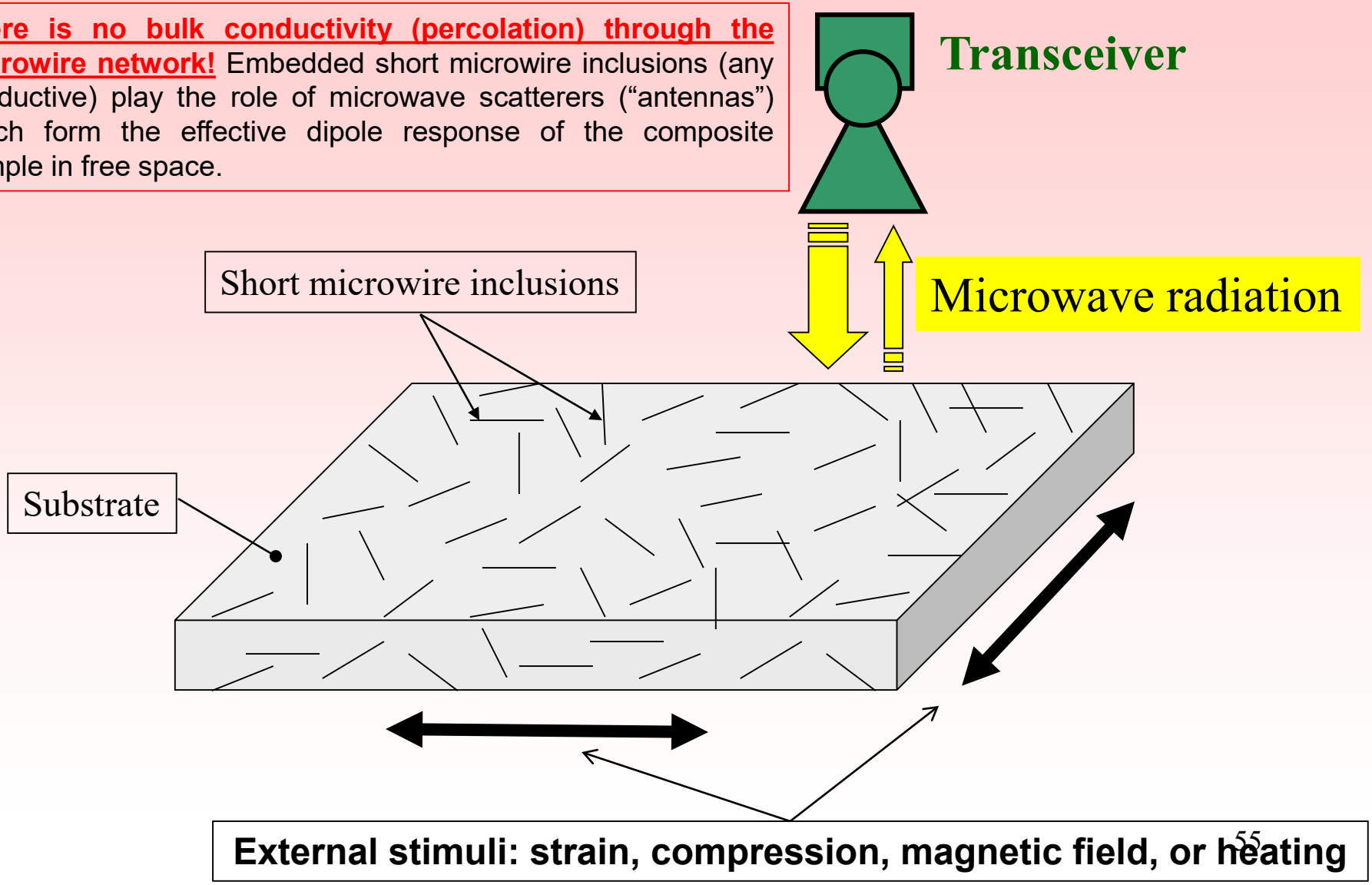


Tuneable Microwave Composites



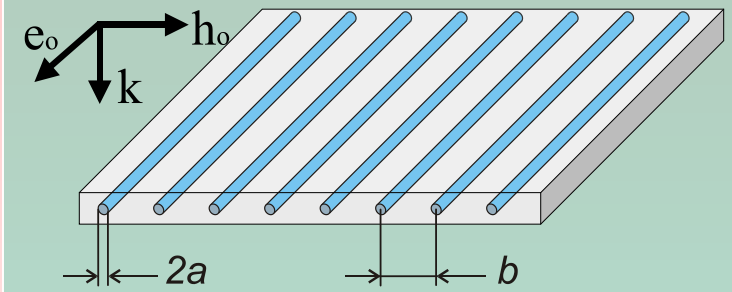
Free-space microwave sensing technique: embedded short ferromagnetic microwires

There is no bulk conductivity (percolation) through the microwire network! Embedded short microwire inclusions (any conductive) play the role of microwave scatterers ("antennas") which form the effective dipole response of the composite sample in free space.

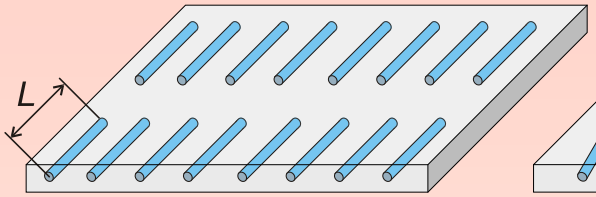


Composites with unusual dispersion of permittivity

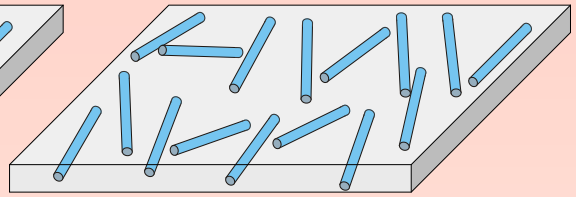
1. Ordered long wire inclusions

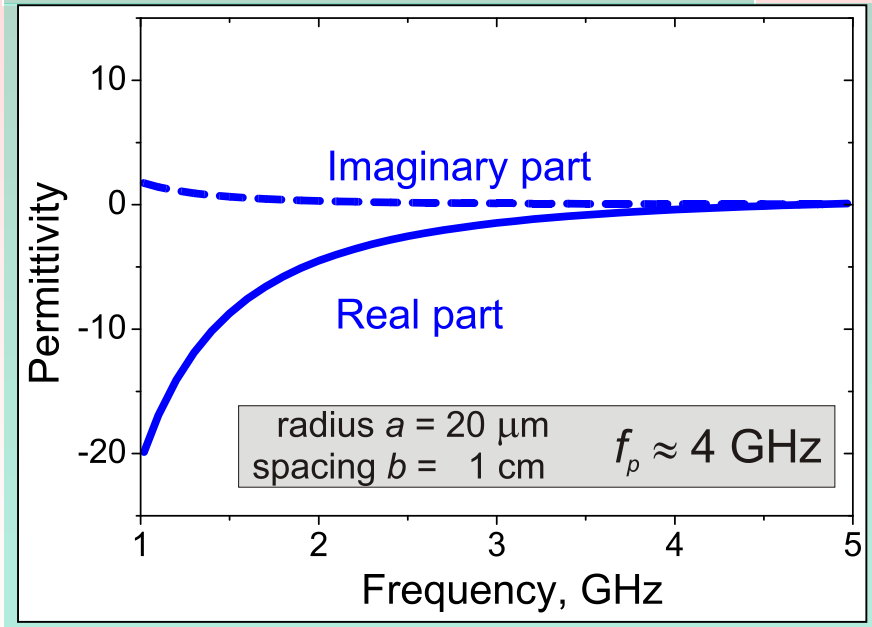


2. Ordered short wire inclusions (0.5-5 cm)



3. Arbitrary directed short wire inclusions (0.5-5 cm)



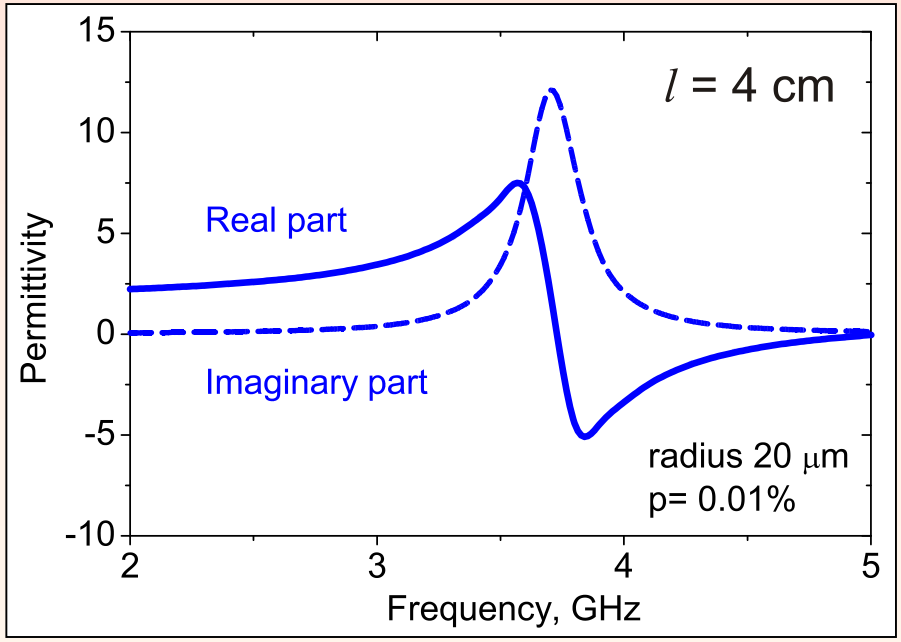


Ordered thin long wire structures behave like a **plasma** in the microwave region with a plasma frequency:

$$\omega_p^2 = \frac{2\pi c^2}{b^2 \ln(b/a)}$$

The short wire composites are characterized by **resonance type** of the ε_{ef} as the wires behave as dipole antennas with the resonance at half wave length:

$$\omega_{res} = \frac{\pi c}{l\sqrt{\varepsilon_d}}$$

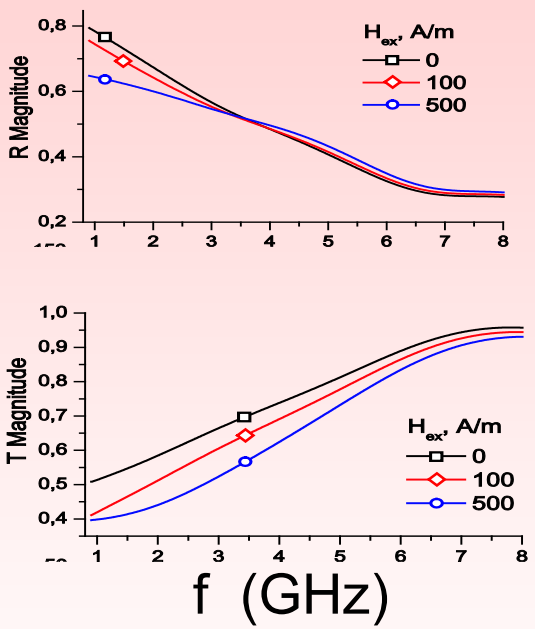


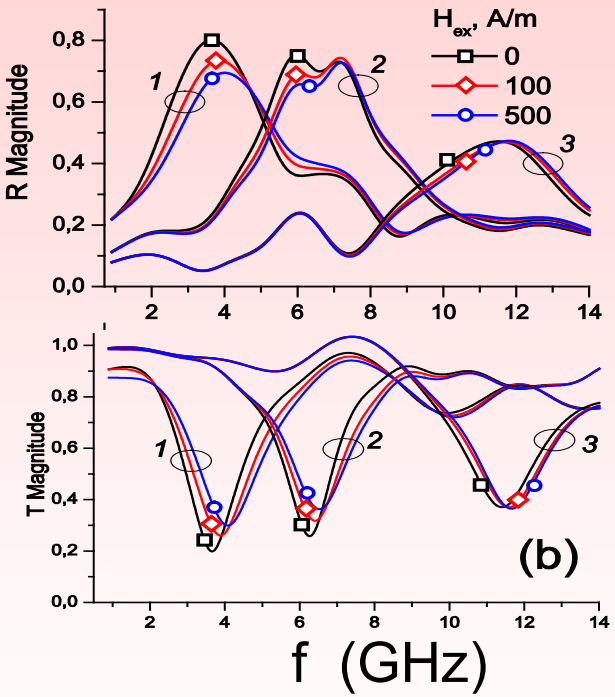
Smart composites with magnetic wire includions

experiment

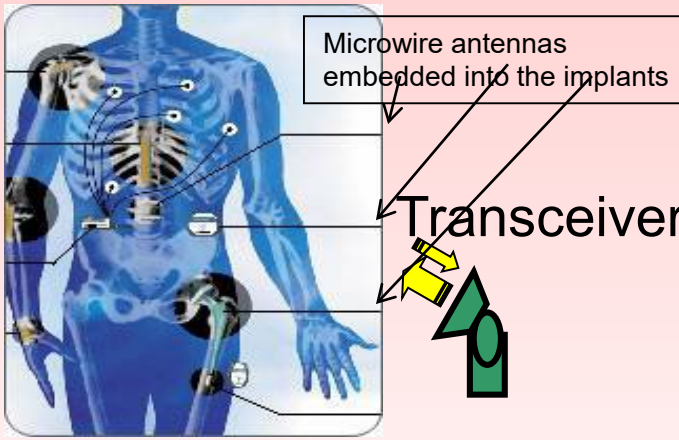
Spectra of *R*, *T* for composites with long wires with H_{ex} as a parameter (H_{ex}=0,100, 500A/m).

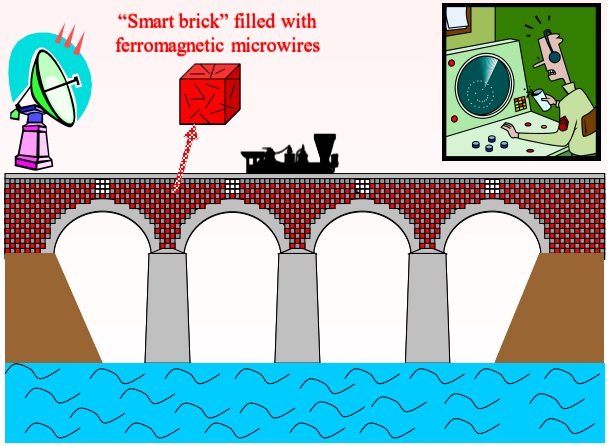
Spectra of *R*, *T* of composites with cut wires of length 40 (1), 20 (2) and 10 (3) mm with the field as a parameter.





Applicaions:



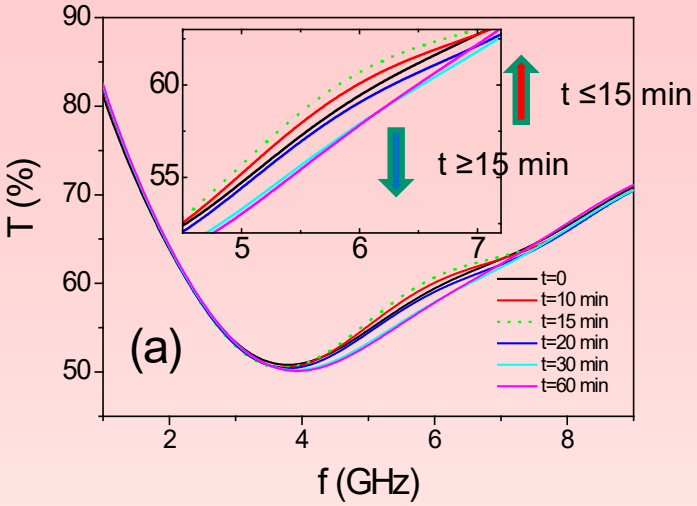


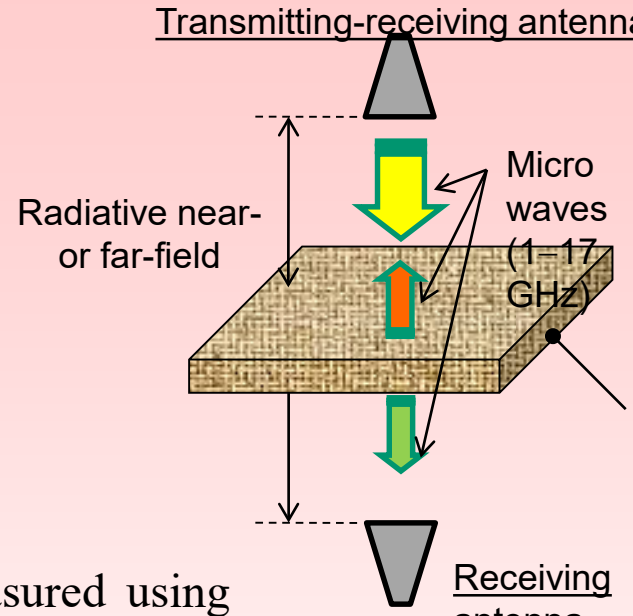
reflection *R* and transmission *T* spectra

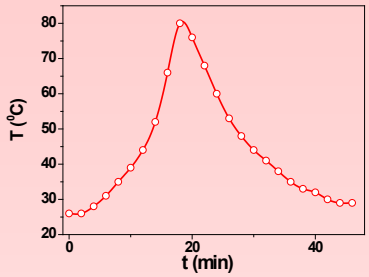
L.V. Panina, M. Ipatov, V. Zhukova, A. Zhukov and J.Gonzalez, Applied Physics A: Materials Science and Processing (2011), DOI: 10.1007/s00339-010-6198-7

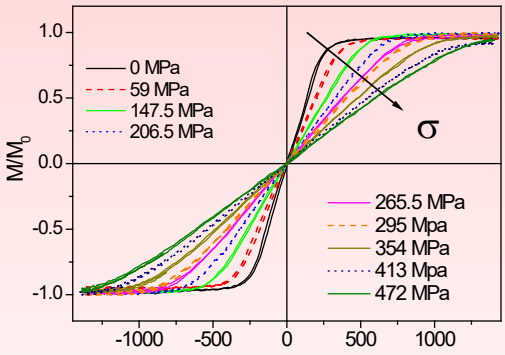
Composites monitoring

Recent results

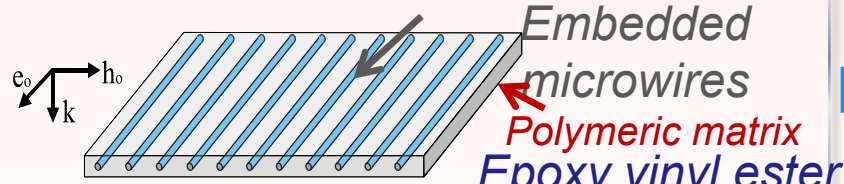








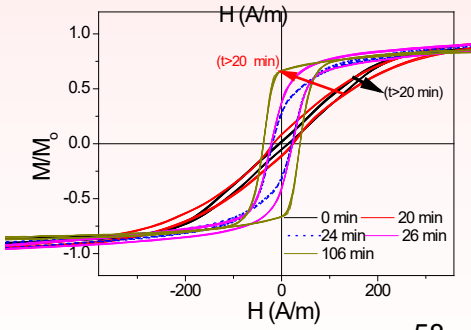
The Transmission, T parameters measured using free-space system during the composite solidification.



FRC: Fiber Reinforced Composite

Composite during polymerization

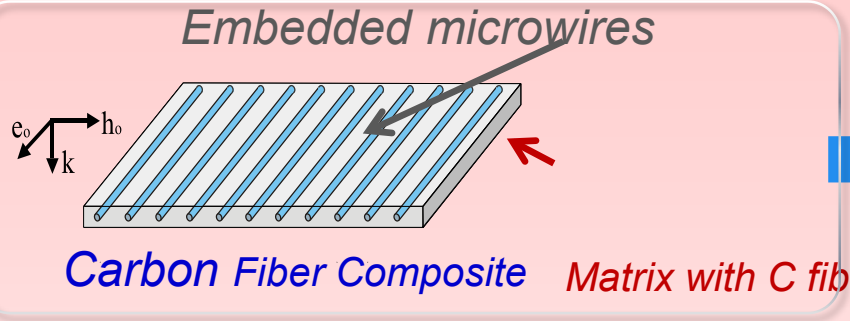
Free-space Measurements



A. Allue, et.al "Composites Part A: Applied Science and Manufacturing, 120 (2019) 12-20

Composite structures in aircraft industry

Free-space Measurements



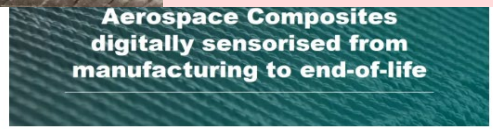
Carbon Fiber Composite

Matrix with C fibers

Both magnetic and mechanical properties are relevant !
Main problem: high electrical conductivity of Carbon fibre (different to Polymer matrix). Magnetic field (low f modulating)allows separate signal from magnetic wires

Modulation magnetic field (80 Hz) OFF and ON, at 2 GHz

Line colors: yellow-S11; green-S22, blue and magenta: S12 and S21 respectively



Aerospace Composites digitally sensorised

The INFINITE project will develop know-how to incorporate advanced sensing technologis in advanced composite components for aerospace applications. The principal achievement of the project will be to develop a calibrated system capable of suppling powerful data for the structural health monitoring process.

First attempt to use the composites with the reinforcement in the [illegible] high strength/stand modulus aerospace carbon fibres stitche polyester yarn.

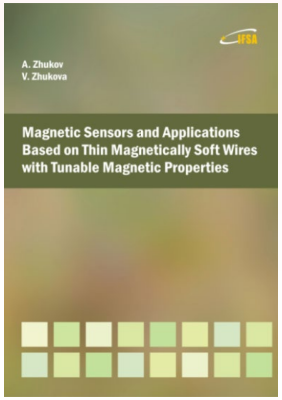
ITE consortium

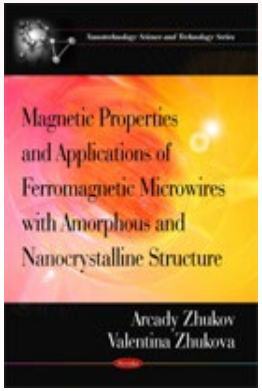
V. Zhukova, et.al. *IEEE Sensors Letters*, vol. 8, no. 1 (2024) pp. 1-4, Art no. 2500104, doi: 10.1109/LSENS.2023.3337071

Conclusions

- Soft magnetic microwires exhibit **high GMI effect** in a wide frequency range suitable for the magnetic field detection, stress and temperature monitoring. But **one should pay attention on stress relaxation and magnetostriction coefficient**.
- GMI effect and it frequency dependence that can be **tailored the magnetoelastic anisotropy**, i.e. modifying the microwires geometry or relaxing the stresses by heat treatment
- Features of **high frequency GMI effect** can be described using **FMR-like approximation**.
- **GMI hysteresis** can be related with bamboo-like domain structure and can be suppressed by the bias magnetic field. The other origin of GMI hysteresis is the **bias field from the inner core (core-shell interaction)**
- **HF GMI can be used for composite monitoring**

Thank you for the attention!





"Advances in Giant Magnetoimpedance Materials" by A. Zhukov, M. Ipatov and V. Zhukov (issue October 2015)