The University of the Basque Country
Faculty of Chemistry
Department of Material Physics
Magnetism Research Group

Magnetic Microwires for Sensor Applications

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Outline

1. INTRODUCTION

1.1. STATE OF THE ART ON MAGNETIC WIRES, MAGNETIC PROPERTIES AND APPLICATIONS

1. 2.MOTIVATION.

2. MEASUREMENTS METHODS

3. MAGNETIC PROPERTIES OF AS-PREPARED MICROWIRES

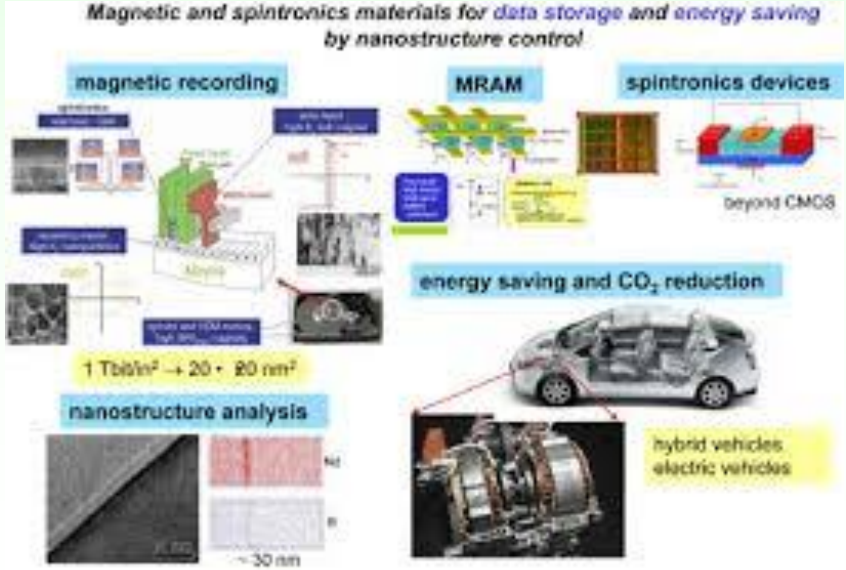
3.1. TUNNING OF DOMAIN WALL DYNAMICS

3.2. TUNNING OF HYSTERESIS LOOPS AND GMI

4. CONCLUSIONS

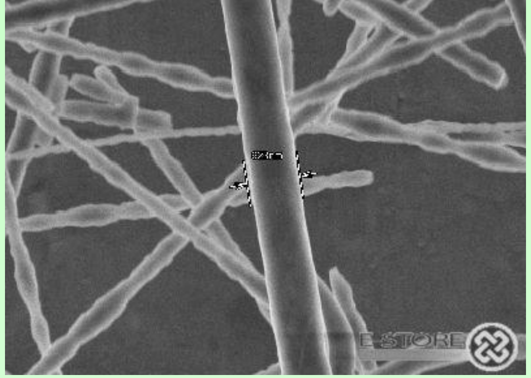
Magnetic materials…

and applications



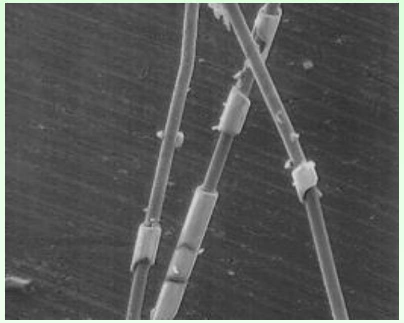
Magnetic wires:

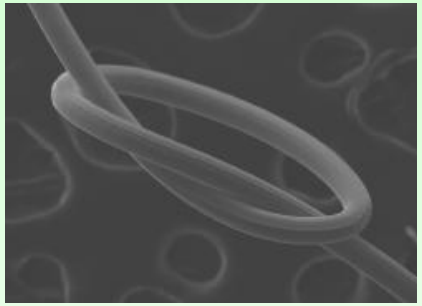
-Iron whiskers
-Wiegan magnetic wires
(CoVFe,1970-th)

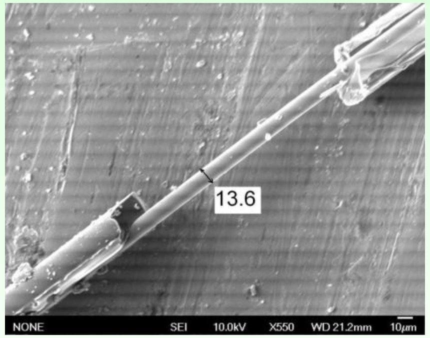


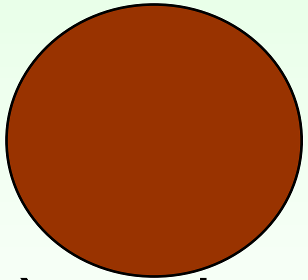
Amorphous: milli
(since 80-th) micro
nano

wires



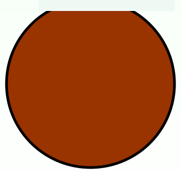




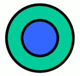


In-rotating water wires
(can be drawn to 20-30 μm) – rough surface

Melt extracted (40-50 μm)- not perfectly cylindrical cross section



Glass coated (0.1-50 μm)- glass coating (stresses)

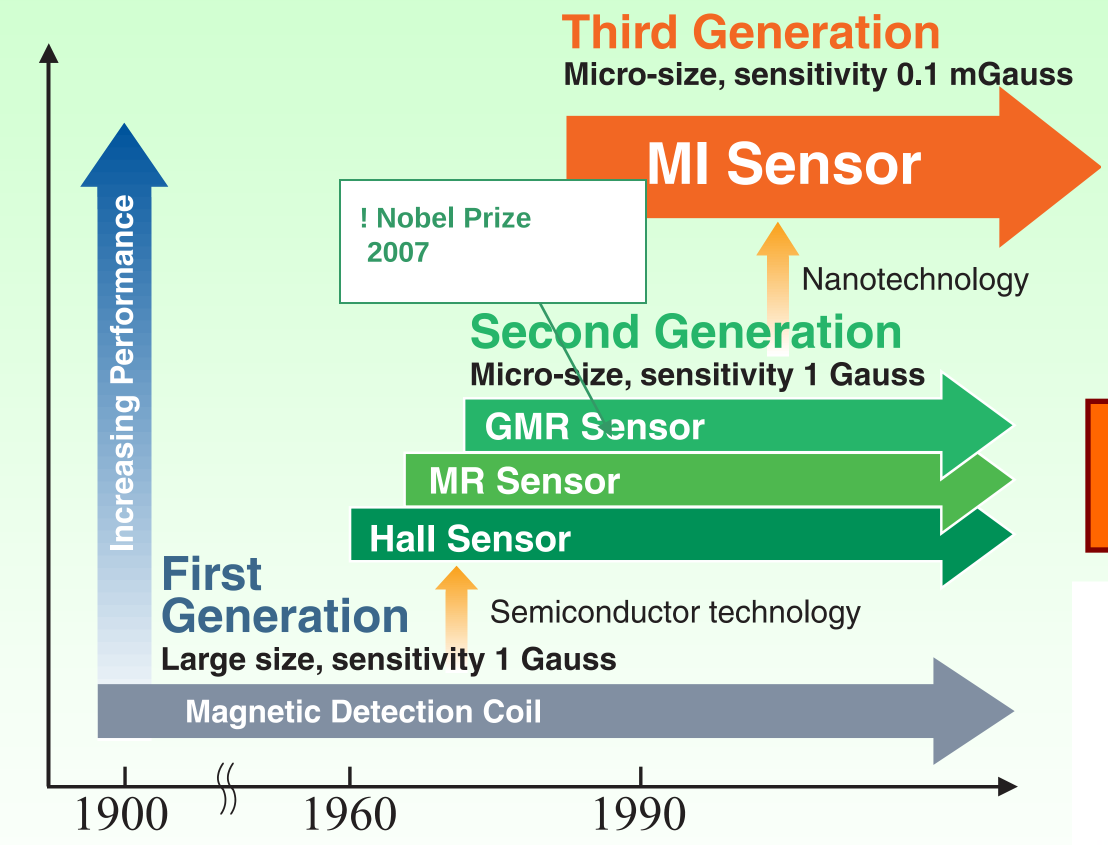


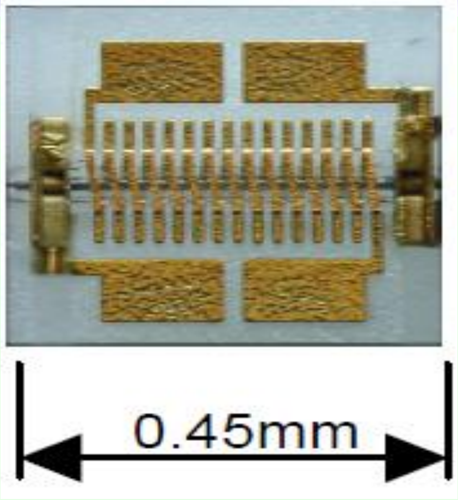
Promising applications: 1. Magnetic sensors and smart composites

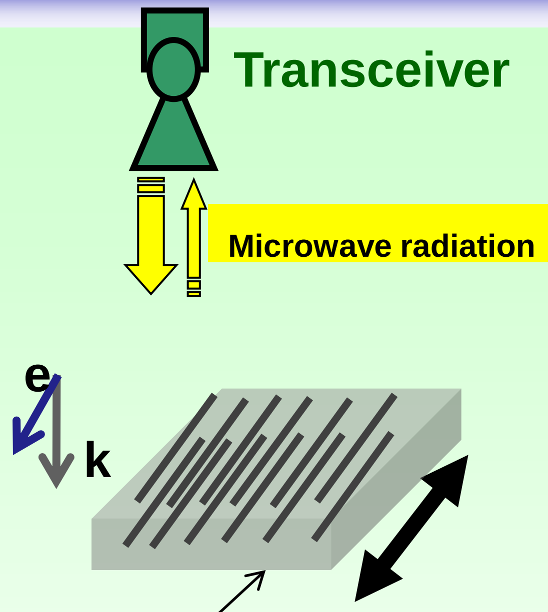
Third Generation of Magnetic Sensors

Smart composites

MI Sensors with excellent performance!

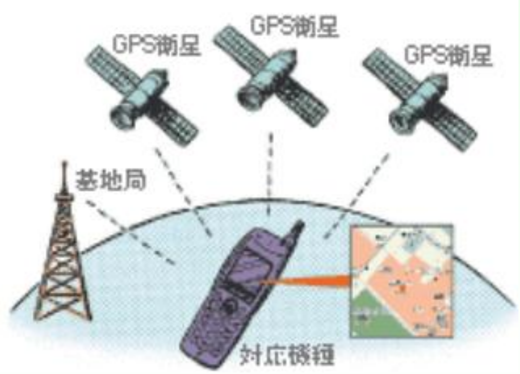






Based on Amorphous Wwire since 2010

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

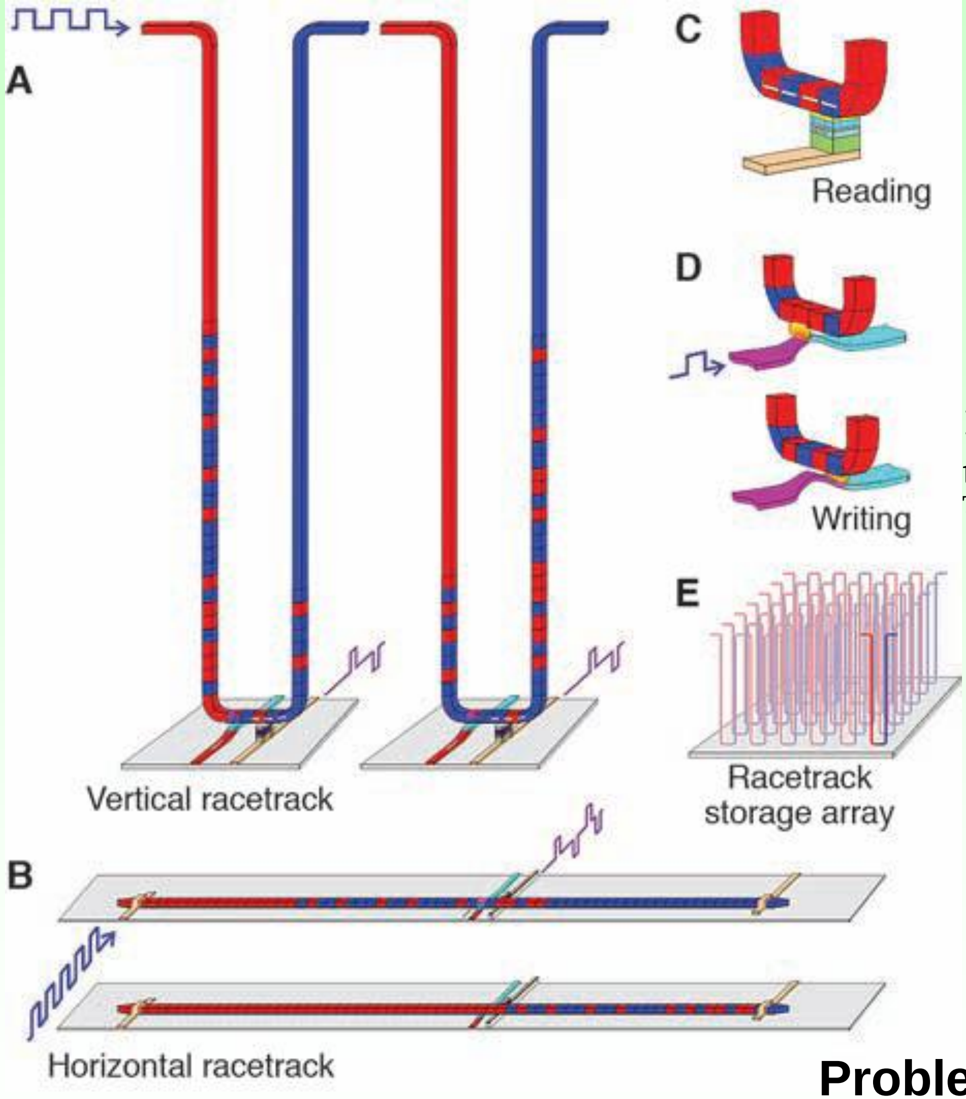
Magnetic Sensor History

Industrial application in Smart phone using MI sensor

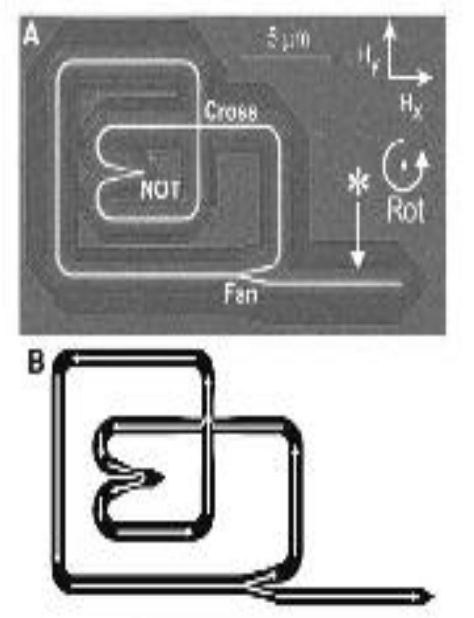
Last tendencies: Size reduction, frequency increasing
Soft magnets are needed

Source: **Aichi Micro Intelligent Corporation**

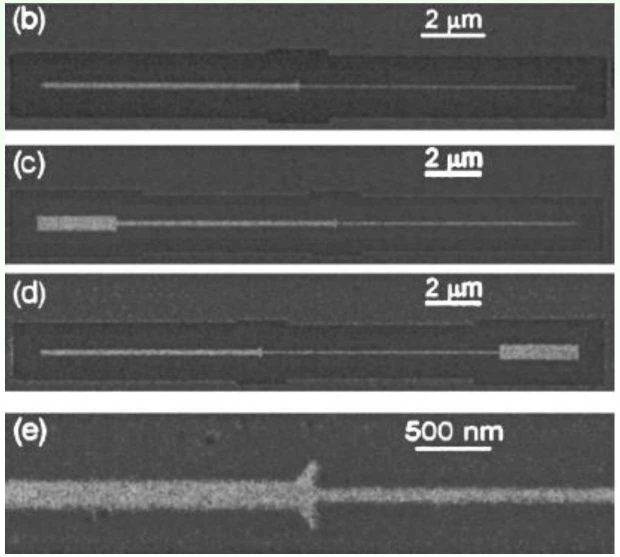
Promising applications: 2. Magnetic magnetic memory and logic based on DWP



Requisite: controlable DWP



1 of 10 most emerging technologies in 2009
Technology review 2009, published by MIT

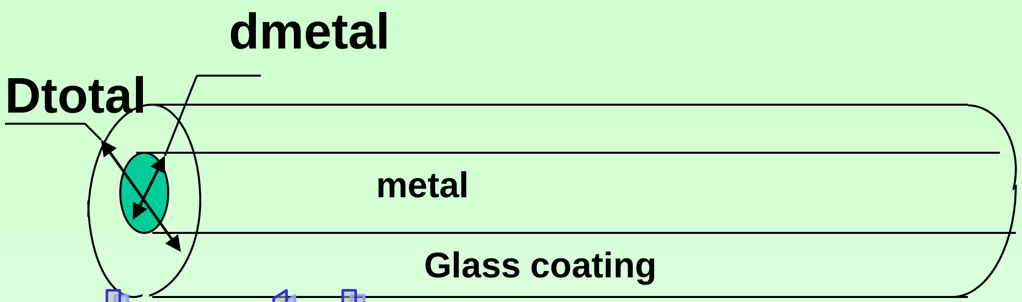


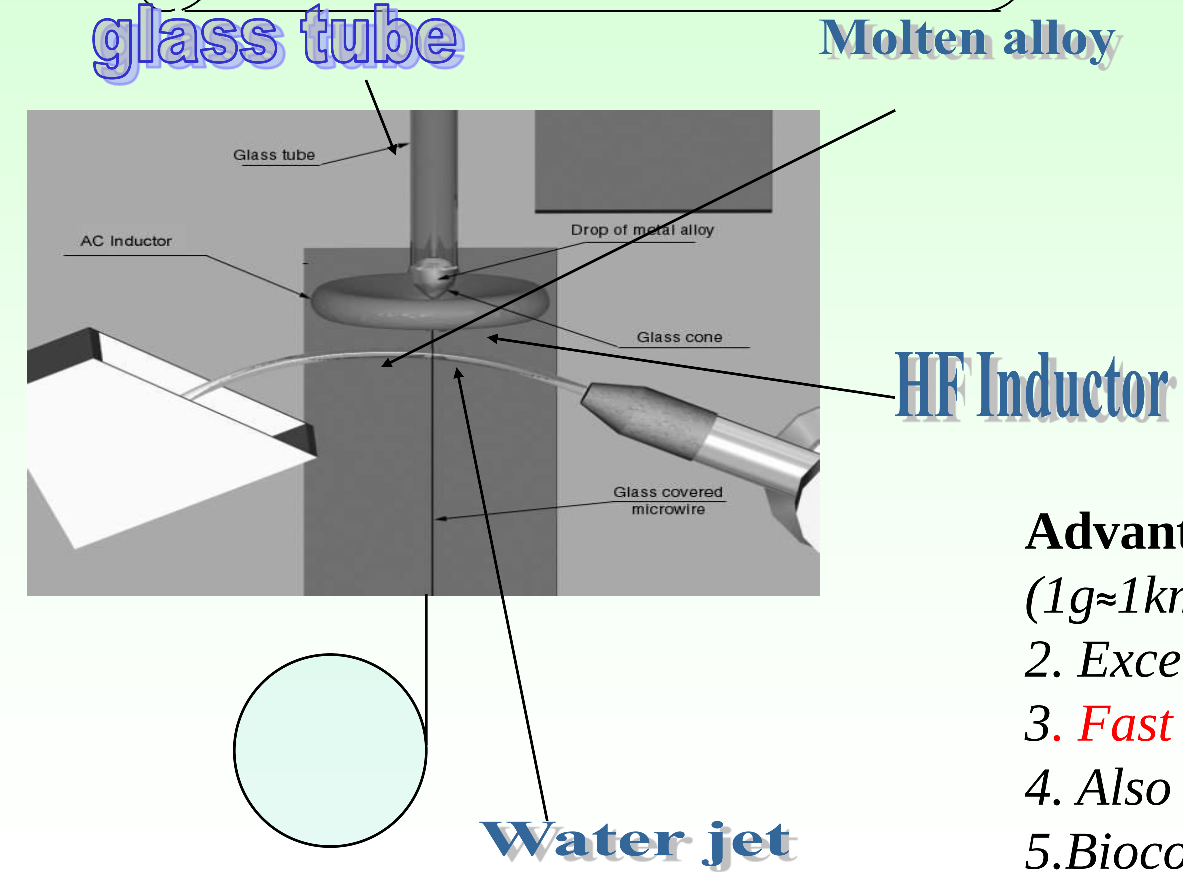
Stuart S. P. Parkin, *et al. Science* 320, 190 (2008);

Problems:
1. Fast DWP (speed)
2. Controlled DW pinning

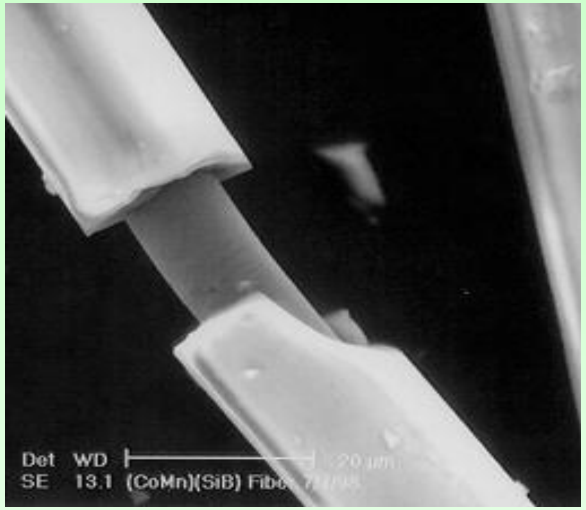
Glass coated microwires

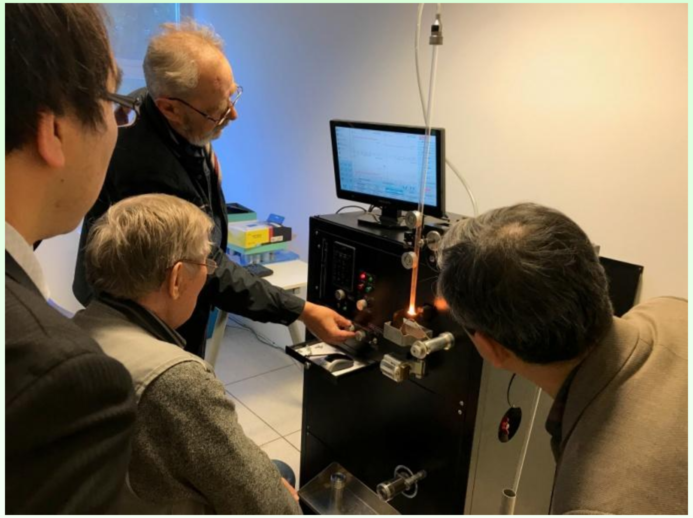
- Co, Ni , Fe and Cu rich compositions





Receiving bobbins





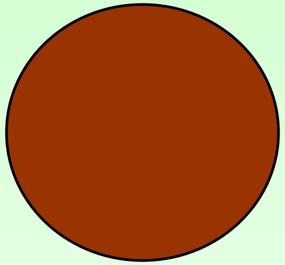
Typical dimensions:
Total diameter 3-40 microns
Metallic nucleus diameter 1-30 microns
Glass coating thickness 1-10 microns
Length - few km (up to 10 in 1 bobbin)

Advantages: *1. Unexpensive and simple fabrication method (1g≈1km)*
2. Excellent soft magnetic properites and high GMI effect
3. Fast DW propagation
4. Also recently Heusler-type and granular microwires
5.Biocompatibility (glass-coating)

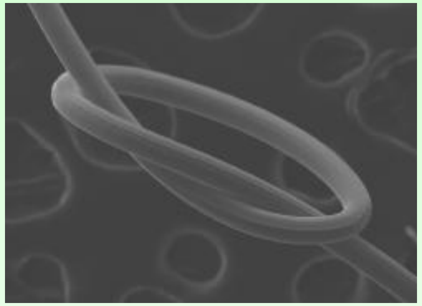
Raw materials saving, better corrosion resistance, robust properties, medical applications…

Comparison of microwires with other soft magnetic materials

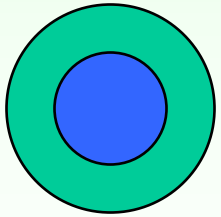
Ribbons, Cross section above 4×10^4 μm^2, fast and cheap fabrication, extremely soft magnetic properties, too big for microsensors applications



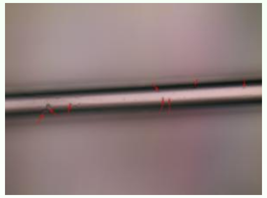
Wires, cross section above 2×10^3 μm^2, fast and cheap fabrication, good magnetic properties, effect of sample Length - too big for microsensors applications



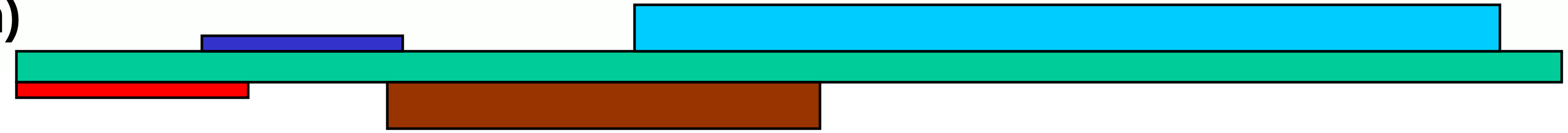
Thin films, cross section 0.1– 10^2 μm^2, slow fabrication, Higher cost, worse magnetic softness, good compatibility in integrated circuits, effect of substrate



Microwires, typical cross section above 4- 2×10^3 μm^2, fast and cheap fabrication, extremely soft magnetic properties, good for microsensors applications

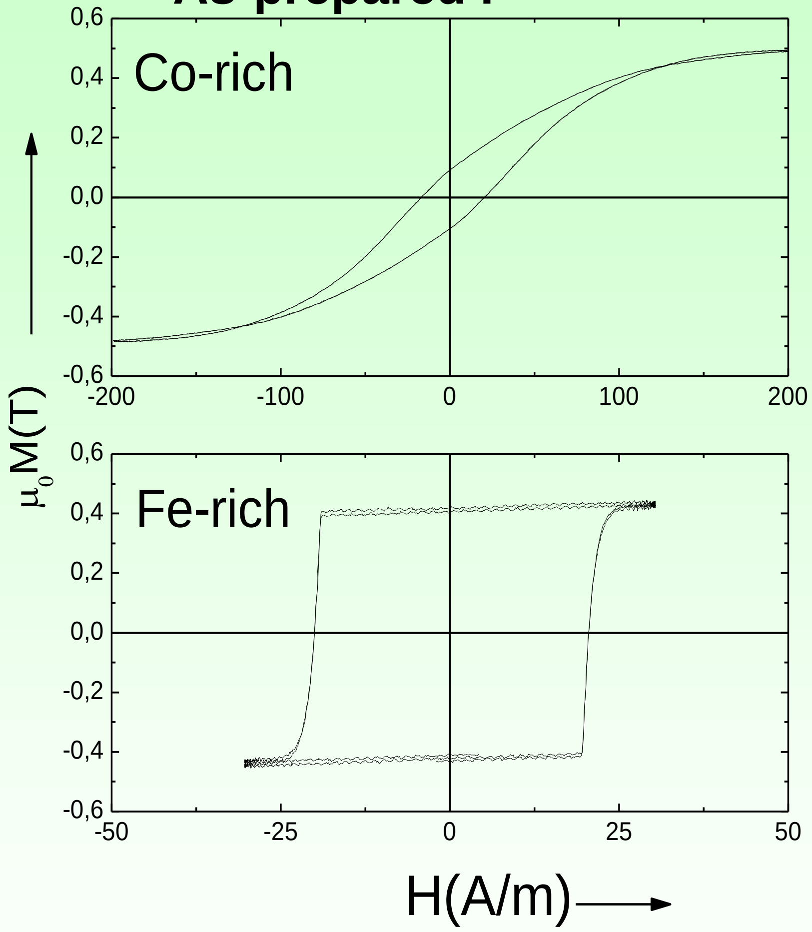


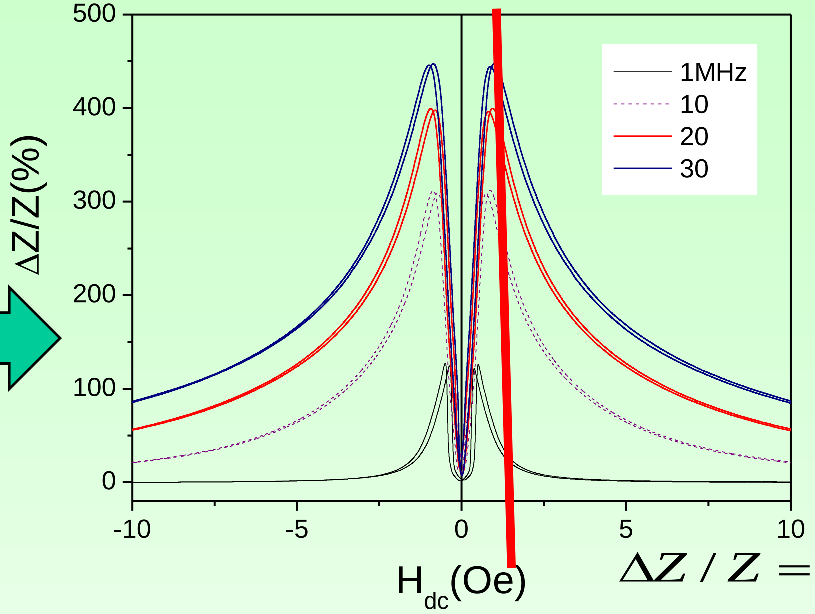
Scale (cross section)



MAGNETIC PROPERTIES OF AMORPHOUS MICROWIRES

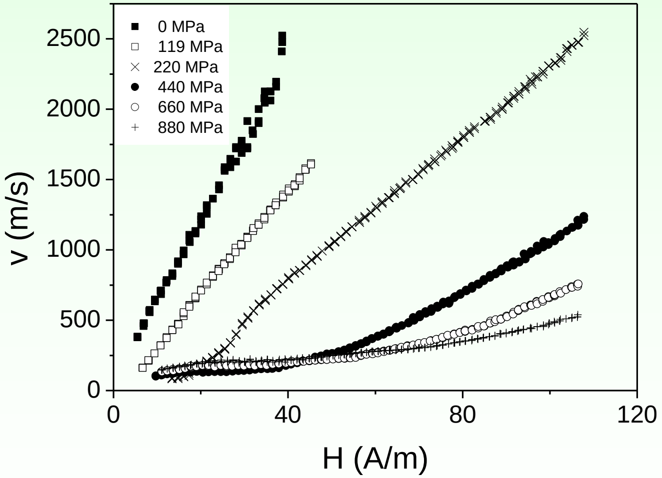
As-prepared !





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

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



Fast magnetization switching,
DW velocity up to 2.5 km/s

$$v = S\,(H-H_0)$$

Performance of devices depends on GMI effect value (defined as MI ratio) and DW velocity values.

Engineering of magnetic properties of magnetic microwires

Wire based sensors

Tuneable Parameters

Non-reversible

First step

- Composition
- Geometric ratio, ρ
- Conditions of thermal treatment (crystallization)

Reversible

Second step: fine tuning

- Local heating
- Mechanical stress
- Axial-circular crossed magnetic field
- Conditions of thermal treatment (crystallization)

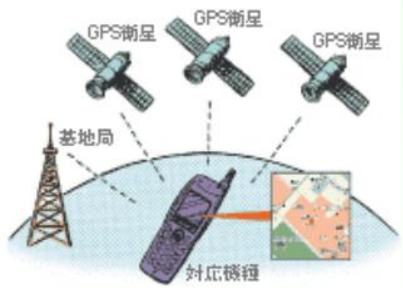
Optimal magnetic properties

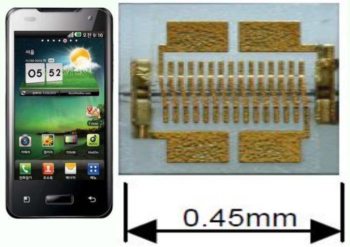
APPLICATIONS

Magnetic microelectronics

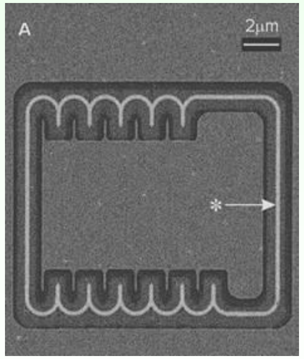
CASIO 2013.June 68250yen

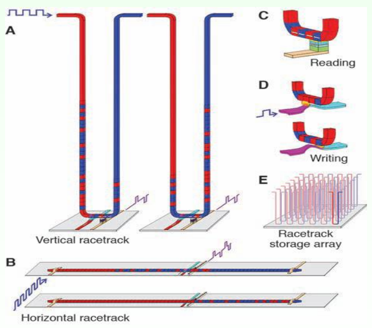
Provided by Prof. K. Mohri





Source: Aichi Micro Intelligent Corporation





S S. P. Parkin, *et al. Science* **320**, 190 (2008)

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), $H_c(s)$

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

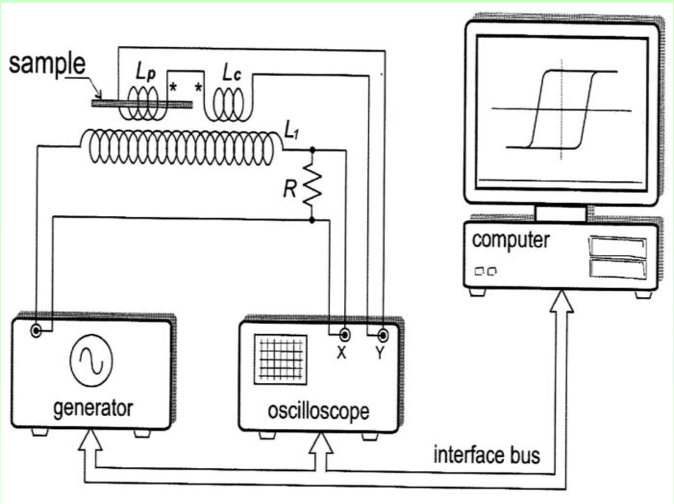
или

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

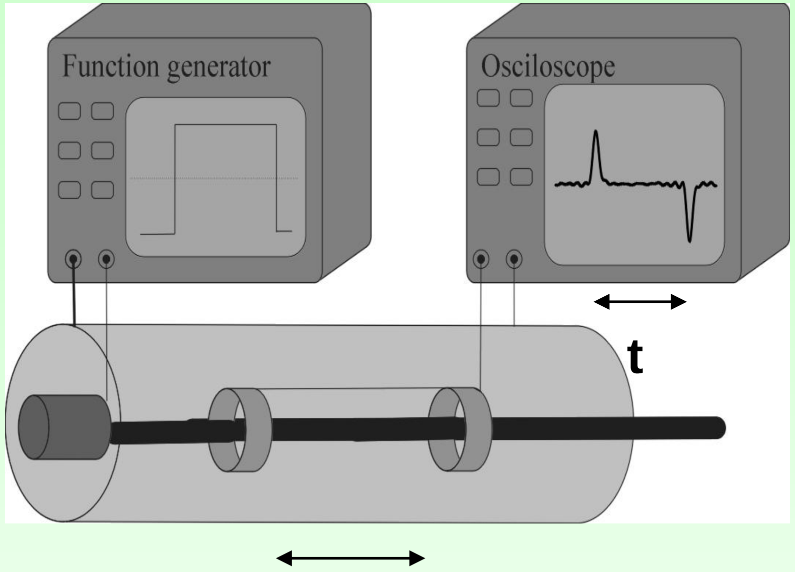
Magnetostriction
Anisotropy (stresses), **induced anisotropy**
Clusters and chemical inhomogeneities (nanocrystallization)
Defects (surface)

Measurements technique

1. Hysteresis loops

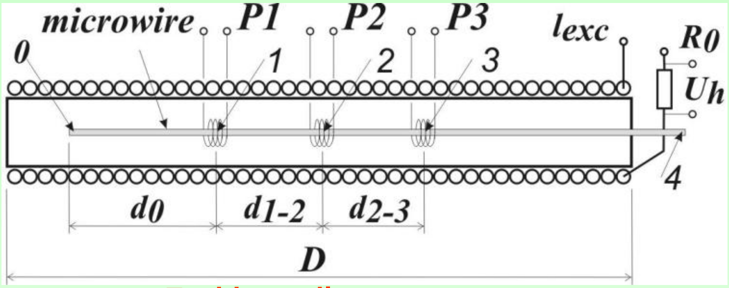


2. Sixtus-Tonks like experiment

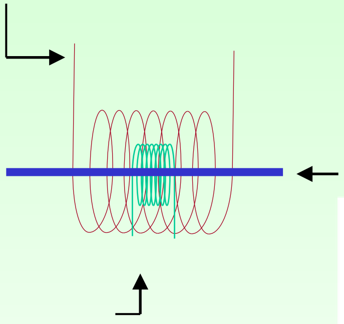


L

V=L/t



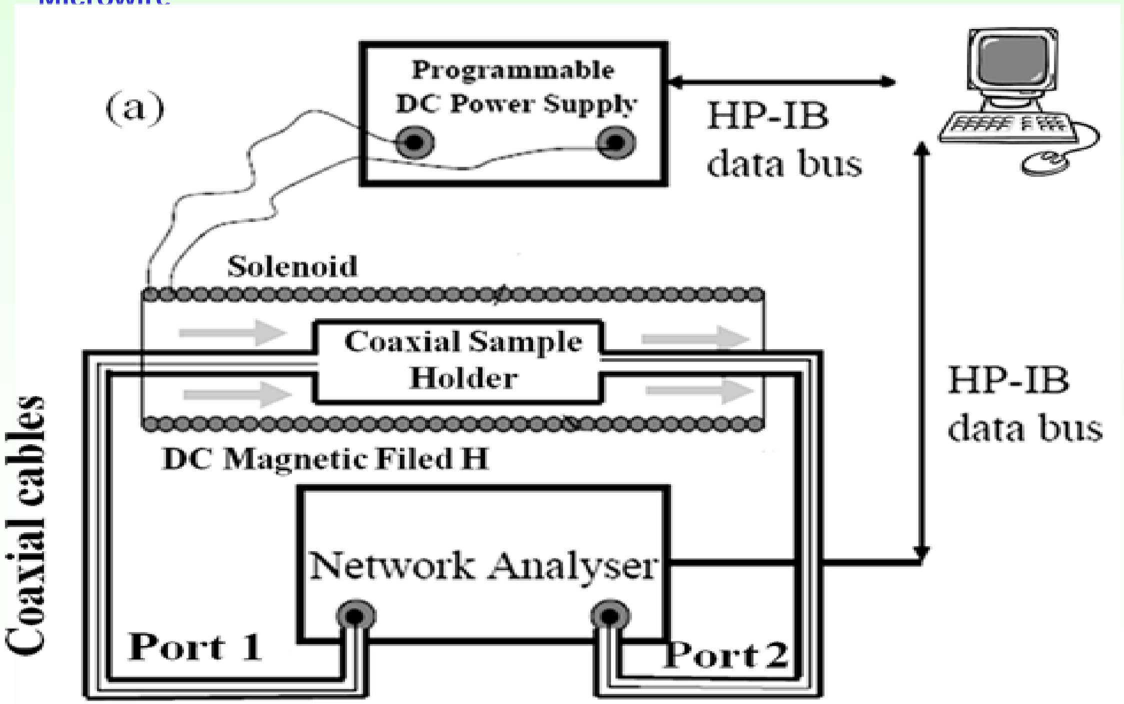
Exciting coil



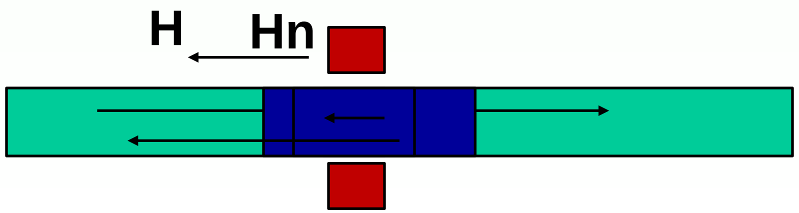
Microwire

Pick up coil

4. Measurements of GMI



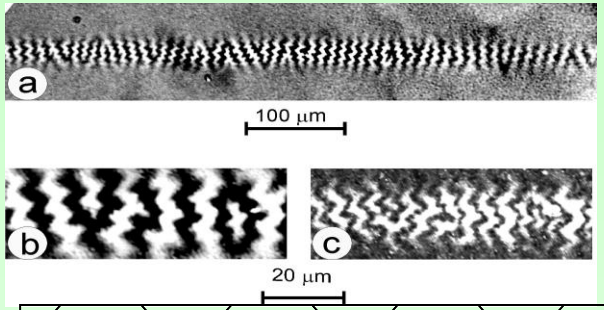
3. Nucleation profile (DW injection)!

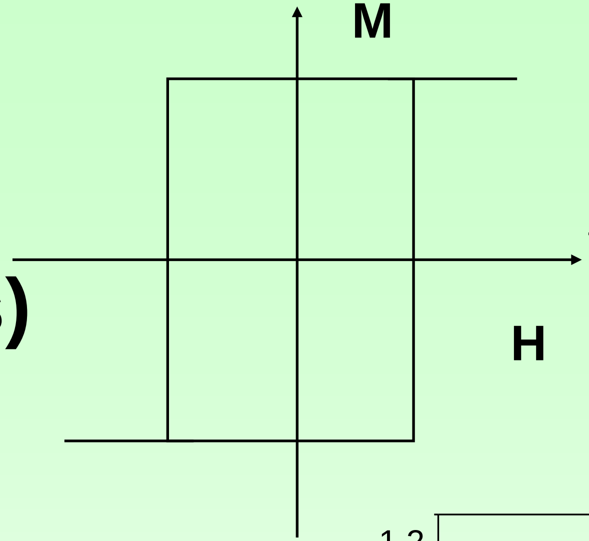


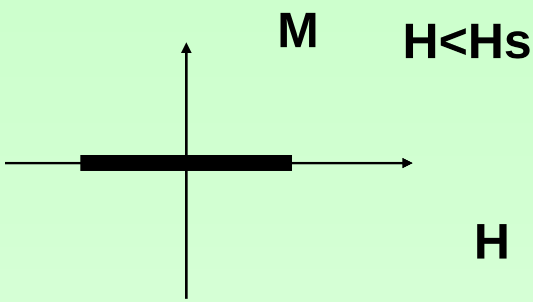
Yu. Kabanov, A. Zhukov, et al,

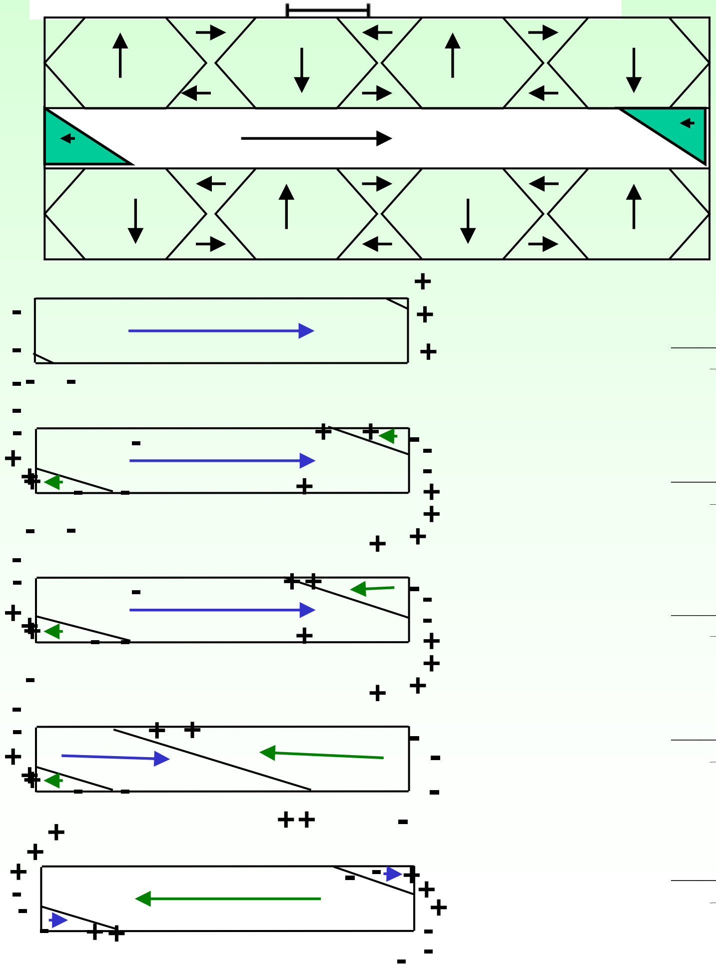
Appl. Phys. Lett. 87 (2005) p142507

Bistable Loops (Fe-based microwires)

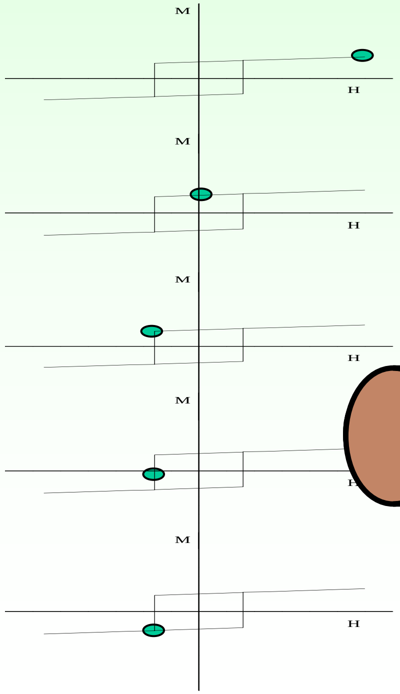


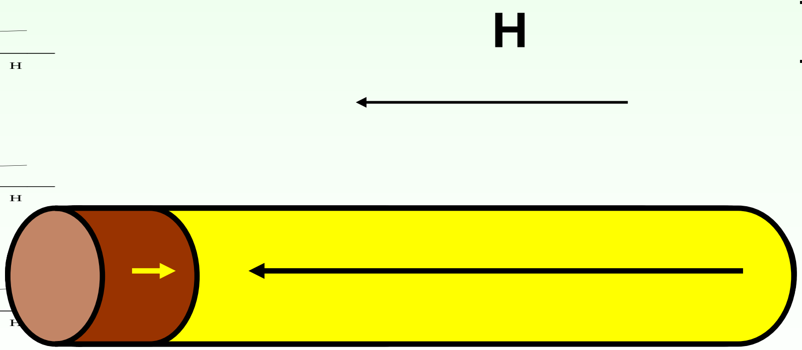


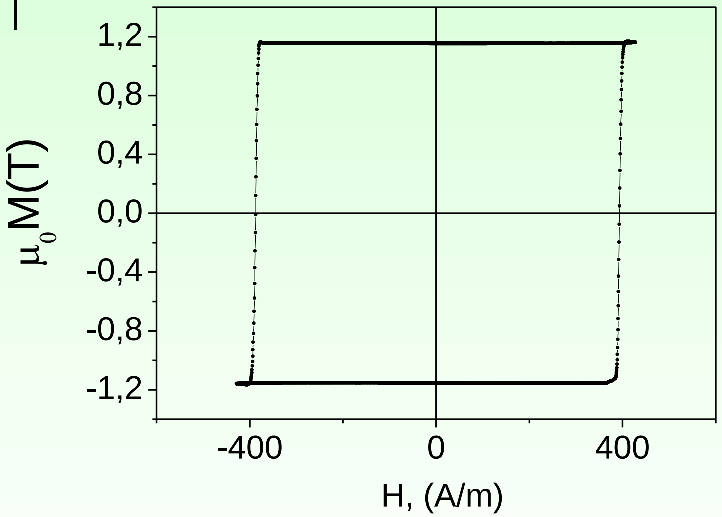




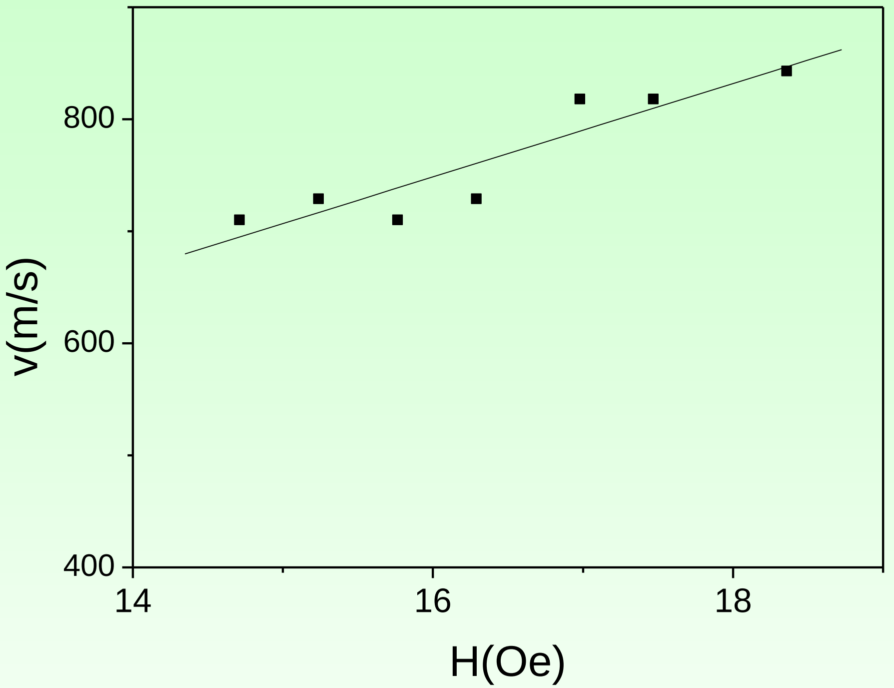
Schematic presentation of the re-magnetization process

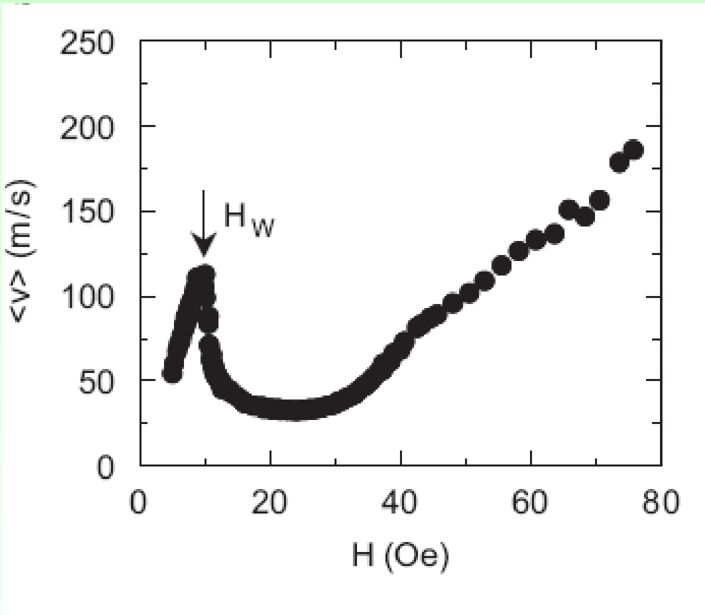


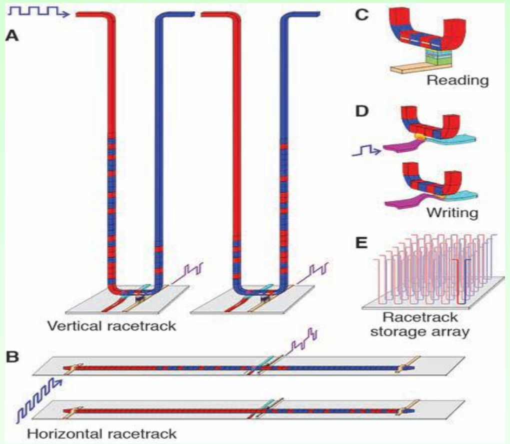




Comparison of domain wall dynamics measured in amorphous Fe –rich microwire and Fe-Ni rich planar nanowires.







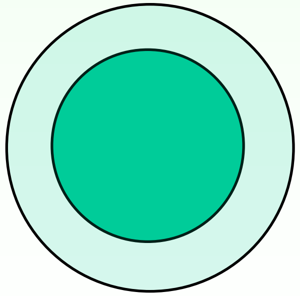
Measured mobility curve for a 490nm×20nm Permalloy nanowire

G.S.D. Beach et al. / J. Magn. Magn. Mater. 320 (2008) 1272–1281

Experimentally observed maximum v ≈110 m/s at 9 Oe

d≈2,8 μm and total diameter D≈ 9μm

ρ=0,31



DW dynamics measured in Fe-rich microwire and in Fe-Ni rich planar nanowires.

Magnetoelastic energy

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

Internal stresses in composite microwires

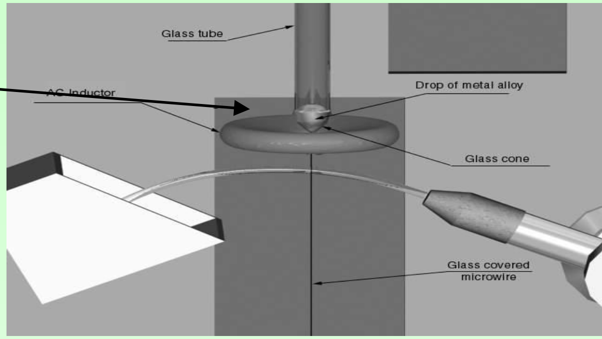
Magnetostriction λ_s -determines by the chemical composition

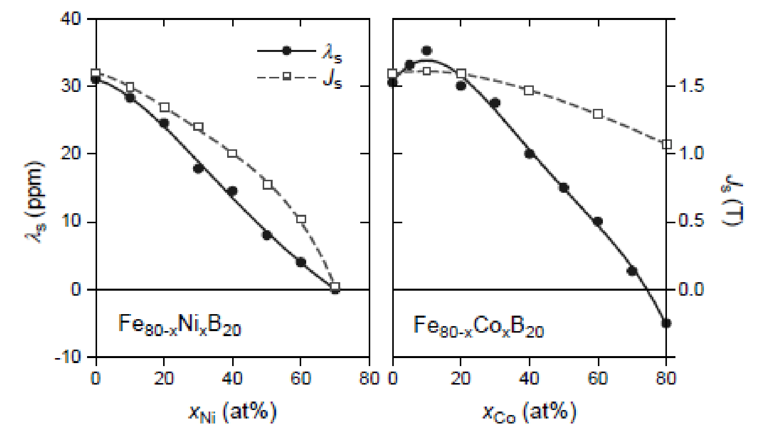
$\sigma = \sigma_{i} + \sigma_{a}$

σ_a- applied stresses

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

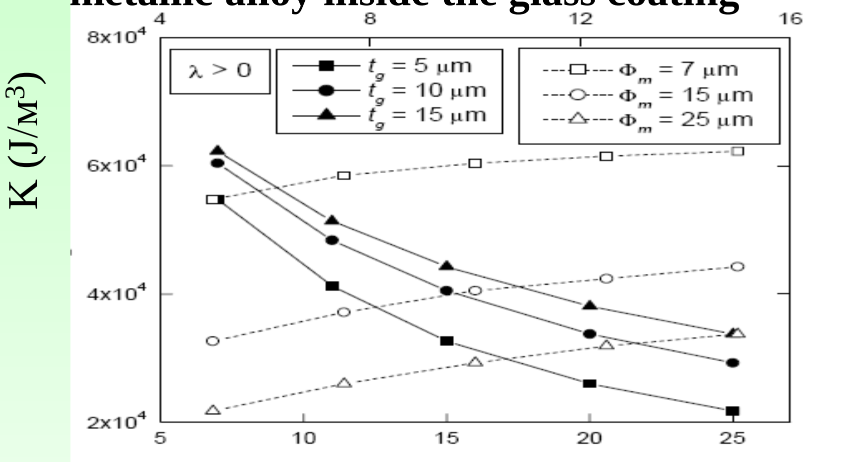
Stress appears at simultaneous solidification of metallic alloy inside the glass coating

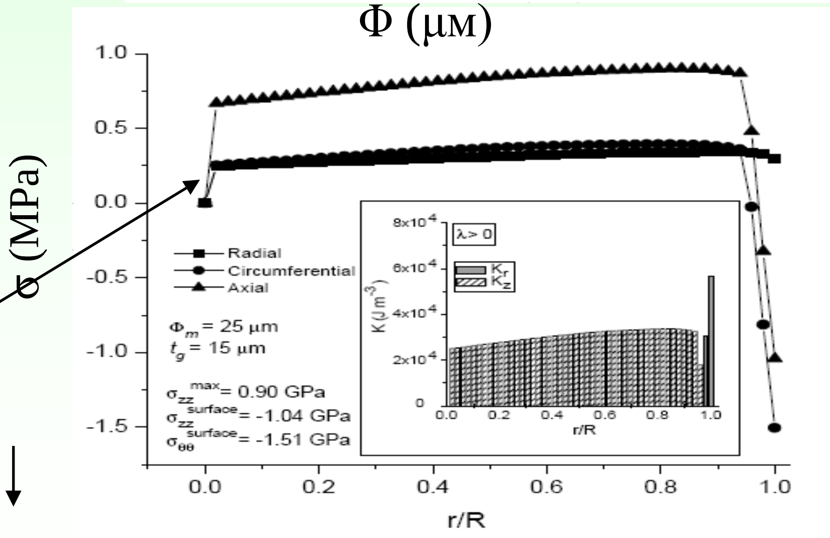


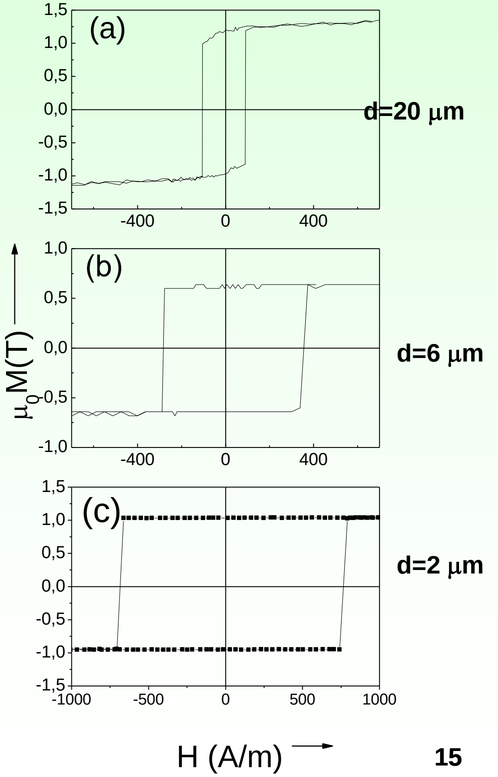


AMORPHOUS AND NANOCRYSTALLINE SOFT MAGNETS

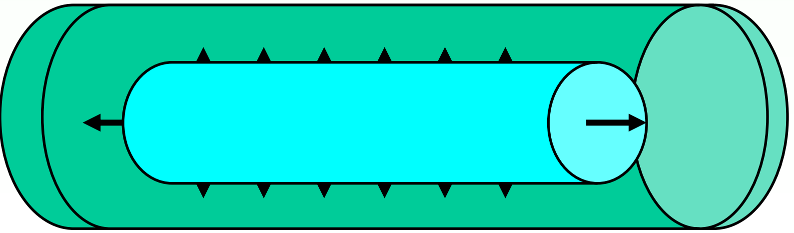
G.Herzer
Vacuumschmelze GmbH & Co KG







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



T ↓

t (μм)

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

Effect of magnetolastic anisitropy on DW propagation

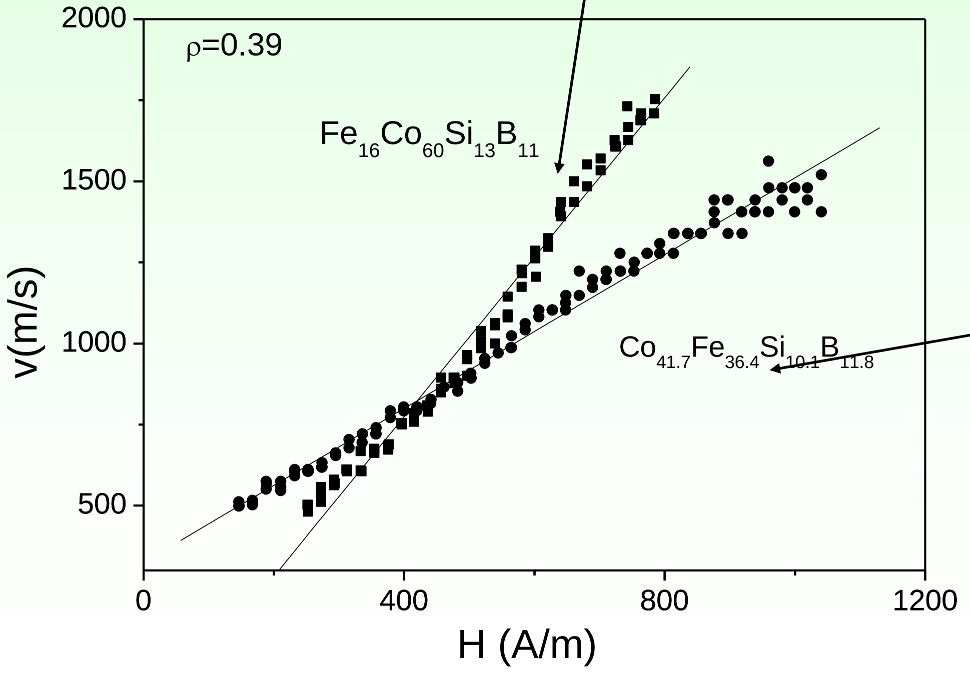
Fe-Co microwires

v=S(H-H0)

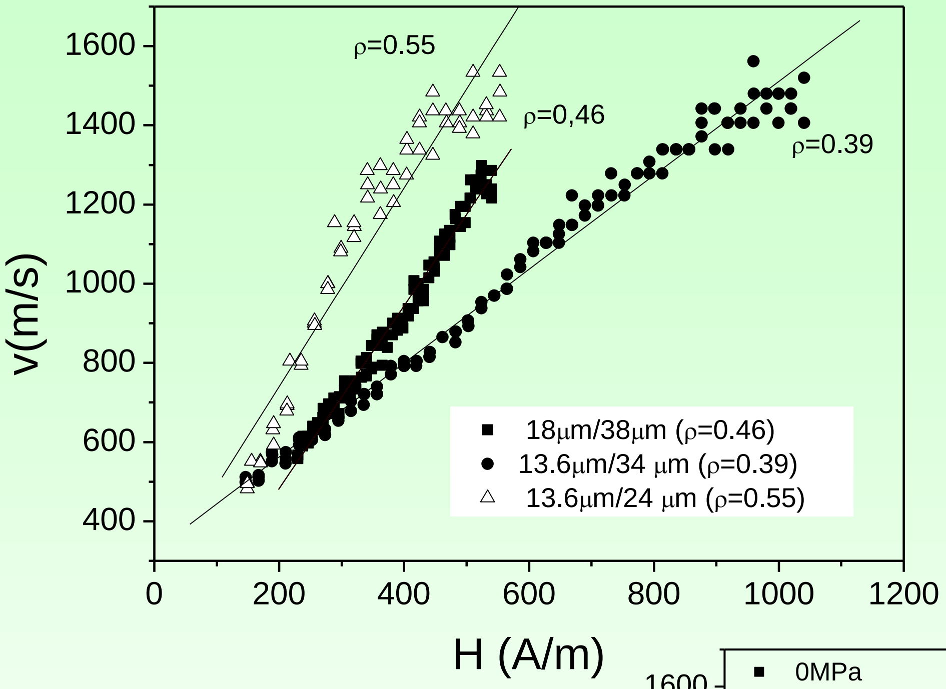
where *S* is the DW mobility, *H* is the axial magnetic field and *H0* is the critical propagation field.

v(H) dependences for Fe16Co60Si13B11 and Co41.7Fe36.4Si10.1B11.8 microwires with ρ=0,39:
effect of magnetostriction

$\lambda_S \approx 20 \times 10^{-6}$



$\lambda_S \approx 40 \times 10^{-6}$



v(H) dependences for Co41.7Fe36.4Si10.1B11.8 microwires with different ratios ρ:
Effect of internal stresses

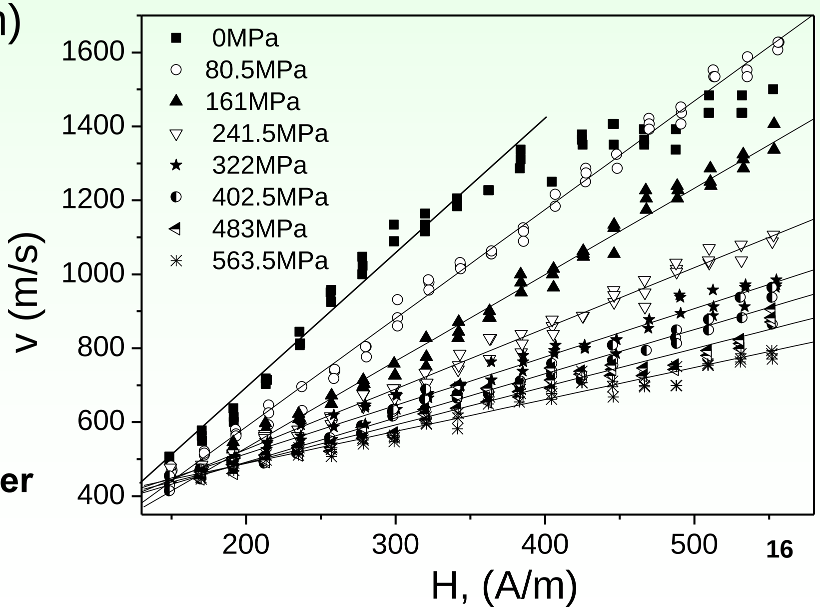
σ=f(ρ)

Different internal stresses!

$$v = S\,(H-H_0)$$

$\lambda_S \approx 20 \times 10^{-6}$

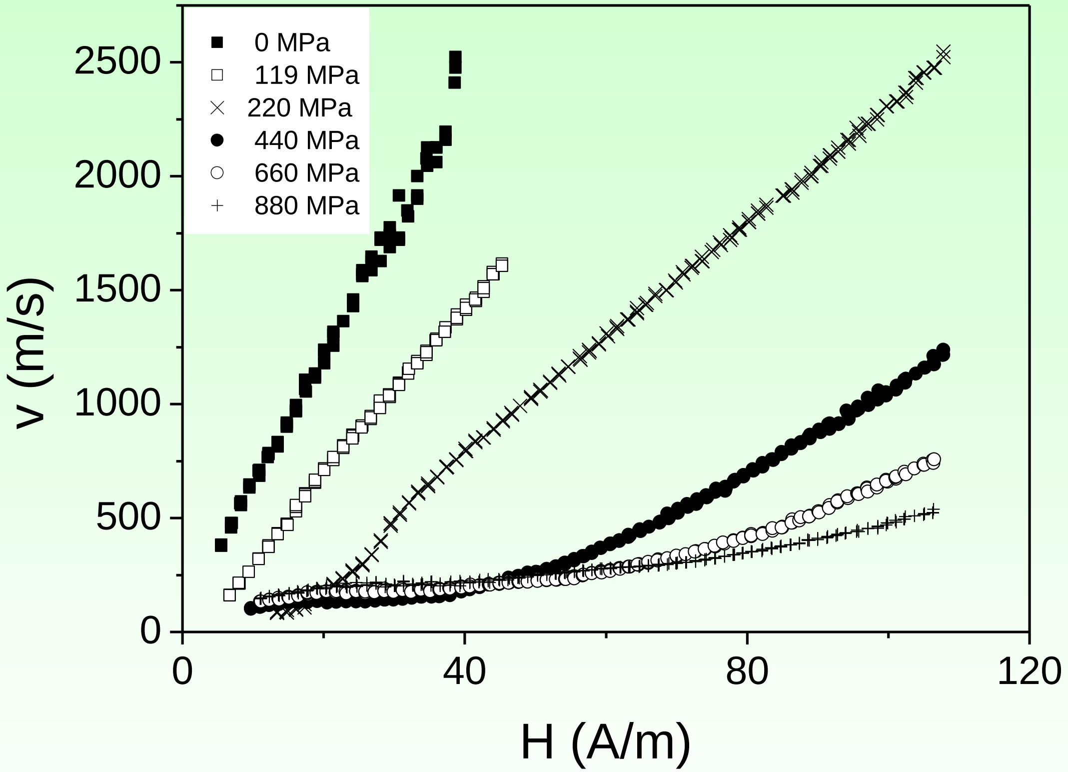
v(H) dependences for Co41.7Fe36.4Si10.1B11.8 3 microwires (d≈ 13,6μm, D≈ 24,6μm, ρ≈ 0,55) measured under application of applied stresses, σa.

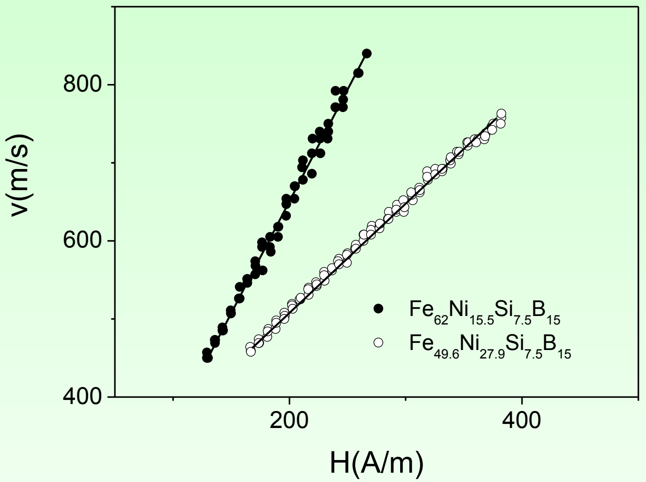


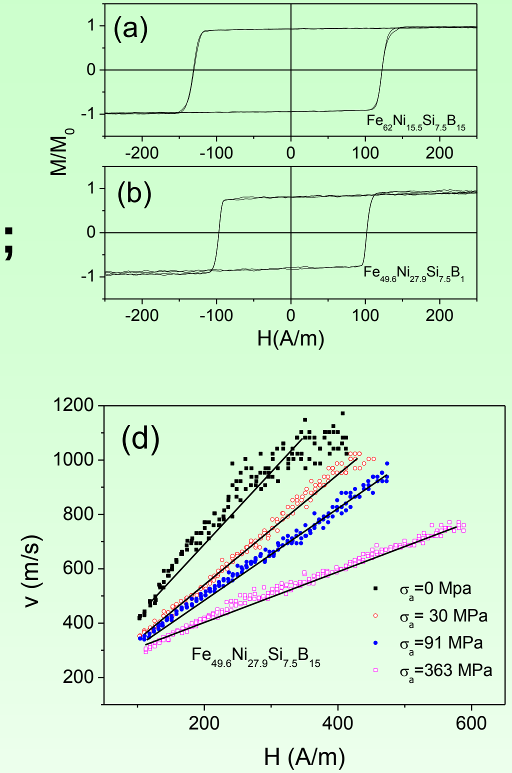
Effect of magnetolastic anisitropy on DW propagation

v=S(H-H$_0$), **where *S* is the DW mobility, *H* is the axial magnetic field and *H$_0$* is the critical propagation field.**

λ_s, $Fe_{62}Ni_{15.5}Si_{7.5}B_{15} \approx 25 \times 10^{-6}$;
λ_s, $Fe_{49,6}Ni_{27.9}Si_{7.5}B_{15} \approx 15 \times 10^{-6}$;







v(H) dependences for Co56Fe8Ni10Si11B16microwires measured under application of applied stresses, σapp.

The domain wall mobility, *S*, is given by:
S=2μ0Ms/β
This damping is related to the Gilbert damping parameter, α and is inversely proportional to the domain wall width δw,

$$\beta r \approx \alpha Ms / \gamma \delta w \approx Ms(Kme/A)^{1/2}$$

Magnetoelastic energy, Kme, is given by Kme ≈ 3/2 λsσ,

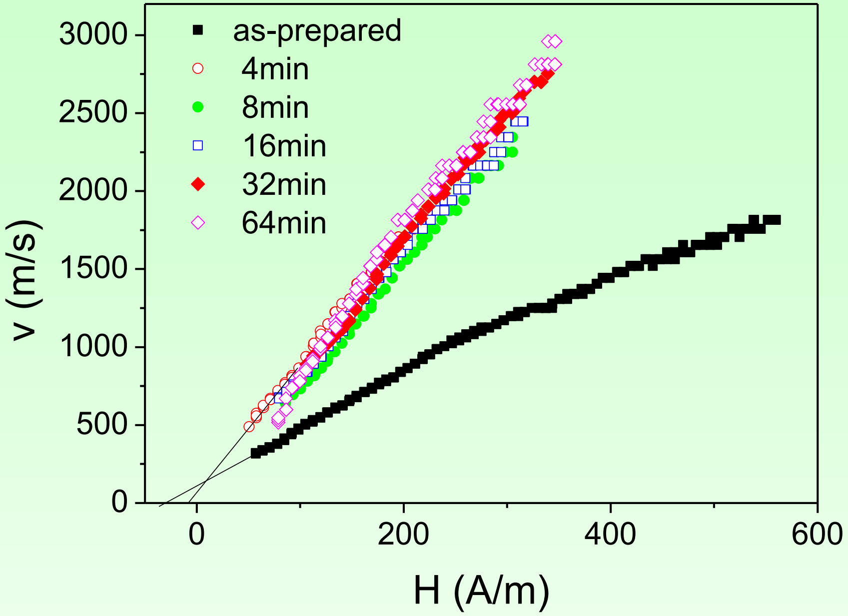
V(H) is affected by K_{me}

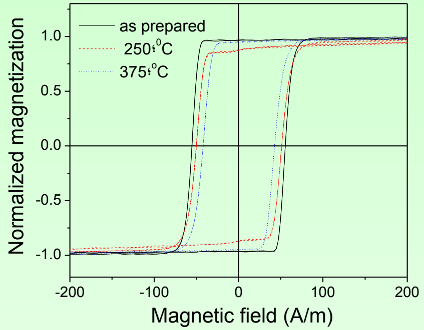
Effect of magnetolastic anisitropy on DW propagation

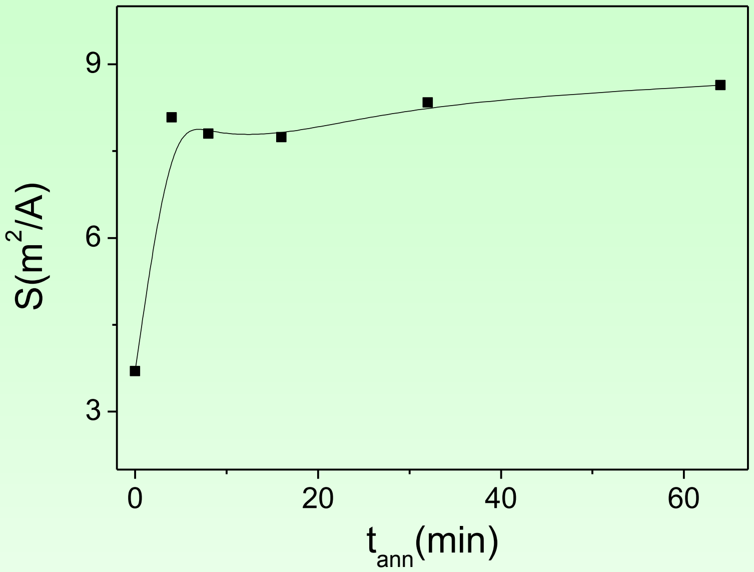
Kme ≈ 3/2 λsσi,

$Fe_{77.5}Si_{7.5}B_{15}$

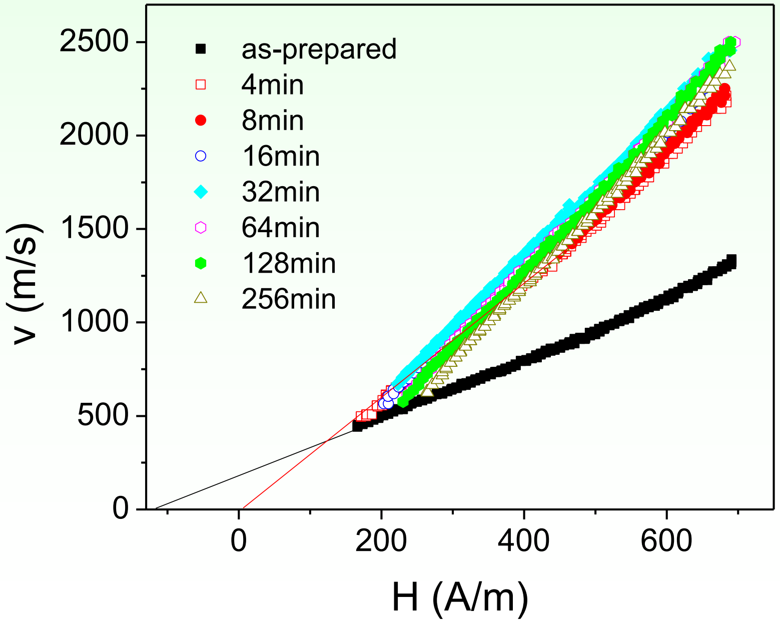
Stress relaxation? Tann ≈410 °C

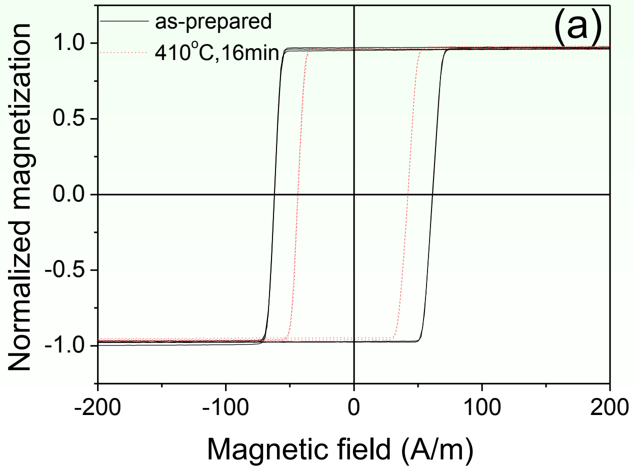


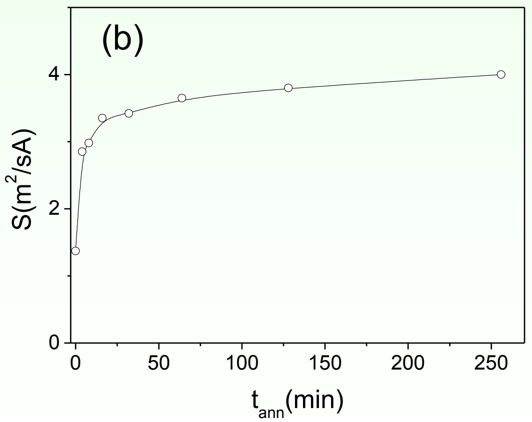




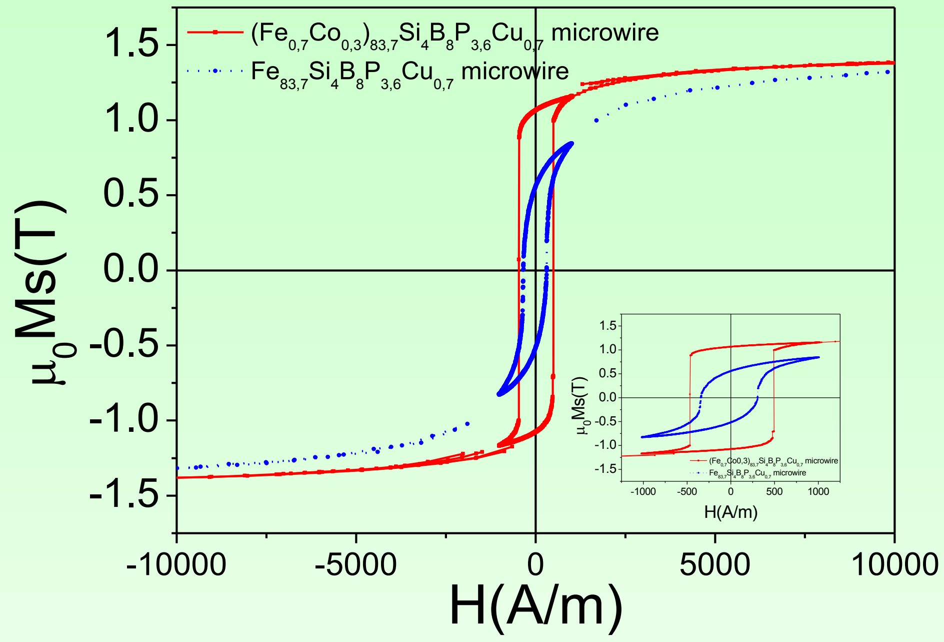
$Fe_{62}Ni_{15}Si_{7.5}B_{15}$ microwires







Effect of saturation magnetization on DW propagation



The domain wall mobility, *S*, is given by:

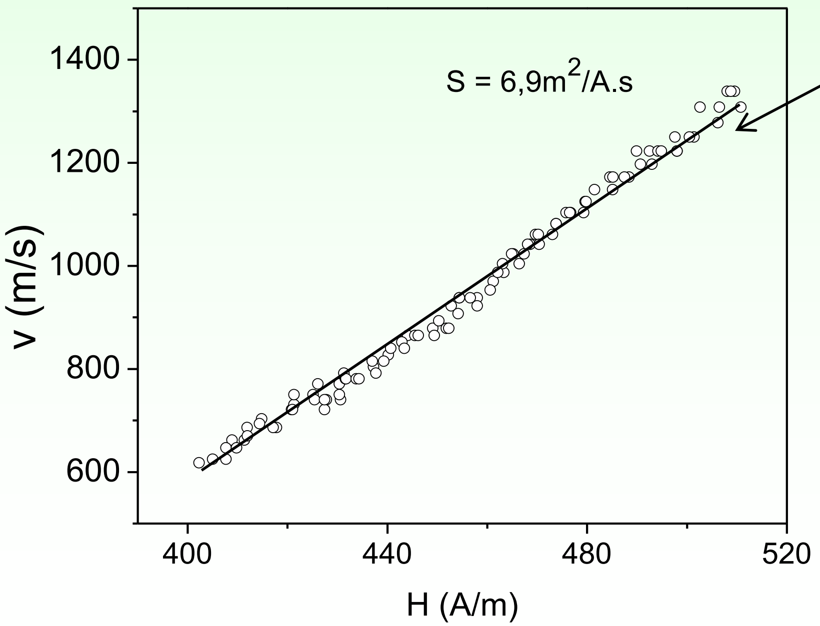
$S=2\mu_0M_s/\beta$

where, μ_0M_s *is the saturation magnetization*

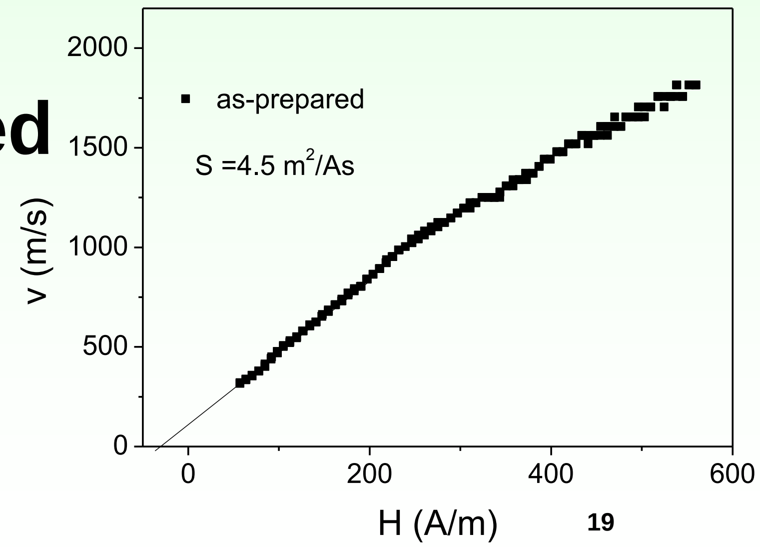
$B_r \approx M_s(K_{me}/A)^{1/2}$

$(Fe_{0,7}Co_{0,3})_{83,7}Si_4B_8P_{3,6}Cu_{0,7}$

$Fe_{77.5}Si_{7.5}B_{15}$



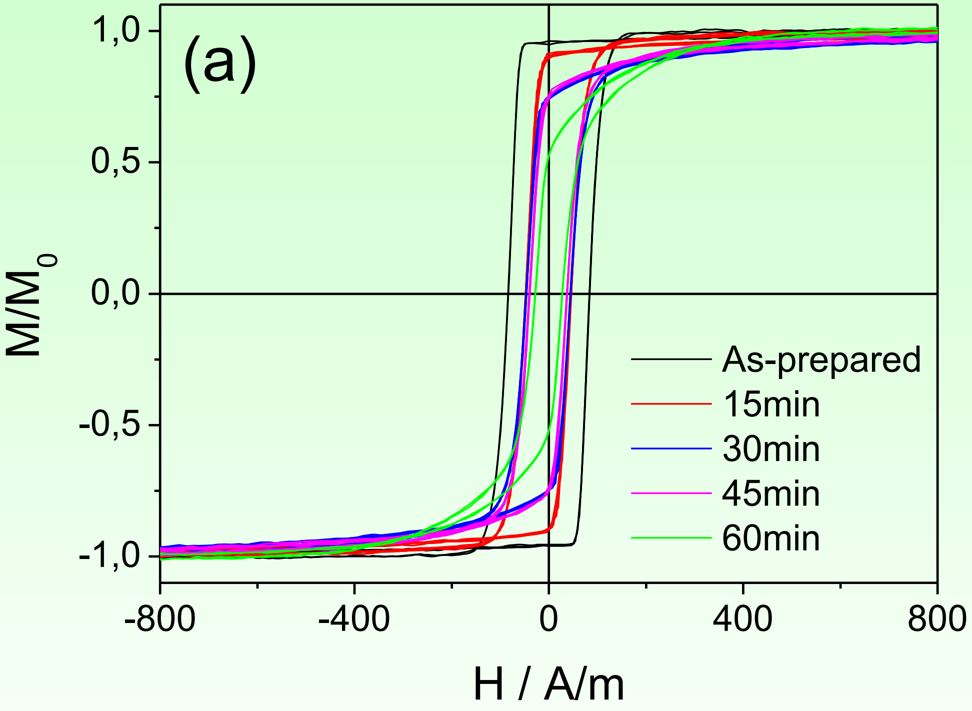
Higher S are observed in new Fe-rich composition with higher $\mu 0Ms$

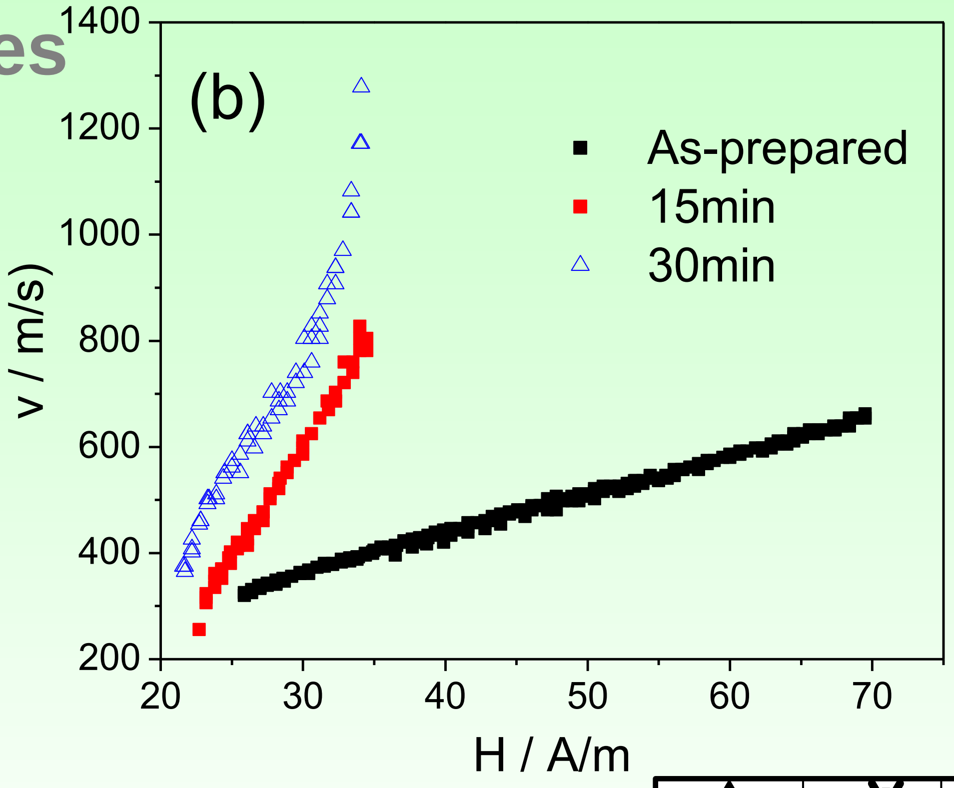


V. Zhukova, M. Ipatov, P. Corte-Leon, J.M. Blanco, E. Zanaeva, A.I. Bazlov, J. Jiang, D.V. Louzguine-Luzgin, J. Olivera, A. Zhukov, Excellent magnetic properties of (Fe0.7Co0.3)83.7Si4B8P3.6Cu0.7 ribbons and microwires, Intermetallics 117 (2020) 106660, doi: 10.1016/j.intermet.2019.106660

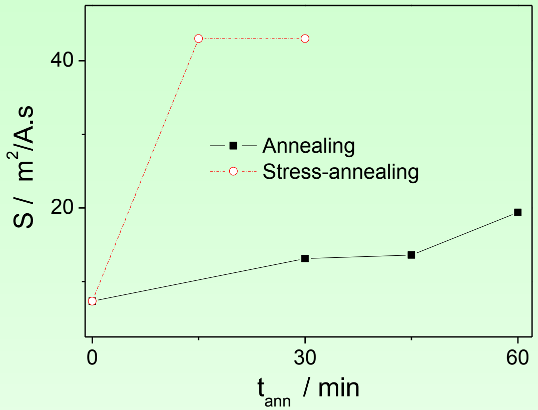
Stress- Annealing

$Fe_{75}B_9Si_{12}C_4$ microwires

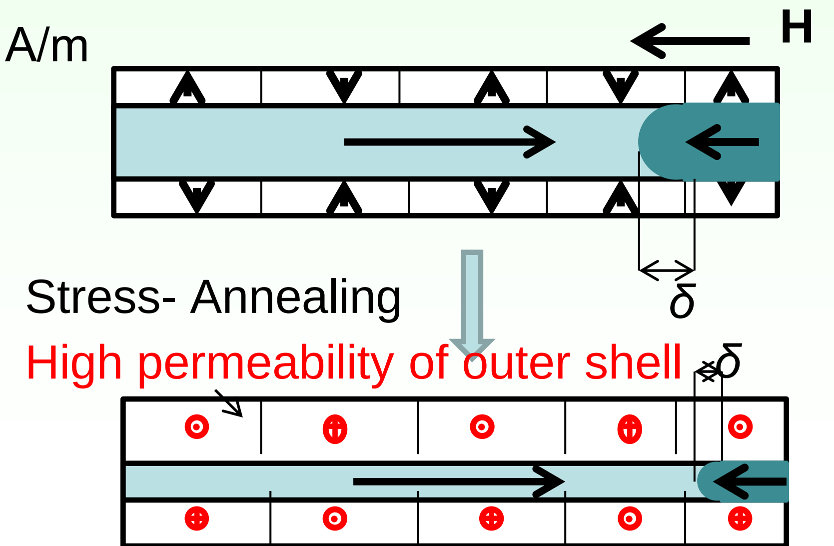




Dependences of DW mobility, *S*, on annealing time for $Fe_{75}B_9Si_{12}C_4$ microwires annealed at T_{ann} = 325 ºC.



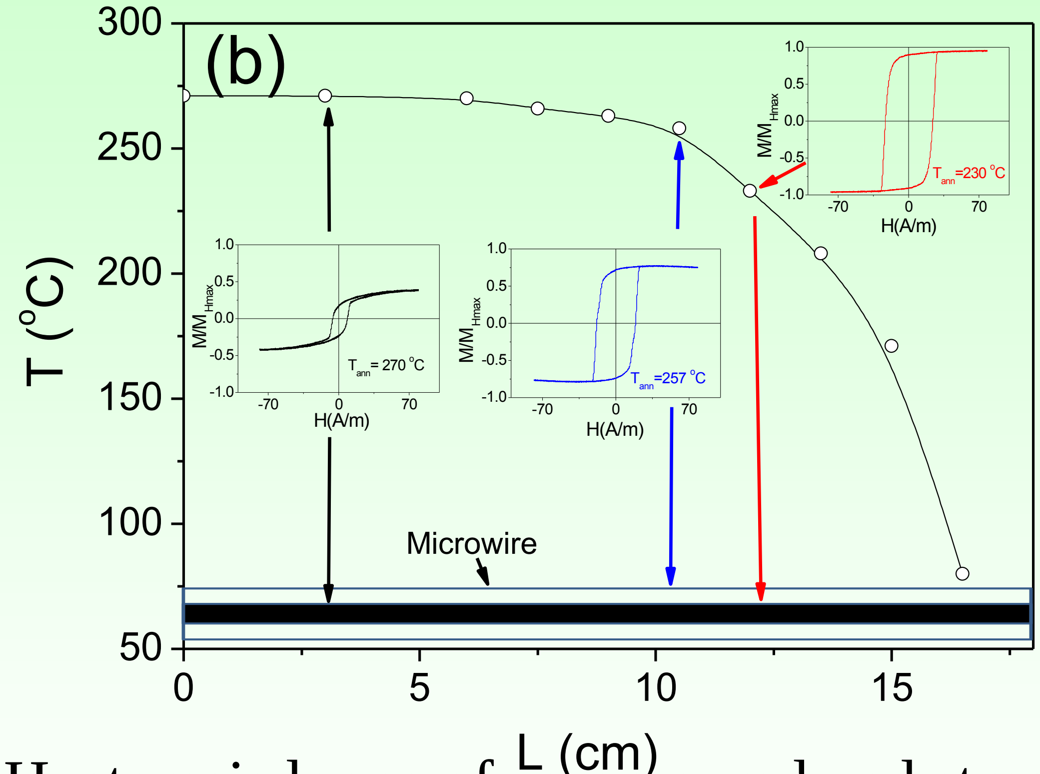
Remarkable DW movility imrpovement by stress-annealing!

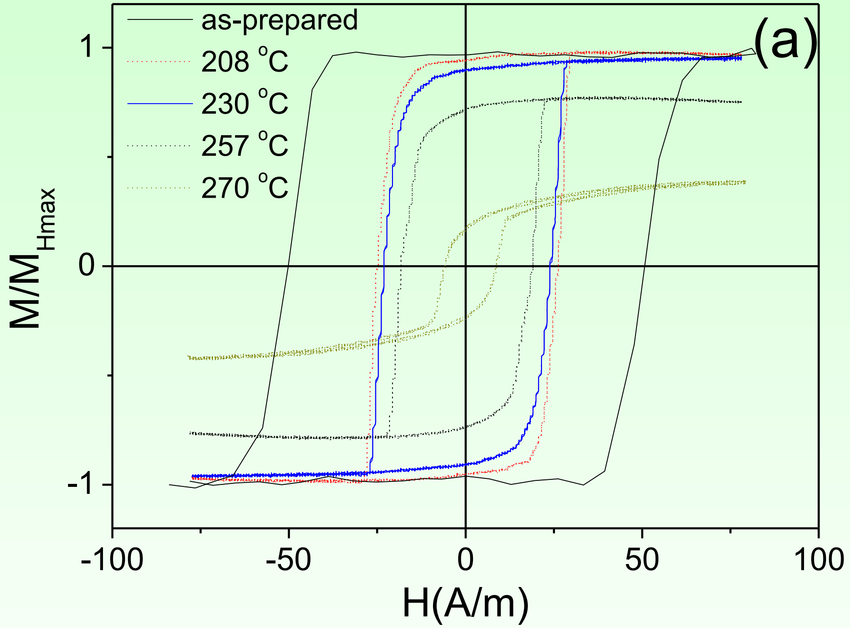


Hysteresis loops (a) and *v(H)* dependencies (b) of as-prepared and stress- annealed at T_{ann} = 325 ºC and σ_m=190 MPa $Fe_{75}B_9Si_{12}C_4$ microwires.

P. Corte-León, J. M. Blanco, V. Zhukova, M. Ipatov, J. Gonzalez, M. Churyukanova, S. Taskaev & A. Zhukov, Sci. Reports, (2019), DOI: https://doi.org/10.1038/s41598-019-48755-4

Grading of magnetic anisotropy and engineering of domain wall dynamics in Fe-rich microwires by stress- annealing



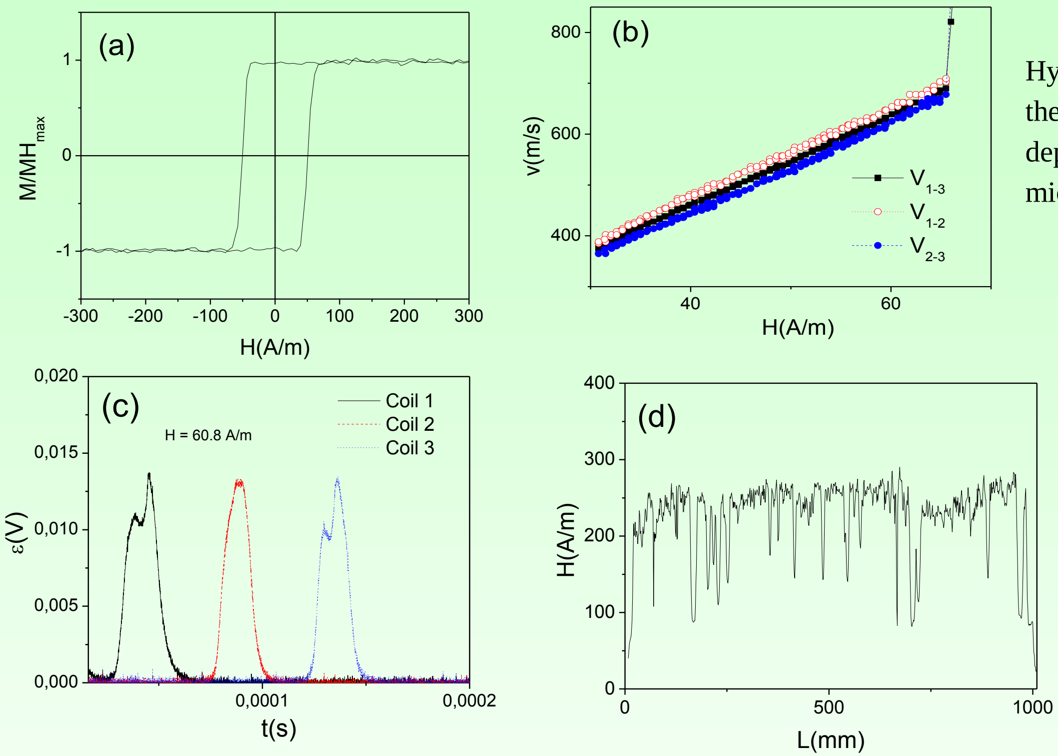


Usially graded anisotropy is obtained varying chemical composition during the sputtering

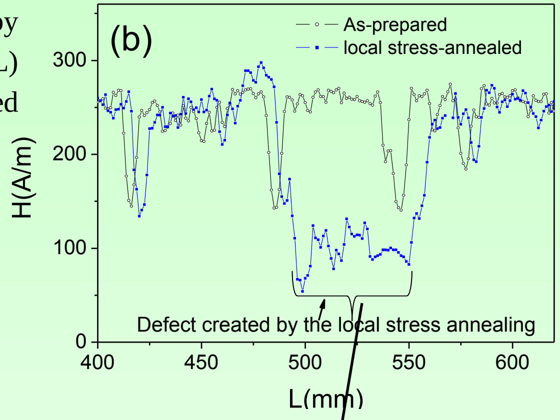
Hysteresis loops of as-prepared and stress-annealed at different T_{ann} $Fe_{75}B_9Si_{12}C_4$ microwires (a) and graded magnetic properties of $Fe_{75}B_9Si_{12}C_4$ microwires annealed at variable T_{ann}.

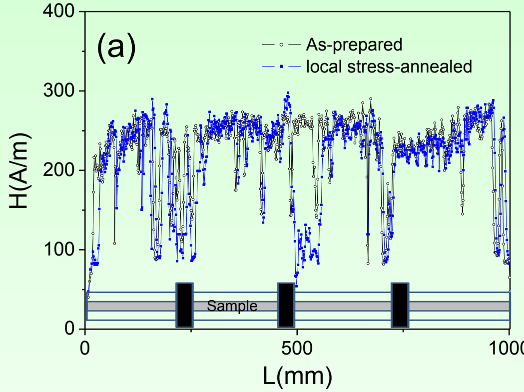
V. Zhukova, J.M. Blanco, P. Corte-Leon, M. Ipatov, M. Churyukanova, S. Taskaev, A. Zhukov, Acta Materialia 155 (2018) 279-285

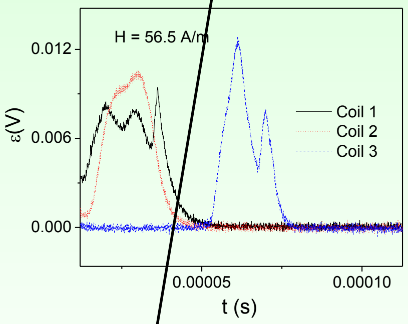
Engineering of domain wall dynamics in Fe-rich microwires by local stress- annealing



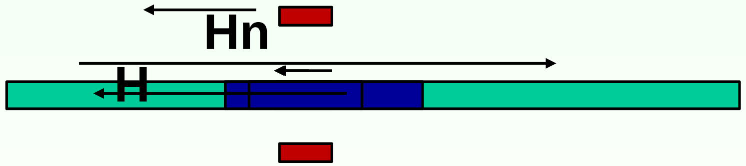
Hysteresis loop (a), *v(H)* dependence (b), voltage peaks induced by the magnetization change in the pick-up coils (c) and $H_n(L)$ dependence (d) of as-prepared $Fe_{75}B_9Si_{12}C_4$ amorphous glass-coated microwire.

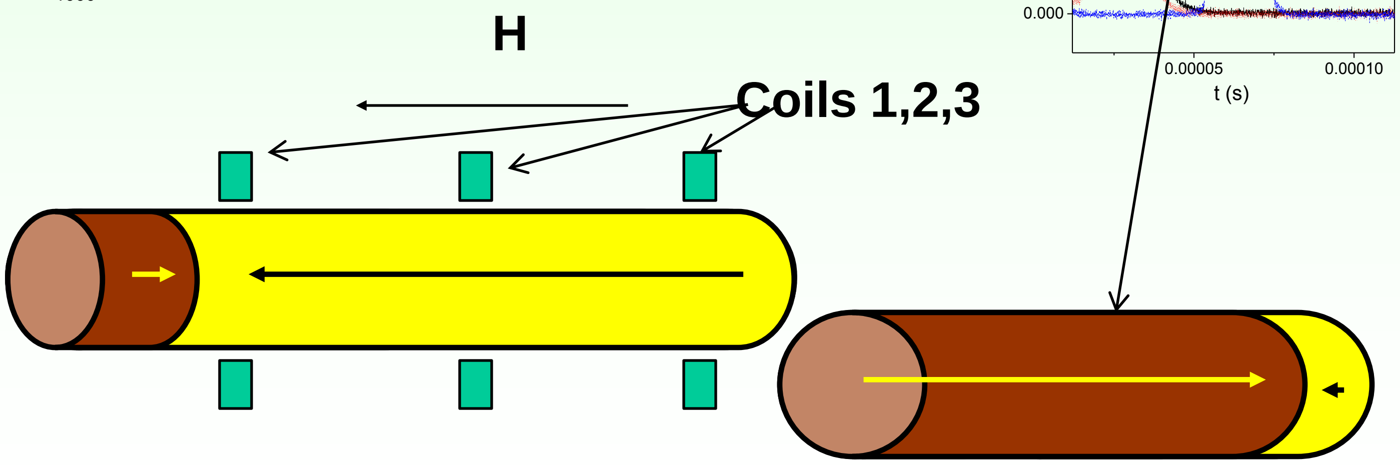


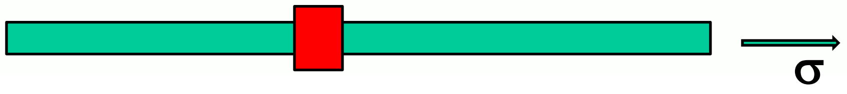




2. Nucleation profile (DW injection)!



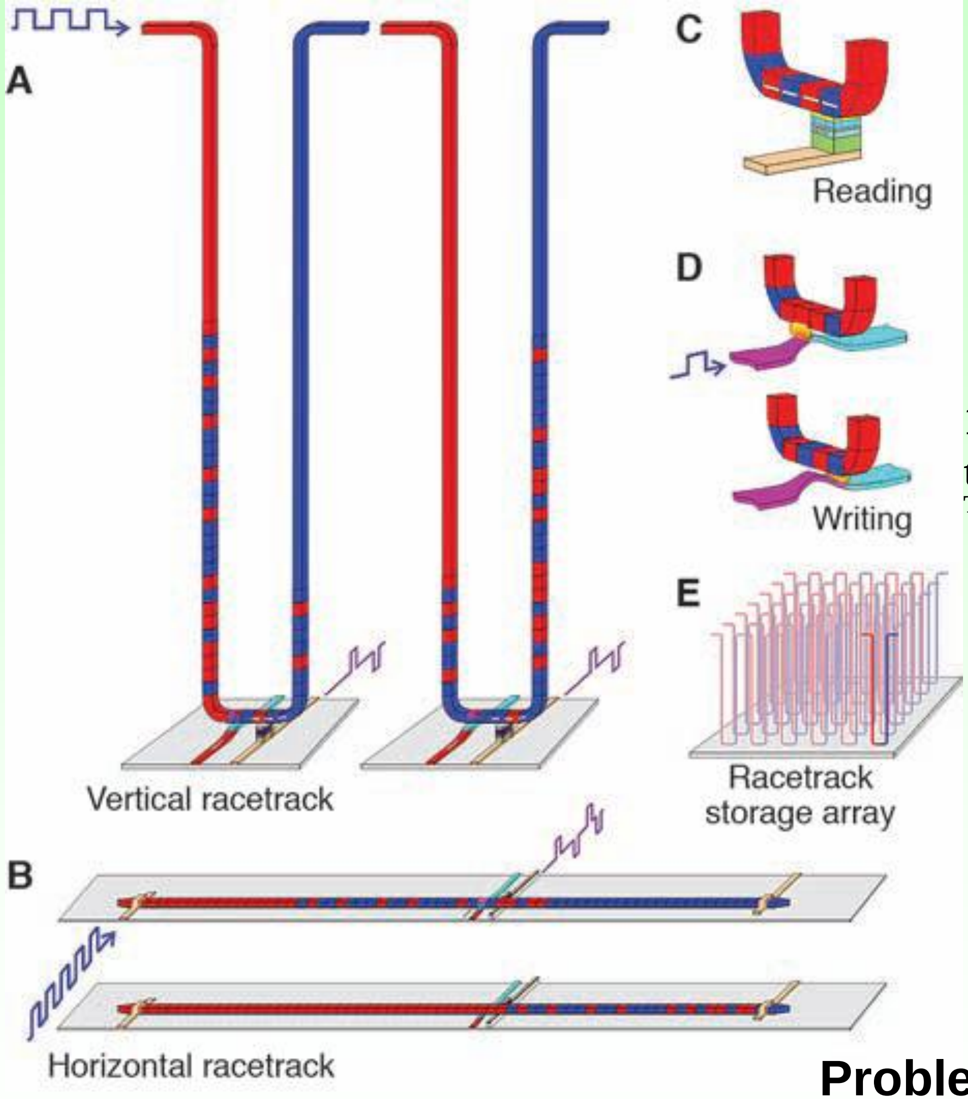




Local heating

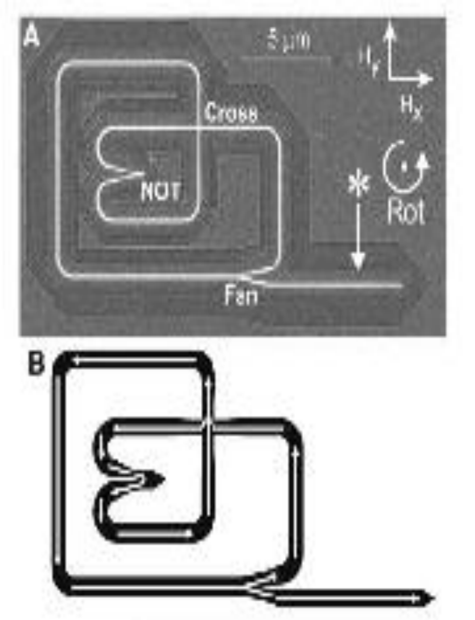
V. Zhukova, J.M. Blanco, P. Corte-Leon, M. Ipatov, M. Churyukanova, S. Taskaev, A. Zhukov, Acta Materialia 155 (2018) 279-285

Promising applications:. Magnetic magnetic memory and logic based on DWP

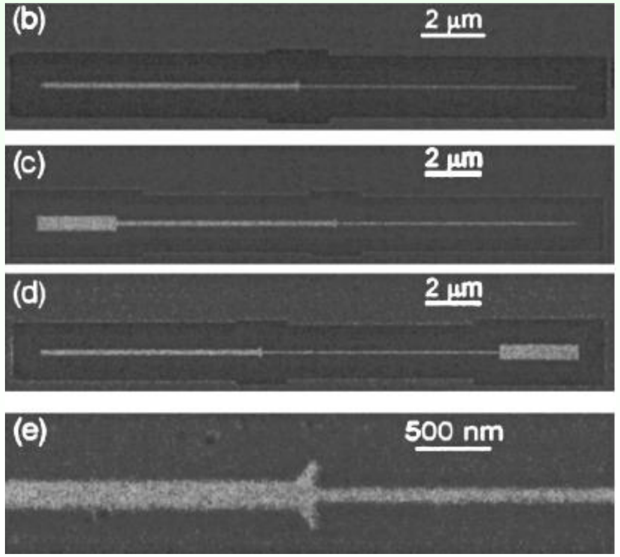


Stuart S. P. Parkin, *et al. Science* 320, 190 (2008);

Requisite: controlable DWP



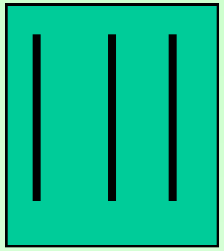
1 of 10 most emerging technologies in 2009
Technology review 2009, published by MIT



Problems:
1. Fast DWP (speed)
2. Controlled DW pinning

APPLICATIONS:

Magnetic codification based on magnetic bistability



Publications

- A. Zhukov, J.González, J.M. Blanco, M.Vázquez and V. Larin, J. Mat. Res 15, (2000), 2107.

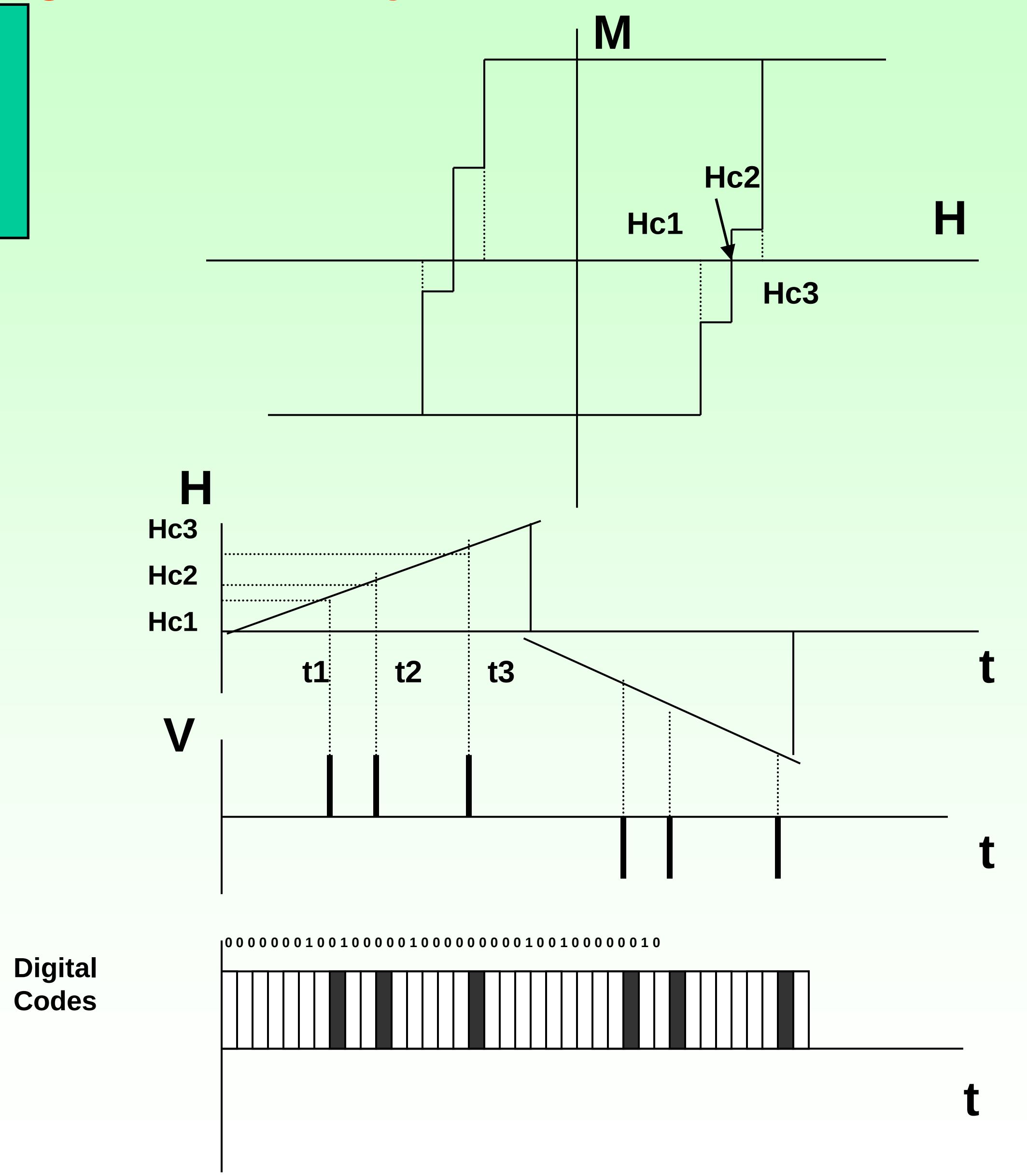
Patentes:

1. V. Larin, A. Torcunov, S. Baranov, M. Vázquez, A. Zhukov and A. Hernando, “Method of magnetic codification and marking of the objects”, Patent (Spain) Nº P 9601993 (1996).

2. M. Vázquez, A. Zhukov, A. Hernando, V. Larin, A. Torcunov, L. Panina, J. Gonzalez and D. Mapps, *TITULO:*
“Microwire and process of their fabrcation. AWP/RPS/56672/000, No0108373.2 *(UE) 01.11.2001*
”Four wnds”, Amotec” and ”Tamag Iberica. S.L.”

3. A. Zhukov, V. Zhukova, M. Vázquez, J. González, V. S. Larin y A.V. Torcunov *“* Amorphous micwories as an element of magnetic sensor based on magnetic bistabily, magneto-impedance and material for the radiation protection”.
P200202248 *(Span) 02.10.2002 ”Tamag Iberica. S.L.”*

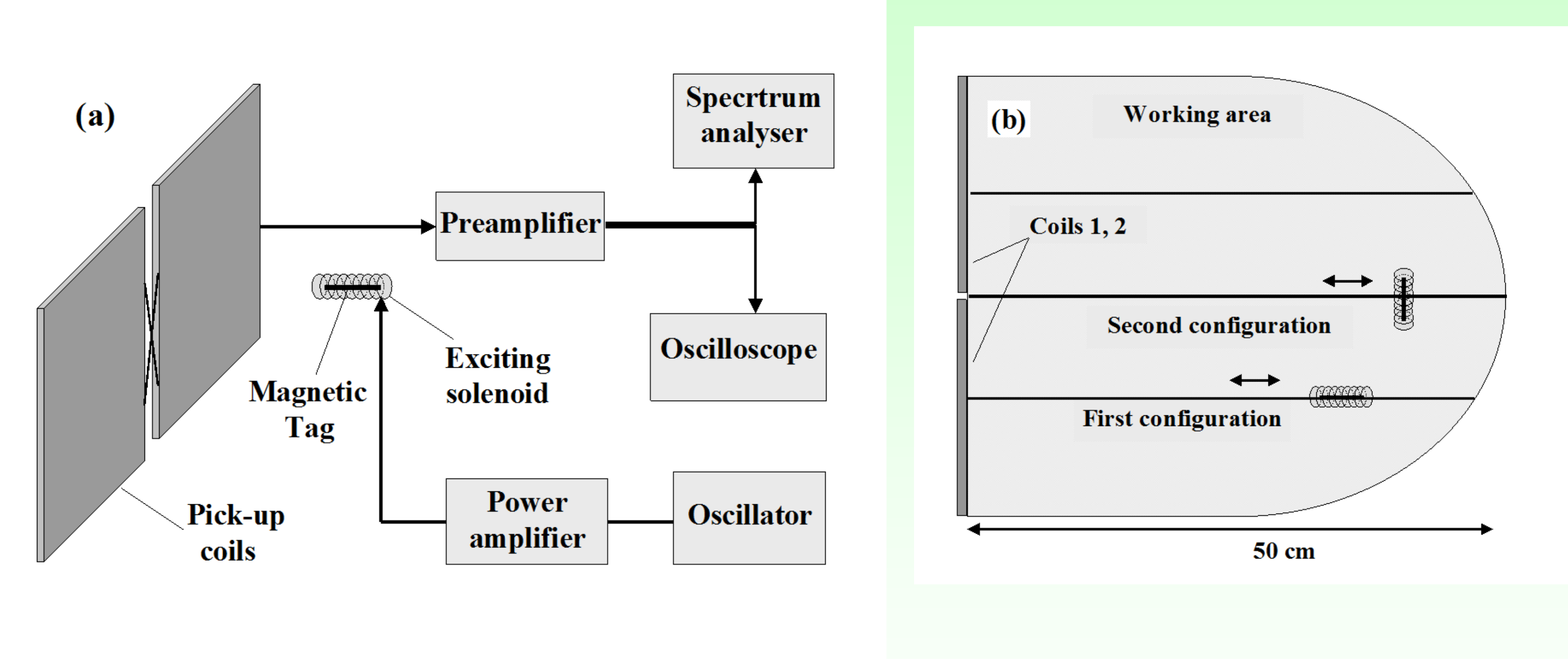
4 A. Zhukov, V. Zhukova, J. González, V. S. Larin y A.V. Torcunov *“*Ultra-thin glass-coated microwires with GMi effect at elevated frequencies.”*PCT Es/2006/000434 (USA)*



APPLICATIONS:

Scheme of the installation to record the EMF signals of magnetic tags;

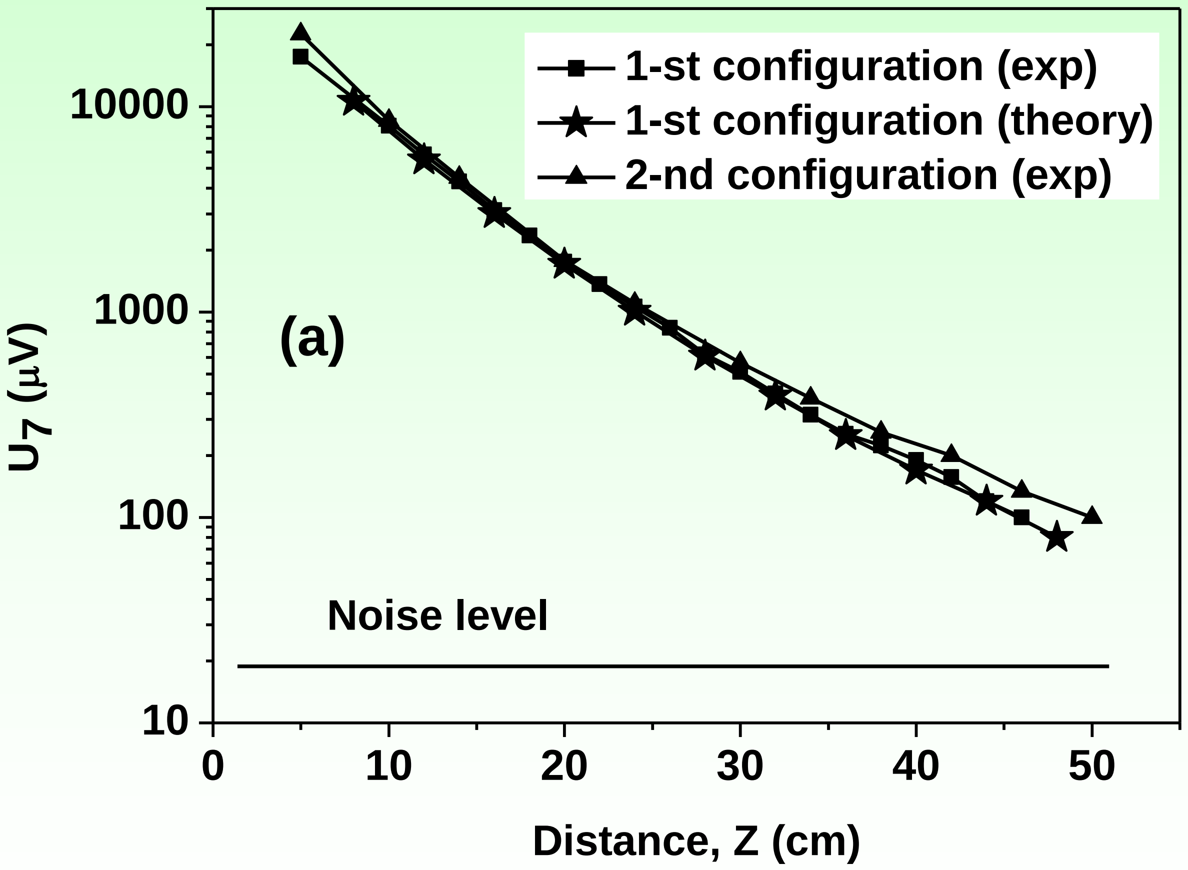
(b) geometry of the working area near the receiving coils.



- receiving coils with a side of *a* = 20 cm were made of 20 turns of thin copper wire.
- small solenoid with a length 5 cm has been used to excite the
- magnetic tags by alternating magnetic field with a frequency
- *f* = 327 Hz and amplitude *H*0 = 5 Oe.

APPLICATIONS:

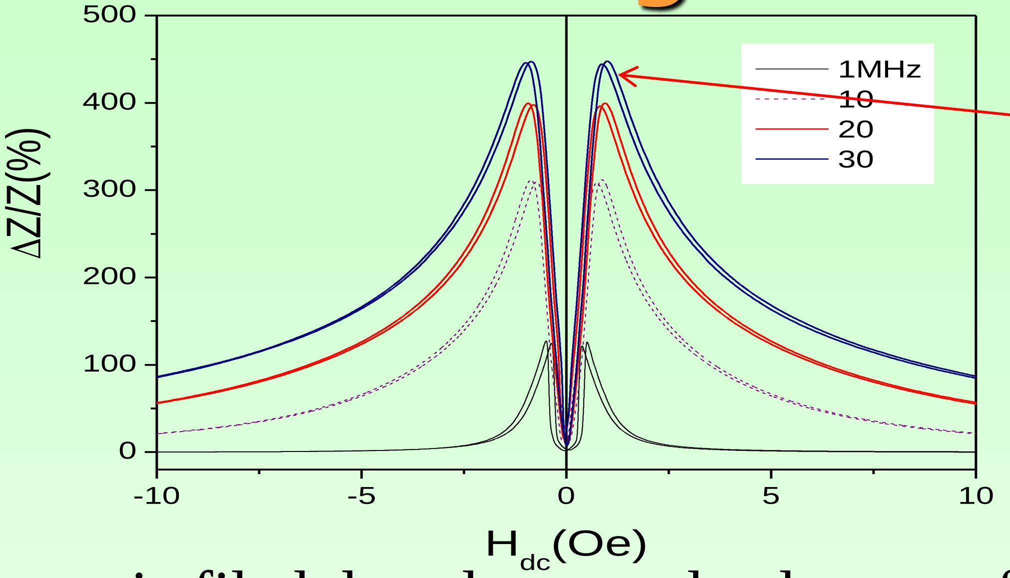
The measured amplitude of 7-th harmonics of the magnetic tag EMF signals as a function of the distance of the tag from the receiving coil plane for the cases when the tag is oriented perpendicular (squares) or parallel (triangles) to the coil plane.



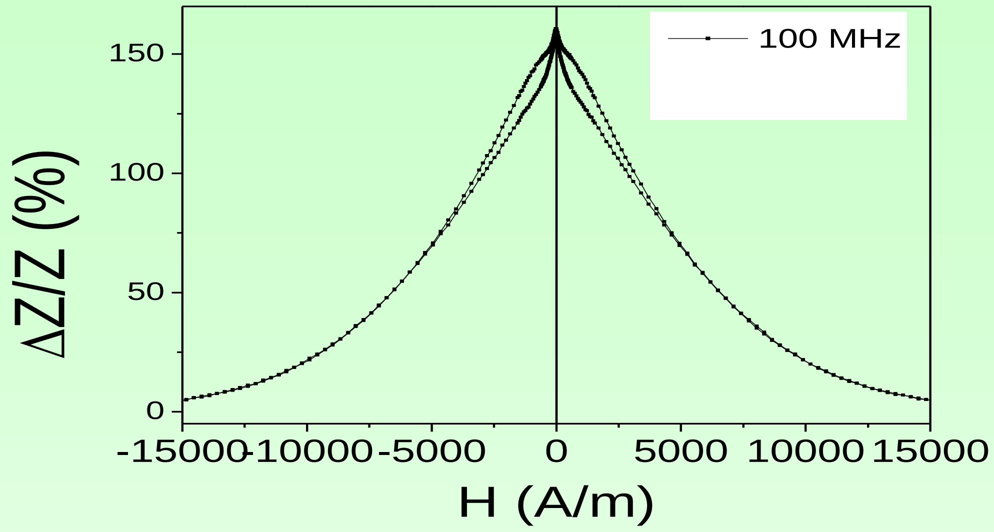
For the given size of the receiving coils the magnetic tag having ~ 100 μm magnetic core diameter can be detected at the distances higher than 45 cm, irrespective of the magnetic tag orientation with respect to the receiving coil plane.

S. Gudoshnikov, N. Usov, A. Zhukov, V. Zhukova, P. Palvanov, B. Ljubimov, O.Serebryakova, and S. Gorbunov,
"Evaluation of use of magnetically bistable microwires for magnetic labels", Phys. Status Solidi A, 208, No. 3, 526–529 (2011)

Giant Magneto-impedance effect



500% change per 1 Oe



Magnetic filed depedence and value are affected by magnetic anisotropy

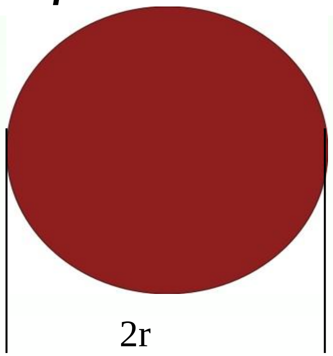
Skin Effect of the Magnetic Conductor

AC current frequency

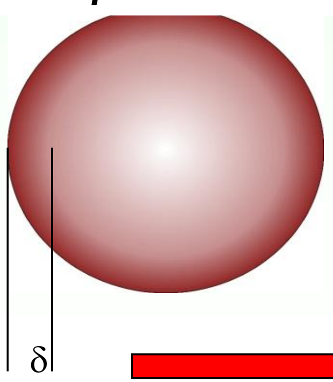
$$\mu_\phi \Downarrow \quad \rightarrow \quad \delta \Uparrow$$

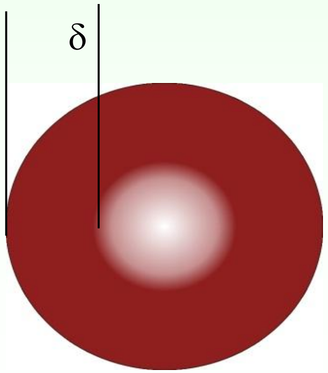
$$\delta = \sqrt{\frac{\rho}{\pi \mu_\phi f}}$$

$f \approx$ kHz



$f \approx$ MHz





$\mu_\phi(H,f)$ $\quad \delta < r$

(at high enough f)

Z(H)

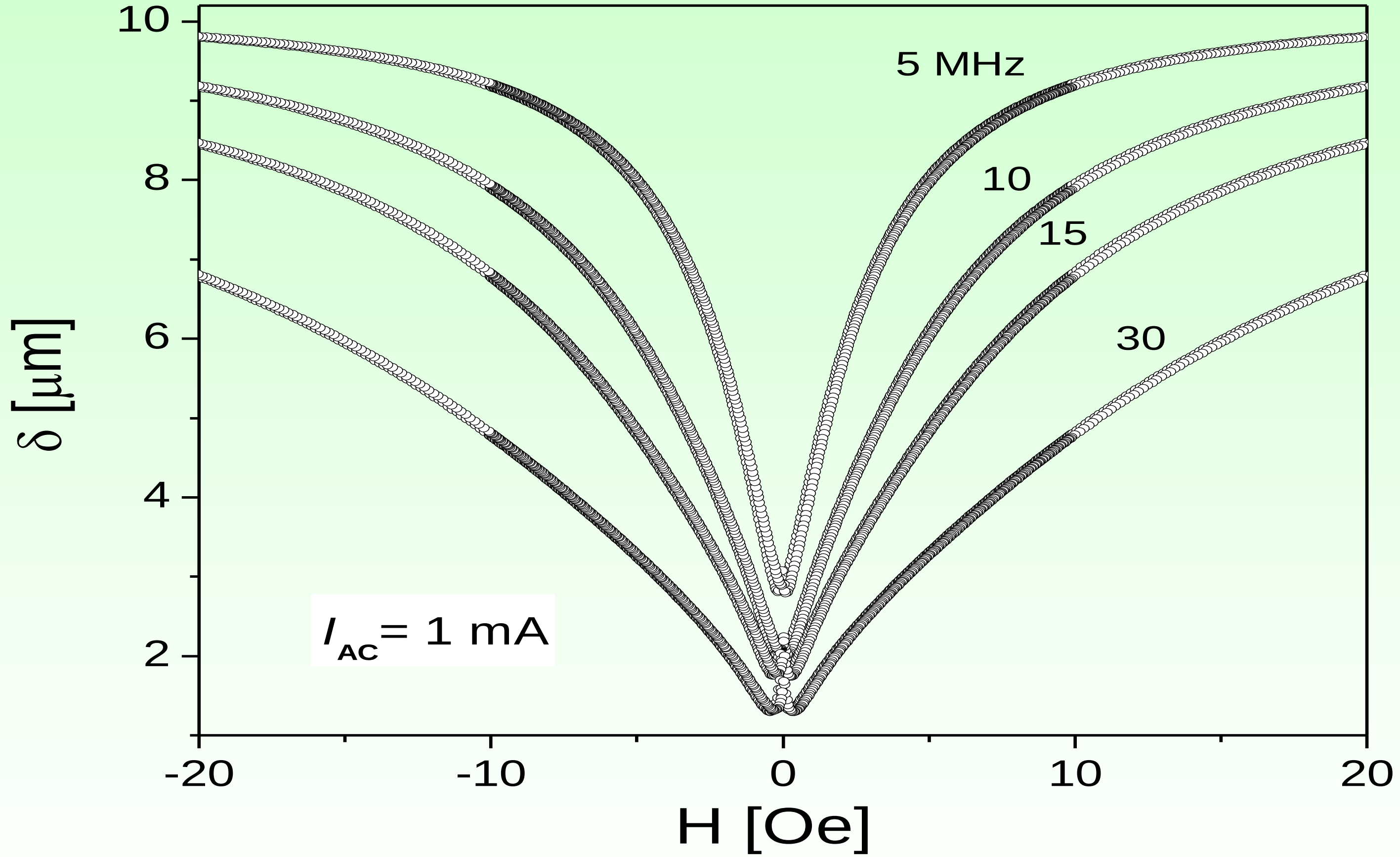
Magnetic field

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

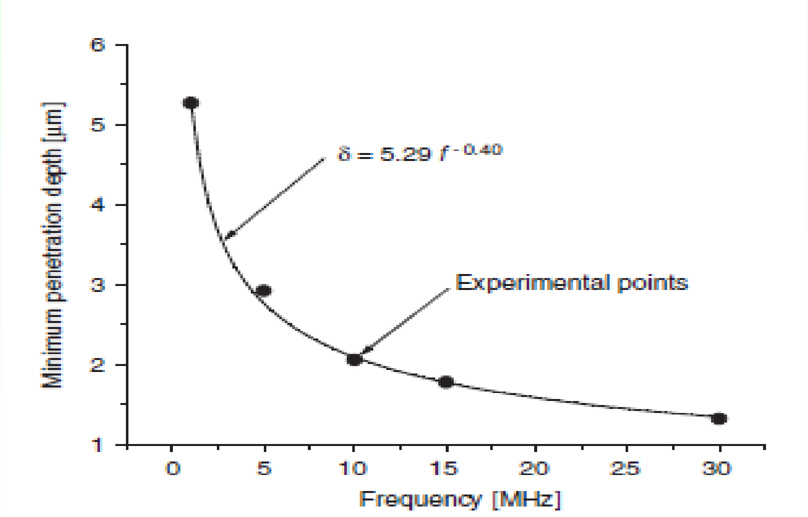
E.P. Harrison, et.al *Nature*, 1935, vol. 135, p. 961

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

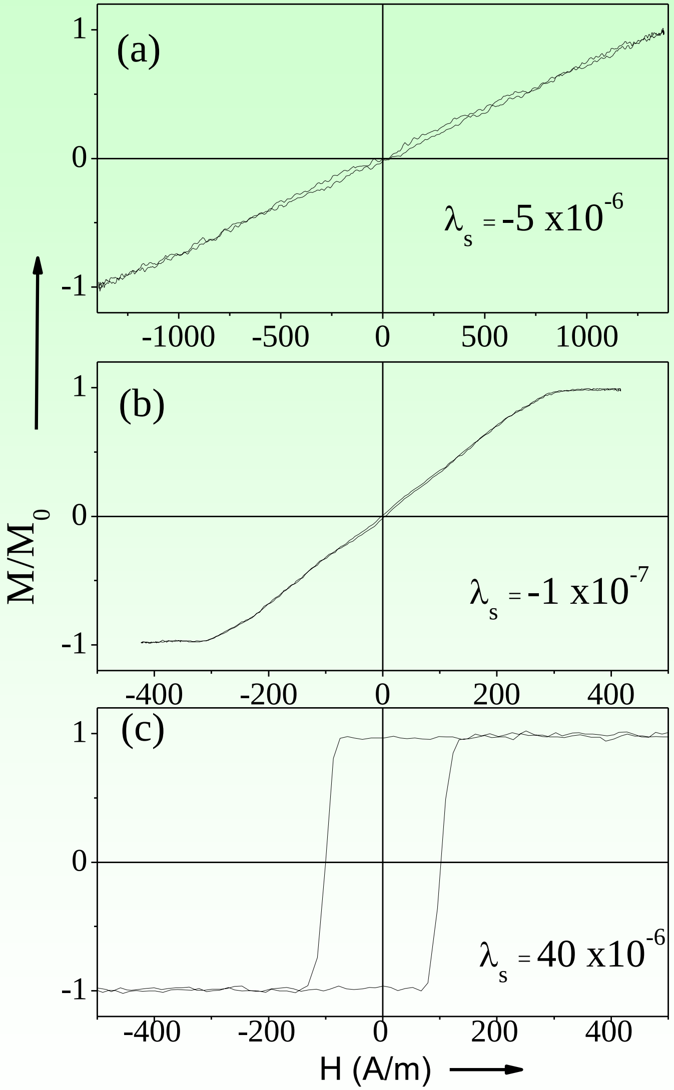


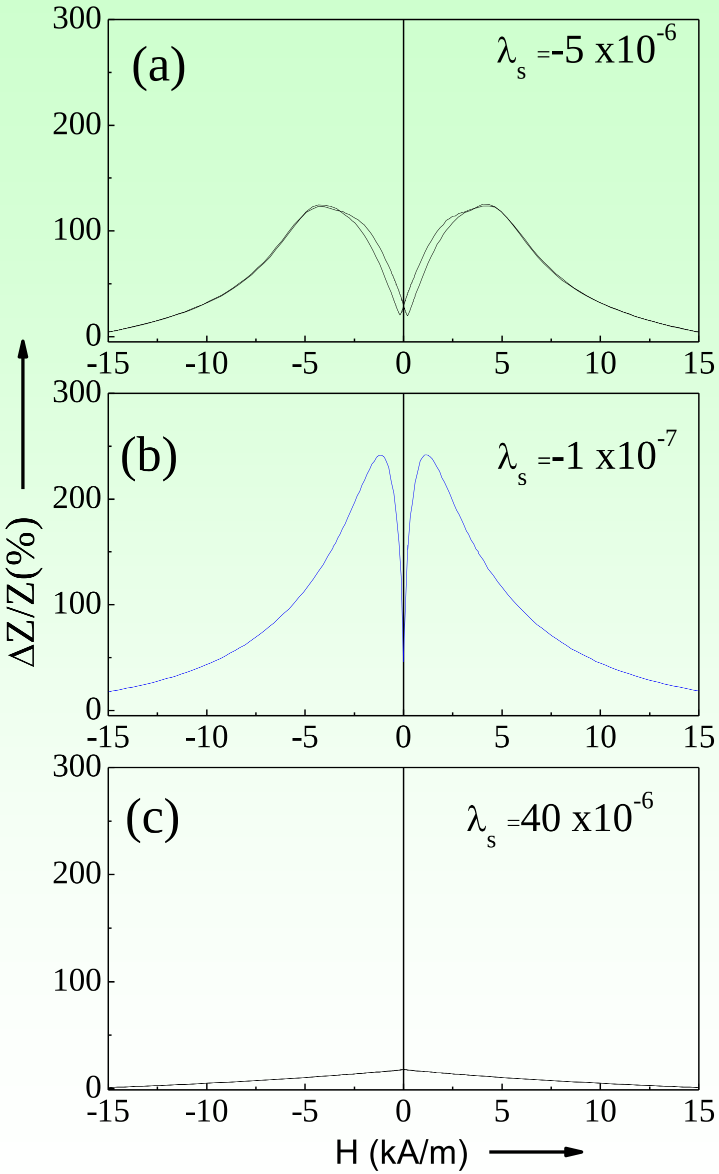
Essentially surface effect. Thin surface layers are involved in the GMI process



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 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)

μ=ΔM/ΔH
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

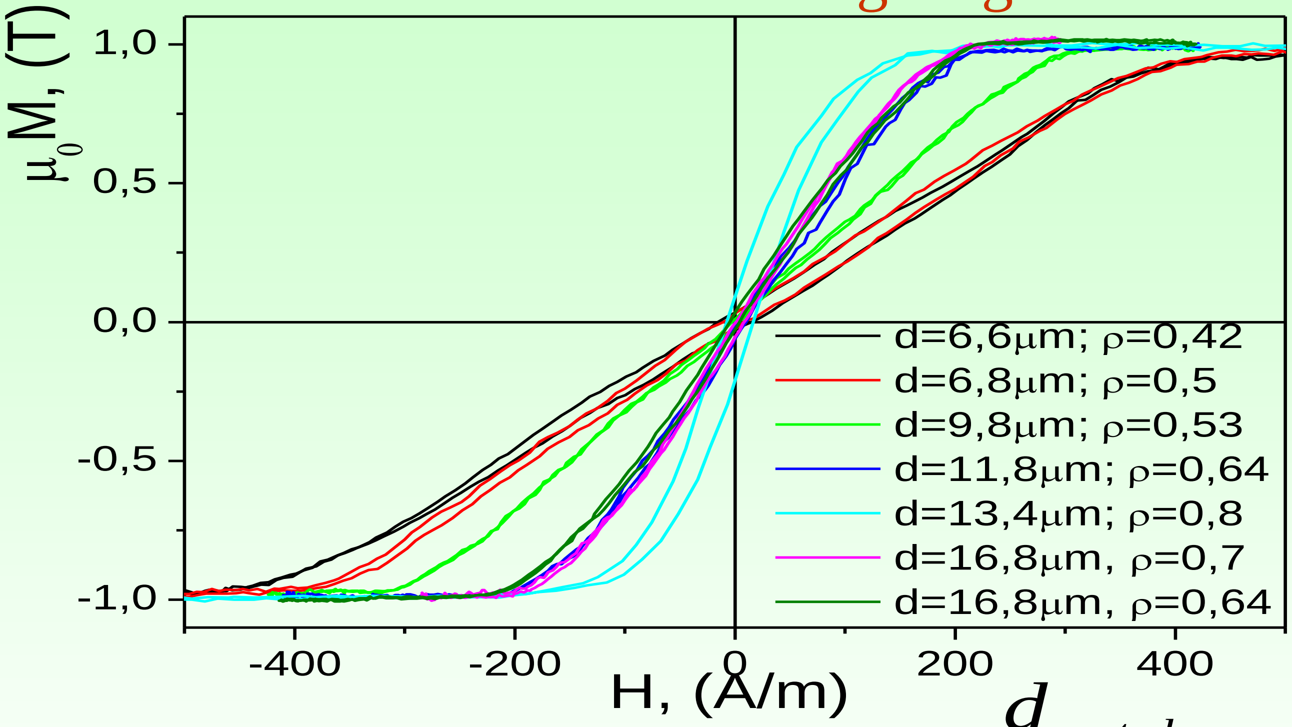
TAILORING OF GMI EFFECT AND MAGNETIC PROPERTIES

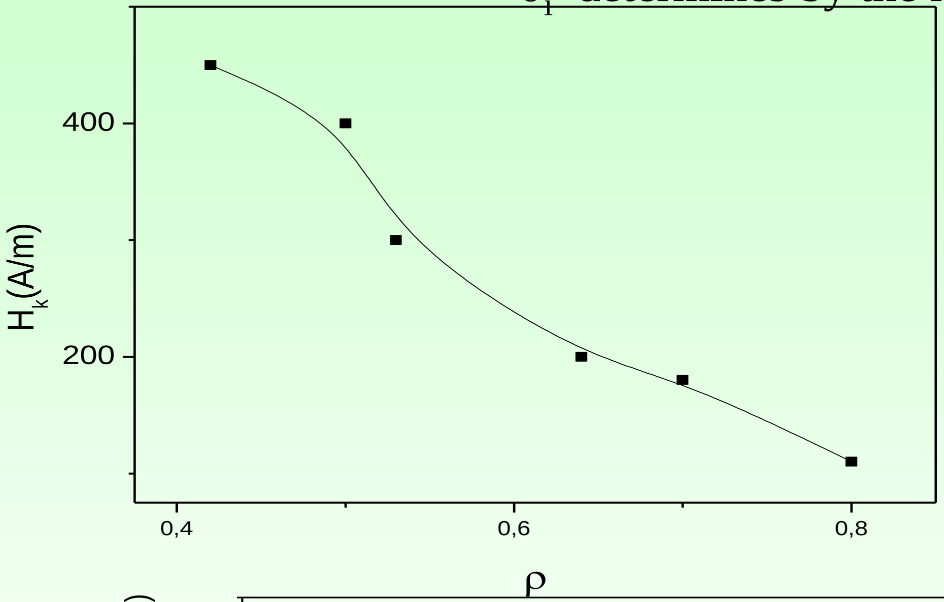
$K_{me} \approx 3/2\, \lambda_s \sigma_i$, :

Magnetostriction λ_s -determines by the chemical composition

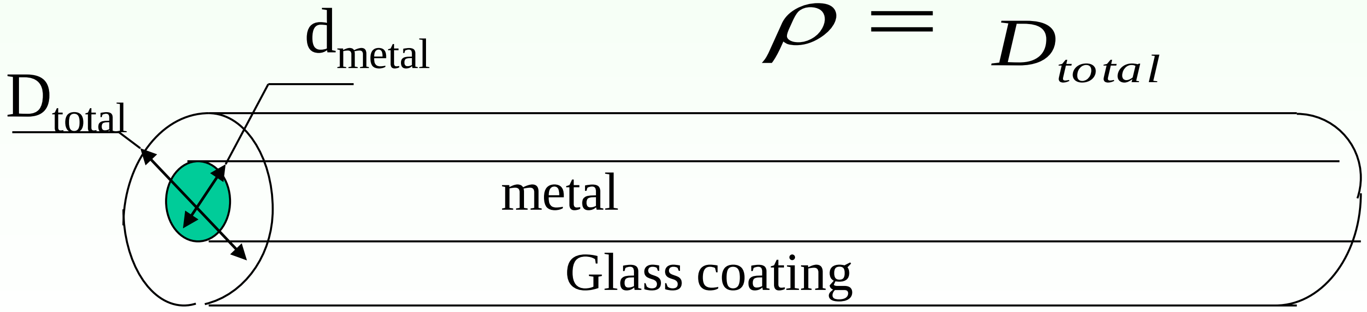
σ_i -determines by the ratio $\rho = d/D$

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

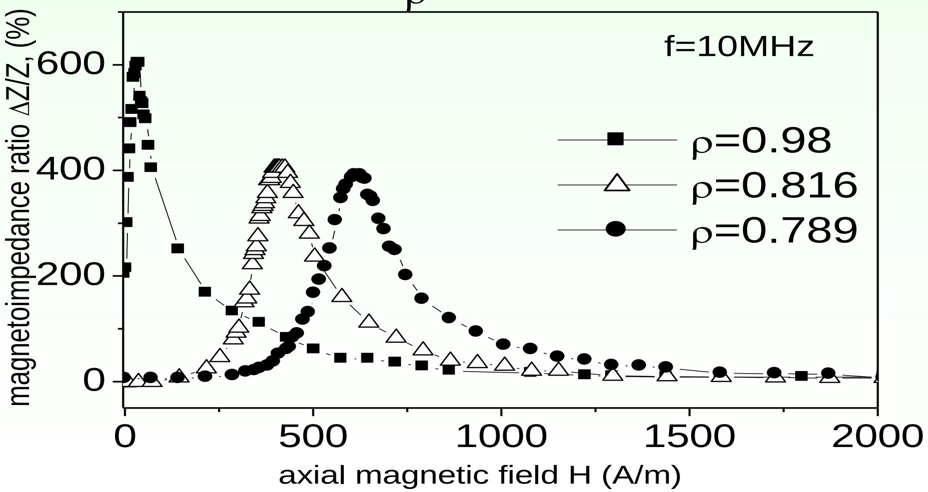




$$\rho = \frac{d_{metal}}{D_{total}}$$



Correlation with magnetic anisotropy

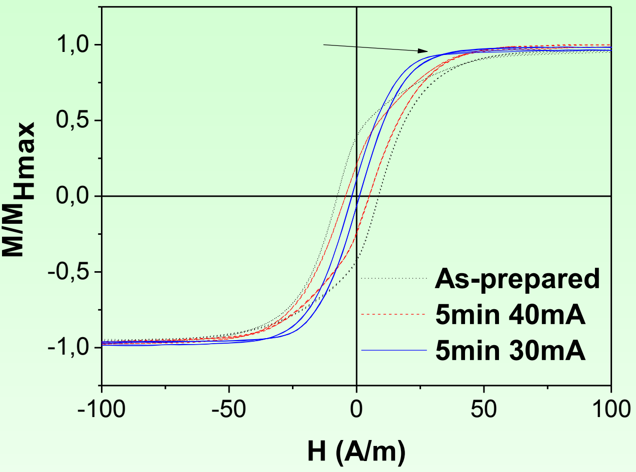


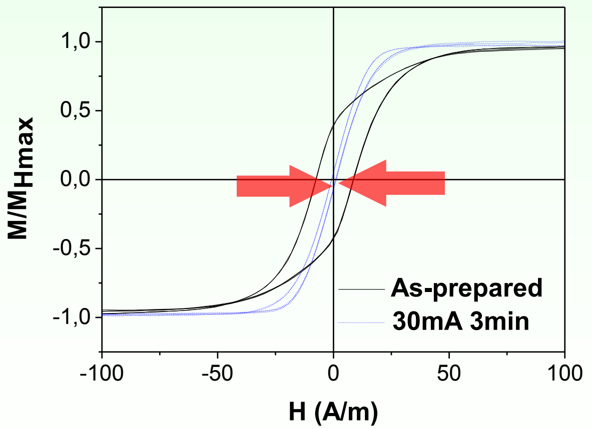
Theoretical GMI ratio value is about 3000%

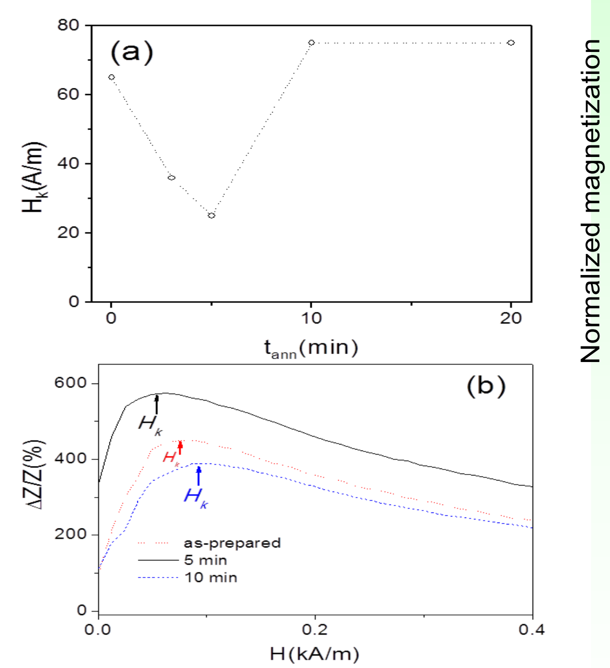
Tailoring by Joule heating

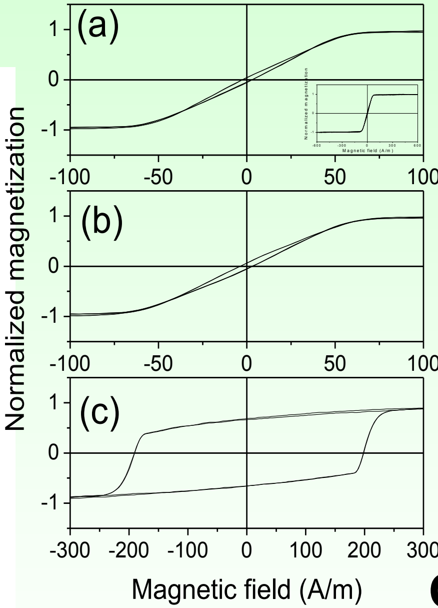
- Internal stresses relaxation
- Induced magnetic anisotropy

H_k=25A/m

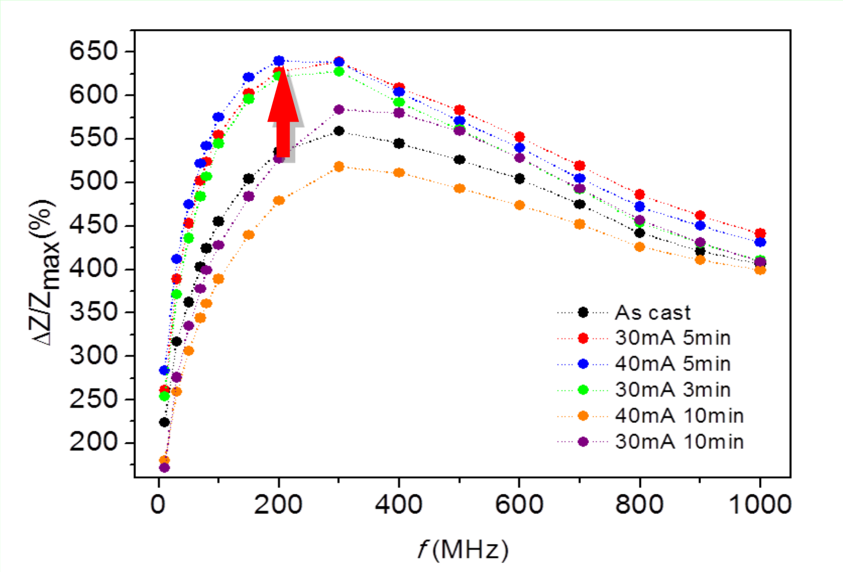




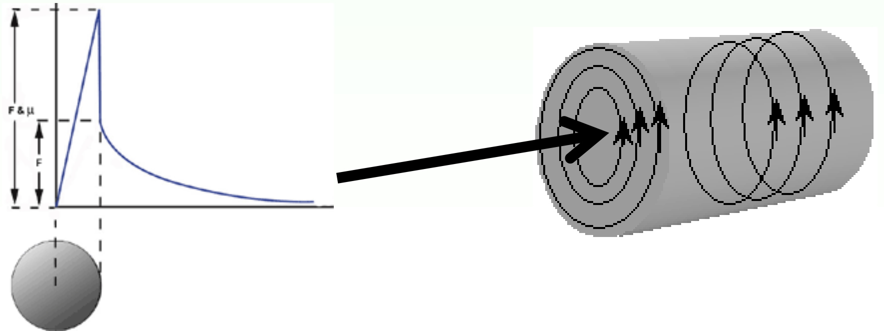




GMI ratio up to 650%



Circular magnetic field by current:

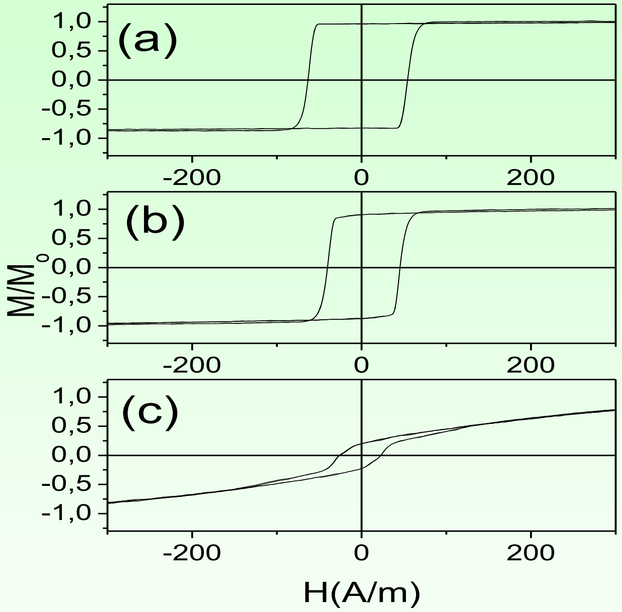


Hc=2 A/m

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

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

Motivation: Co- critical element!

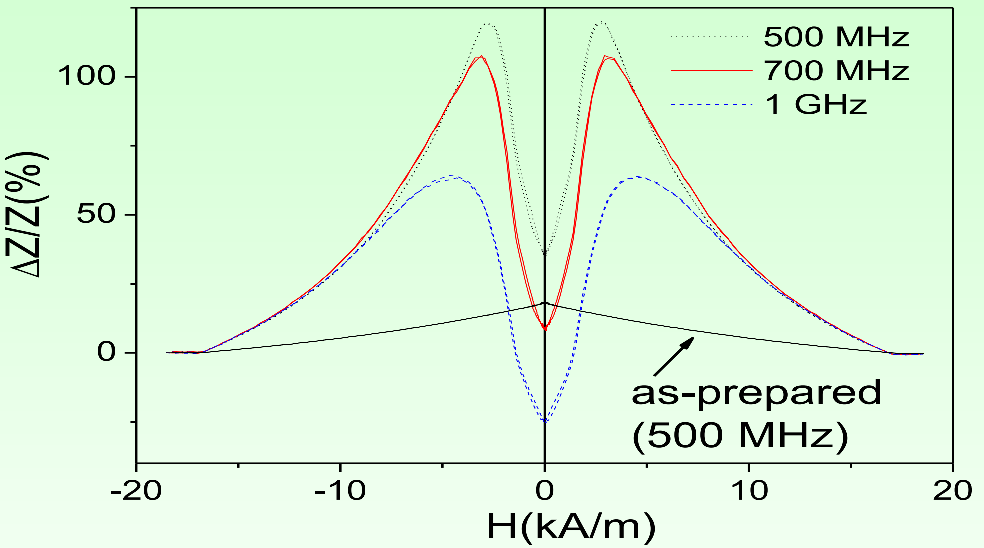


$Fe_{75}B_9Si_{12}C_4$

As-prepared

Stress annealed 200 ^oC

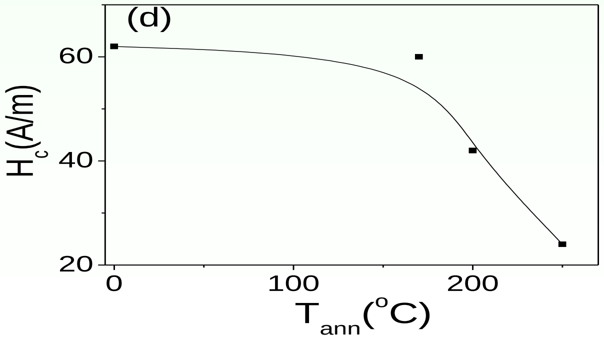
Stress annealed 250 ^oC



i) considerable transversal magnetic anisotropy and magnetic softening and GMI enhancement

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

iii) Excellent mechanical properties (amorphous material)

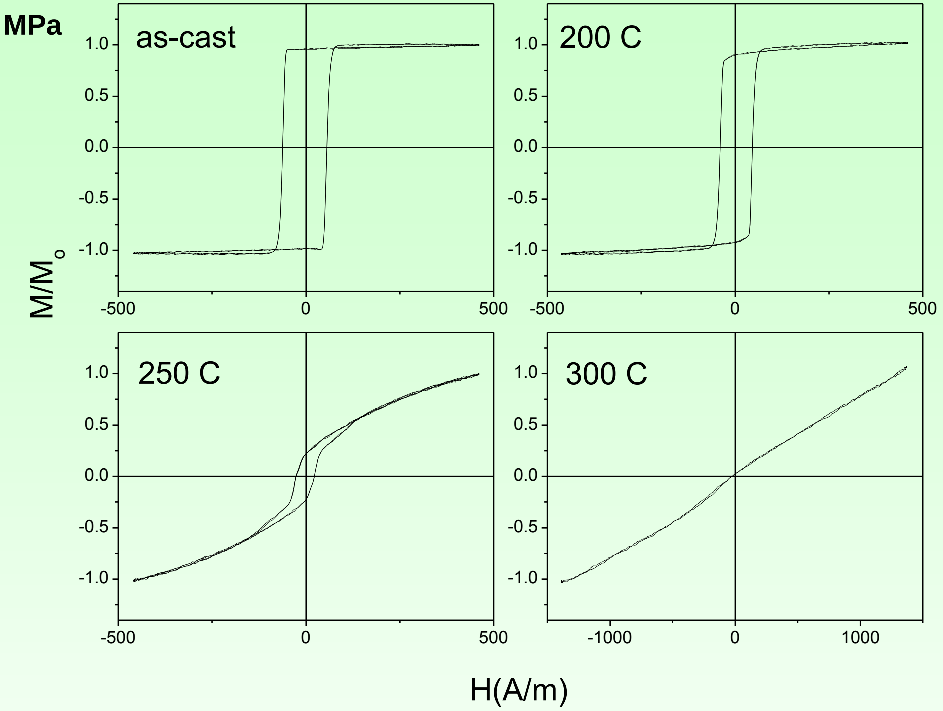


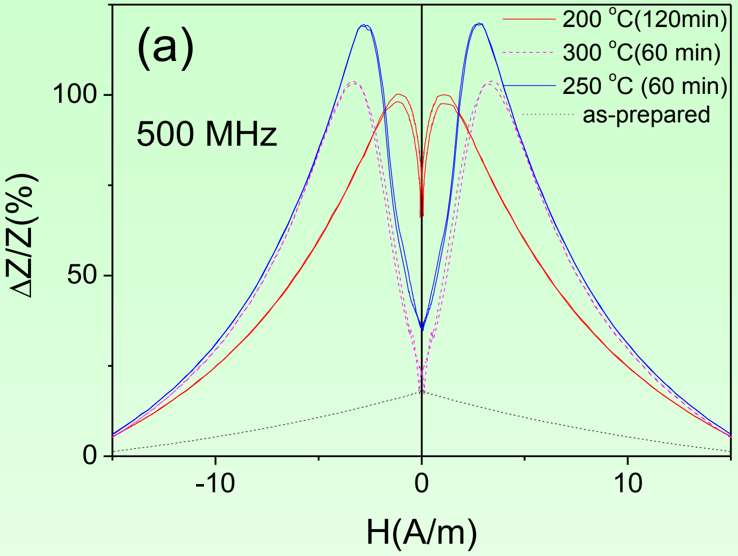
V. Zhukova, M. Ipatov, A. Talaat, J. M. Blanco, M.Churyukanova, S. Taskaev and A. Zhukov, “Effect of stress-induced anisotropy on high frequency magnetoimpedance effect of Fe and Co-rich glass-coated microwires” J. Alloys Compound. 735 (2018) 1818-1825;

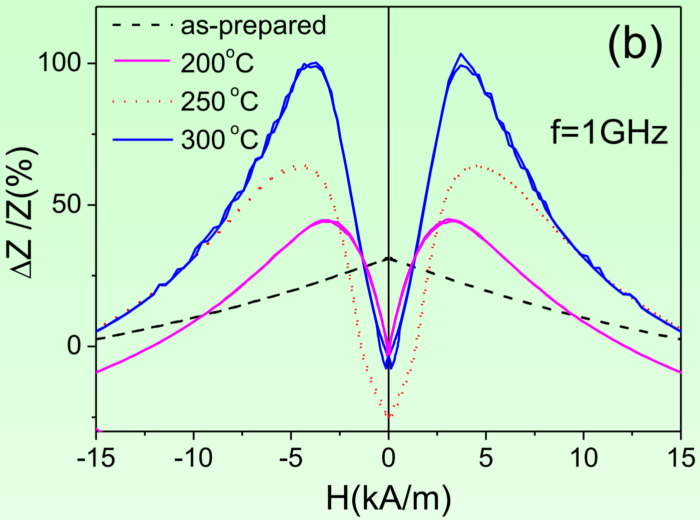
V. Zhukova, J.M. Blanco, M. Ipatov, J. Gonzalez, M. Churyukanova A., Zhukov, Scripta Materialia, Vol. 142, (2018) 10–14, doi: 0.1016/j.scriptamat.2017.08.014

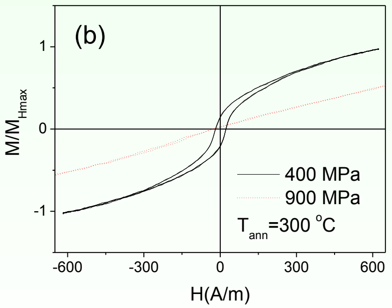
Ways to improve GMI in Fe-rich microwires

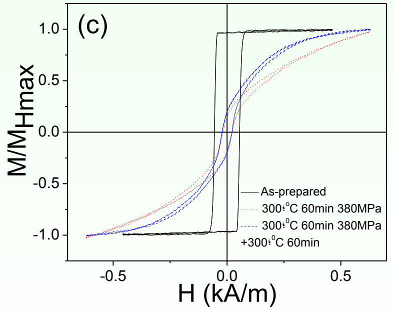
Effect of stress annealing on GMI of Fe -rich microwires



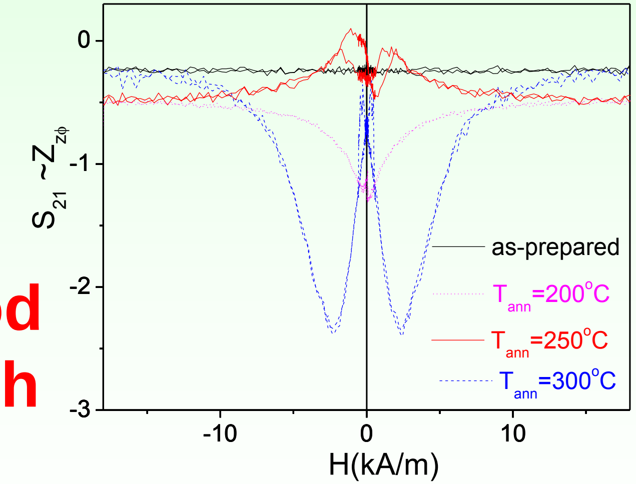








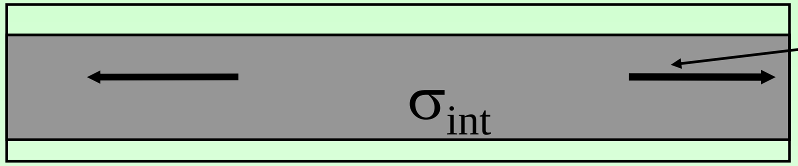
1. **Depend on T, σ**
2. **Only partially reversible**
3. **SA is a promisng method for MI optimization in Fe-rich microwires**



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

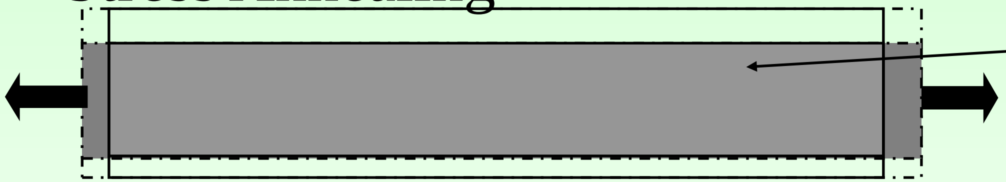
Origin of stress-induced anisotropy 1

As-prepared microwire



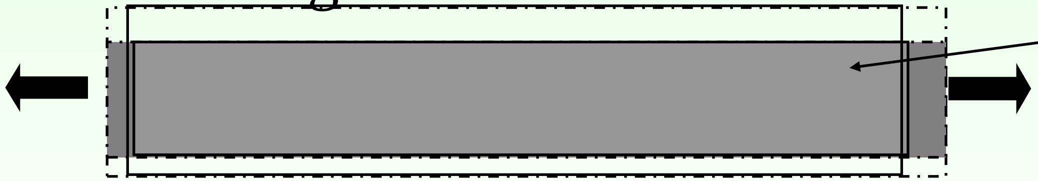
Internal stresses with mainly axial component

Stress Annealing



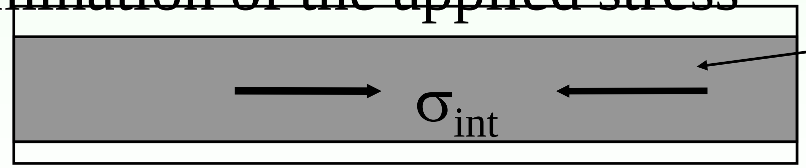
Induction of magnetic anisotropy during stress annealing

Slow Cooling under stress



Stress relaxation in the stressed state at room temperature

Elimination of the applied stress



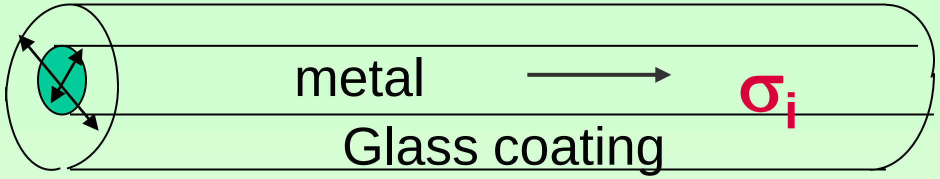
Induction of the compressive stresses at room-temperature (so-called “Back stresses”)

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

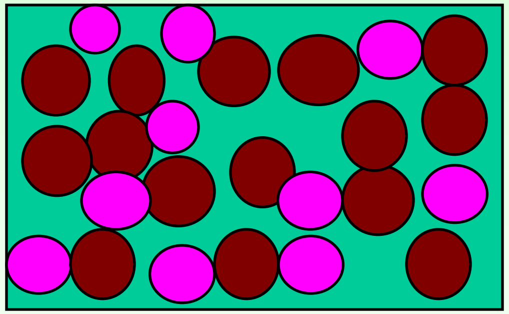
Compensation of axial internal stress

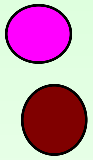
Origin of induced anisotropy 2

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



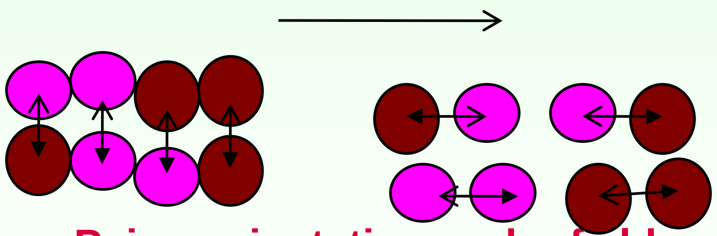
Origin: Pair ordering usually considered





TM1 (Co)
TM2 (Fe)

H or/and σ



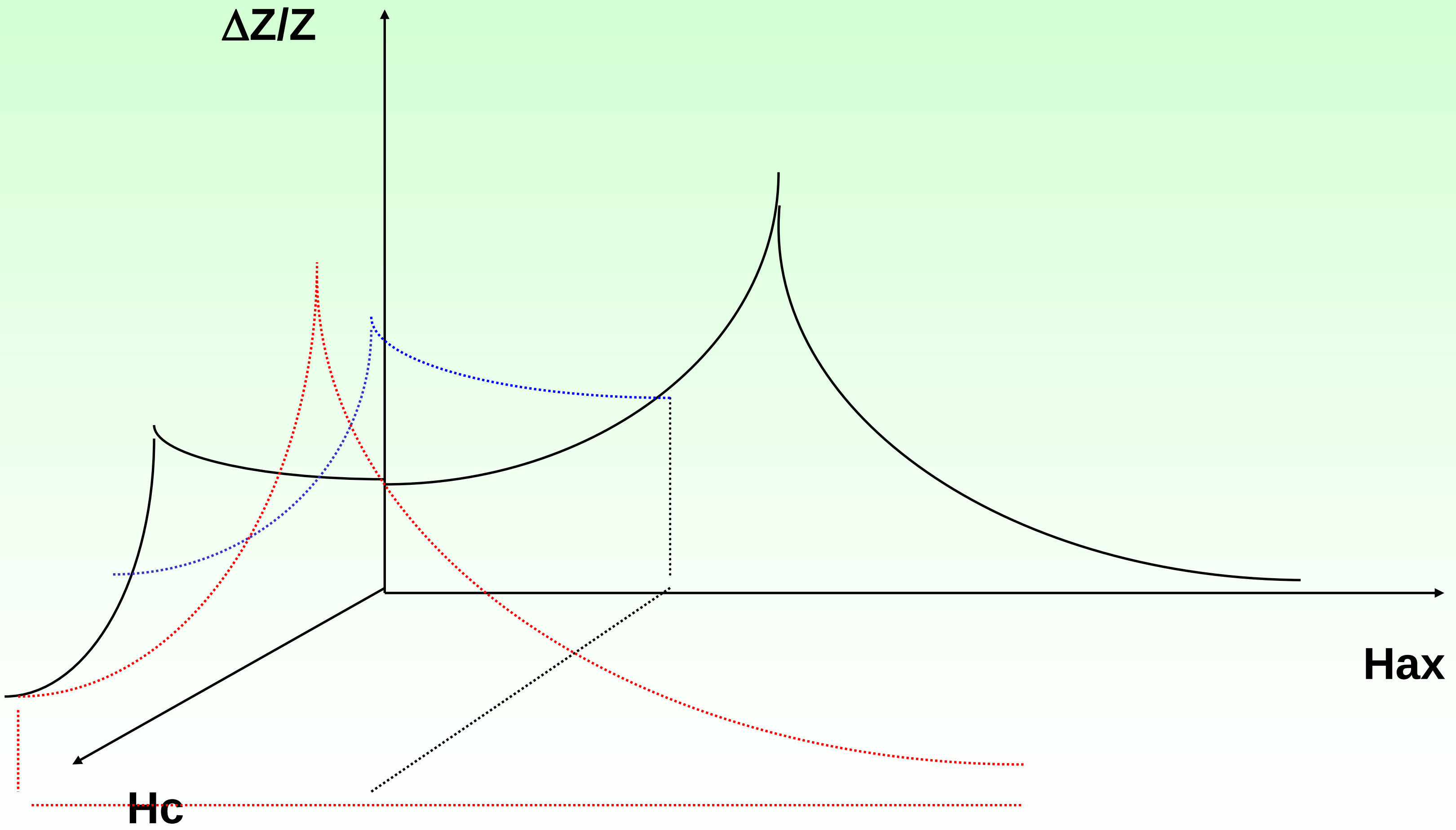
Pair reorientation under field and/or stress annealing (after Neel)

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.

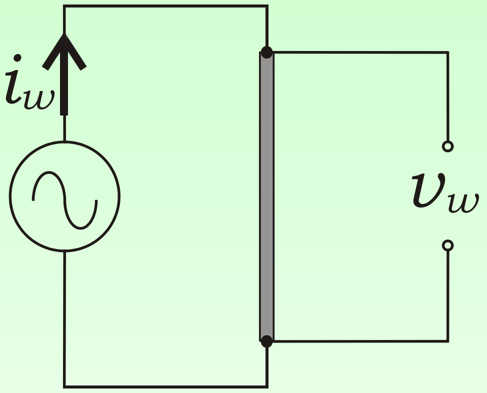
Tensor character of GMI

Schematic representation

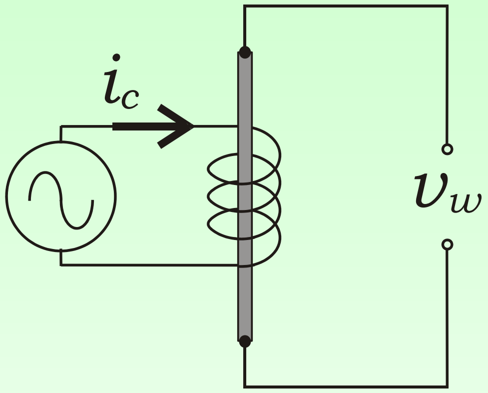


A.S. Antonov, I.T. Iakubov, A.N. Lagarkov, J. Magn. Magn. Mat. 187 (1998), 252
P. Aragoneses, A. Zhukov, J. Gonzalez, J.M. Blanco and L. Dominguez, Sensors and Actuators A, 81/1-3 (2000) 86-90

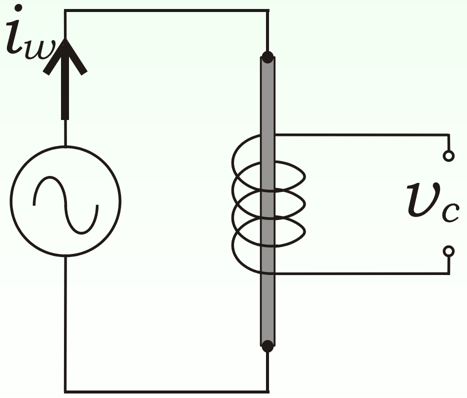
Methods for revealing the impedance matrix elements: (a) ς_{zz}, (b) $\varsigma_{z\varphi}$, (c) $\varsigma_{\varphi z}$, (d) $\varsigma_{\varphi\varphi}$



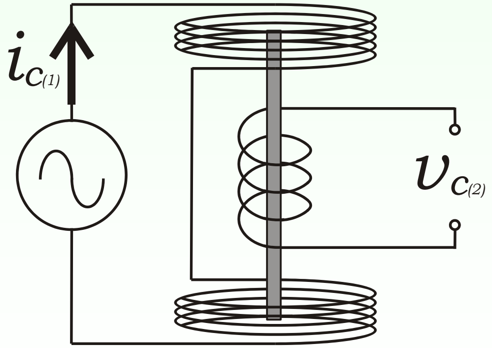
(a) $v_w \equiv \varsigma_{zz} i_w$



(b) $v_w \equiv \varsigma_{z\varphi} i_c$



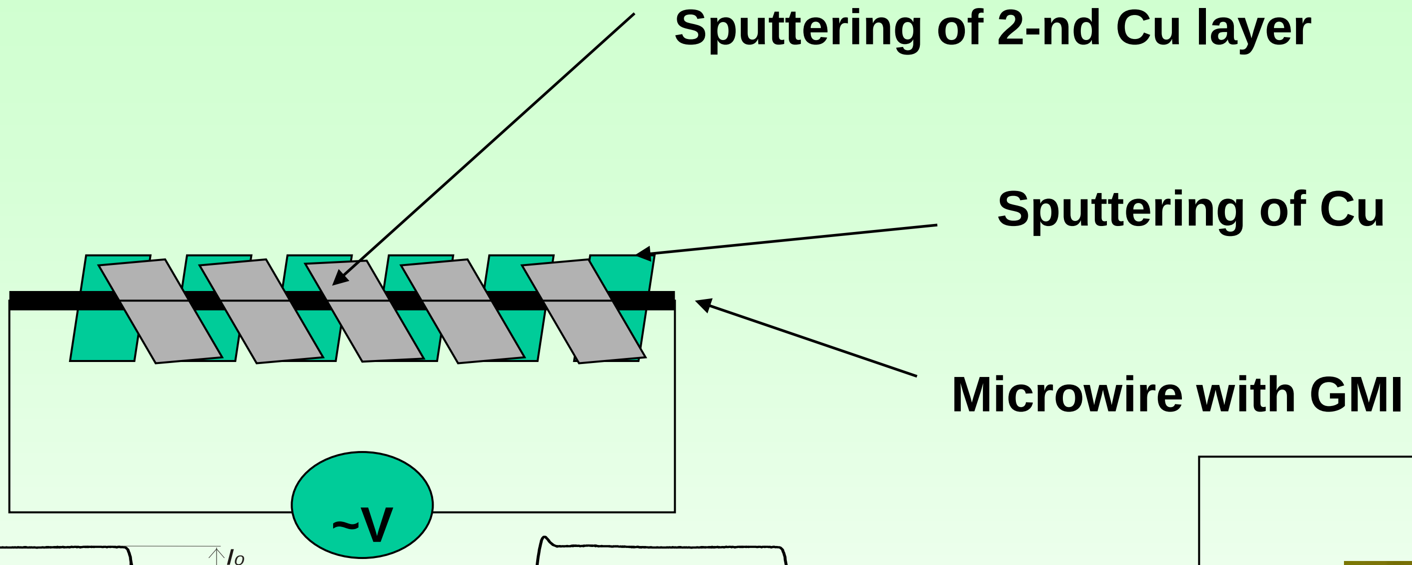
(c) $v_c \equiv \varsigma_{\varphi z} i_w$

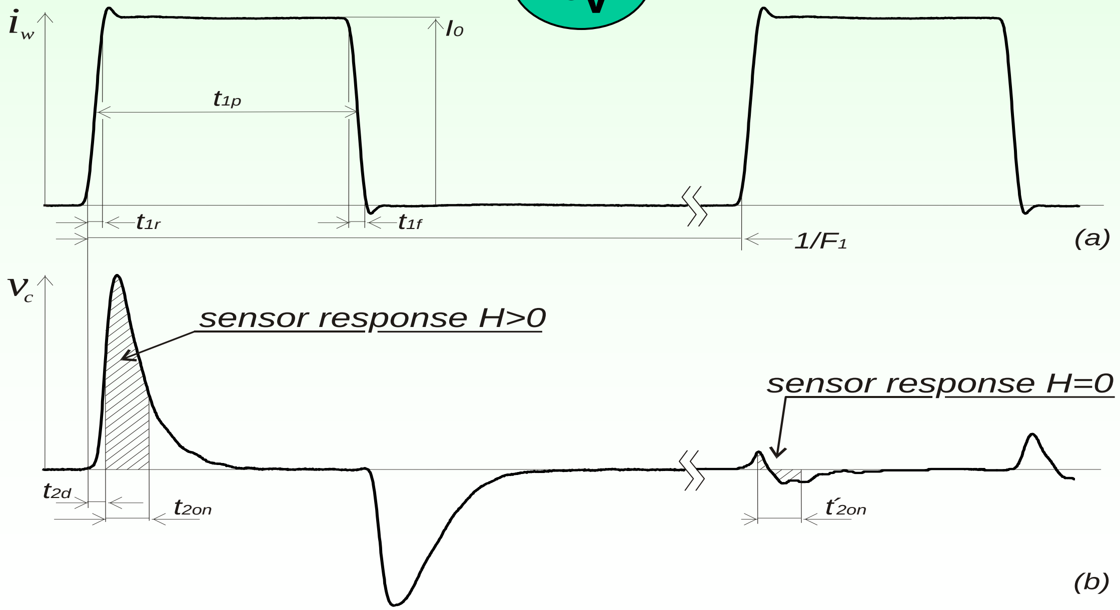


(d) $v_{c(2)} \equiv \varsigma_{\varphi\varphi} i_{c(1)}$

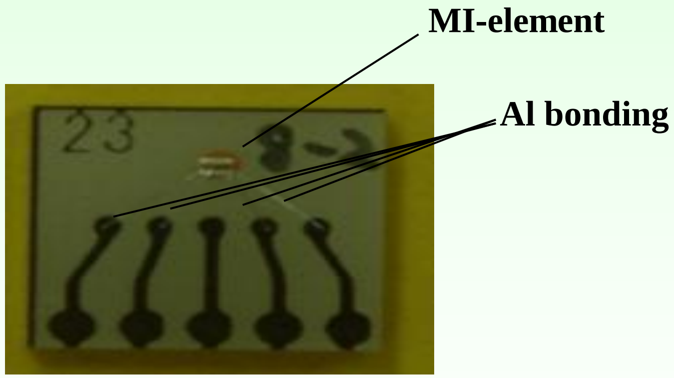
D.P.Makhnovskiy, L.V. Panina and D.J. Mapps, Phys Rev B 63 (2001), 1444241.
Or
V. A. Zhukova, A.B. Chizhik, J.Gonzalez , D.P. Makhnovskiy, L.V. Panina, D.J. Mapps and A.P. Zhukov, J Magn Magn Mat. 249 (2002), 3124.

MI element



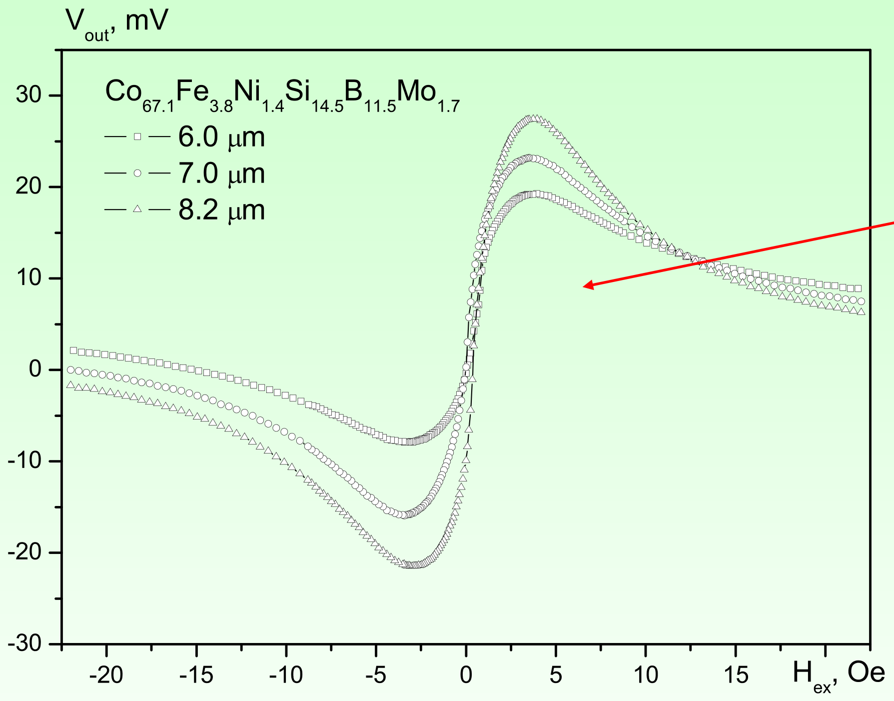


Excitation current pulse in the wire (a) and voltage induced in the pickup coil (b).



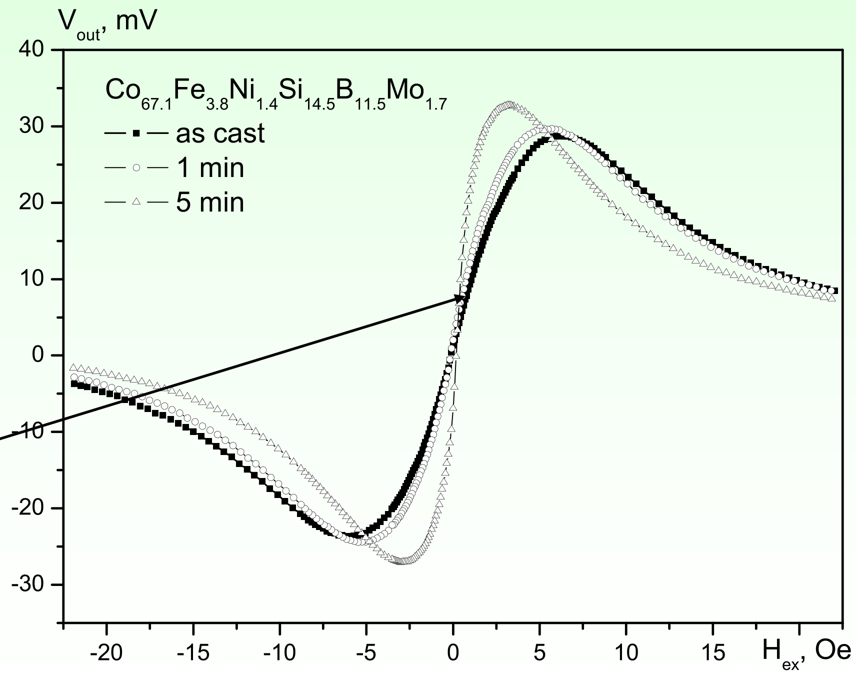
Before bonding of resin

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



Asymmetrical shape,
Almost linear region

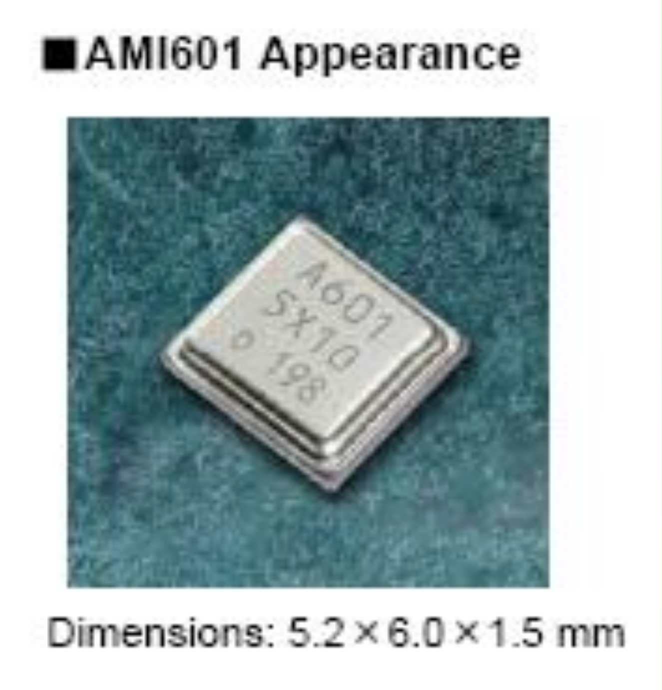
Linear region and maximum
Position depends on geometry

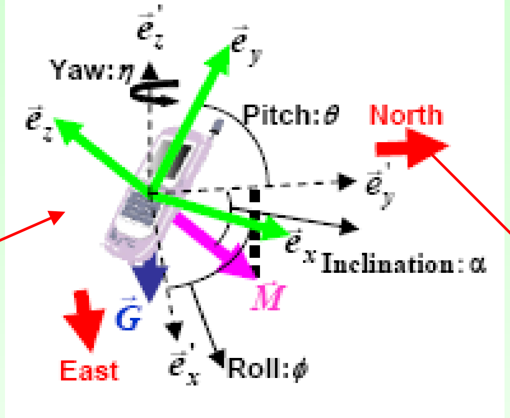


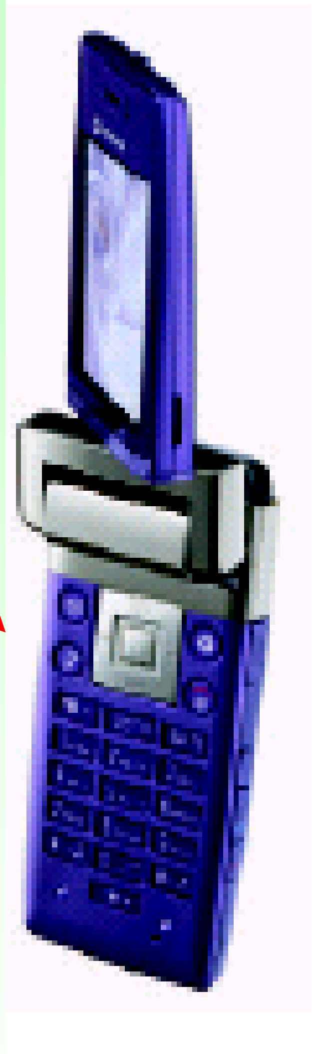
Tailoring of GMI by heat treatment

APPLICATIONS:

m-wires –GMISince 2010







MI-element

AMI 601 –Aichi Steel Corp.

6-axis sensor

3 axis of magnetic earth sensing

3 axis acceleration sensing

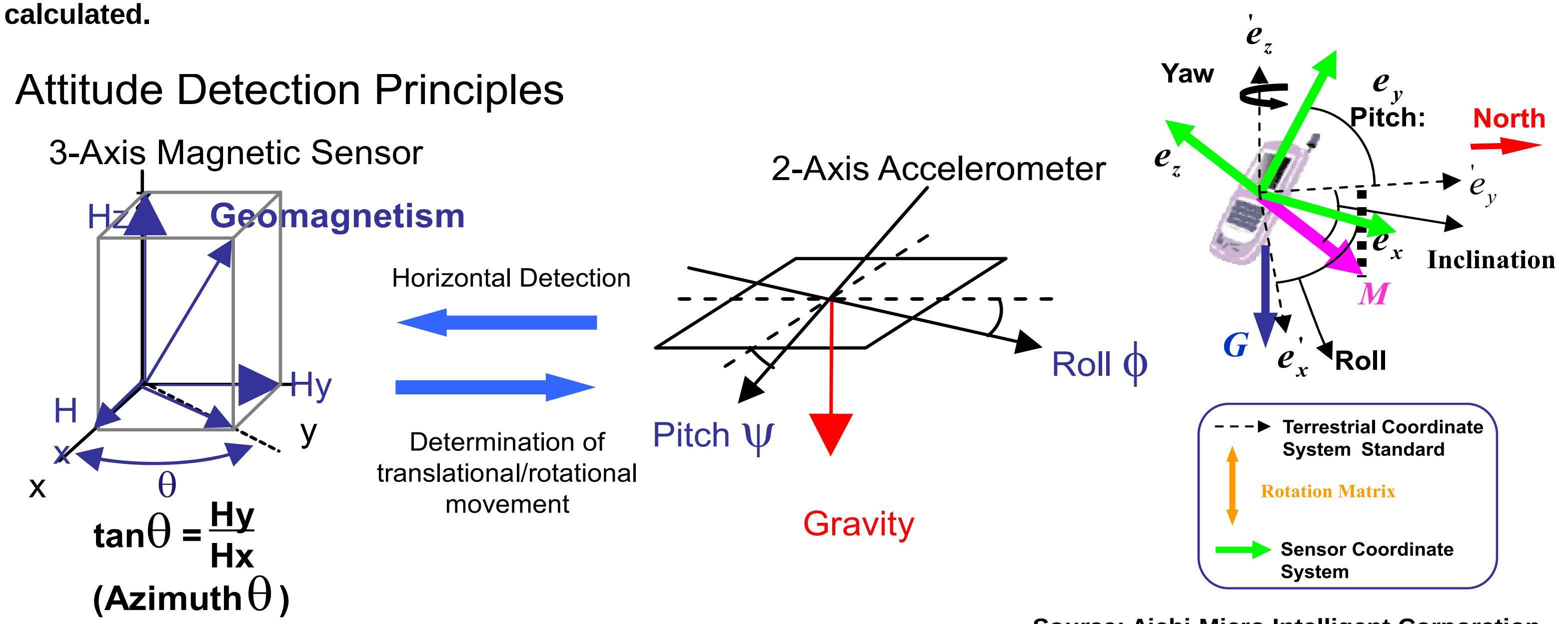
Size – 1 mm

APPLICATIONS:
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.

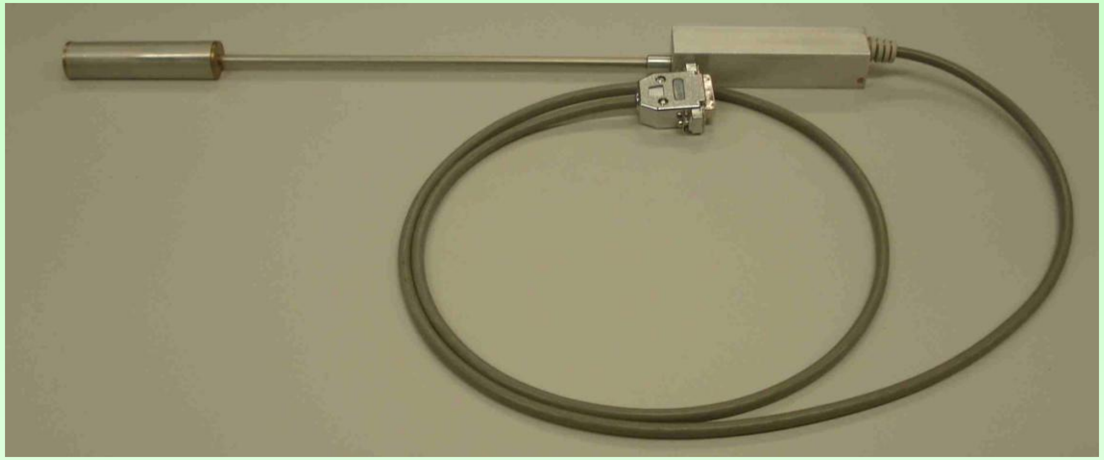


Source: Aichi Micro Intelligent Corporation

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

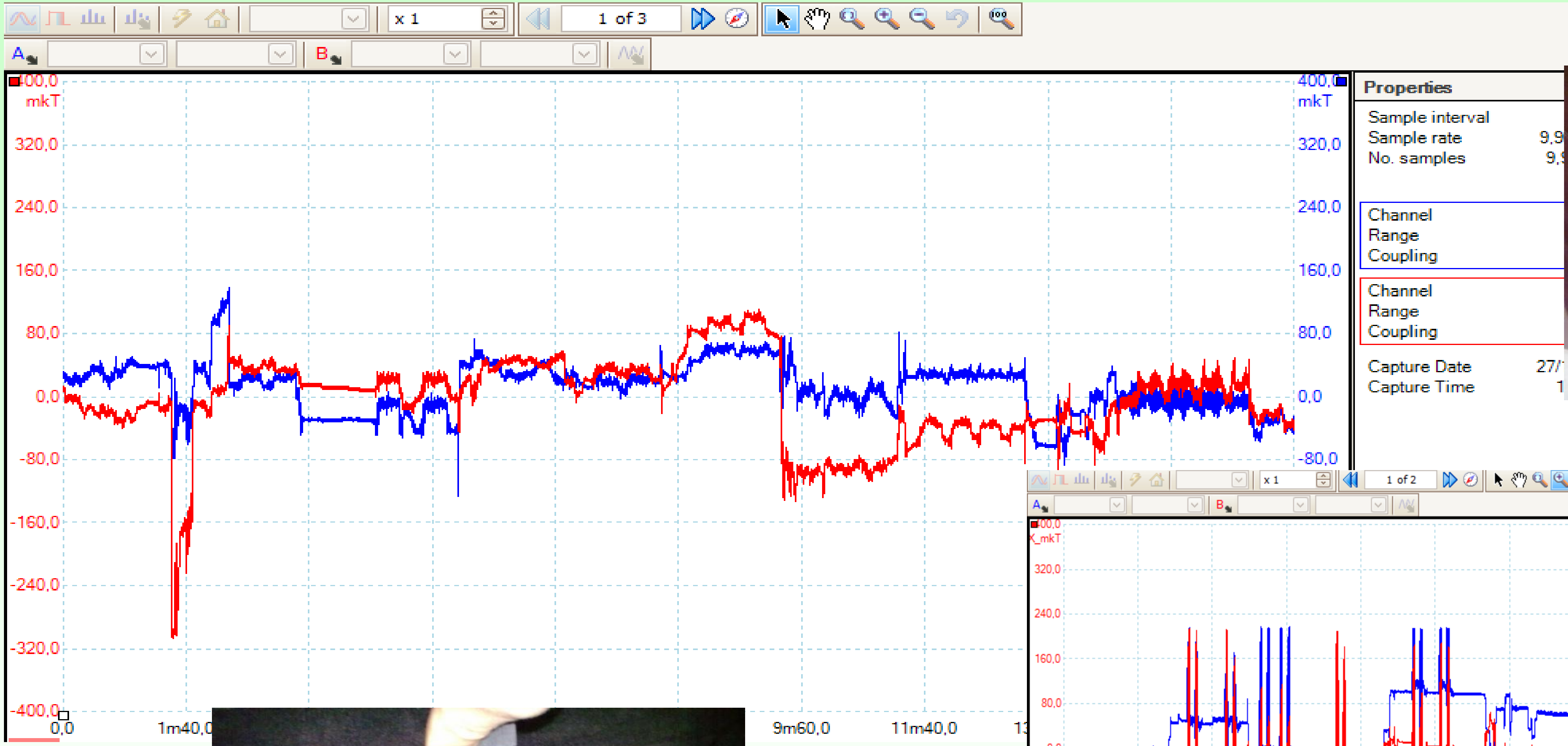
Requirements: high sensitivty at low H (up to few Oe)

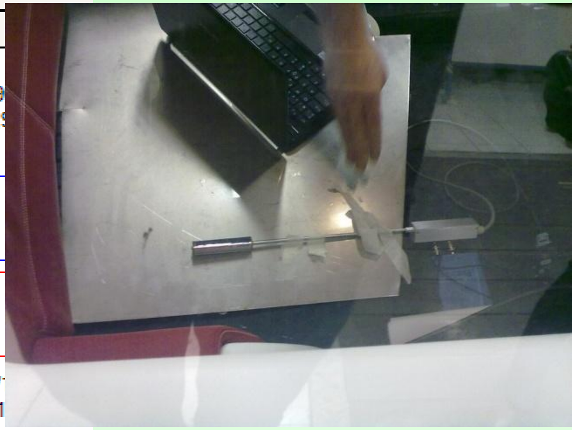
Designed by us magnetometer

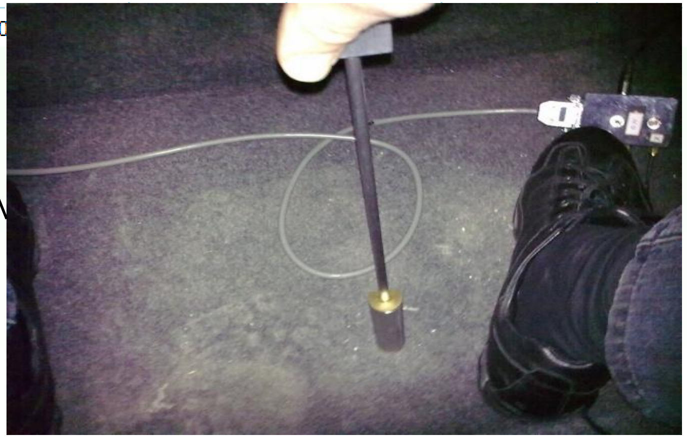


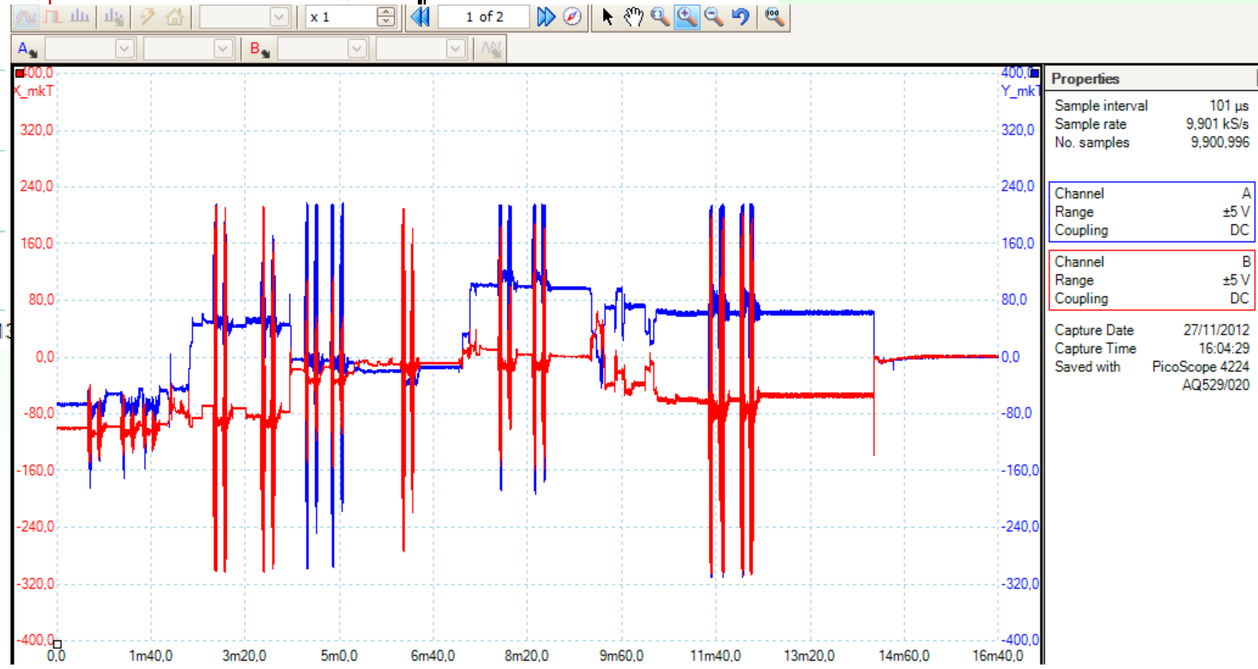
<u>**Technical characteristics**</u>	
Channel number	**3 (X, Y, Z components);**
Size of the 3-component sensing element	**cube with 14 mm edge;**
Input voltage of the channel, not less	**± 4.5 V;**
Dynamic range, not less	**± 2.5 Oe;**
Frequency range, not less	**1 kHz;**
Power voltage	**0 + 5.5V;**
Consuming current	**~ 250 mA;**
<u>**Transmission coefficient of the channels**</u>	
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)

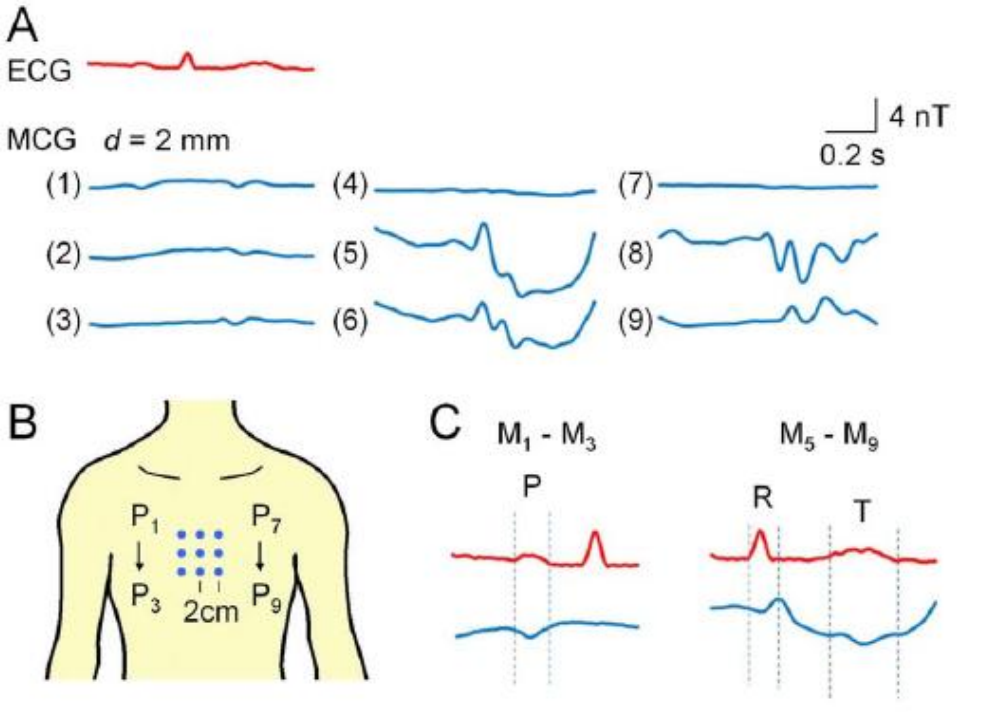


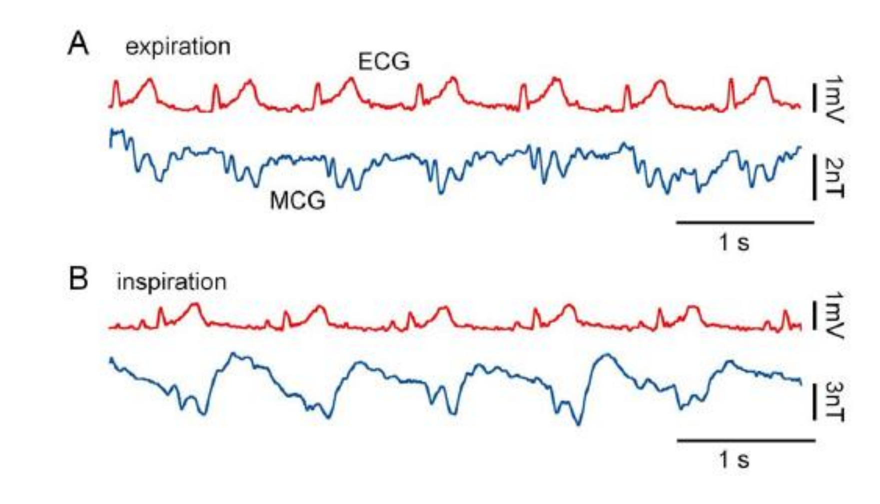






Prospective applications of GMI magnetic fild sensors





OPEN ACCESS Freely available online

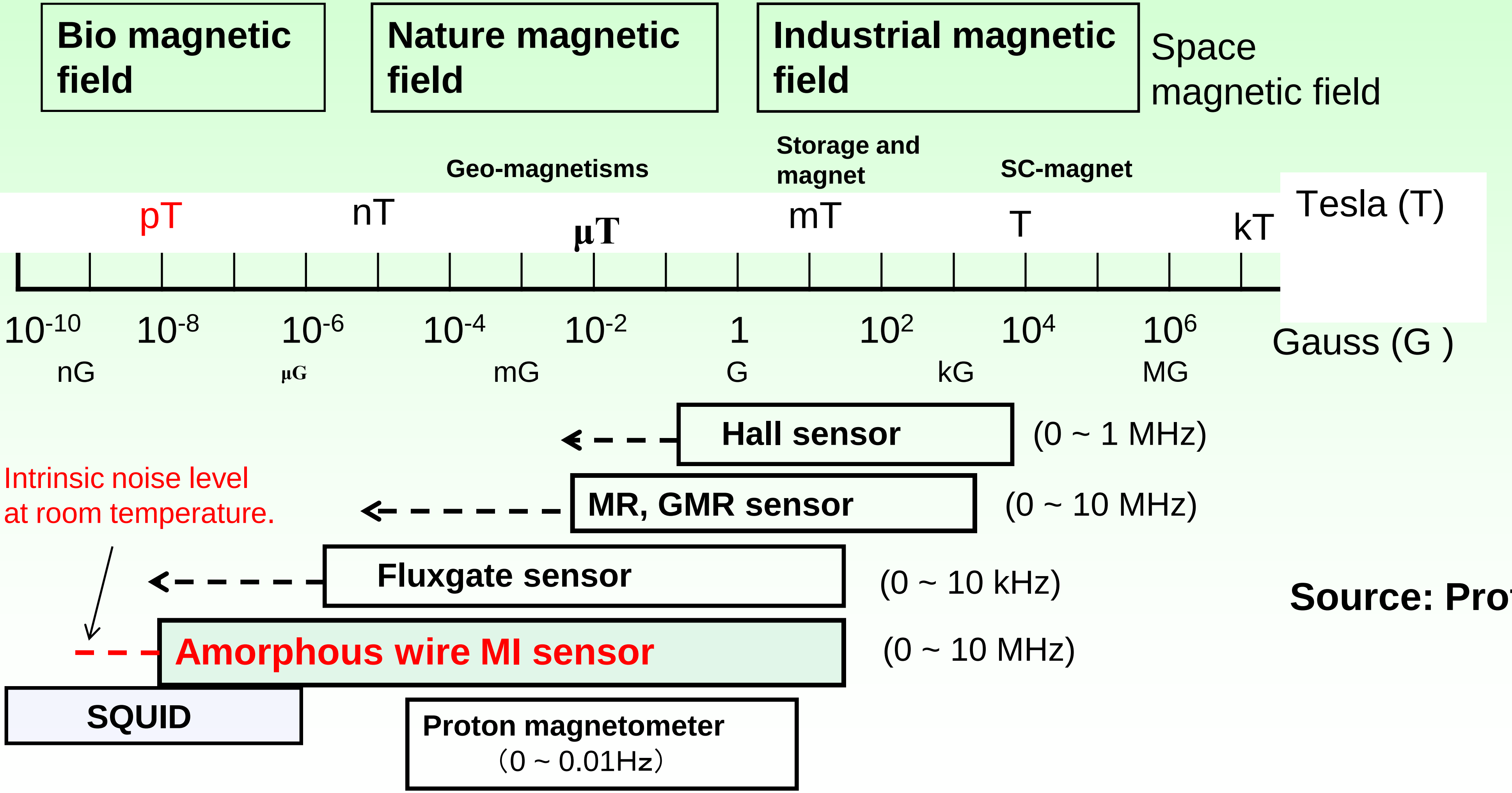
PLoS one

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

Magnetic Field and Magnetic Sensors



Source: Prof. K. Mohri

Tuneable composites with ferromagnetic wires

Magneto-impedance effect (MI)
in ferromagnetic wires

Composite materials with metallic wires

MI at Radio Frequencies
(MHz)

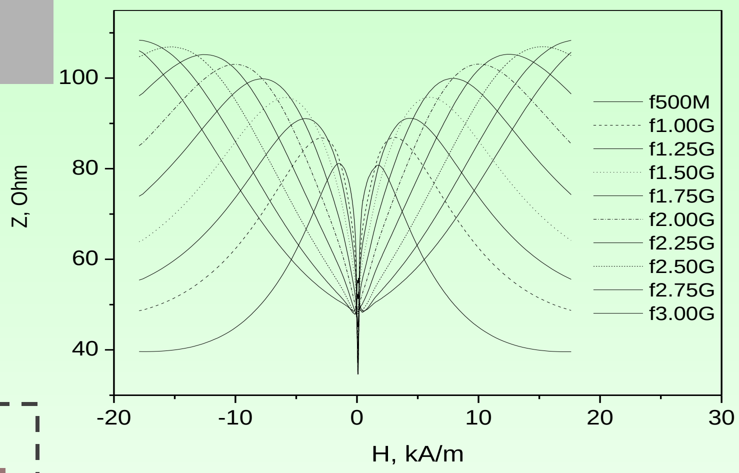
Strong dispersion of the
effective permittivity

High sensitivity
magnetic,
stress,
temperature
sensors

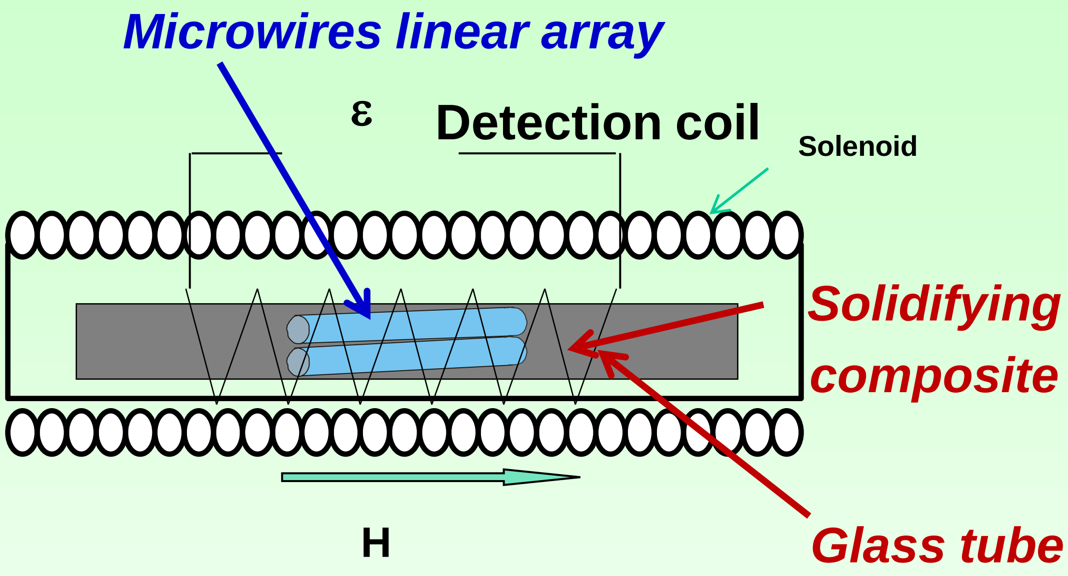
MI at GHz

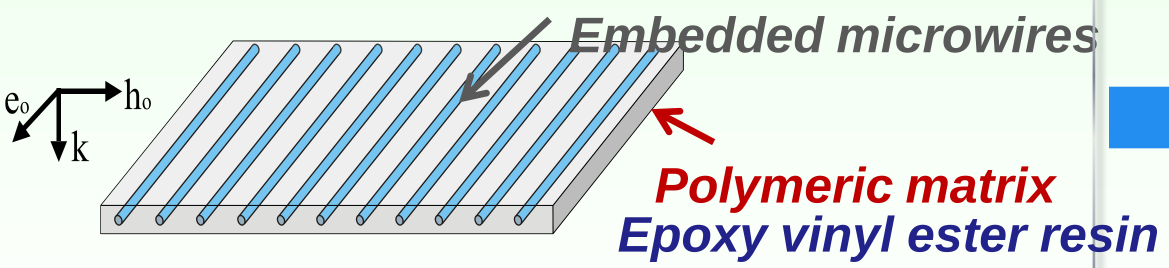
Magnetically tuneable
composite

1) Tuneable selective microwave coatings
2) Stress-sensitive media
for remote non-destructive health monitoring.
3) Temperature monitoring composites



Composite structures





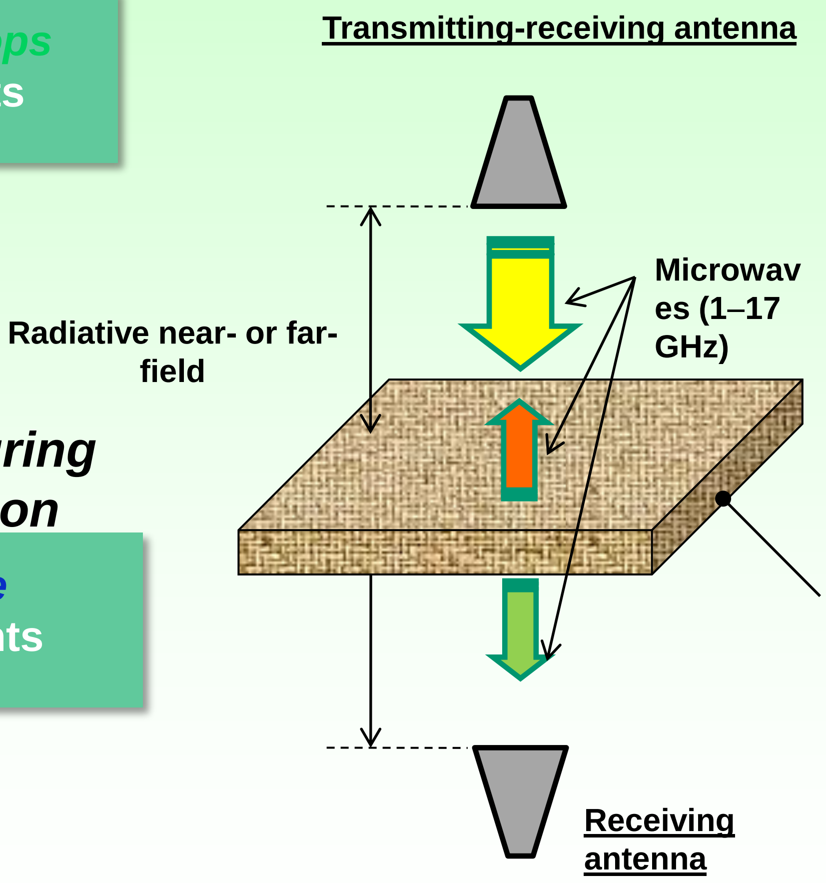
FRC: Fiber Reinforced Composite

Microwires in a thermoset matrix during polymerization

Hysteresis loops Measurements

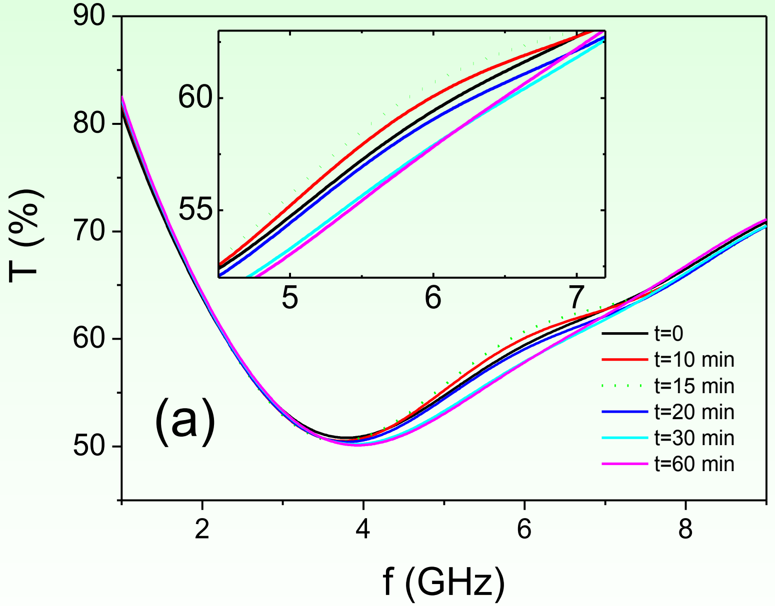
Composite during polymerization

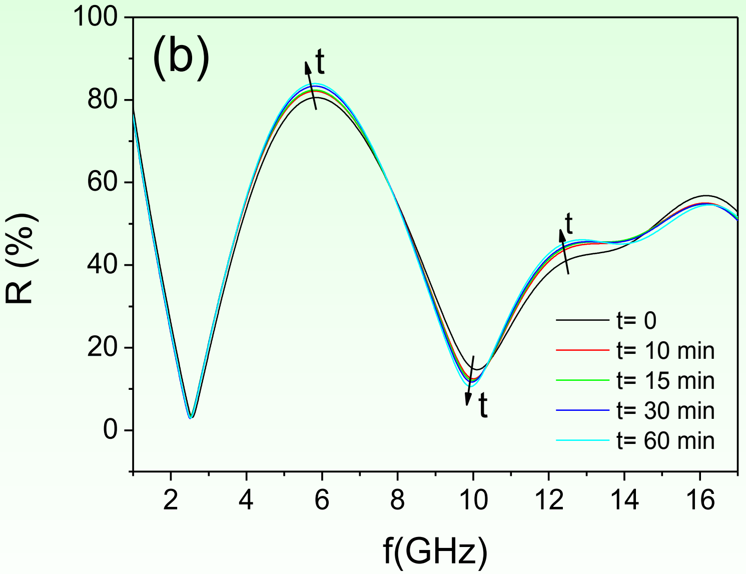
Free-space Measurements

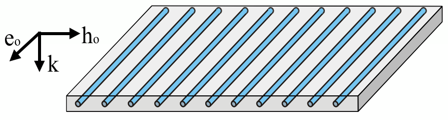


Electromagnetic properties of composites with glass-coated microwire inclusions

The Transmission, T (a) and reflection,R (a) parameters measured using free-space system during the composite solidification.

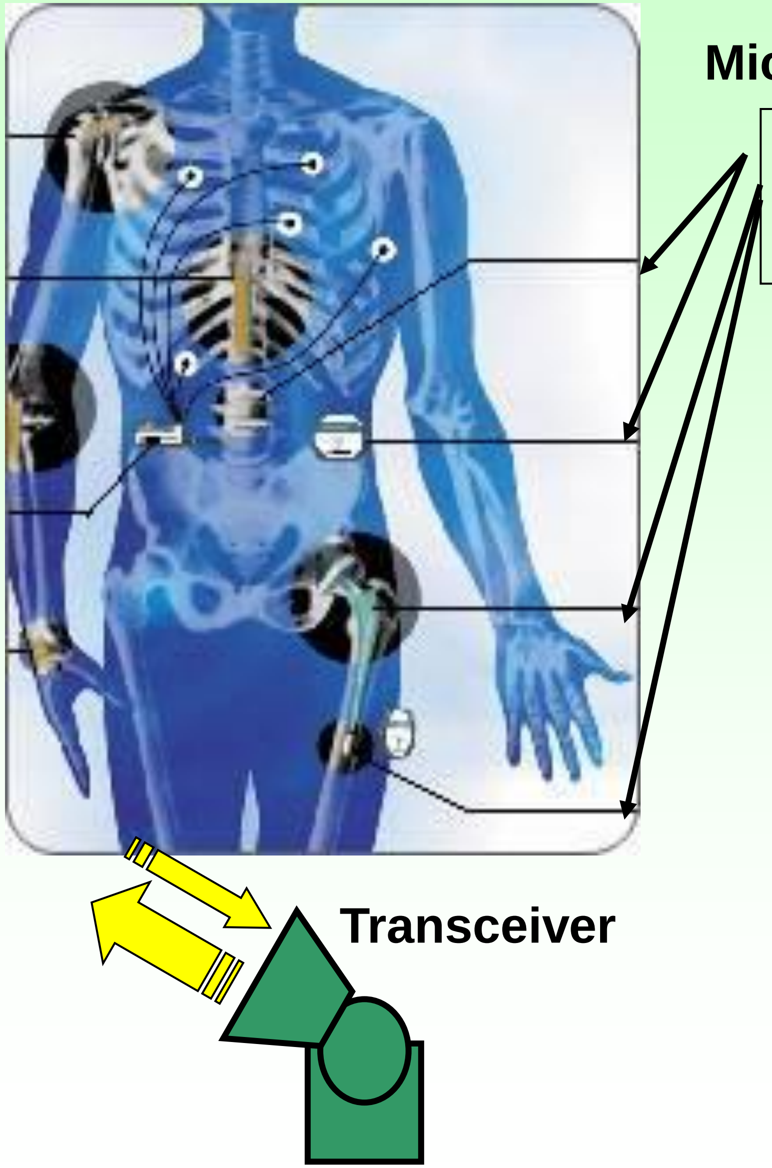


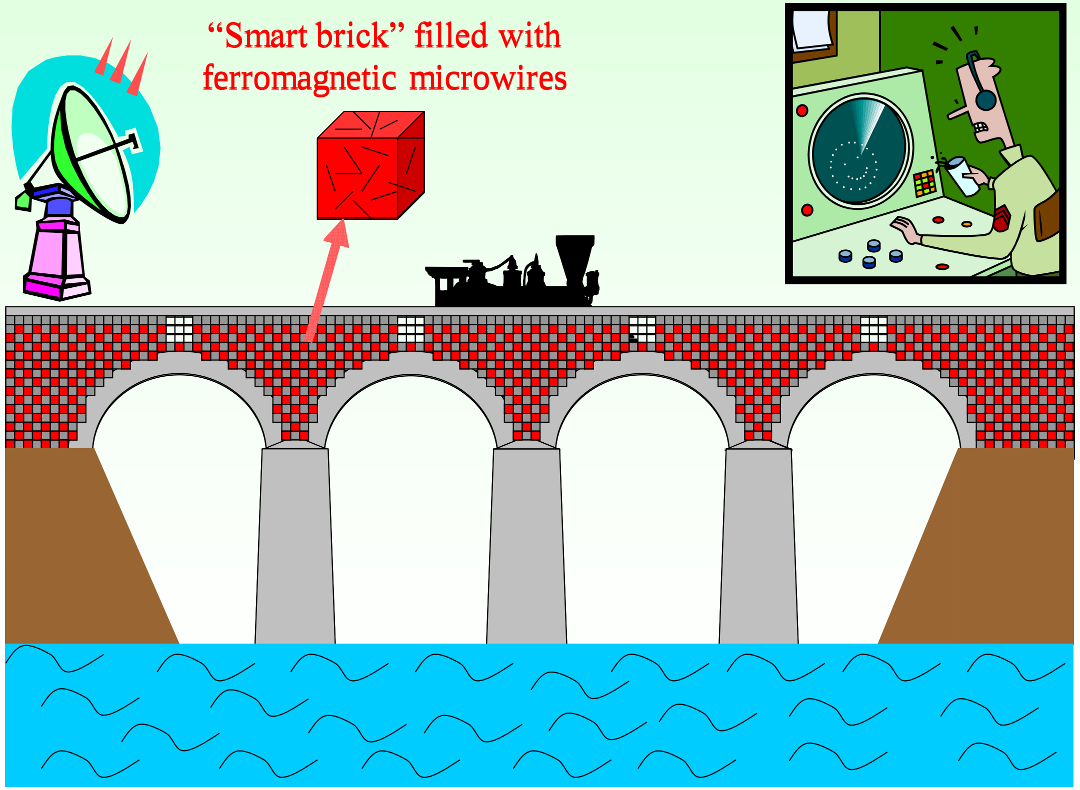




48

Potential application for stress-sensitive microwires: remote local stress control





Existing and proposed applications

1. Mobile phones (navigation and games)
2. Bio- and medical applications
3. Tags
4. Smart composites

3070 IEEE TRANSACTIONS ON MAGNETICS, VOL. 47, NO. 10, OCTOBER 2011

Measurement of Spontaneous Oscillatory Magnetic Field of Guinea-Pig Smooth Muscle Preparation Using Pico-Tesla Resolution Amorphous Wire Magneto-Impedance Sensor

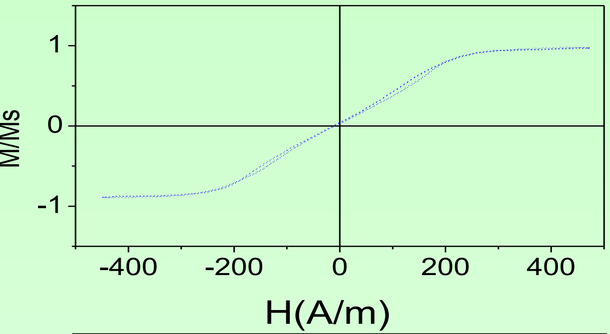
Tsuyoshi Uchiyama[1], Kaneo Mohri[2], *Life Fellow, IEEE*, and Shinsuke Nakayama[3]

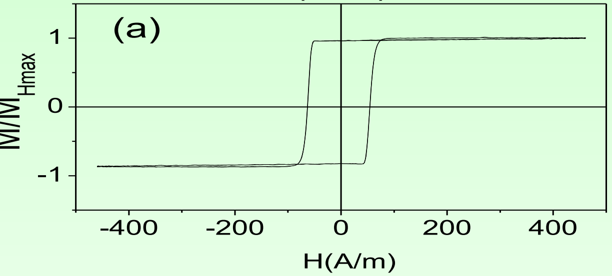
240 PIERS Proceedings, Kuala Lumpur, MALAYSIA, March 27–30, 2012

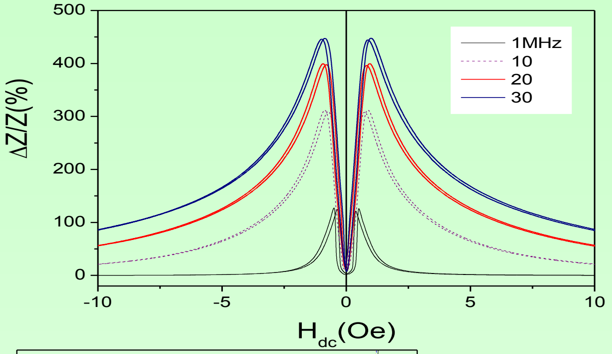
Health Recovery Effect of Physiological Magnetic Stimulation on Elder Person's Immunity Source Area with Transition of ECG and EEG

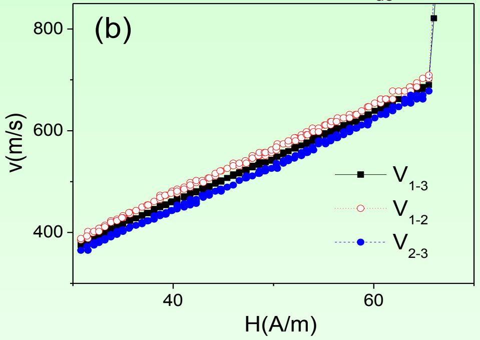
K. Mohri[1], Y. Inden[2], M. Yamada[3], and Y. Mohri[4]

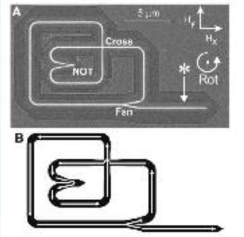
Present talk : magnetic softness and GMI effect of amorphous microwires

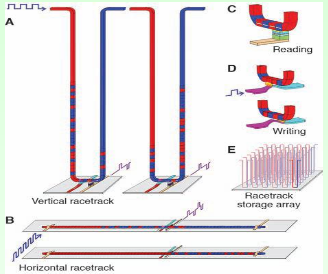




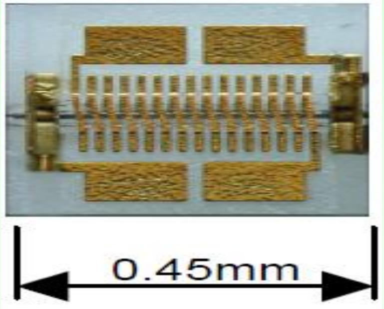








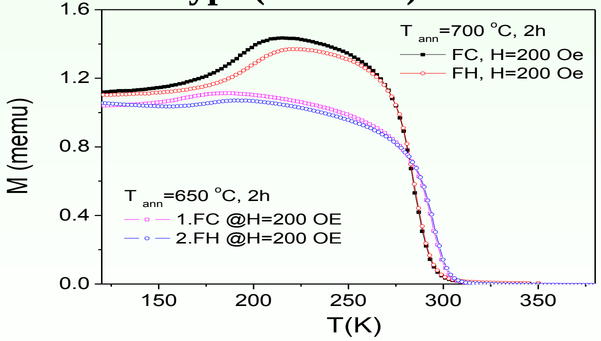
1. A. Zhukov , J.M. Blanco, M. Ipatov, A. Talaat, V. Zhukova,, “Engineering of domain wall dynamics in amorphous microwires by annealing”, J. Alloys Compounds, Volume 707, 15 (2017), p. 35–40
2. V. Zhukova, J. M. Blanco, A. Chizhik, M. Ipatov, A. Zhukov, “AC-current-induced magnetization switching in amorphous microwires”, Front. Phys. 13(2), 137501 (2018)
3. 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
4. V. Zhukova, J.M. Blanco, M. Ipatov, J. Gonzalez, M. Churyukanova A., Zhukov, “Engineering of magnetic softness and giant magnetoimpedance effect in Fe-rich microwires by stress-annealing”, Scripta Materialia Vol. 142, 1 January 2018, 10–14,



Other features of amorphous microwires:

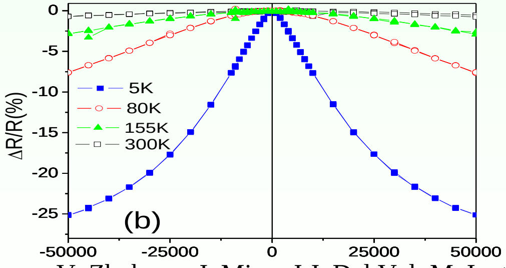
Crystalline microwires:

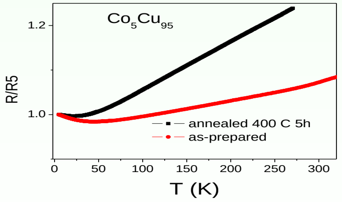
Heusler-type (NiMnGa)



A. Zhukov, M. Ipatov, J.J. del Val, S. Taskaev, M. Churyukanova and V. Zhukova, “First-order martensitic transformation in Heusler-type glass-coated microwires”, Appl.Phys. Lett. DOI: 10.1063/1.5004571

Granular microwires Co-Cu





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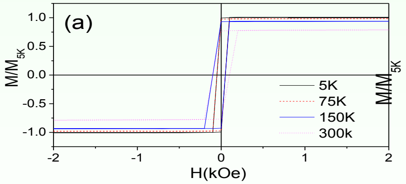
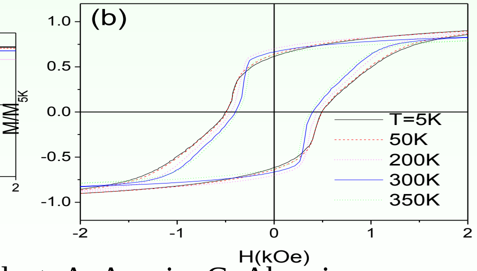
Magnetric hardening: FePt





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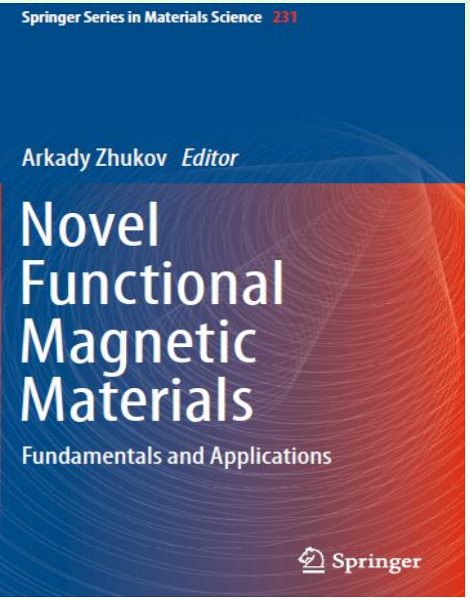
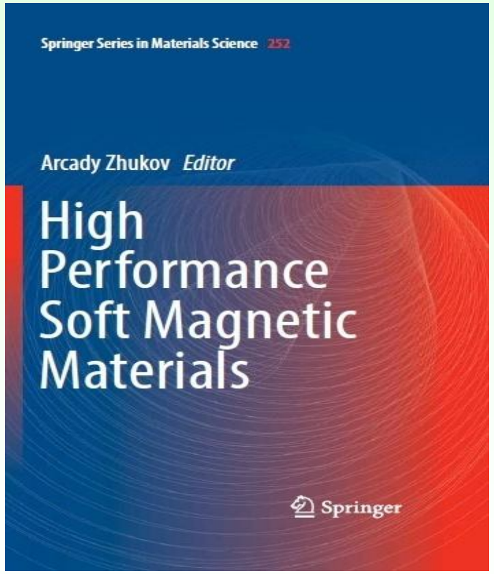
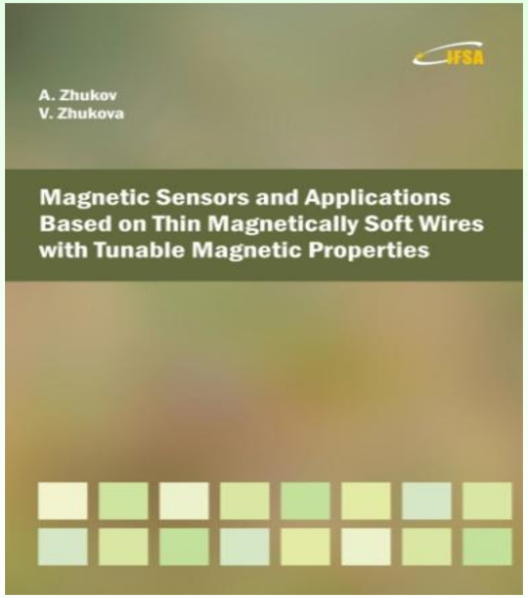
Conclusions

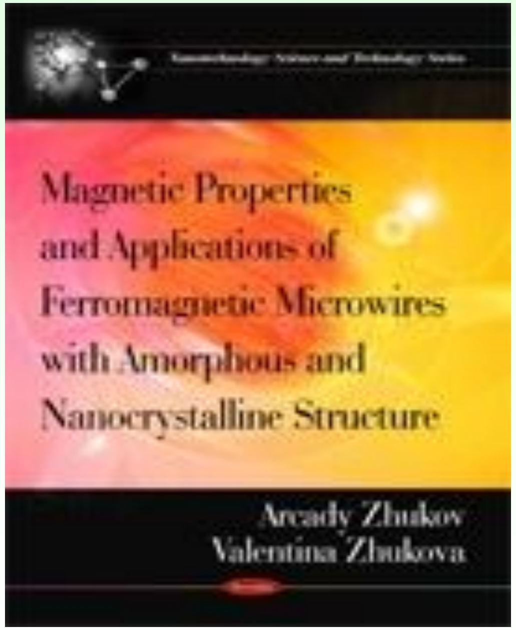
- **Soft magnetic properties, GMI and fast DW propagation are observed in magnetic microwires.**
- **By appropriate selection of chemical composition and post-processing conditions we can considerably improve GMI effect and magnetic softness in Co-rich microwires and DW velocity in Fe-rich microwires**
- **Excellent magnetic properties are suitable for several sensor applications**

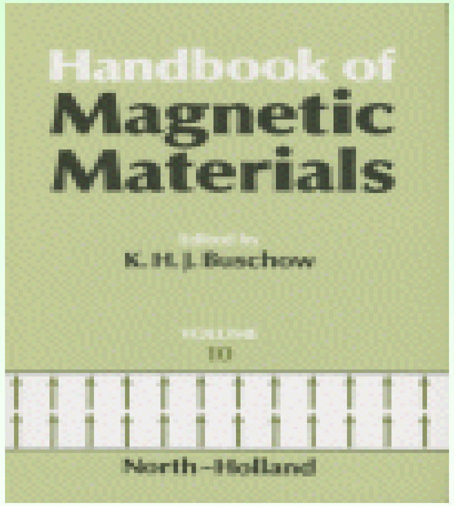
Thank you for the attention!











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

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