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Basque Foundation for Science

The University of the Basque Country
Faculty of Chemistry
Department of Polymers and Advanced Materials
Magnetism Research Group

Optimization of GMI effect and magnetic softness of Co-rich microwires

P. Corte-León[1], V. Zhukova [1,2,3], A. Gonzalez[1], J. M. Blanco[2] and A. Zhukov[1,2,3,4]

[1]*Dept. Polymers and Advanced Mater., UPV/EHU, San Sebastián 20009, Spain*
[2]*Dpto. de Fís. Aplicada., EIG, UPV/EHU San Sebastián 20009, Spain*
[3]*EHU Quantum Center, University of the Basque Country, UPV/EHU*
[4] *Ikerbasque, Basque Foundation for Science , Bilbao, Spain.*

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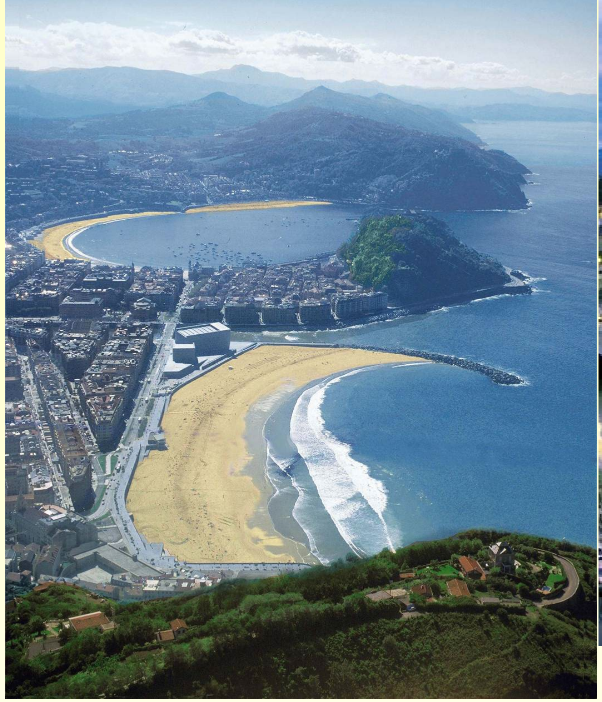
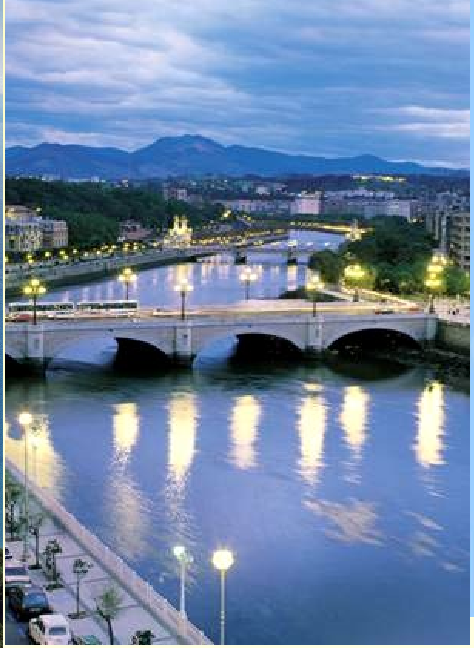




Outline

1. INTRODUCTION
1.1. STATE OF THE ART ON MICROWIRES, MAGNETIC PROPERTIES AND APPLICATIONS
1. 2.MOTIVATION :
2. MAGNETIC PROPERTIES OF AS-PREPARED MICROWIRES
2.1. TUNNING OF HYSTERESIS LOOPS AND GMI BY DIFFERENT POST-PROCESSING
3. DISCUSSION
4. CONCLUSIONS

Invited papers in J. Alloys Compounds:

-A. Zhukov, M. Ipatov, M.Churyukanova, A. Talaat, J.M. Blanco and V. Zhukova, Trends in optimization of giant magnetoimpedance effect in amorphous and nanocrystalline materials (Review paper), J. Alloys Compound. 727 (2017) 887-901 DOI: 10.1016/j.jallcom.2017.08.119

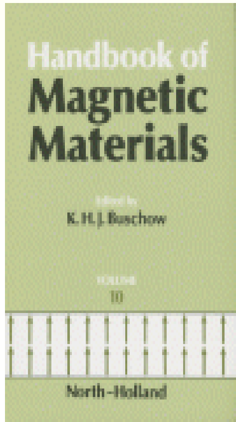
-A. Zhukov, M. Ipatov, P. Corte-León, L. Gonzalez- Legarreta, M. Churyukanova, J.M. Blanco, J. Gonzalez, S. Taskaev, B. Hernando and V. Zhukova, "Giant magnetoimpedance in rapidly quenched materials", J. Alloys Compound 814 (2020) 152225, doi: https://doi.org/10.1016/j.jallcom.2019.152225 (Jubilee issue)

Advances in Giant Magnetoimpedance of Materials

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

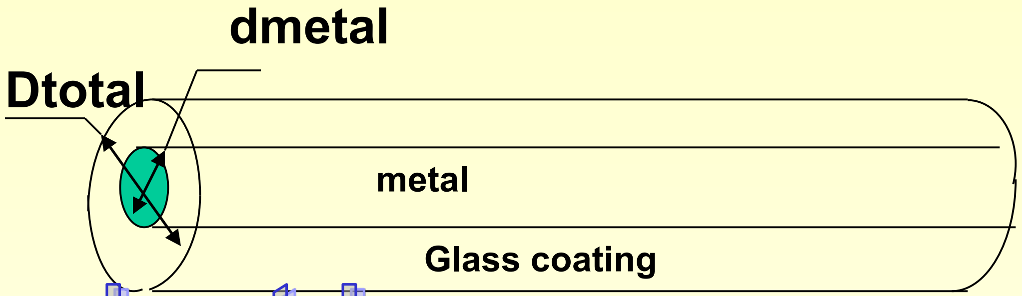
Handbook of Magnetic Materials, Volume 24. http://dx.doi.org/10.1016/bs.hmm.2015.09.001

October 2015

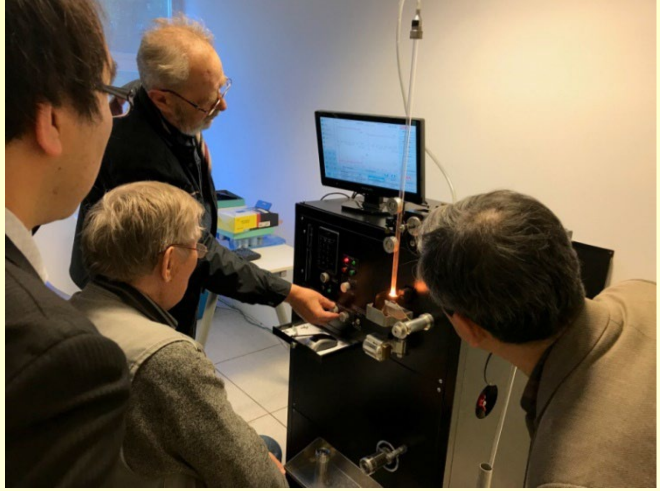


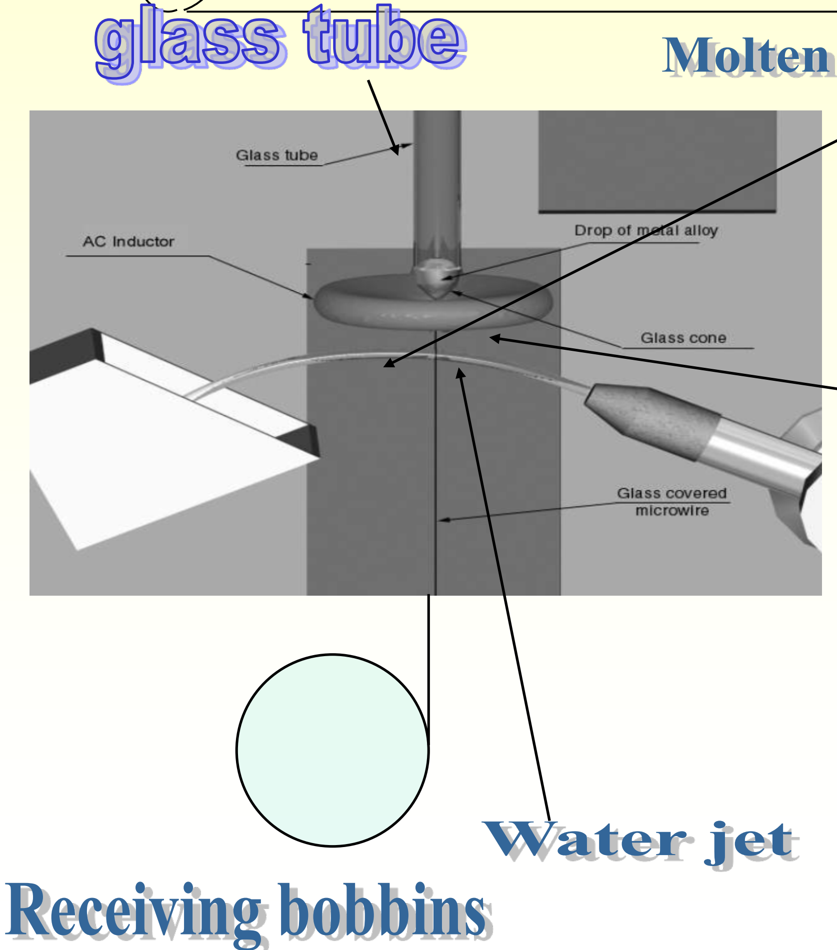
Glass coated microwires

- Co, Ni , Fe and Cu rich compositions

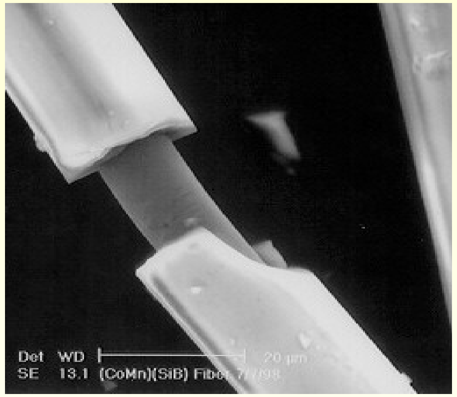


Typical dimensions:
Total diameter 3-40 microns
Metallic nucleus diameter 1-30 microns
Glass coating thickness 1-10 microns
Length - few km (up to 10 in 1 bobbin)





HF Inductor



Advantages: (functionalities)

1. Unexpensive and simple fabrication method

2. Excellent soft magnetic properites (if amorphous)

3. Magnetic bistability (DW propagation)

4. Thin dimensions (Raw materials saving)

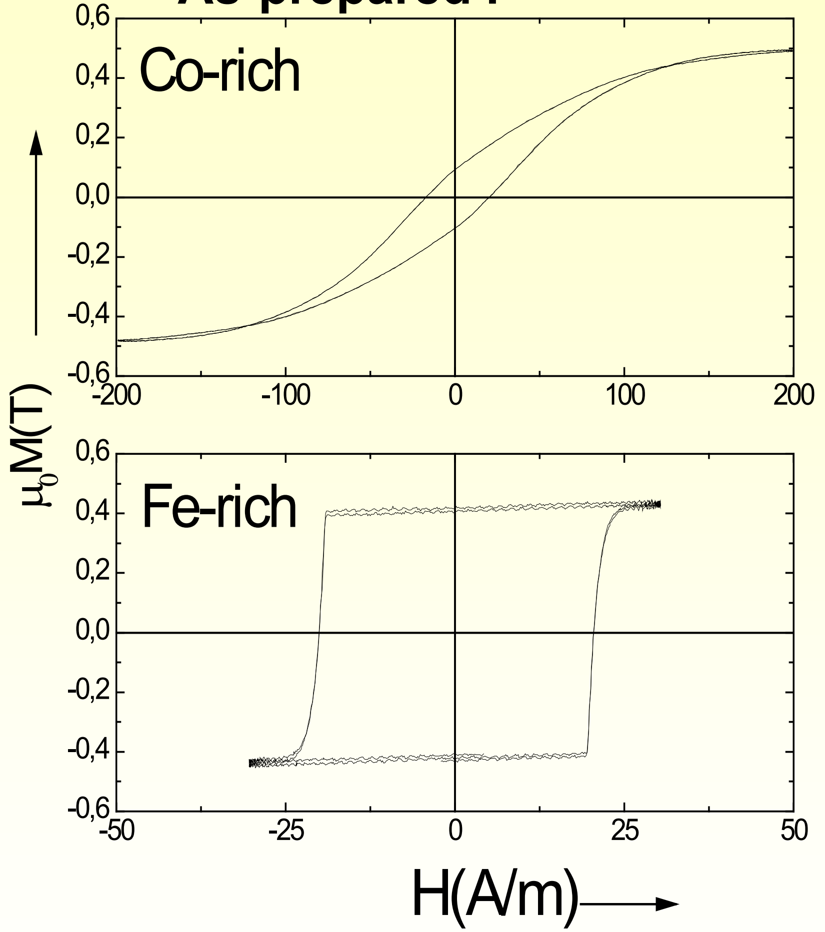
5.Biocompatibility (glass-coating)

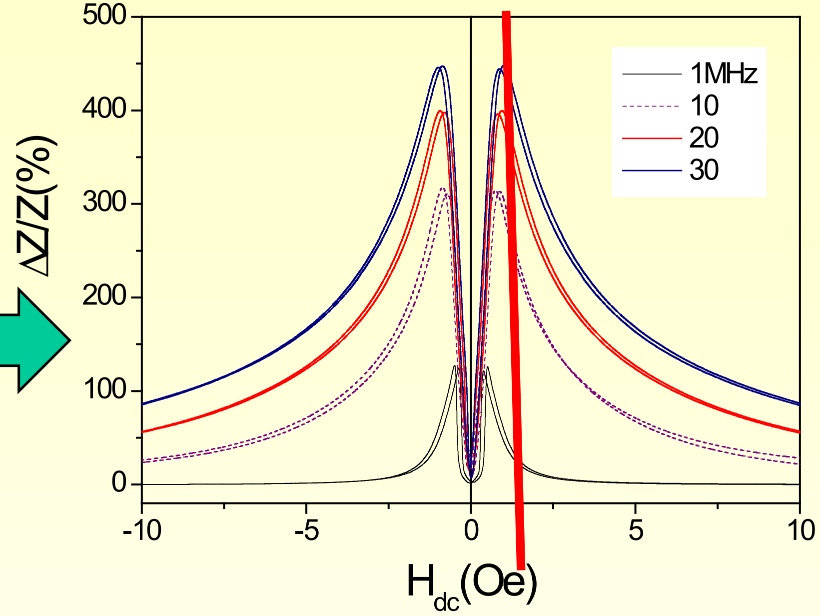
6. Better corrosion resistance (glass-coating)

7.Robust properties,

MAGNETIC PROPERTIES OF AMORPHOUS MICROWIRES

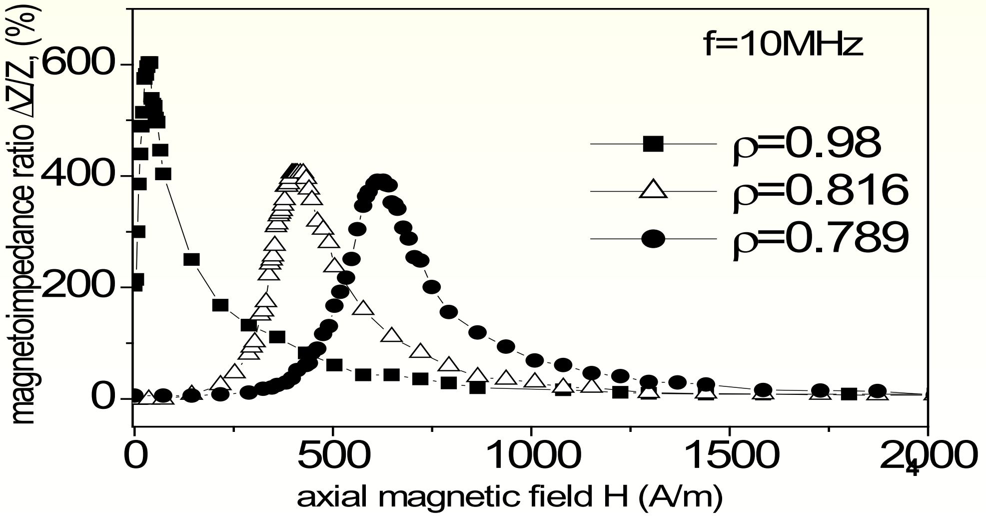
As-prepared !





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

Up to now maximum GMI ratio of 600 % is reported



However 3000% is predicted

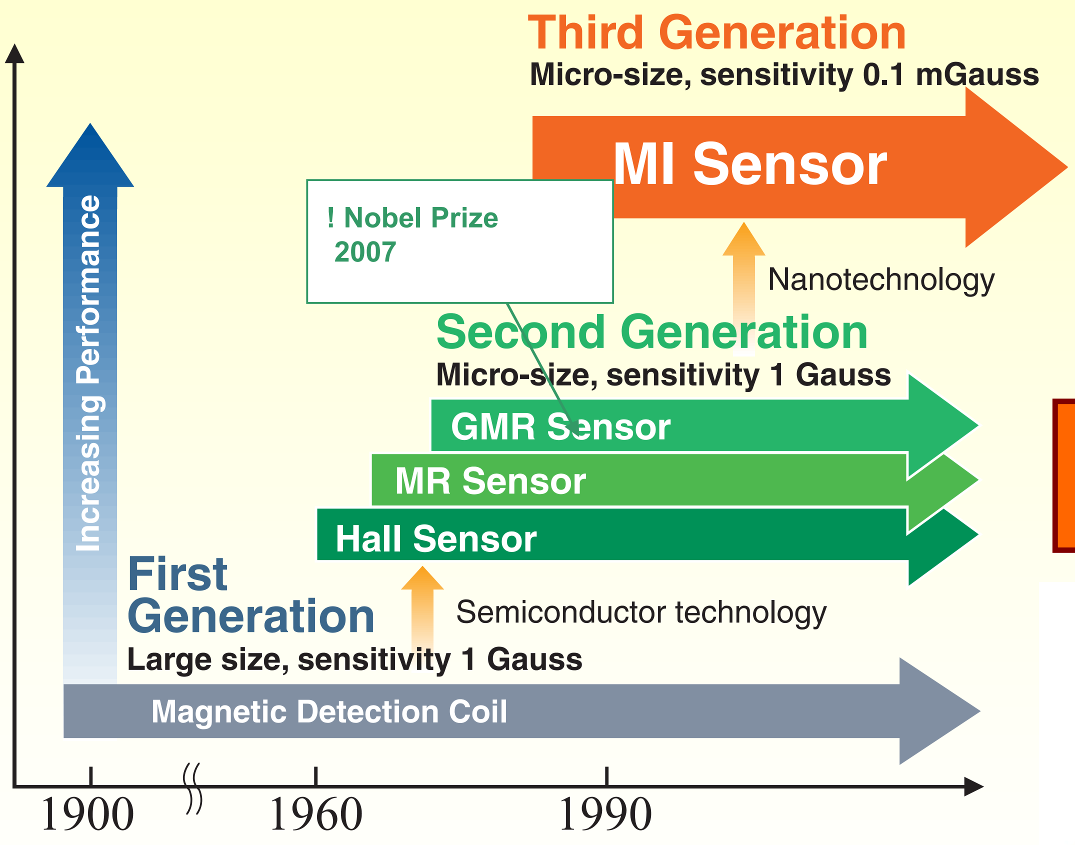
1.L. Kraus, "Theory of giant magneto-impedance in the planar conductor with uniaxial magnetic anisotropy", *J. Magn. Magn. Mater.*, vol. 195, pp. 764-778, 1999.
2. M. Ipatov *et al.*, "Low-field hysteresis in the magnetoimpedance of amorphous microwires", *Phys. Rev. B*, Vol. 81, p. 134421, 2010.

Promising applications: 1. Magnetic sensors and smart composites (GMI effect involved)

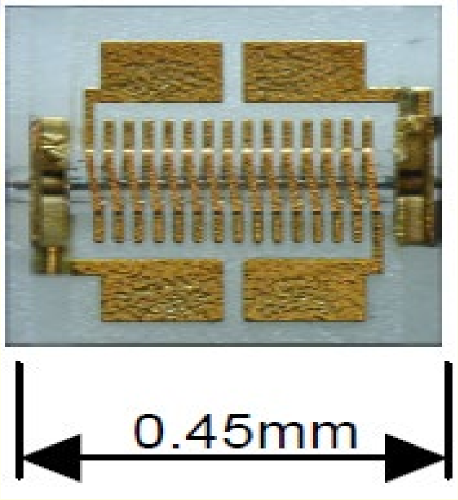
Third Generation of Magnetic Sensors

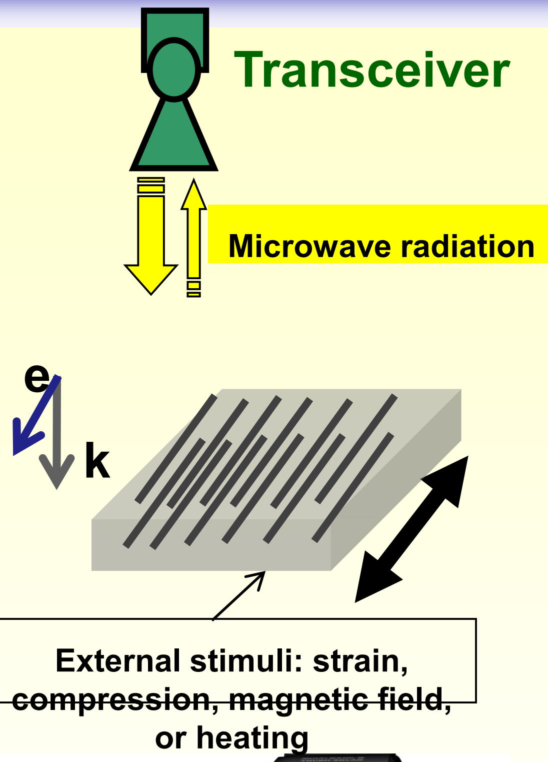
Smart composites

MI Sensors with excellent performance!

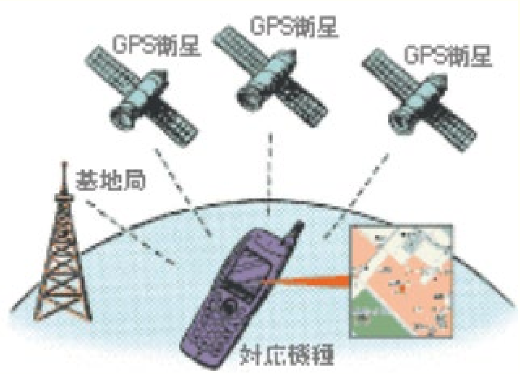


Magnetic Sensor History





Based on Amorphous Wwire since 2010



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 V_{dd}	1.7 V
Power current I_{dd}	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

Industrial application in Smart phone using MI sensor

Advanced 3−axis MI sensor chip installed in watch

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

Source: Aichi Micro Intelligent Corporation

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)

Magnetoelastic energy

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

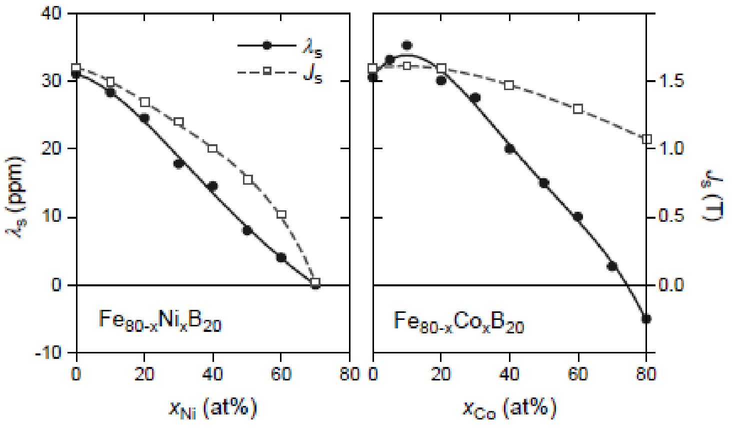
Internal stresses in composite microwires

Magnetostriction λ_s -determines by the chemical composition

$\sigma = \sigma_i + \sigma_a$

σ_a- applied stresses

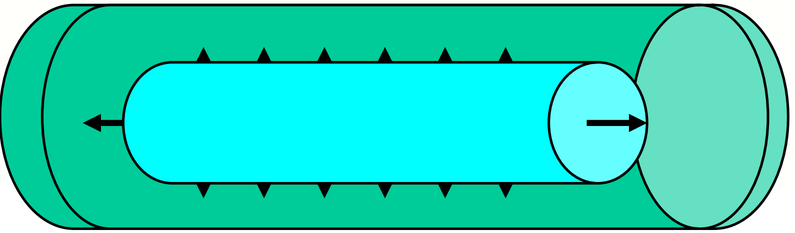
σ_i -determines by the ratio $\rho = d/D$



AMORPHOUS AND NANOCRYSTALLINE SOFT MAGNETS

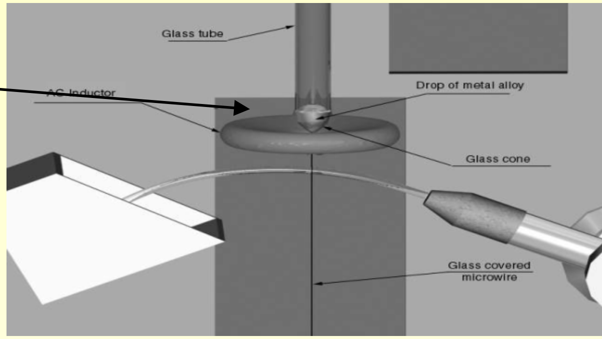
G.Herzer
Vacuumschmelze GmbH & Co KG

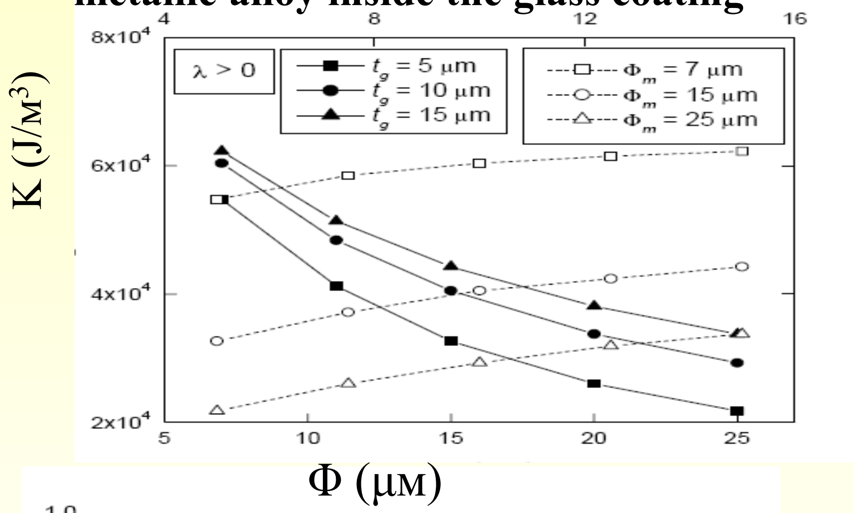
$\sigma = f(\rho)$, $\rho = d/D$

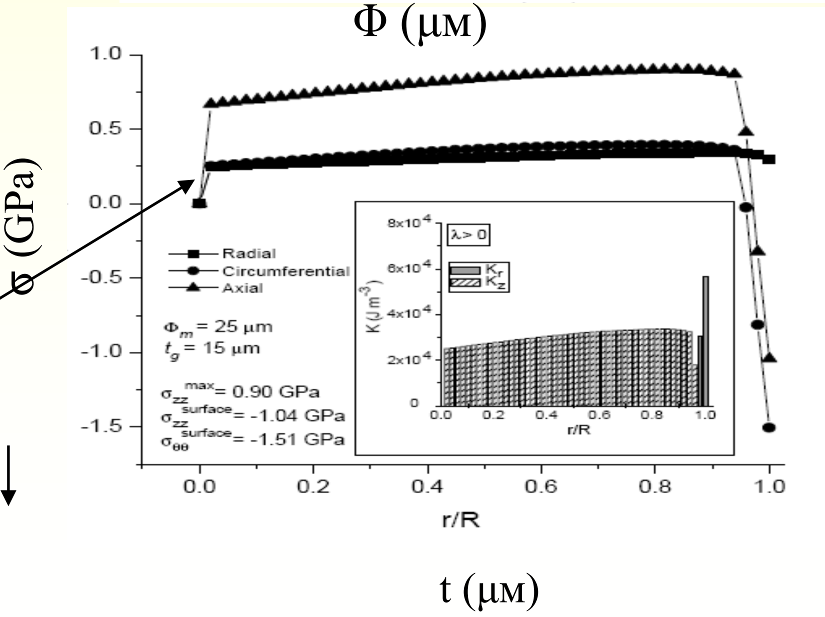


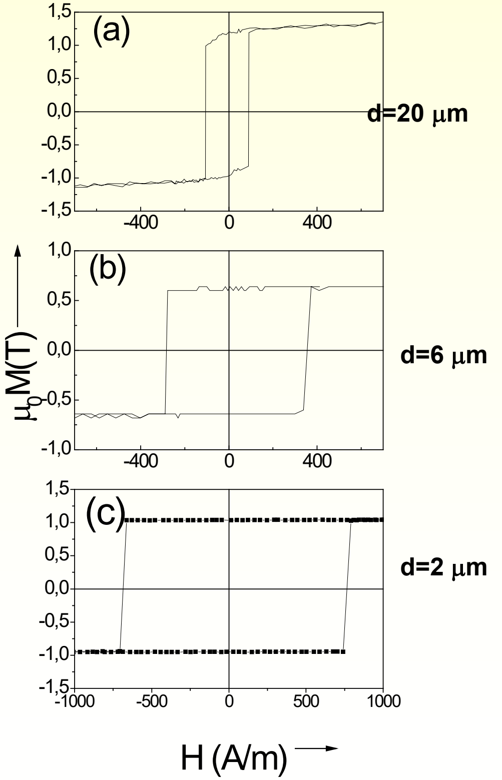
T ↓

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





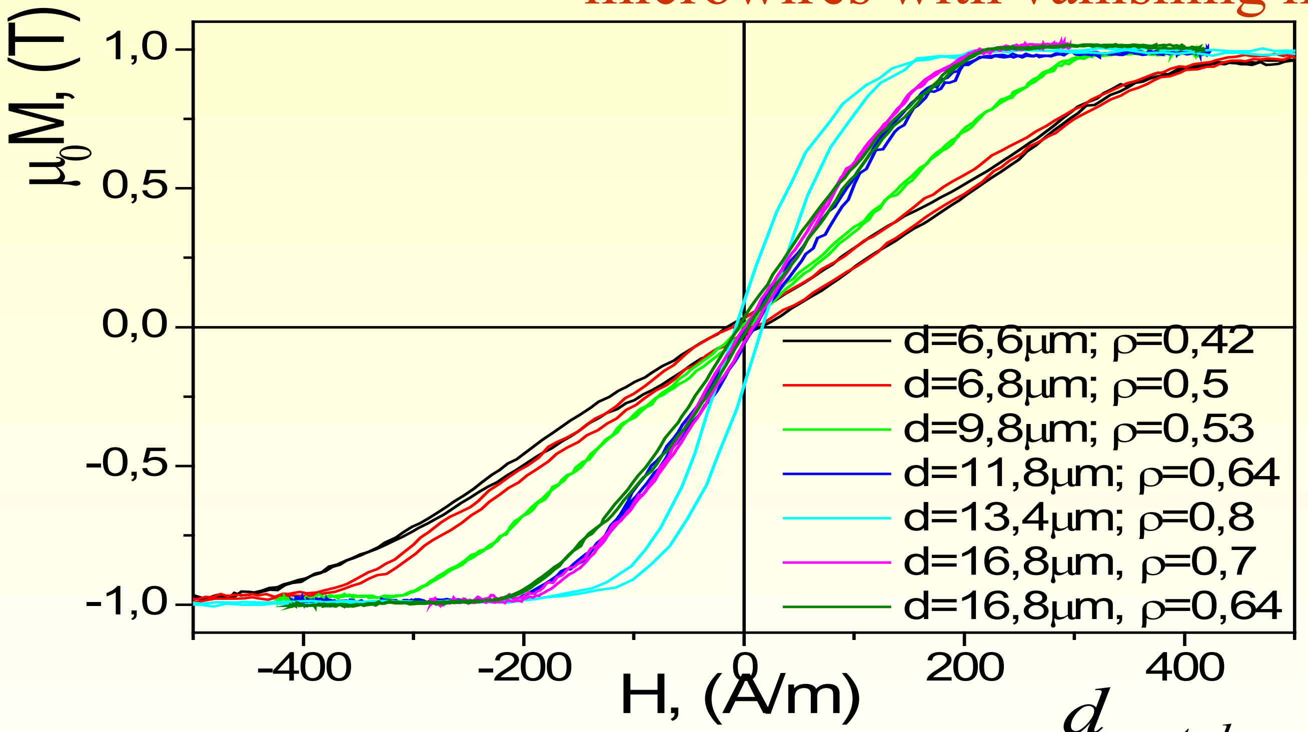


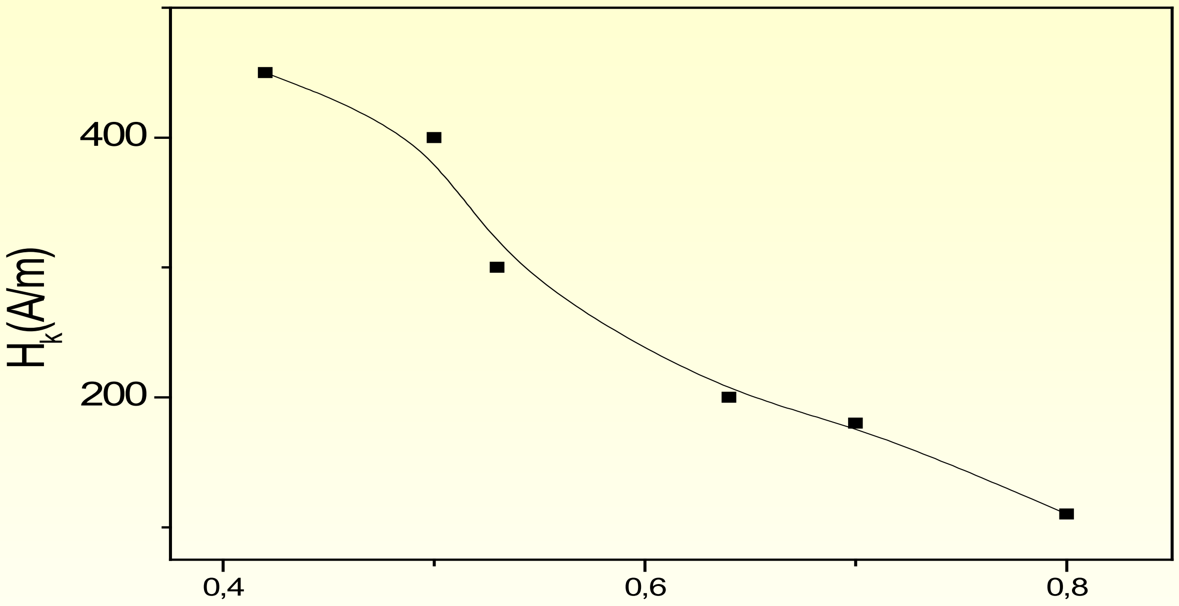


H. Chiriac, T.-A. Ovari, A. Zhukov, J. Magn. Magn. Mater. 254–255 (2003) 469–471

TAILORING OF GMI EFFECT AND MAGNETIC PROPERTIES

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

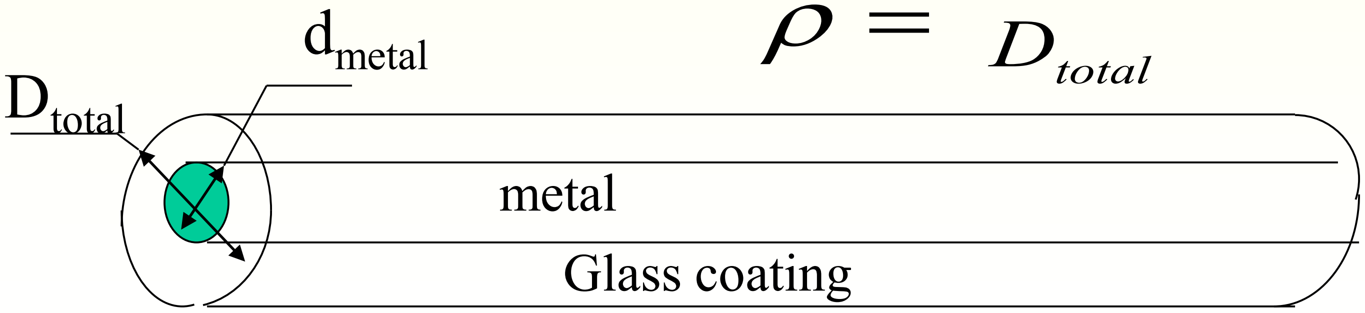


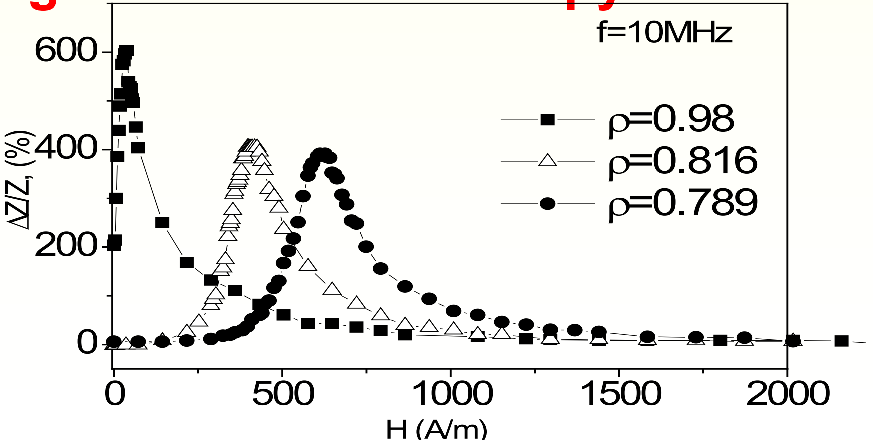


Large σ= high Hk, Reduced μ

Magnetoelastic anisotropy is relevant!

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



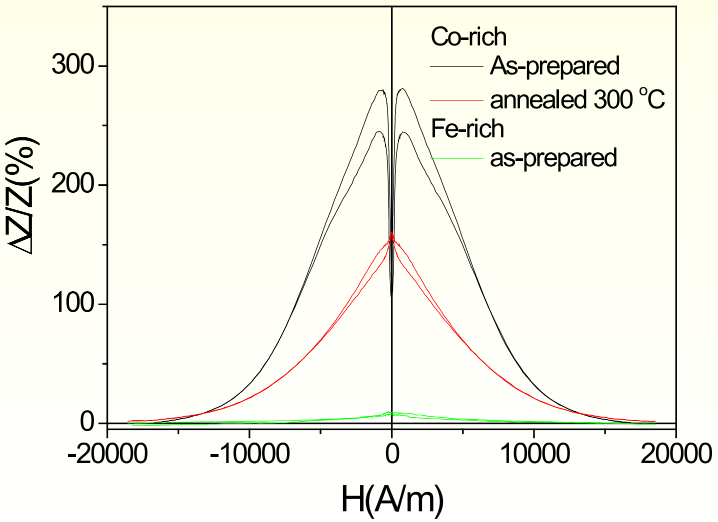


Correlation with magnetic anisotropy

Stress relaxation?

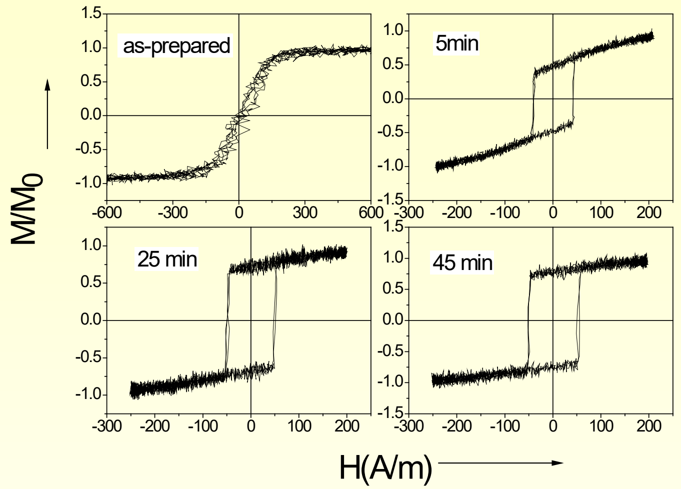
Annealing

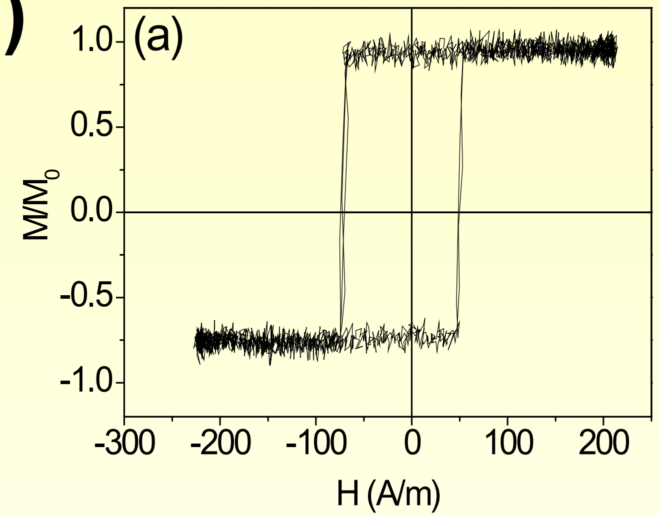
Annealing:
Hysteresis loops and DW dyamics
-Co-rich –induced magnetic bistability and substantial magnetic hardening



Such hardedning was observed in several Co-rich microwires

Co-based (λ_s<0)

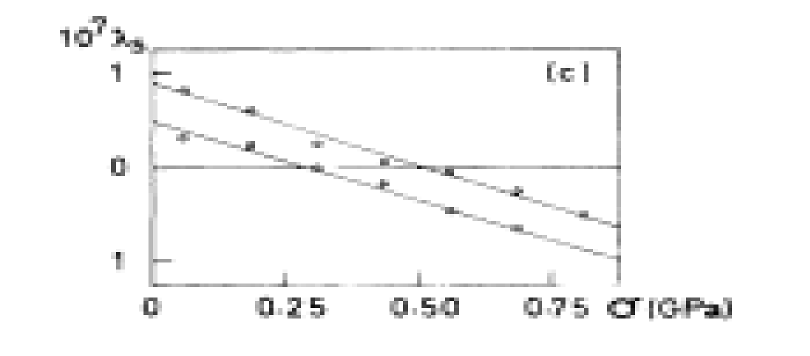


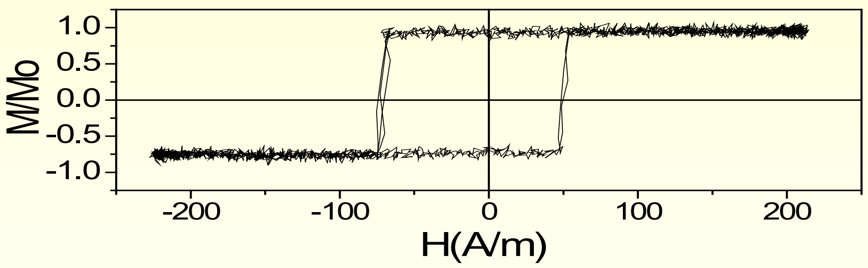


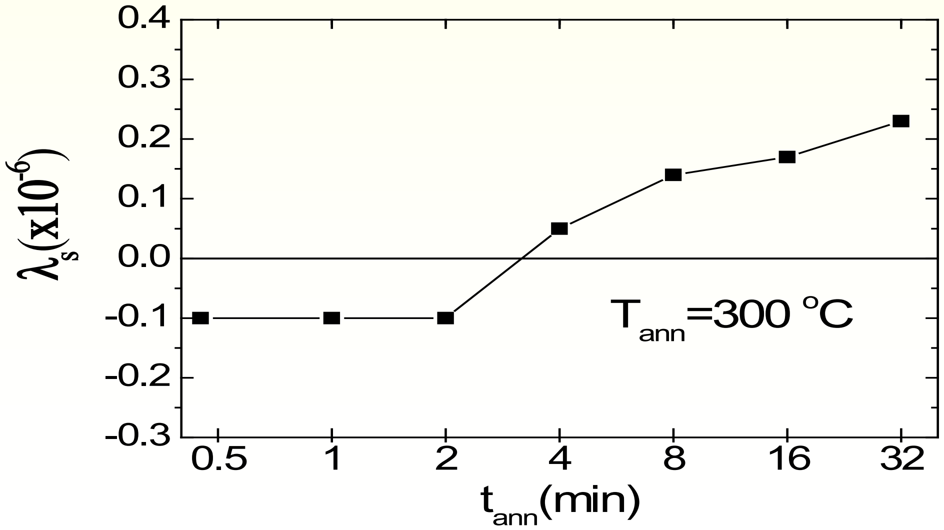
GMI:
Co-rich – decrease

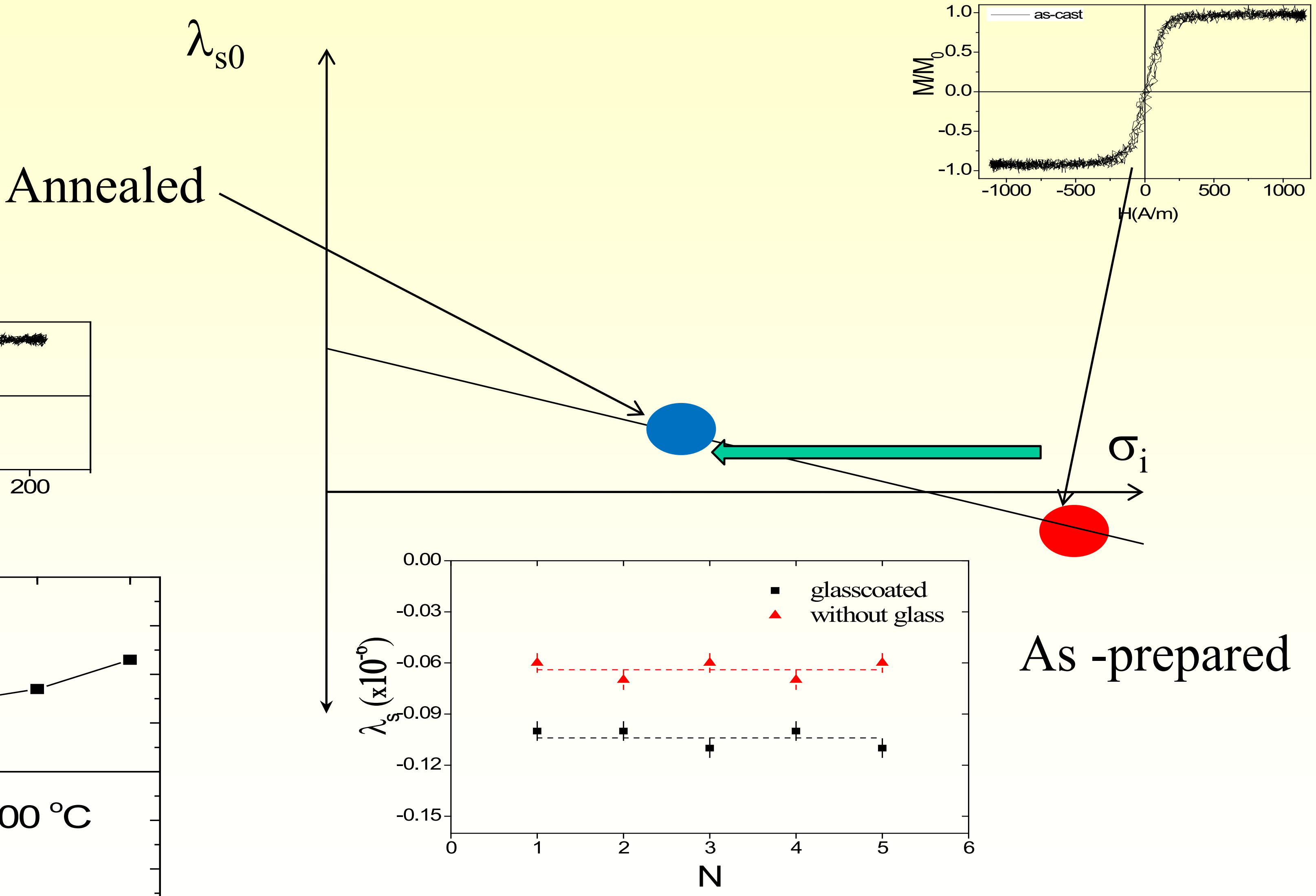
For GMI is not a solution!

Origin of annealling induced changes in Co-rich microwires





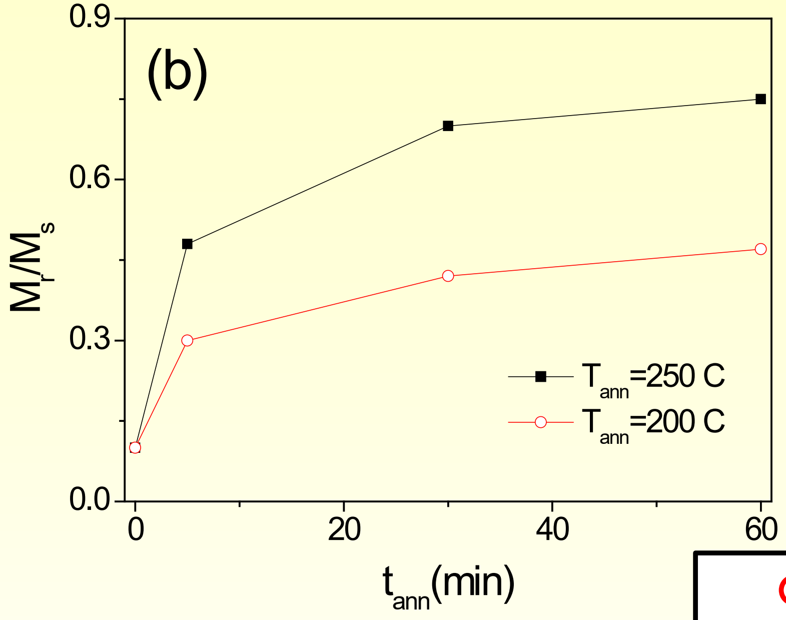




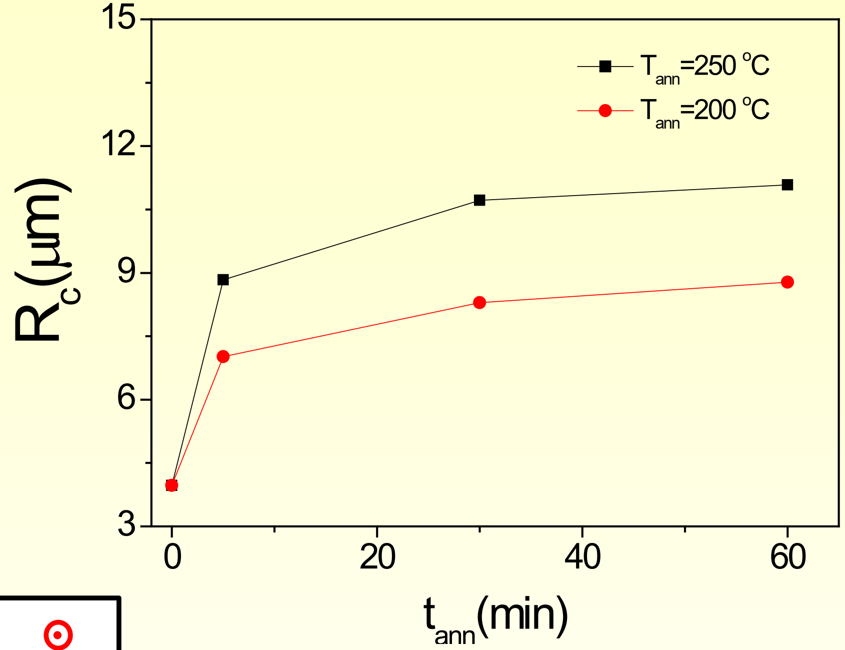
A. ZHUKOV, et.al J. ELECTRONIC MATERIALS (2015)
DOI: 10.1007/s11664-015-4011-2

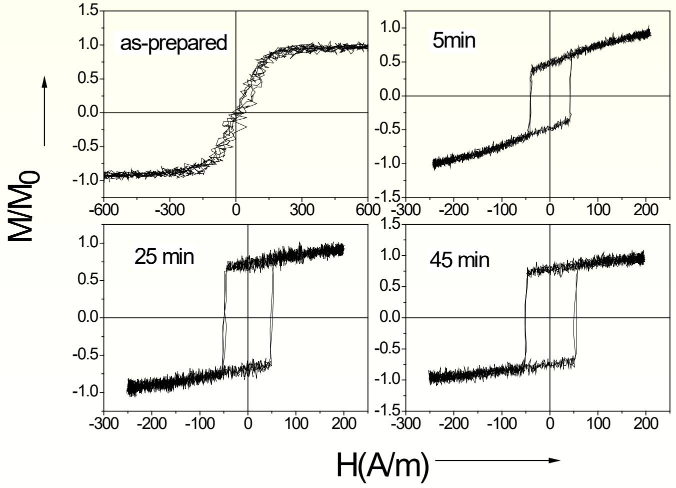
Origin of annealling induced changes in Co microwires

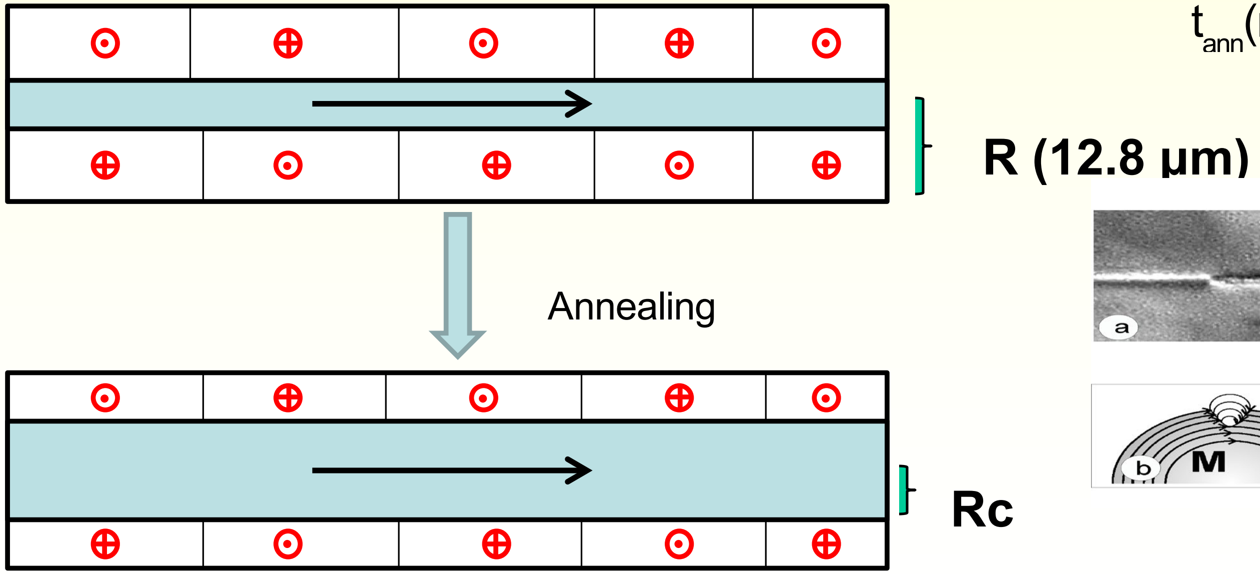
Stress relaxation?

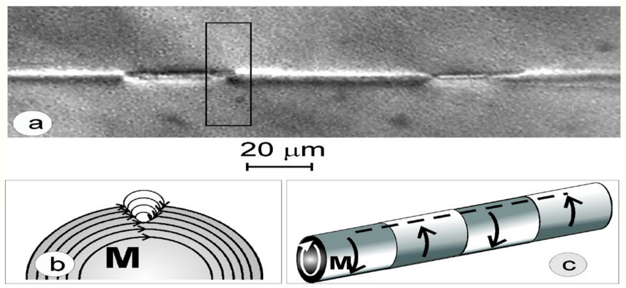


$$R_c = R(M_r/M_s)^{1/2},$$









A. Zhukov, M. Ipatov, M.Churyukanova, A. Talaat, J.M. Blanco and V. Zhukova, Trends in optimization of giant magnetoimpedance effect in amorphous and nanocrystalline materials (Review paper), J. Alloys Compound. 727 (2017) 887-901

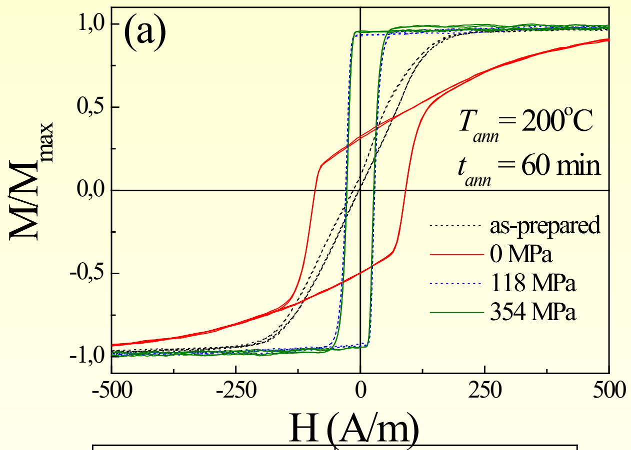
Induced anisotropy

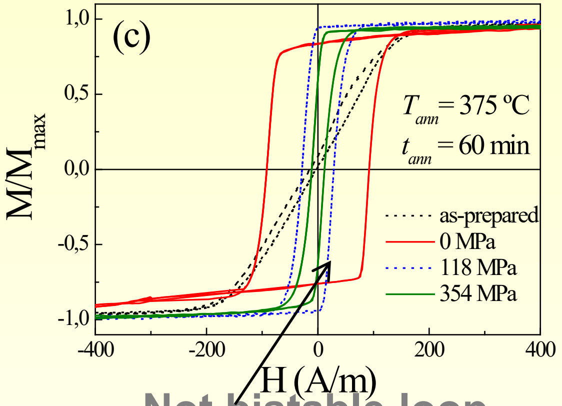
Stress-annealing

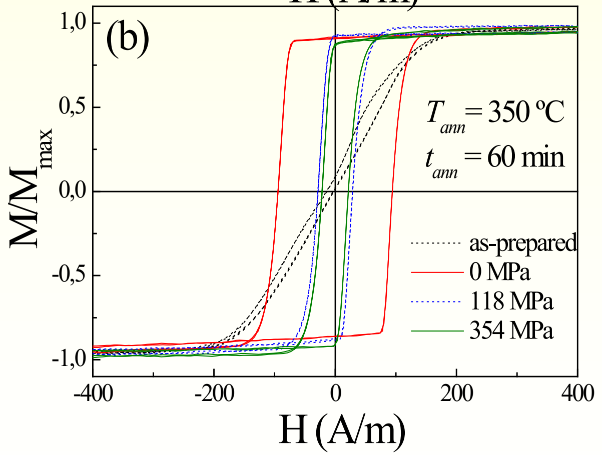
Co-rich microwires

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

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

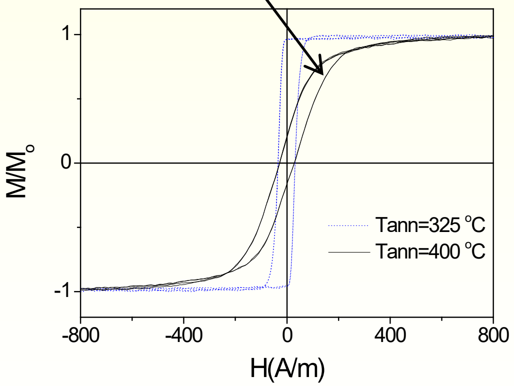


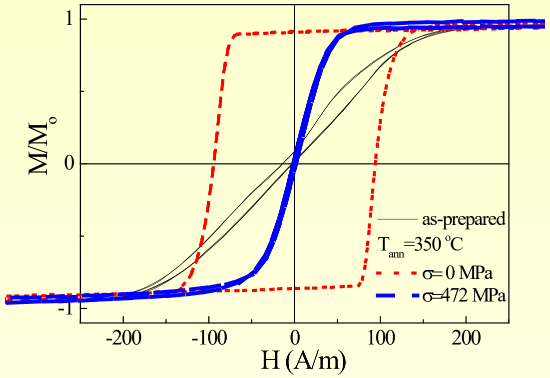


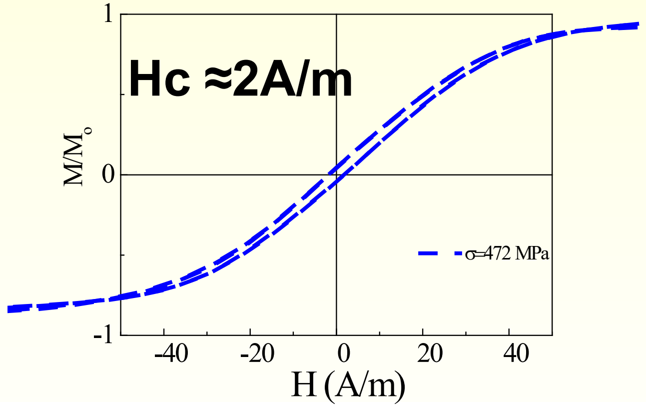


Not bistable loop

σ=118 MPa







comparison of hysteresis loops of as-prepared, annealed at *Tann*=350 °C and stress-annealed at *Tann*=350 °C and *σ* =472 MPa microwires.

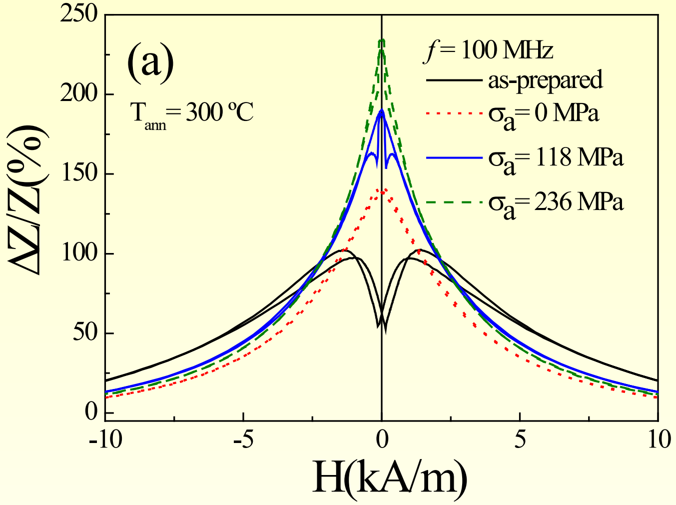
Better magnetic softness

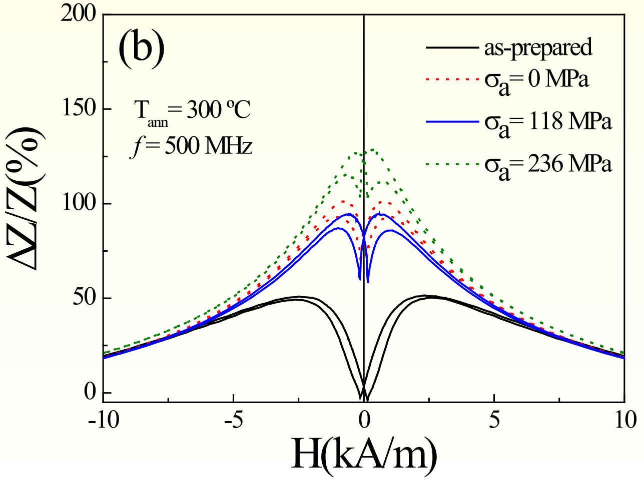
At high enough T_{ann} or σ a transverese anisotropy can be indiced (similalrly to Fe-rich microwires, but at Higher T_{ann} or σ)

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

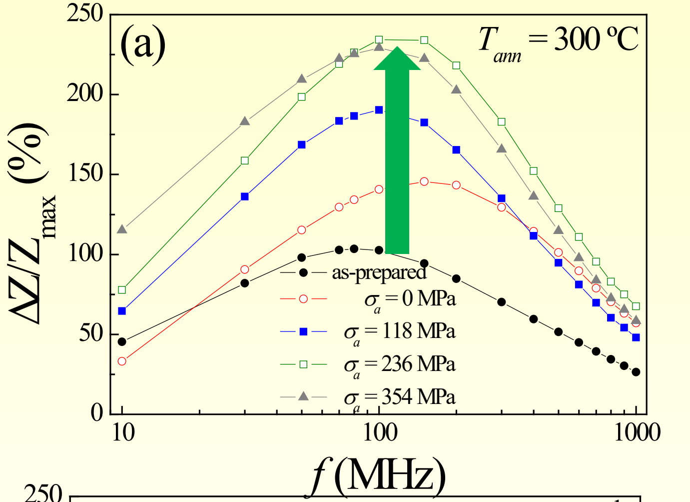
ΔZ/Z(H) dependences of as-prepared and stress-annealed at T_{ann} = 300 ºC samples at different σ_a measured at 100 MHz (a) and 500 MHz (b).

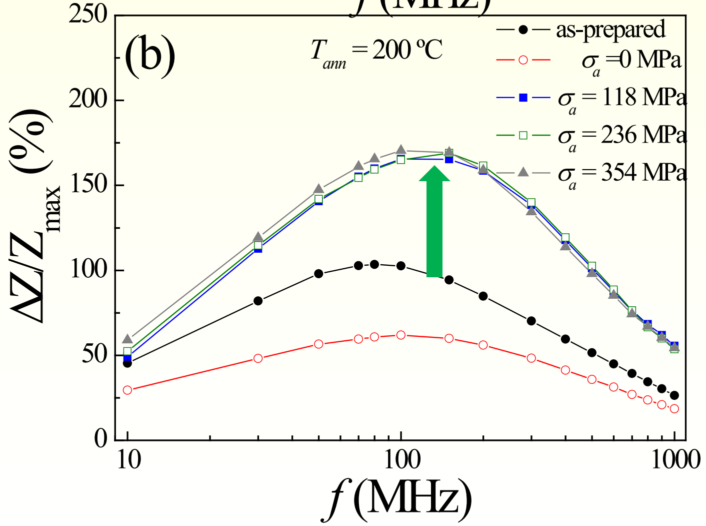




SA allows more remarkable GMI improvement

$\Delta Z/Z_{max}(f)$ evaluated for different σ_a – values for the samples annealed at T_{ann} = 300 ºC (a) and T_{ann} = 200 ºC (b)





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

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) $Co_{72}Fe_4B_{13}Si_{11}$ sample (40 μm).

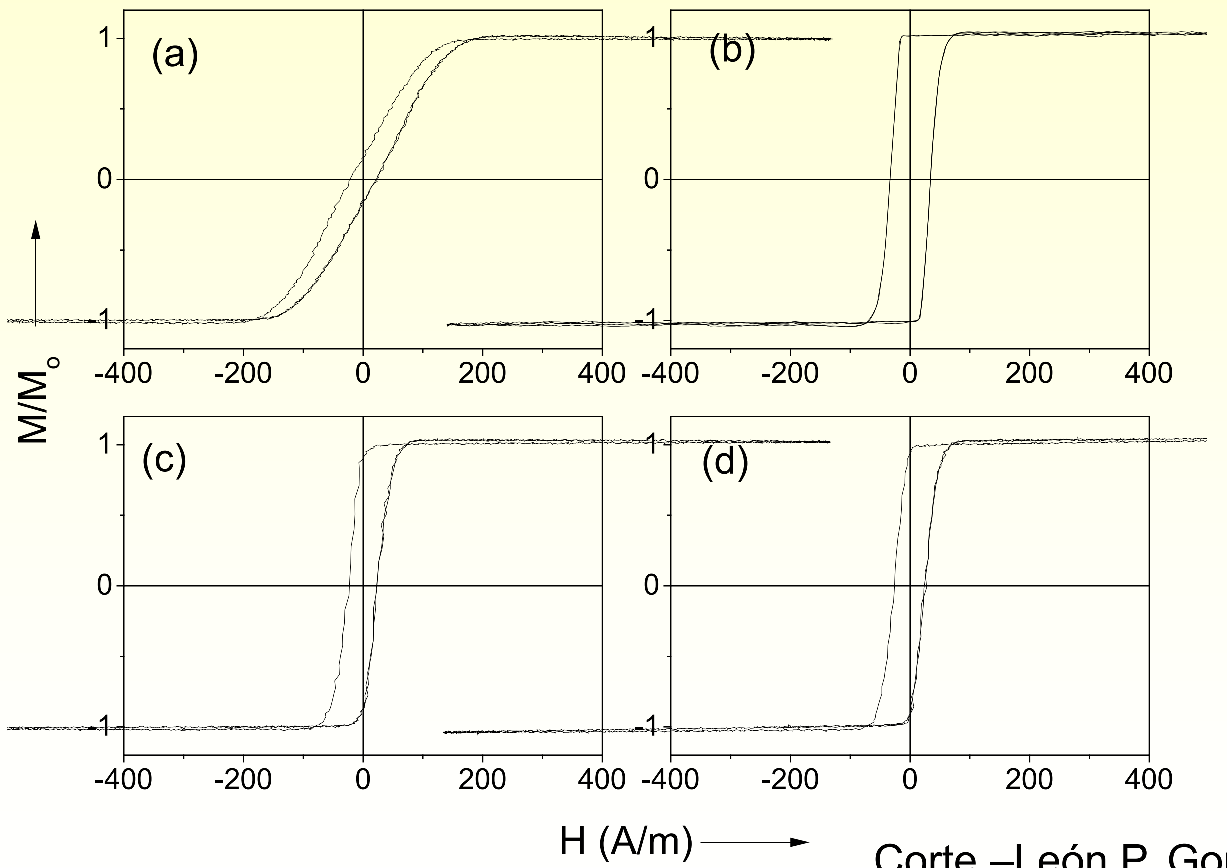
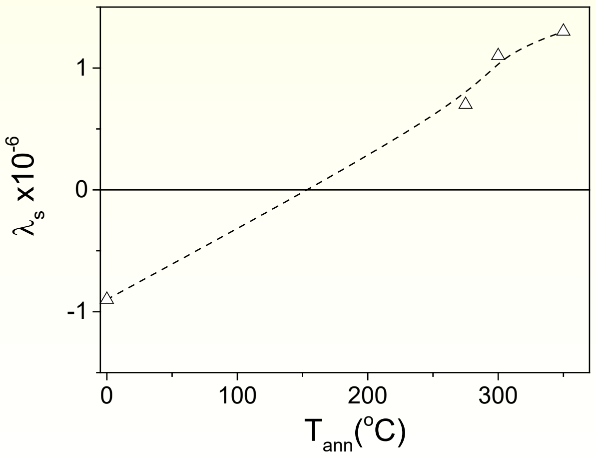


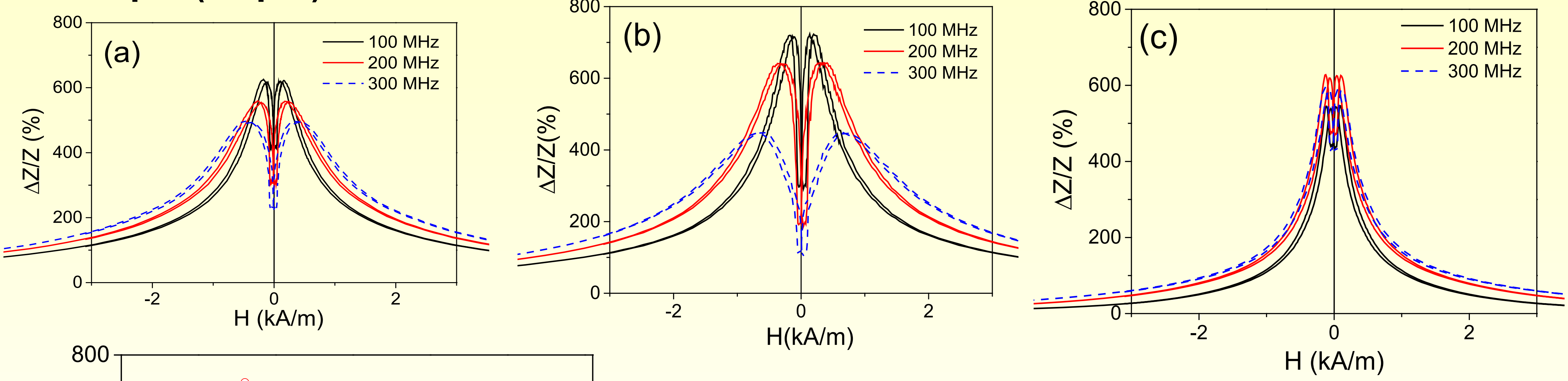
Table 1. The magnetostriction coefficient of as-prepared and annealed $Co_{72}Fe_4B_{13}Si_{11}$ microwires.	
Sample	l_s (x10^{-7})
As-prepared	-9
Annealed at 275 °C	+7
Annealed at 300 °C	+11
Annealed at 350 °C	+13

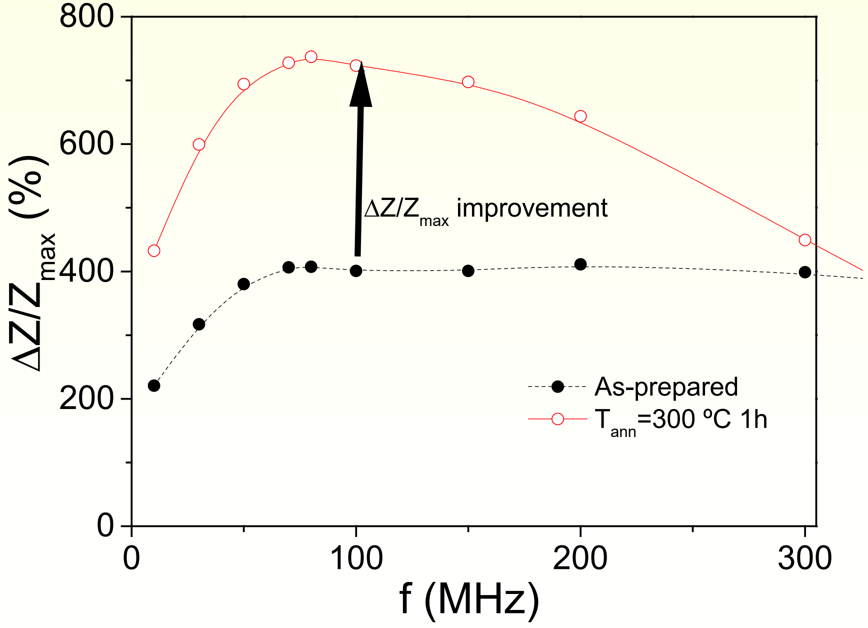


Corte –León P, Gonzalez A, Zhukova V, Ipatov M, Blanco J M, Zhukov A, Optimization of giant magnetoimpedance effect in Co-rich glass-coated microwires by annealing, J. Alloys Compound, Vol. 999 (2024) p. 175023

Looking for the highest GMI effect

GMI of annealed at Tann= 350 ºC (a); Tann= 300 ºC (b) Tann= 275 ºC (c) $Co_{72}Fe_4B_{13}Si_{11}$ sample (40 μm).

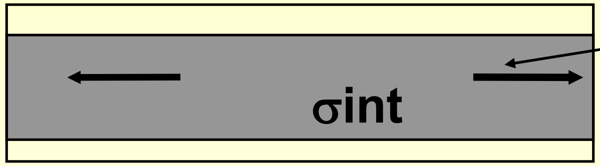




Corte –León P, Gonzalez A, Zhukova V, Ipatov M, Blanco J M, Zhukov A, 2024, Optimization of giant magnetoimpedance effect in Co-rich glass-coated microwires by annealing, J. Alloys Compound, Volume 999, p. 175023

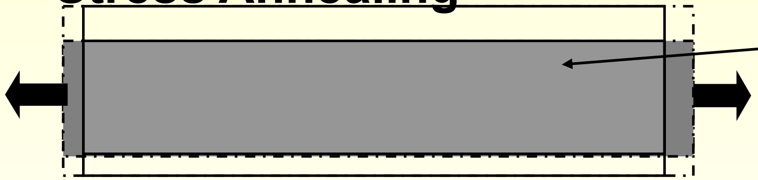
Origin of stress-annealing induced anisotropy

As-prepared microwire



Internal stresses with mainly axial component

Stress Annealing

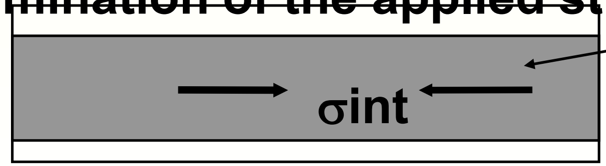


Induction of magnetic anisotropy during stress annealing

Slow Cooling under stress

Stress relaxation in the stressed state at room temperature

Elimination of the applied stress

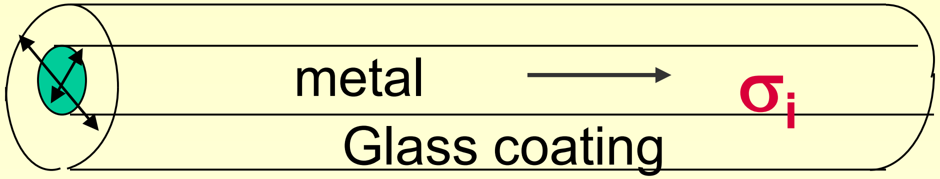


Induction of the compressive stresses at room-temperature (so-called "Back stresses")

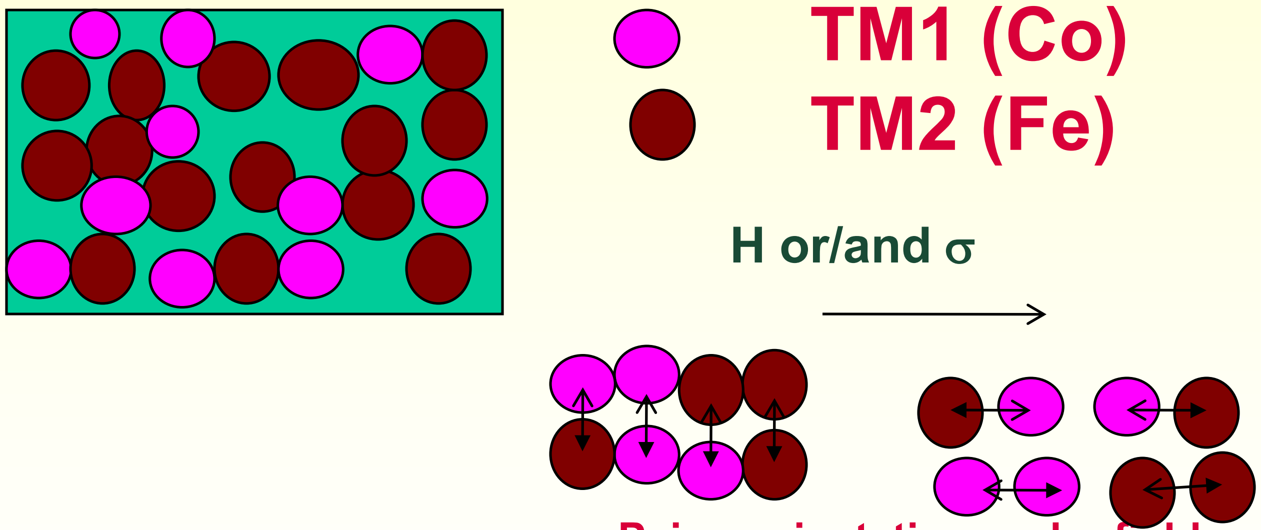
A. Zhukov, Advanced Funcional Materials Volume 16, Issue 5, 2006, pp.675-680

Origin of induced anisotropy

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



Origin: Pair ordering usually considered

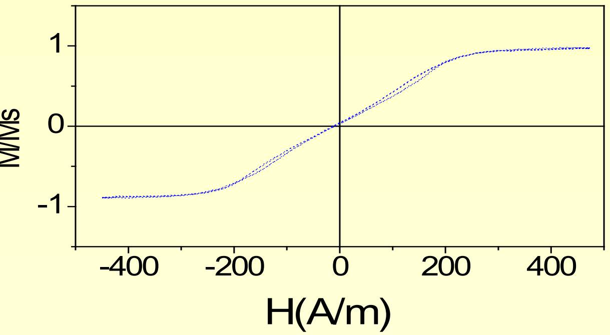


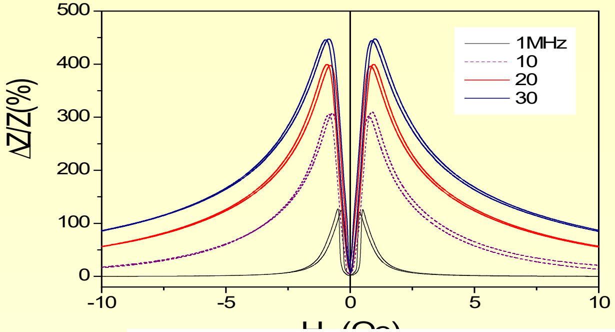
Pair reorientation under field and/or stress annealing (after Neel)

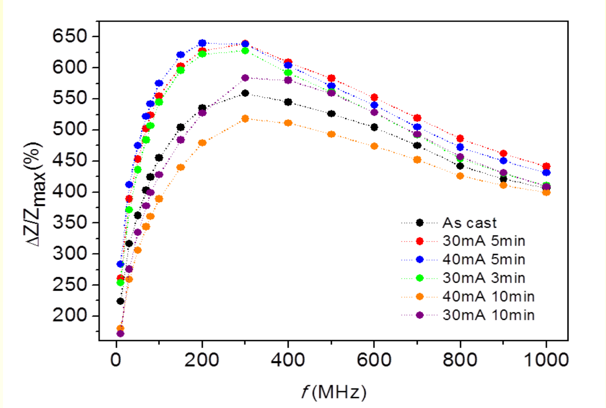
Possible origin 3:
The topological short range ordering (also known as structural anisotropy) can play an important role. This involves the angular distribution of the atomic bonds and small anisotropic structural rearrangements at temperature near the glass transition temperature

[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.

Present talk : magnetic softness and GMI effect of amorphous microwires

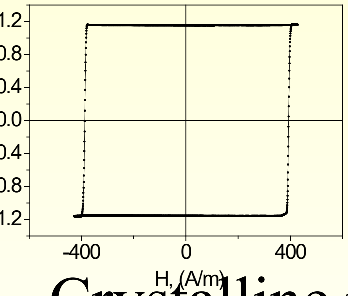


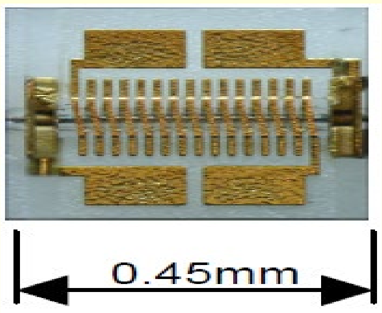




1. A. Zhukov, J.M. Blanco, M. Ipatov, A. Talaat, V. Zhukova, “Engineering of domain wall dynamics in amorphous microwires by annealing”, J. Alloys Compounds, Volume 707, 15 (2017), p. 35–40
2. V. Zhukova, J. M. Blanco, A. Chizhik, M. Ipatov, A. Zhukov, “AC-current-induced magnetization switching in amorphous 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,

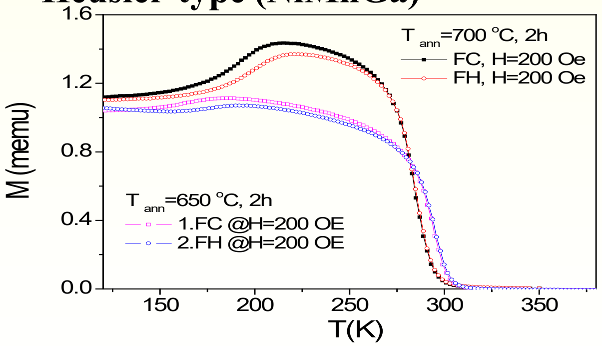
Other features of amorphous microwires:





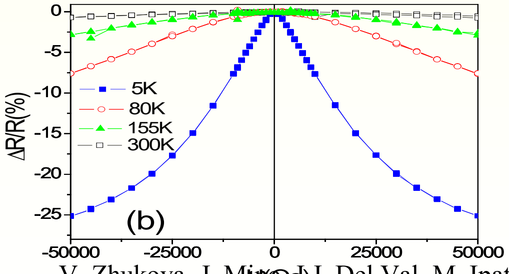
Crystalline microwires:

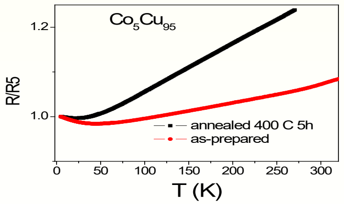
Heusler-type (NiMnGa)



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

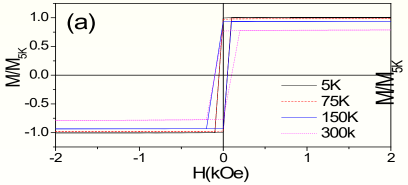
Granular microwires Co-Cu

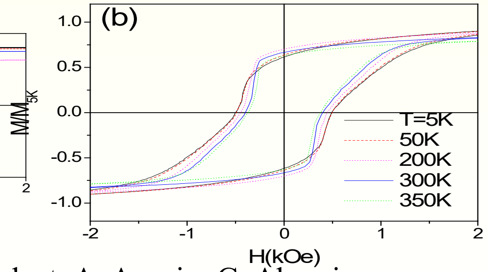




V. Zhukova, J. Mino, J.J. Del Val, M. Ipatov, A. Martinez-Amesti, R. Varga, M. Churyukanova, A. Zhukov, “Magnetoresistance and Kondo-like behaviour in Co5Cu95 microwires”, J. Alloys Compound. 674 (2016) 266-271

Magnetric hardening: FePt

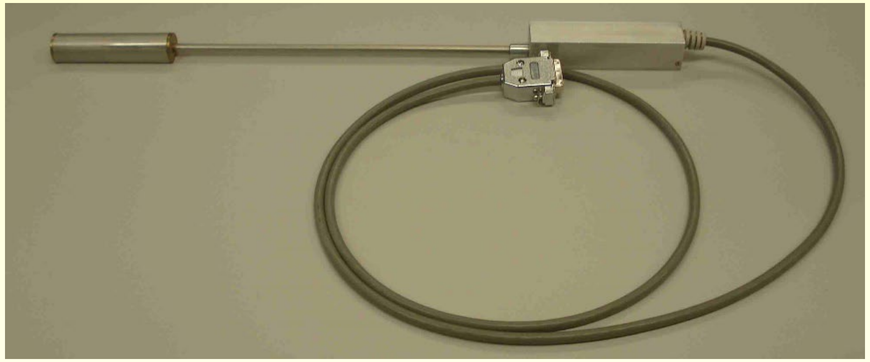




A. Zhukov, M. Ipatov, A. Talaat, A. Aronin, G. Abrosimova, J.J. del Val and V. Zhukova, Magnetic hardening of Fe-Pt and Fe-Pt- M (M=B, Si) microwires, J. Alloys Compound., Volume 735, (2018) pp.1071–1078

GMI magnetometer versus SQUID and fluxgate

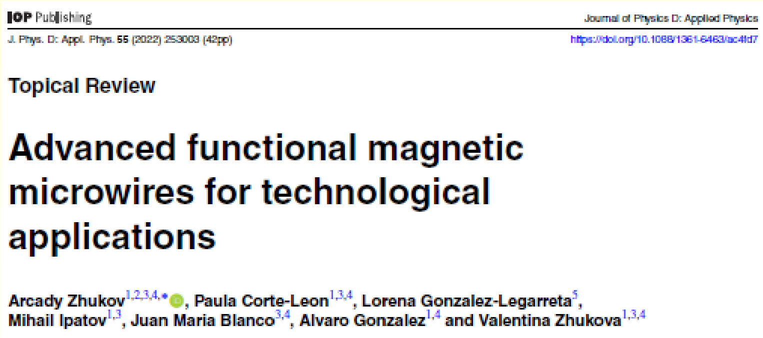
Advantages:
-Lower cost
-Smaller size
-pT magnetic field sensitivity (comparable to SQUID)



SQUID (superconducting quantum interference device)

Conclusions

- Soft magnetic properties can be observed in Co-rich magnetic microwires
- By appropriate post-processing (stress-annealing or annealing) we can considerably improve GMI effect and magnetic softness in Co-rich microwires
- For interpretation of observed effect of stress annealing we considered internal stresses relaxation after annealing and interplay of compressive stresses and axial internal stresses after stress annealing.

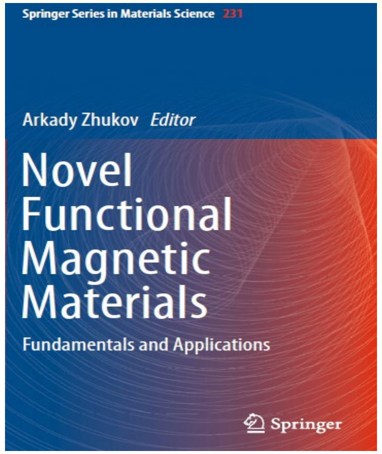

IOP Publishing Journal of Physics D: Applied Physics
J. Phys. D: Appl. Phys. 55 (2022) 253003 (42pp) https://doi.org/10.1088/1361-6463/ac4fd7

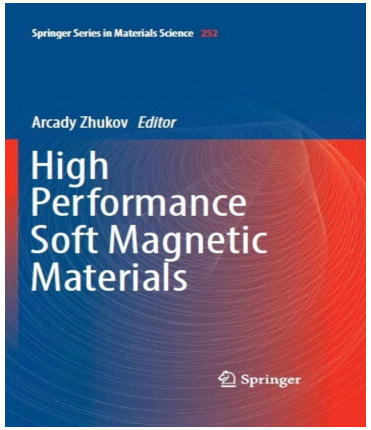
Topical Review

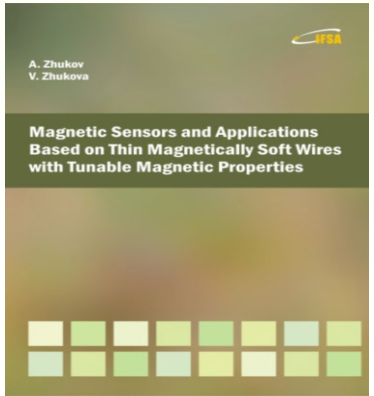
Advanced functional magnetic microwires for technological applications

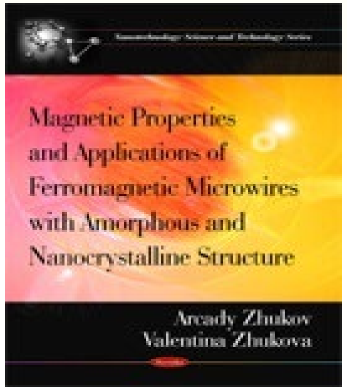
Arcady Zhukov[1,2,3,4,*], Paula Corte-Leon[1,3,4], Lorena Gonzalez-Legarreta[5], Mihail Ipatov[1,3], Juan Maria Blanco[3,4], Alvaro Gonzalez[1,4] and Valentina Zhukova[1,3,4]

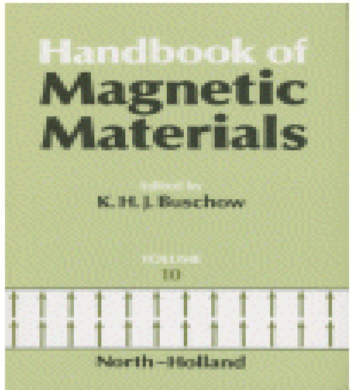
Thank you for the attention!











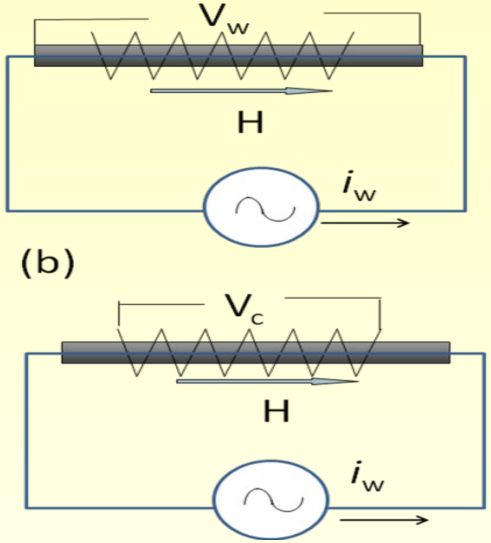
"Advances in Giant Magnetoimpedance Materials" by A. Zhukov, M. Ipatov and V. Zhukov (issue October 2015)

Measurements of GMI

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

$\Delta Z/Z$, is defined as:

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



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

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

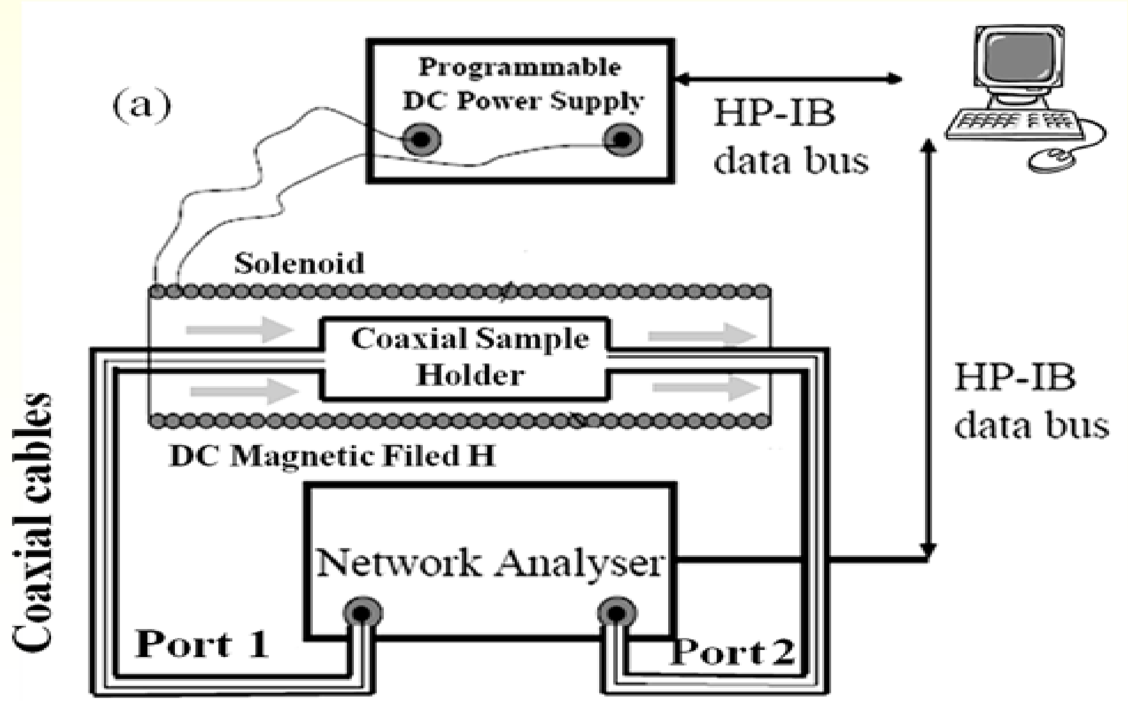
$$Z_{zz} \propto Z = \frac{1+S_{11}}{1-S_{11}} Z_0$$

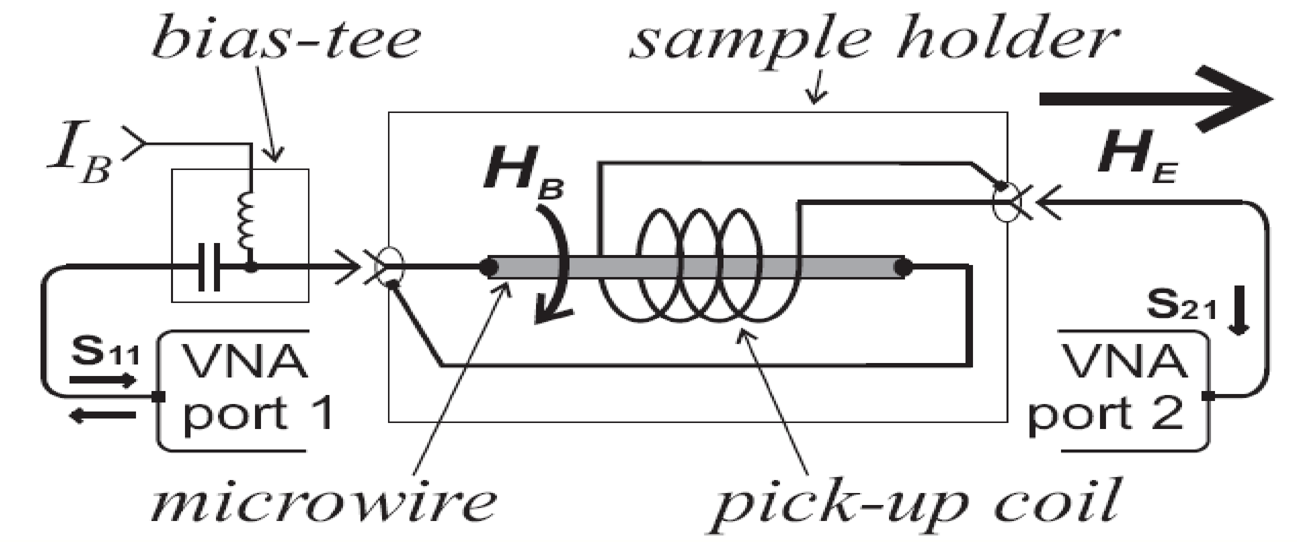
$$i_Z \rightarrow h_\varphi \rightarrow [\hat{\mu}]$$

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

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

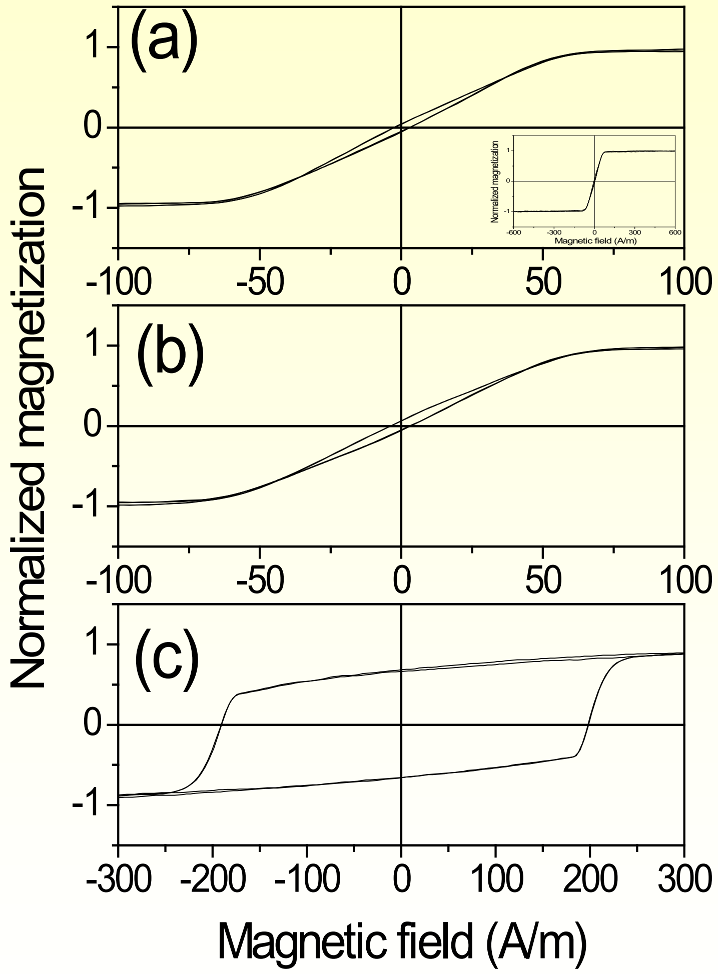
$$Z_{\varphi z} \propto V_c = S_{21}$$





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

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.

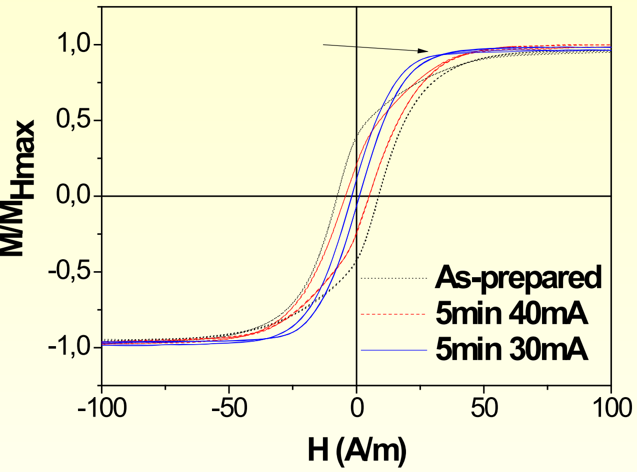
Looks that Joule heating prevents magnetic hardening reported for Co-based microwires after conventional annealing

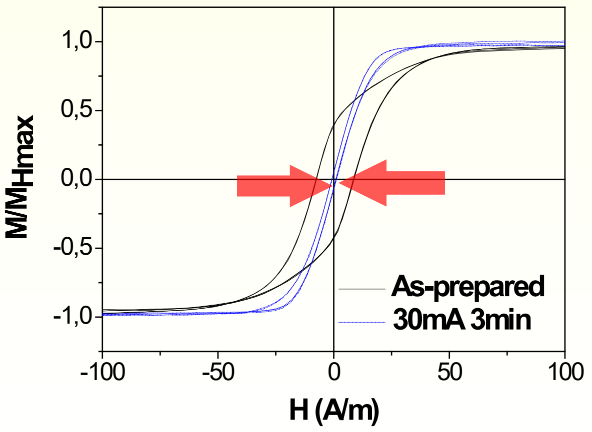
V. Zhukova, J.M. Blanco, M. Ipatov, M. Churyukanova, J. Oliver, S. Taskaev, A. Zhukov, Optimization of high frequency magnetoimpedance effect of Fe-rich microwires by stress-annealing, Intermetallics, 94 (2018) 92-98

Tailoring by Joule heating

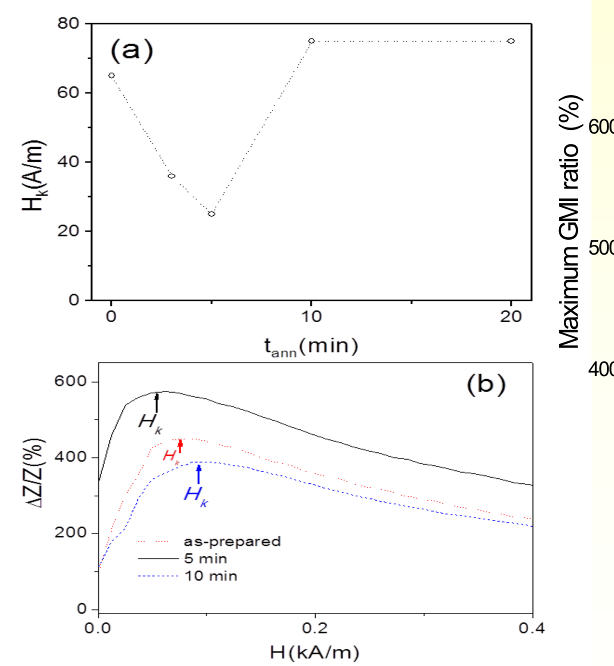
- Internal stresses relaxation
- Induced magnetic anisotropy

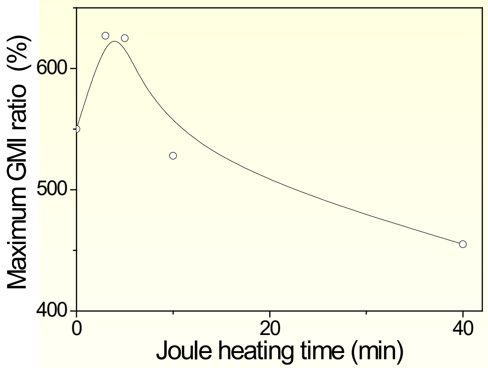
H_k=25A/m



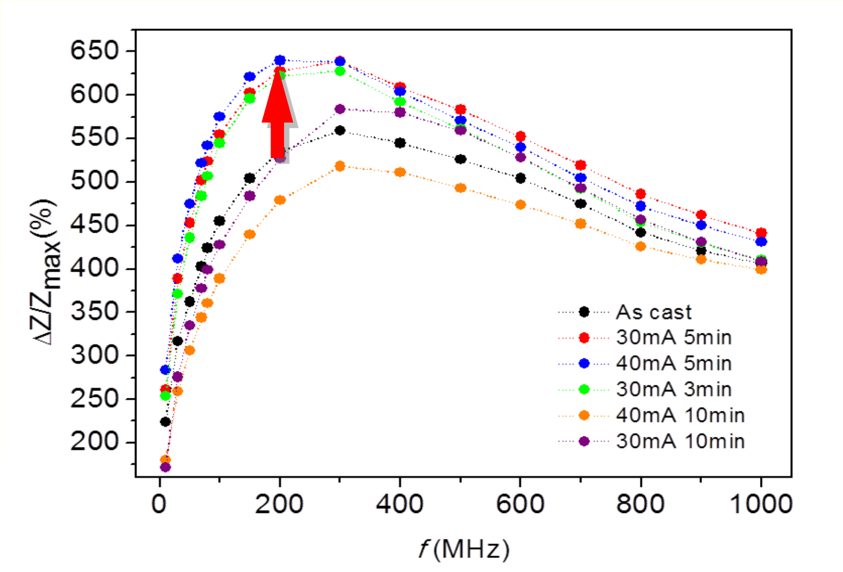


Hc=2 A/m

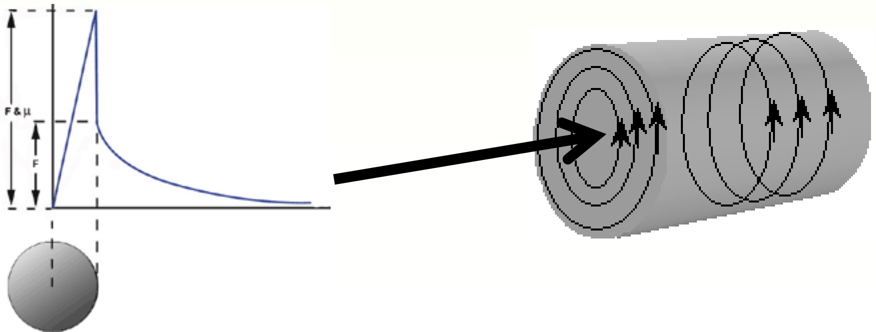




GMI ratio up to 650%



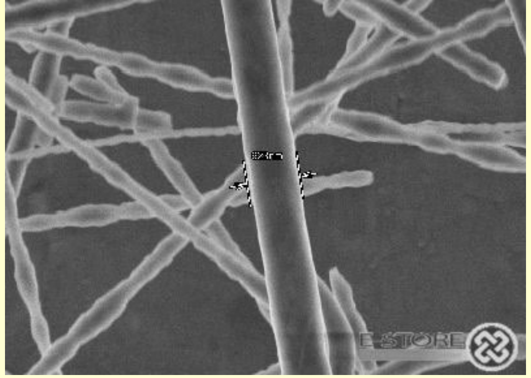
Circular magnetic field by current:



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

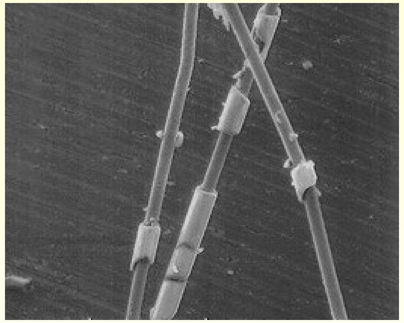
Magnetic wires:

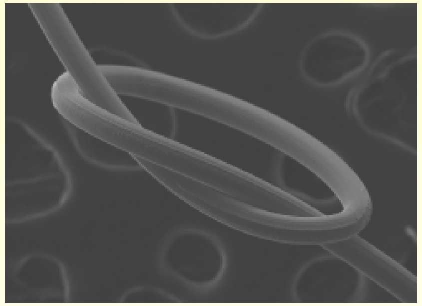
-Iron whiskers
-Wiegan magnetic wires
(CoVFe,1970-th)

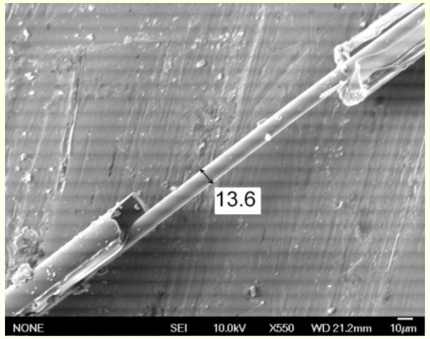


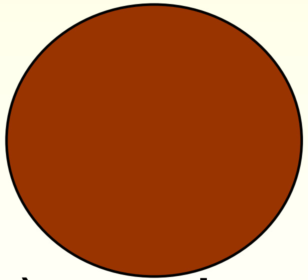
Amorphous: milli
(since 80-th) micro
nano

wires

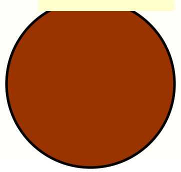




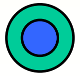




In-rotating water wires
(can be drawn to 20-30 μm) – rough surface

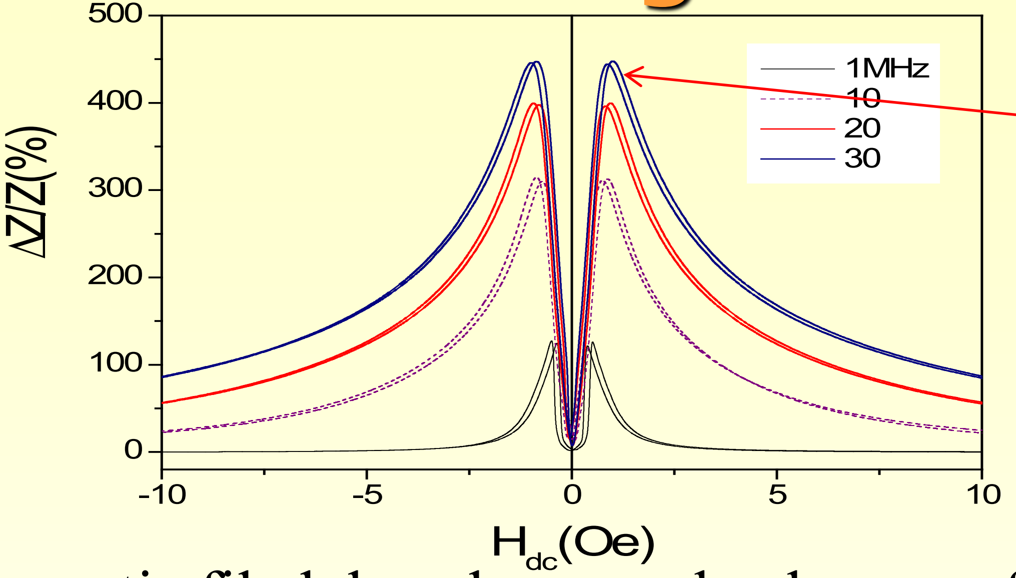


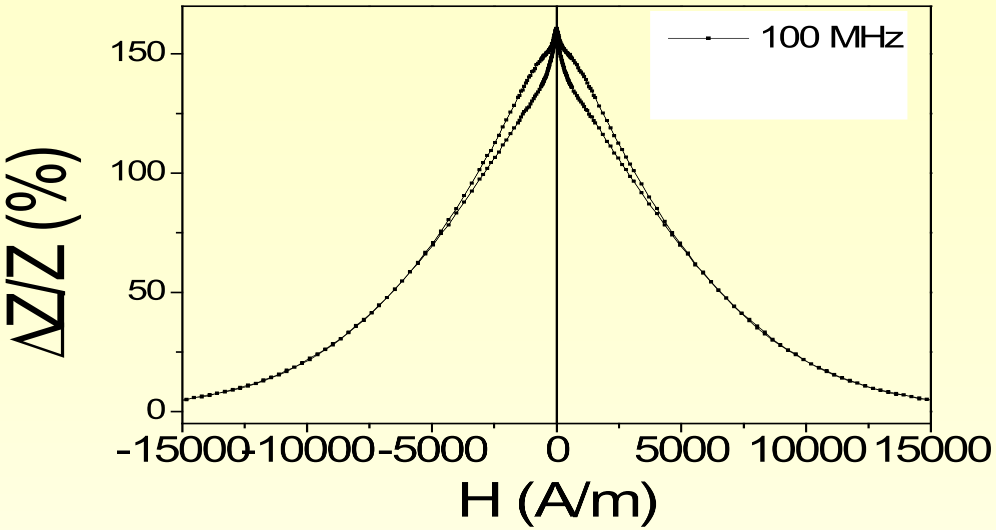
Melt extracted (40-50 μm)- not perfectly cylindrical cross section



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

Giant Magneto-impedance effect





Magnetic filed depedence and value are affected by magnetic anisotropy

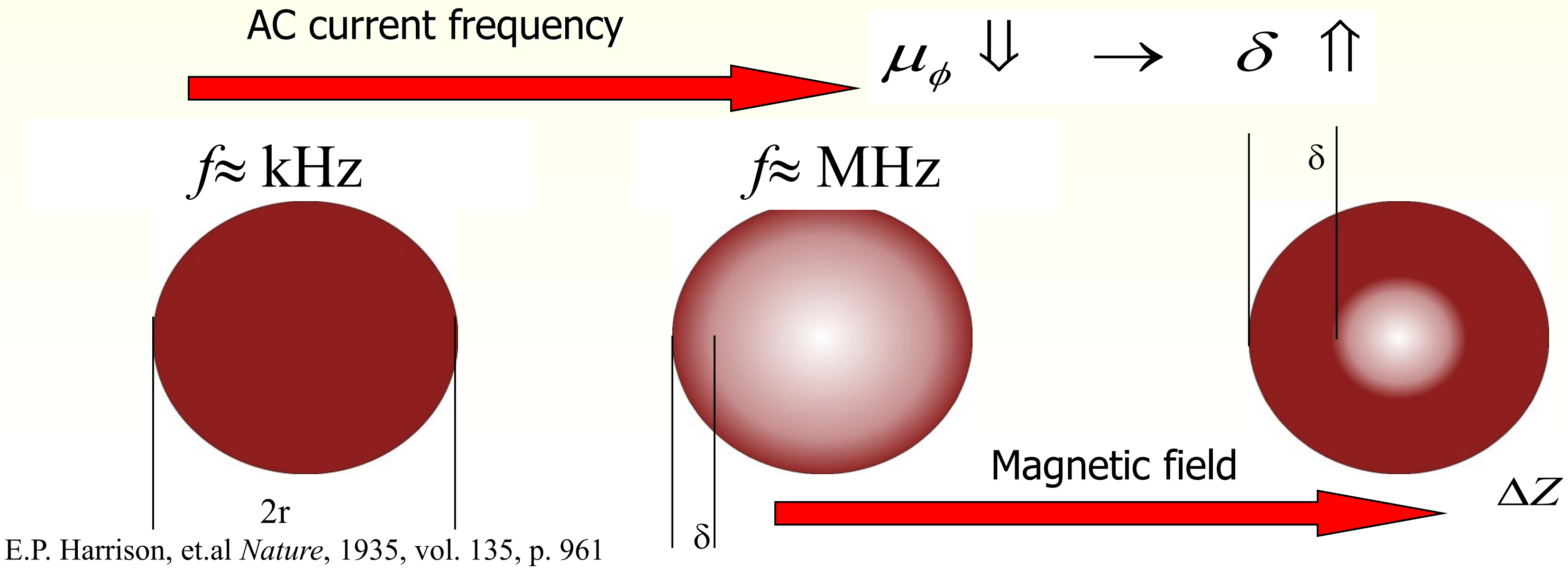
- Skin Effect of the Magnetic Conductor

$$\delta = (\pi \sigma \mu\phi f)^{-1/2}$$

1. $\mu\phi(H,f)$ *(Soft magnets)*

2. $\delta < r$ (at high enough f) **(Low dimensions)**

Z(H)



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

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

Essentialy to have magnetically soft conductor – cyllindrical geometry best