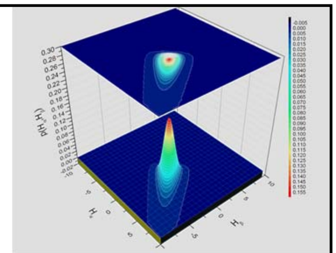
Sevilla, December 2015



FORC diagram method as general characterization tool of hysteretic processes

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1

Email: ALSTANCU@UAIC.RO

Spain-Italy-Romania

2

Iași – *personalities*

- Ștefan Procopiu
- 1912 – first evaluation of the theoretical magneton

N° 71.
COLLECTION ARMAND COLIN
(Section de Physique)

Le Magnétisme

par

Pierre WEISS
Correspondant de l'Institut
Professeur à la Faculté
des Sciences de Strasbourg

Gabriel FOEX
Maître de Conférences
à la Faculté des Sciences
de Strasbourg

69 figures

LIBRAIRIE ARMAND COLIN
103, Boulevard Saint-Michel, PARIS

1926
Tous droits réservés

Résumé.

1) En supposant qu'un magnéton, est un électron, circulant autour de la molécule, on a obtenu une relation pour h, facteur d'action de Planck, dans laquelle n'entrent que la valeur du magnéton et le rapport $\frac{e}{m}$. Ceci en partant de l'énergie de mouvement, $m v^2$. La relation est

$$h = 4 \pi M \frac{m}{e} \text{ avec la valeur } 1,73.\ 10^{-27}.$$

1) Koenigsberger. Physik. Zeitschrift. 1911. p. 3.

$$M = \frac{eh}{4\pi m}$$

1. Voir pour plus de détails : *J. de Phys.*, t. V, p. 192, 1924.
2. Pierre Weiss, *J. de Phys.*, 5e s., t. I, 1911, pp. 900 et 965.
3. Einstein, Procopiu, Chalmers, Wereide. Voir la déduction, chap. XV, p. 204, éq. (52).

Iasi 300.000 inhabitants

Acknowledgement (work on FORC technique)

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Prof. Liliana Mitoseriu
Prof. Cristian Enachescu
Dr. Dorin Cimpoesu
Dr. Ioan Dumitru
Dr. Petronel Postolache
Dr. Radu Tanasa
Dr. Aurelian Rotaru
Dr. Irina Ursachi
Dr. Ilie Bodale
Dr. Florica Matau
Dr. Costin Dobrota
Dr. Alexandru Atitoaie
Dr. Mihai Nica

Prof. Leonard Spinu (USA)
Prof. Petru Adrei (USA)
Prof. Irinel Chiorescu (USA)
Prof. Dan Ricinschi (Japan)
Prof. Francois Varret (France)
Prof. Jorge Linares (France)
Prof. Wolfgang Wernsdorfer (France)
Prof. Marie-Laure Boillot (France)
Prof. Ioannis Panagiotopoulos (Greece)
Prof. Horia Chiriac (Romania)
Dr. Liviu Clime (Canada)

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Outline

- ☐ Motivation. History
- ☐ Classical Preisach Model and FORC identification technique
- ☐ Qualitative *versus* quantitative FORC diagrams
- ☐ Quantitative analysis of the FORC distribution in magnetic nanostructures.
- ☐ Hard/soft magnetic materials
- ☐ Quantum FORC – single molecule magnets.
- ☐ Hysteresis in spin transition materials
- ☐ Discussion. Conclusion

6

Rectangular hysteron – Preisach plane

P. Weiss, J. de Freudenreich, Etude de l'aimantation initiale en fonction de la temperature. *Arch. Sc. Phys. et Nat.* **42**, 449-470 (1916).

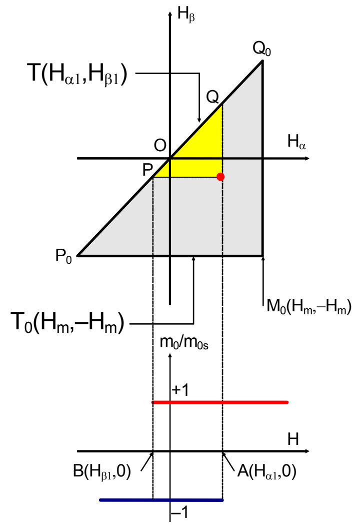
F. Preisach, Uber die magnetische Nachwirkung. *Zeitschrift für Physik* **94**, 277-302 (1935).

M. A. Krasnosel'skiĭ, A. V. Pokrovskiĭ, *Sistemy s gisterezisom*. ("Nauka," Glav. red. fiziko-matematicheskoĭ litry, Moskva, 1983), pp. 271 p.

M. A. Krasnosel'skiĭ, A. V. Pokrovskiĭ, *Systems with hysteresis*. Universitext (Springer-Verlag, Berlin ; New York, 1989), pp. xviii, 410 p.

I. D. Mayergoyz, Hysteresis models from the mathematical and control theory points of view. *J Appl Phys* **57**, 3803 (1985).

I. D. Mayergoyz, *Mathematical models of hysteresis*. (Springer-Verlag, New York, 1991), pp. xx, 207 p.



Classical Preisach Model identification using FORCs

$$F(\alpha,\beta) = f_\alpha - f_{\alpha\beta}\,. \tag{3}$$

It can be proved that by knowing the function $F(\alpha,\beta)$, we can determine the weight function as follows:

$$\mu(\alpha,\beta) = -\frac{1}{2}\frac{\partial^2 F(\alpha,\beta)}{\partial\alpha\partial\beta}\,. \tag{4}$$

Thus, the experimental data provided by the set of first-order reversal curves allows one to determine the weight function $\mu(\alpha,\beta)$. Then, using the model [Eq. (1)], higher-order reversal curves can be determined. It means that the mathematical model [Eq. (1)] has prediction power.

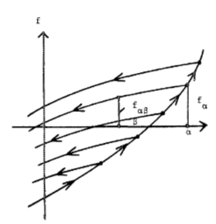


FIG. 7. First-order reversal curves.

I. D. Mayergoyz, Hysteresis models from the mathematical and control theory points of view. *J Appl Phys* **57**, 3803 (1985).

FORC diagram technique

J. Appl. Phys., Vol. 85, No. 9, 1 May 1999

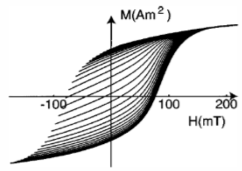


FIG. 1. A set of first order reversal curves (FORCs) for a piece of a typical floppy magnetic recording disk.

A FORC distribution, by contrast, is not based on any assumptions. It is not part of a theoretical model. It is simply a well-defined transform [i.e., Eq. (1)] of the set of first order reversal curves that is useful in making the structure of these data apparent to the human eye.

C. R. Pike, A. P. Roberts, K. L. Verosub, Characterizing interactions in fine magnetic particle systems using first order reversal curves. *J Appl Phys* **85**, 6660-6667 (1999).

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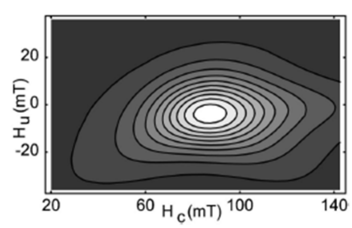
“Magnetic fingerprinting”



H. G. Katzgraber, G. Friedman, G. T. Zimányi, Fingerprinting hysteresis. Physica B: Condensed Matter 343, 10-14 (2004).

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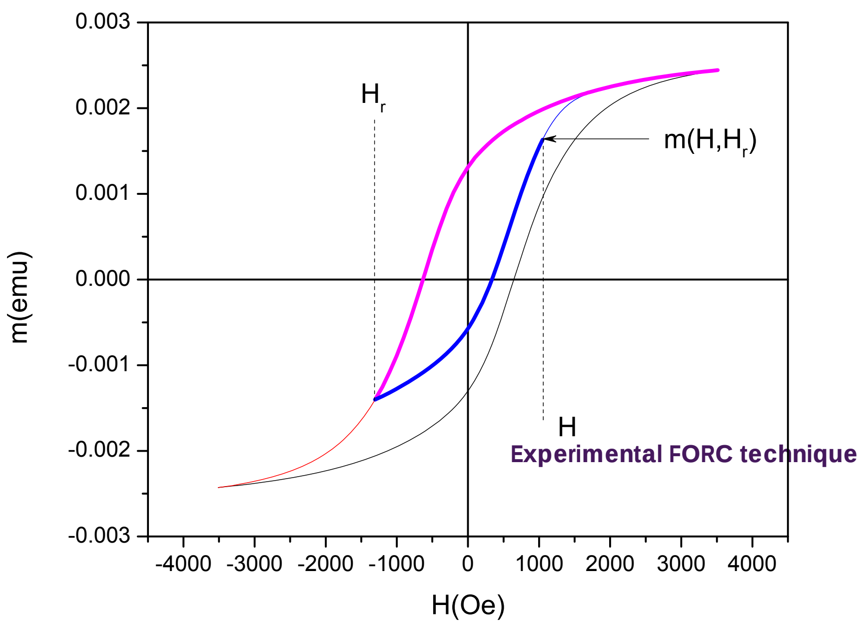
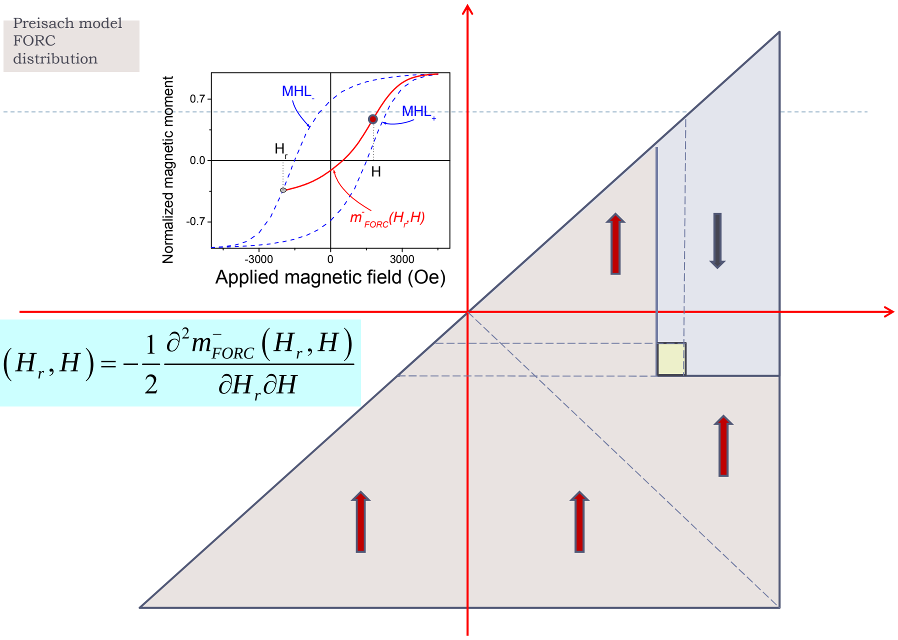
- FORC-type experiment



Preisach model FORC distribution



$$\rho(H_r,H) = -\frac{1}{2}\frac{\partial^2 m_{FORC}^-(H_r,H)}{\partial H_r \partial H}$$

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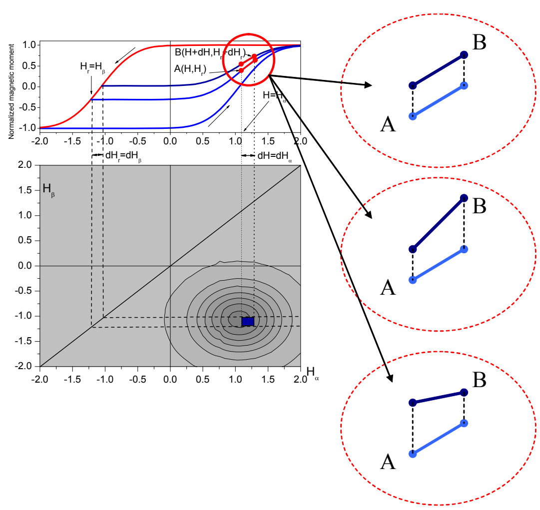
FORC diagram (positive and negative)



Case A
$\rho = 0$

Case B
$\rho < 0$

Case C
$\rho > 0$

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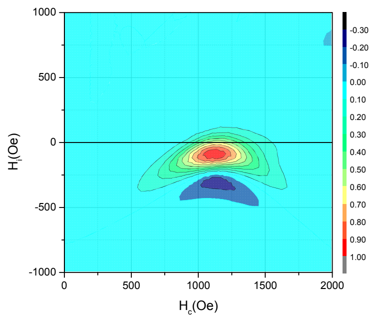
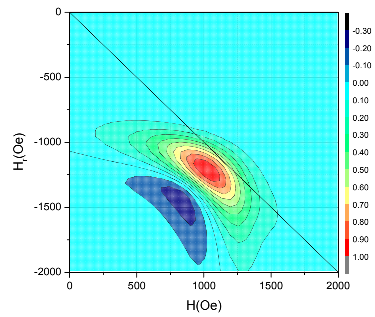
Two types of representations

Preisach plane – coercivity/interaction



R_{FORC}

Preisach plane – switching fields



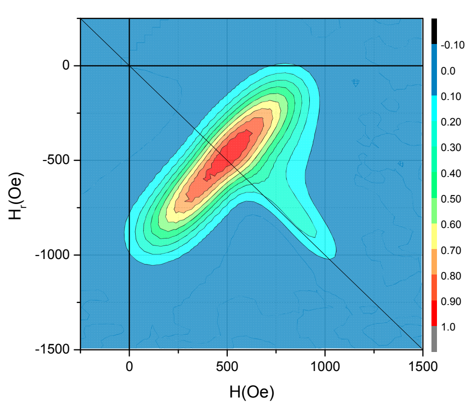
$R_{Preisach}$

Is FORC diagram method a qualitative or a quantitative technique?

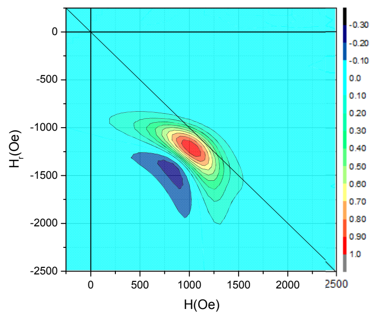
- Theoreticians – FORC technique is giving the Preisach distribution (distribution of rectangular hysterons as a function of coercivity and interactions) only for CPM systems (congruency+wiping-out)
- Experimentalists – FORC as a distorted version of the Preisach distribution

Qualitative FORC analysis

Wishbone type FORC diagrams



Boomerang type FORC diagrams



▶ 19

JOURNAL OF APPLIED PHYSICS VOLUME 93, NUMBER 10 15 MAY 2003

Micromagnetic and Preisach analysis of the First Order Reversal Curves (FORC) diagram

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Christopher Pike
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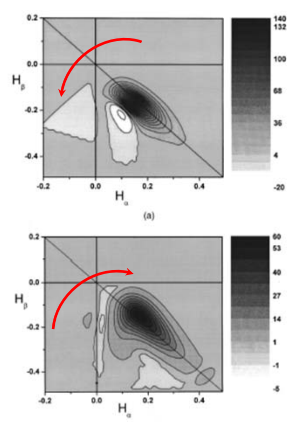
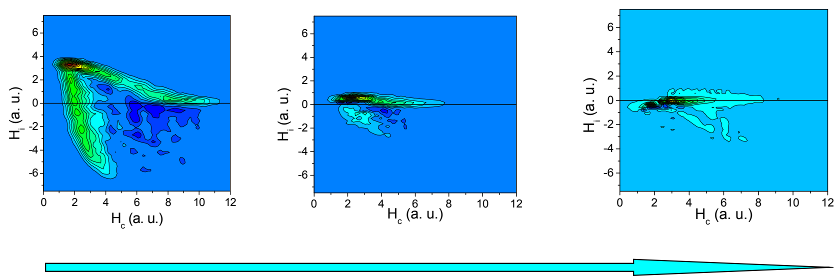
Laurentiu Stoleriu, Petronel Postolache, and Dorin Cimpoesu
Faculty of Physics, "Alexandru Ioan Cuza" University, Iasi, 6600, Romania

(Presented on 12 November 2002)



▶ 20

FORC – patterned medium



P. Postolache, M. Cerchez, L. Stoleriu, A. Stancu, Experimental evaluation of the Preisach distribution for magnetic recording media. Ieee T Magn 39, 2531-2533 (2003)

R. Tanasa, A. Stancu, Statistical Characterization of the FORC Diagram. *IEEE Trans. Magn.* **42**, 3246-3248 (2006).

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From qualitative to quantitative

- In order to clarify the "quantitative" qualities of the FORC diagram one should study the relation between the fundamental physical magnetic & hysteretic entities and their contribution to the FORC distribution.

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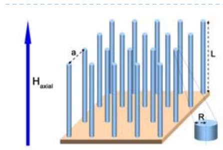
AIP Journal of Applied Physics

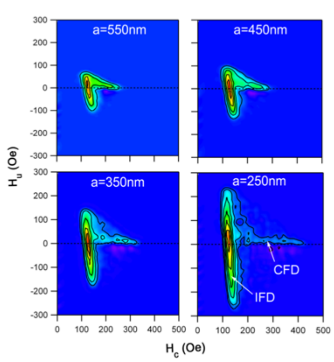
What does a first-order reversal curve diagram really mean? A study case: Array of ferromagnetic nanowires

Costin-Ionuț Dobrotă and Alexandru Stancu

Citation: J. Appl. Phys. **113**, 043928 (2013); doi: 10.1063/1.4789613
View online: http://dx.doi.org/10.1063/1.4789613
View Table of Contents: http://jap.aip.org/resource/1/JAPIAU/v113/i4
Published by the American Institute of Physics.

FORC diagram for 2D magnetic nanowire arrays

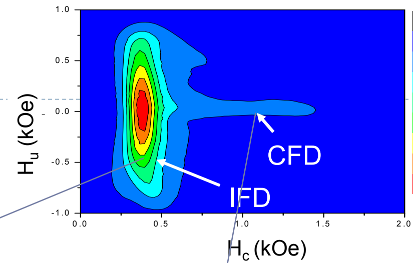


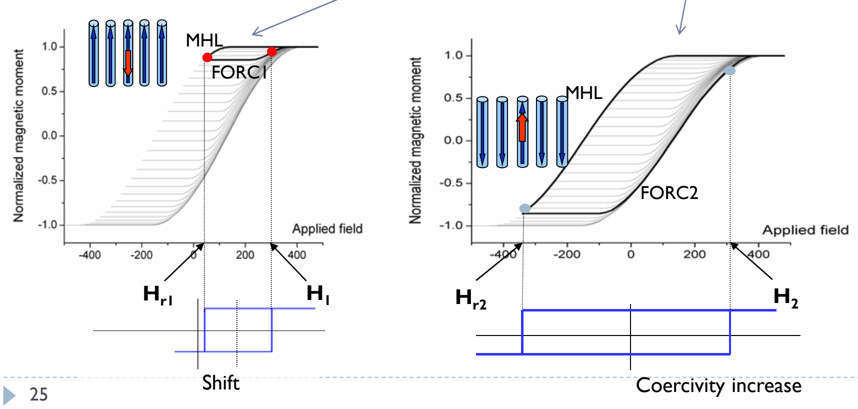


Nanowire array:
40 x 40 nano-elements
a = **250**, 350, 450, 550 nm
R = 40 nm
L = 6 μm
M_s = 485 emu/cm^3
H_{c0} = 150 Oe
$H_{c\sigma}$ = 20 Oe

C.-I. Dobrota, A. Stancu, What does a first-order reversal curve diagram really mean? A study case: Array of ferromagnetic nanowires. J Appl Phys 113, 043928 (2013).

Two different effects of interactions depending on the intrinsic coercivity of the wires





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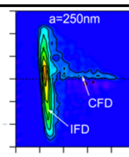
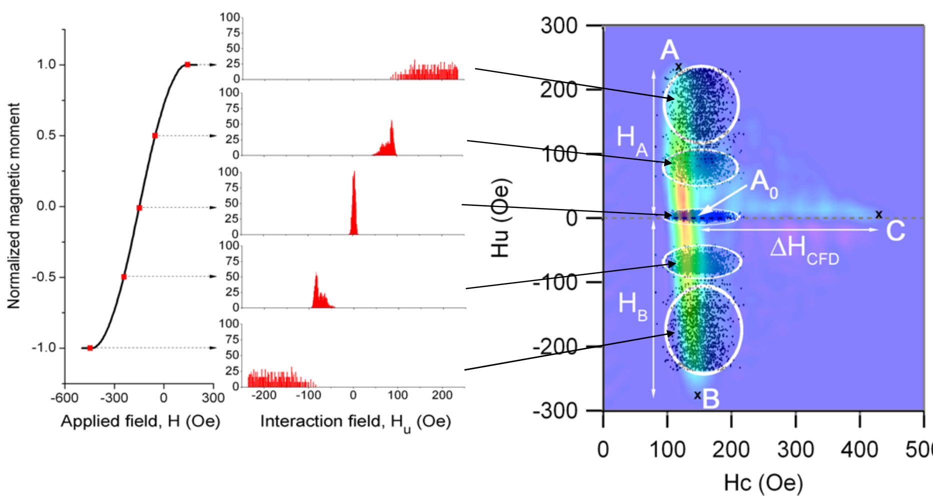
Effect of interactions only as a shift of the hysteron – not sufficient!





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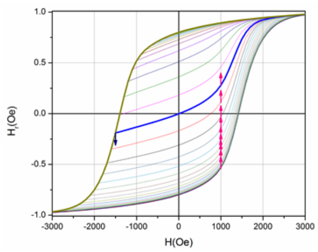
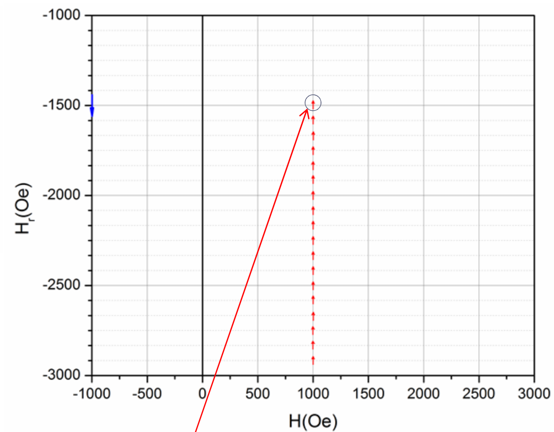
Biunivocal correspondence physical element / "image" on FORC





The result on the FORC distribution is **unique** in this case and is given only by the switch observed on the highest value of the reversal field.

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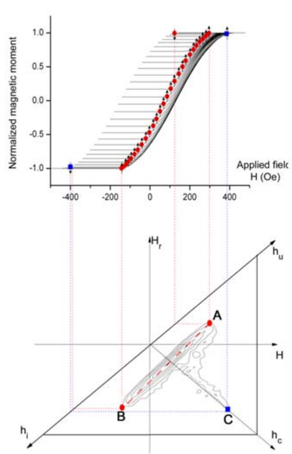
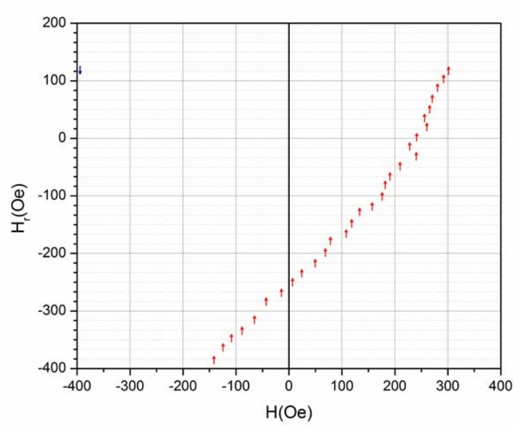
One physical element / multiple "images" on FORC





For the nanowire system the correspondence is **not unique**!

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Physica B 457 (2015) 280–286

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ELSEVIER

Tracking the individual magnetic wires' switchings in ferromagnetic nanowire arrays using the first-order reversal curves (FORC) diagram method

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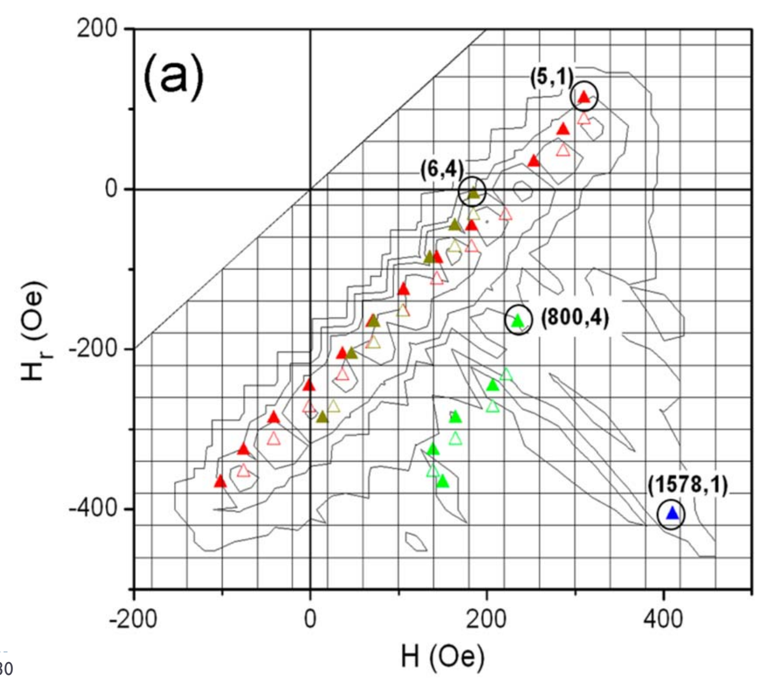
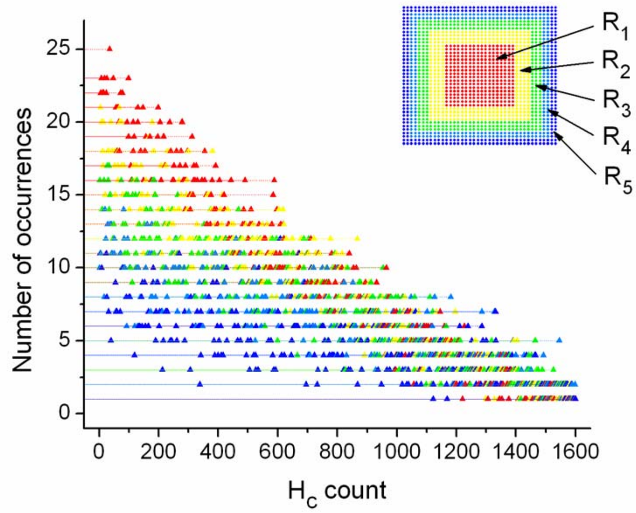


Results:

multiplicity



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More complex magnetic systems

Journal of Magnetism and Magnetic Materials 323 (2011) 1671–1677

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

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ELSEVIER

Magnetization reversal in $[Ni/Pt]_6/Pt(x)/[Co/Pt]_6$ multilayers

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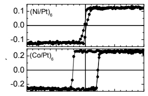
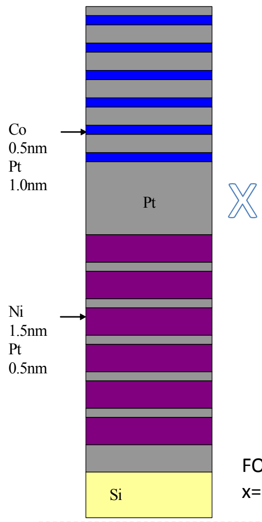
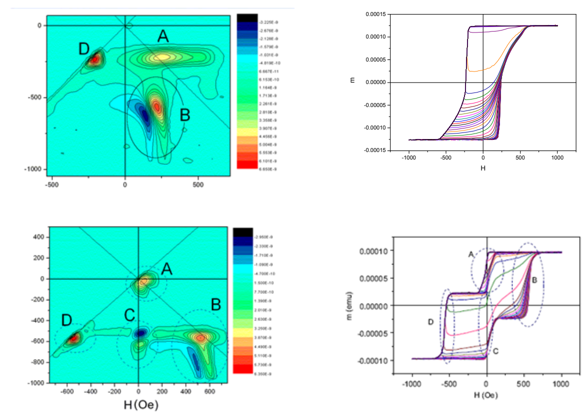
Soft/hard



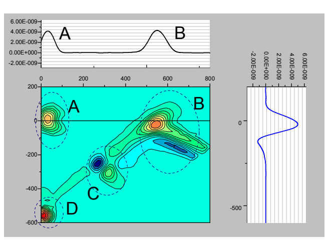


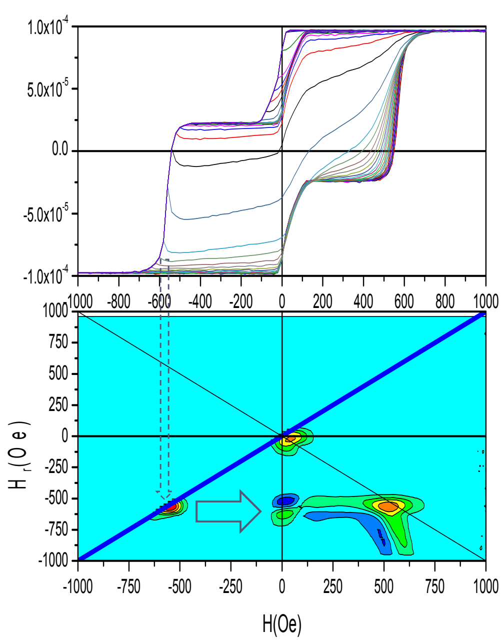


FORC diagrams for the samples Si/Pt/$[Ni/Pt]_6$/Pt(x)/$[Co/Pt]_6$ with x=1 and 5nm (from top to bottom panel).

- N. Siadou, M. Androutsopoulos, I. Panagiotopoulos, L. Stoleriu, A. Stancu, T. Bakas, V. Alexandrakis, Magnetization reversal in [Ni/Pt]6/Pt(x)/[Co/Pt]6 multilayers. J Magn Magn Mater 323, 1671-1677 (2011)10.1016/j.jmmm.2011.01.035).

X=5nm





APPLIED PHYSICS LETTERS VOLUME 83, NUMBER 18 3 NOVEMBER 2003

First-order reversal curves diagrams for the characterization of ferroelectric switching

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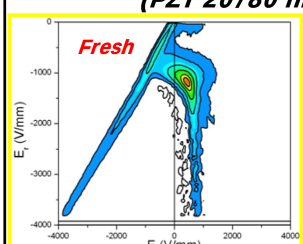
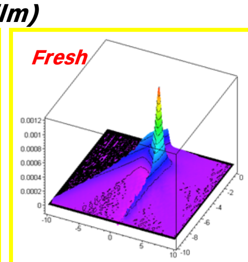
(Received 5 May 2003; accepted 6 September 2003)

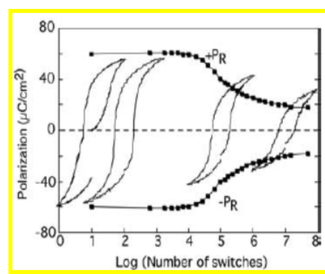
Ferroelectric hysteresis

FORC sensitive to fatigue

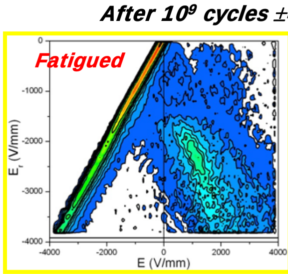
(PZT 20/80 film)

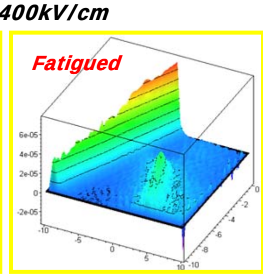






After 10^9 cycles ±400kV/cm





Author(s): Stancu, A; Ricinschi, D; Mitoseriu, L; Postolache, P; Okuyama, M
Title: First-order reversal curves diagrams for the characterization of ferroelectric switching
Source: APPLIED PHYSICS LETTERS, 83 (18): 3767-3769 NOV 3 2003

PHYSICAL REVIEW B **71**, 014431 (2005)

First-order reversal curve analysis of spin-transition thermal hysteresis in terms of physical-parameter distributions and their correlations

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(Received 5 August 2004; published 24 January 2005)

PHYSICAL REVIEW B **72**, 054413 (2005)

First-order reversal curves analysis of rate-dependent hysteresis: The example of light-induced thermal hysteresis in a spin-crossover solid

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(Received 20 April 2005; revised manuscript received 15 June 2005; published 9 August 2005)

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PHYSICAL REVIEW B **83**, 224107 (2011)

Pressure effect investigated with first-order reversal-curve method on the spin-transition compounds $[Fe_xZn_{1-x}(btr)_2(NCS)_2]\cdot H_2O$ ($x = 0.6, 1$)

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Eur. Phys. J. B **84**, 439–449 (2011) DOI: 10.1140/epjb/e2011-10903-x

Size effect in spin-crossover systems investigated by FORC measurements, for surfacted $[Fe(NH_2\text{-}trz)_3](Br)_2{\cdot}3H_2O$ nanoparticles: reversible contributions and critical size

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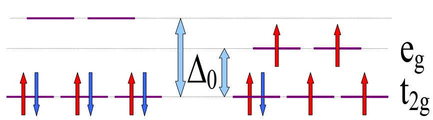
Spin crossover systems



Low spin state

High spin state

Fe(II)
d^6

Diamagnetic S=0

Paramagnetic S=2

Different colors

Different volumes

Different vibrational properties

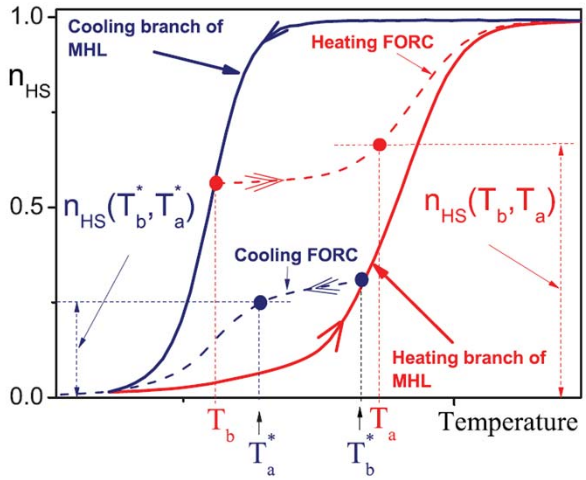
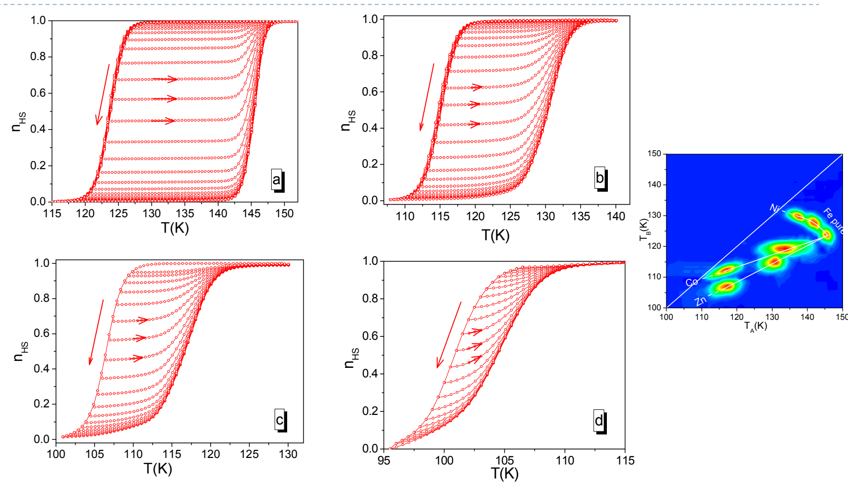


FIG. 1. (Color online) Definition of FORC in the warming and cooling modes. Starred labels stand for the cooling mode.

Thermal hysteresis in spin transition materials



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Hysteretic behavior of $Fe(phen)_2(NCS)_2$ spin-transition microparticles vs. the environment: A huge reversible component resolved by first order reversal curves

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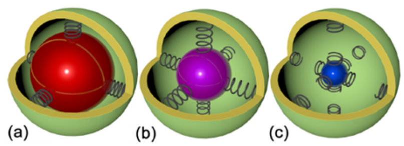

FIG. 4. A spin-crossover particle in a matrix: (a) pre-existent elastic forces between matrix and saturate HS particles; (b) upon the HS to LS transition the particle size diminishes, the matrix induced pressure progressively becomes negative; and (c) the particle size is too small and its interaction with the matrix is cut: the matrix induced pressure is now zero.

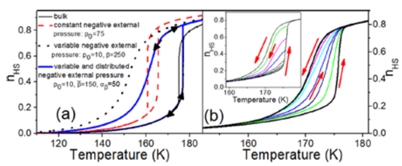

FIG. 5. Simulated thermal transition curves with various external pressures (a) FORCs with $\bar{\beta} = 60$, $p_0 = 0$, $\sigma_\beta = 20$ starting from the cooling branch (main figure) and (b) the heating branch (inset).

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Mulţumesc pentru atenţie !

Thank you !

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Merci !

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Grazie !

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