Tuning magnetic anisotropy in nanostructures for biomedical applications

…the story of anisotropy…

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Fellow –American Physical Society

2019 IEEE Magnetics Society

Distinguished Lecturer

Group Leader –Functional Materials Laboratory

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Dr. Hafsa Khurshid (Asst. Prof. American Univ of Sharjah, UAE)

Students

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Dr. Vijaysankar Kalappattil
Joshua Robles
Dr. Eleanor Clements
Richa Madhogaria
Valery Ortiz
Hana Nazari
Yen Pham
Jason Cardarelli (UG)

Our group's current focus areas….

- Magnetic Nanostructures
- Nanomedicine
- Tunable Microwave Materials
- Spin Seebeck Effect
- Multicaloric oxides
- Helical magnets
- Magnetic Refrigeration
- Giant Magnetoimpedance Magnetic Sensors

DC, AC Magnetization
Transport measurements
RF transverse susceptibility
MCE
GMI
MOKE
SAR for hyperthermia
Spin Seebeck Effect
Spin Hall Magnetoresistance

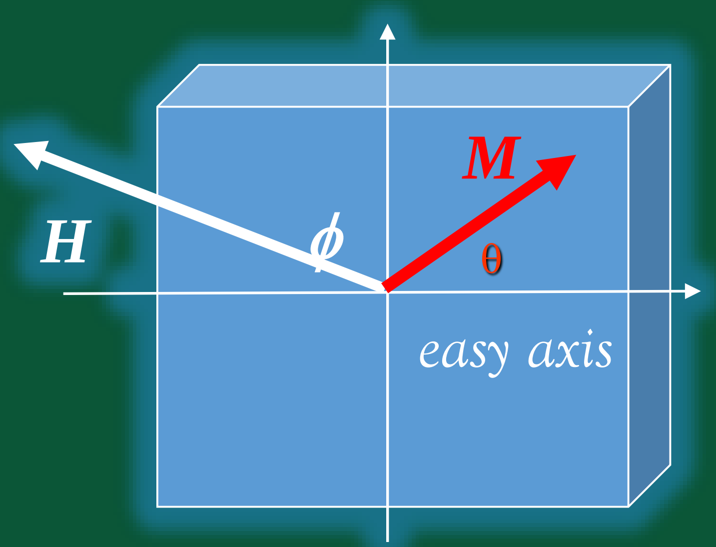
Outline

- Magnetic anisotropy

- Anisotropic nanoparticles for biomedical applications

- Dancing with the SARs

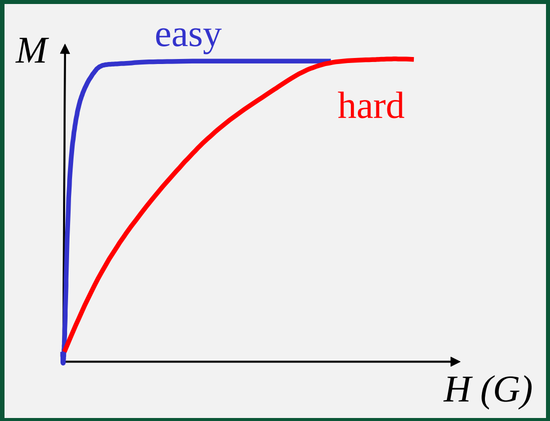
Magnetic Anisotropy -basic idea



Zeeman Uniaxial

$$U = -MH\cos(\phi - \theta) - K_1 \sin^2(\theta)$$

$$\frac{\partial U}{\partial \theta} = 0$$



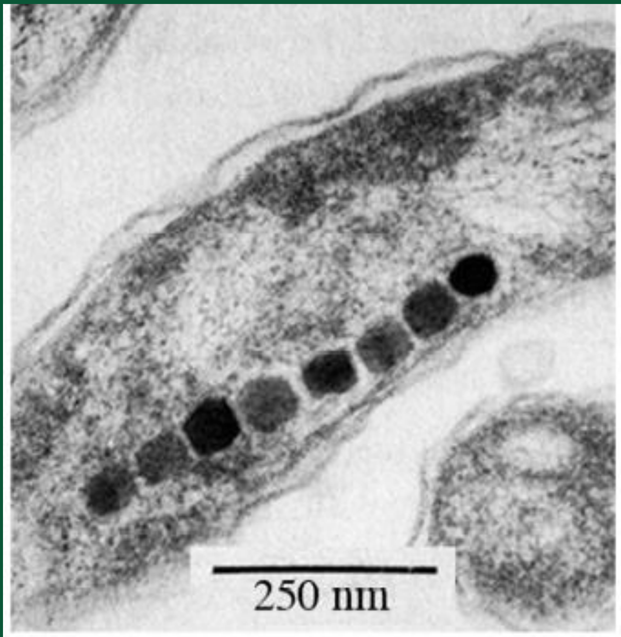
$$U_A = K_1(\alpha_1^2\alpha_2^2 + \alpha_1^2\alpha_3^2 + \alpha_2^2\alpha_3^2) + K_2\alpha_1^2\alpha_2^2\alpha_3^2$$ Cubic

…And if you thought that's it…..think again!

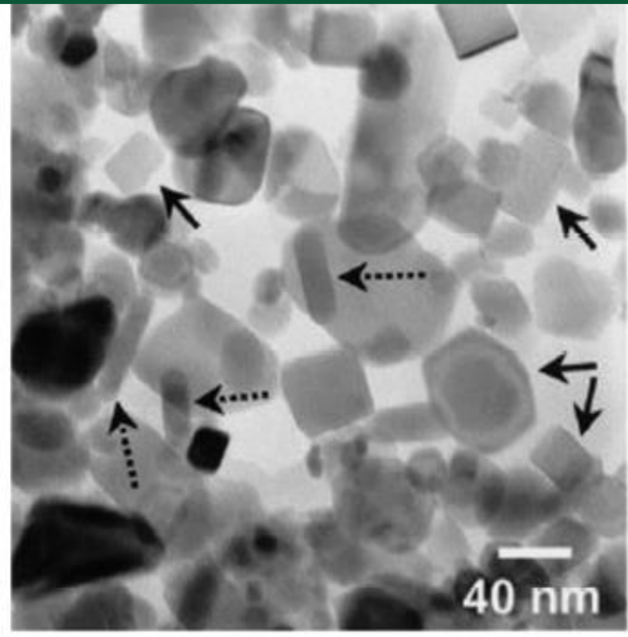
Surface Strain/Striction Unidirectional/Exchange

Shape Configuration

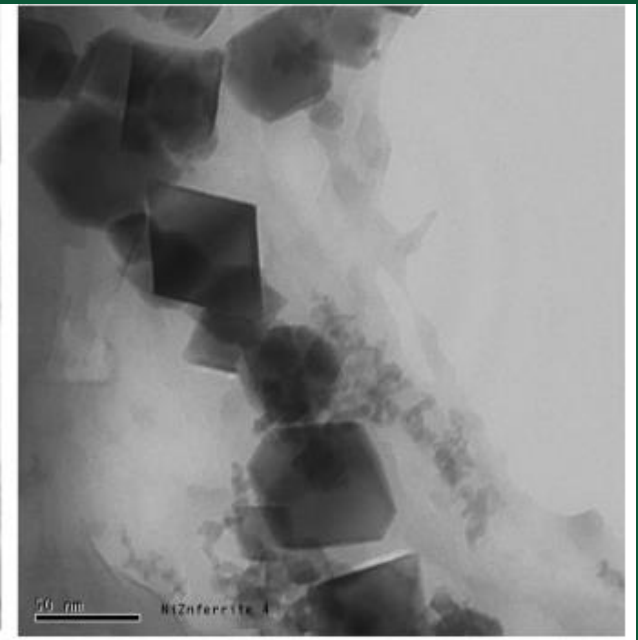
Anisotropic nanoparticles are omnipresent!



Magnetotactic bacteria



Magnetite crystals in Allen Meteorite from Mars



Ferrite crystals produced in plasma chamber at CMU

Available online at www.sciencedirect.com
SCIENCE DIRECT
ELSEVIER
Acta Materialia 54 (2006) 807–816
Acta MATERIALIA
www.actamat-journals.com

Experimental observations and nucleation and growth theory of polyhedral magnetic ferrite nanoparticles synthesized using an RF plasma torch

R. Swaminathan [a,*], M.A. Willard [b], M.E. McHenry [a,*]

[a] Department of Materials Science and Engineering, Carnegie Mellon University, Pittsburgh, PA 15213, United States
[b] US Naval Research Laboratory, Physical Metallurgy Branch, Code 6320, Washington, DC 20375, United States

Received 18 July 2005; received in revised form 9 October 2005; accepted 12 October 2005

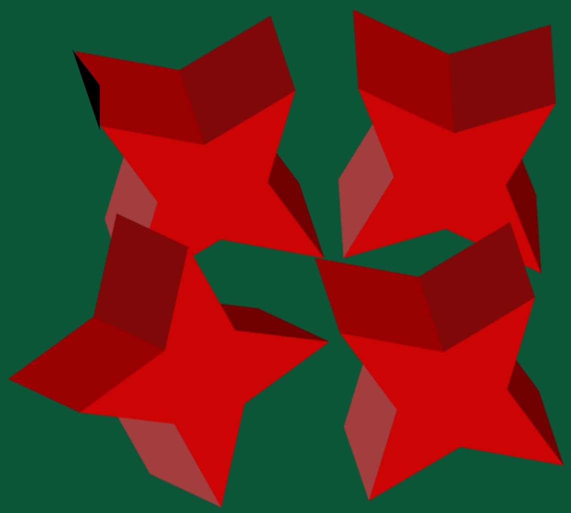
Tuning the anisotropy

NANORODS

The high aspect ratio of the nanorods gives rise to an enhanced **shape anisotropy.**

OCTOPODS

By deforming the surface of the nanoparticles, the **surface anisotropy** can be increased.



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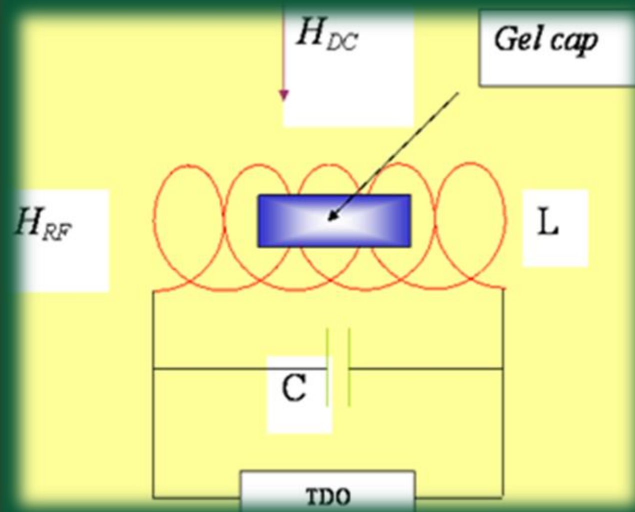
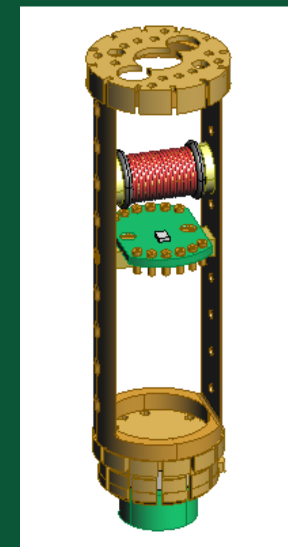
Transverse susceptibility using a resonant RF TDO method

- Ultrastable Tunnel Diode Oscillator
- LC Tank circuit self-resonant at ~ 10 – 25 MHz
- Operates in a PPMS
- Sensitivity 1-10Hz in 25 MHz
- Temperature range: 2K < T < 300K
- Variable DC field: 0 < H < 7T





$$\Delta\chi_T/\chi_T \propto \Delta f/f$$

- P. Poddar, G. T. Woods, S. Srinath and H. Srikanth, IEEE Trans. Nanotech. **4**, 59 (2005)
- P. Poddar, J. L. Wilson, H. Srikanth, D. F. Farrell, S. A. Majetich, PRB **68**, 214409 (2003)

REVIEW OF SCIENTIFIC INSTRUMENTS VOLUME 70, NUMBER 7 JULY 1999

Radio-frequency impedance measurements using a tunnel-diode oscillator technique

H. Srikanth,[a)] J. Wiggins, and H. Rees
Advanced Materials Research Institute, University of New Orleans, New Orleans, Louisiana 70148

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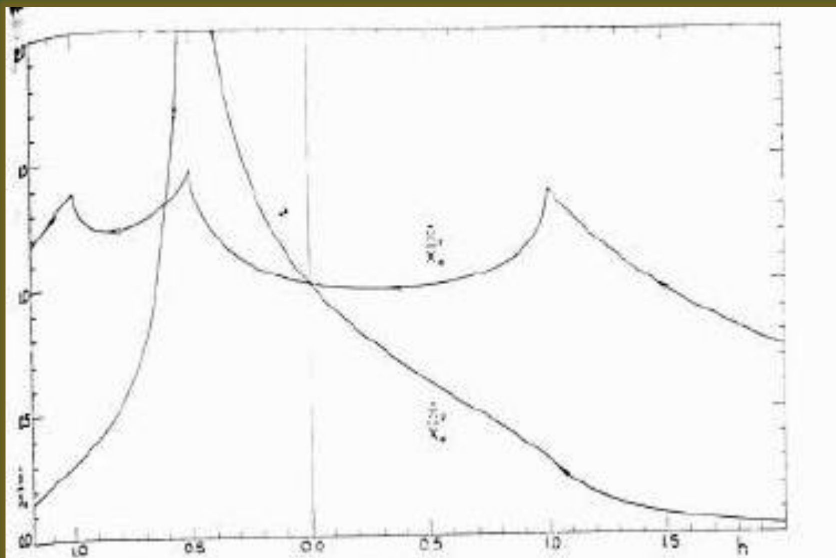
Transverse Susceptibility



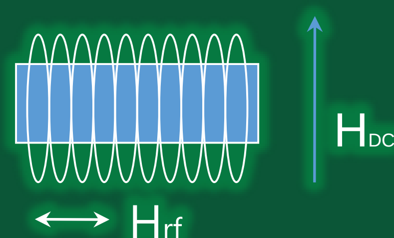
- Aharoni, 1957

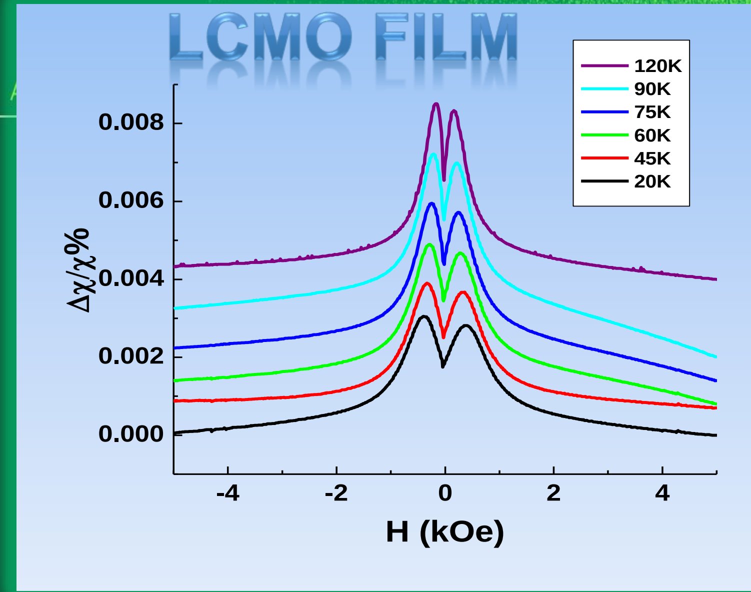
$$\chi_P = \frac{dM_Z}{dH_Z}$$

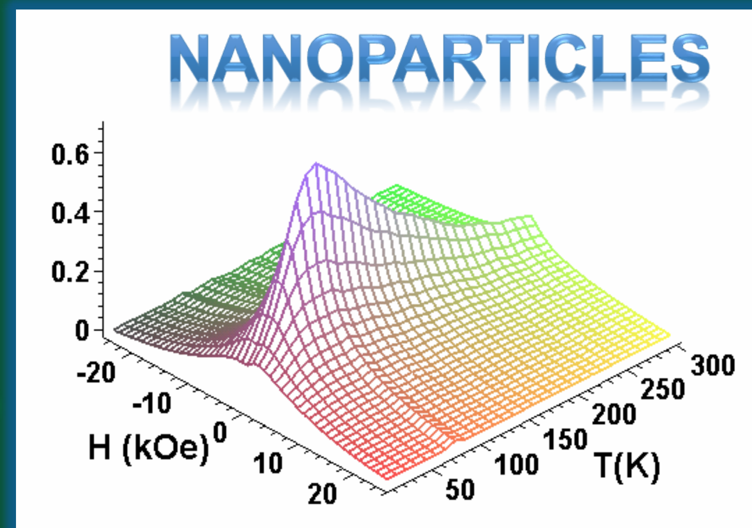
$$\chi_T = \left(\frac{dM_x}{dH_z}\right)$$

$h = H/H_K$

$H_k = 2K/M_s$





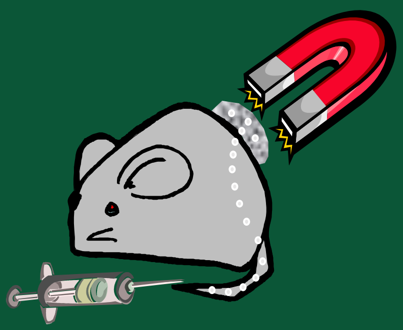


JOURNAL OF APPLIED PHYSICS 104, 063901 (2008)

Transverse susceptibility study of the effect of varying dipolar interactions on anisotropy peaks in a three-dimensional assembly of soft ferrite nanoparticles

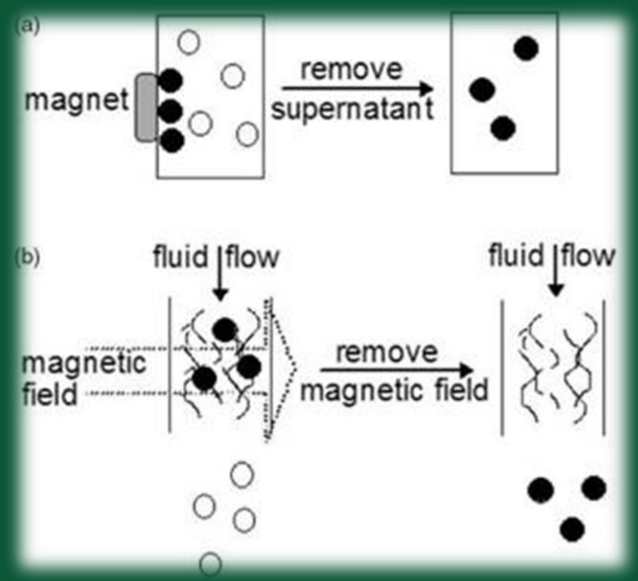
Pankaj Poddar,[1,2,a)] Marienette B. Morales,[1] Natalie A. Frey,[1] Shannon A. Morrison,[3] Everett E. Carpenter, and Hariharan Srikanth[1,b)]

Nanoparticles for biomedical applications

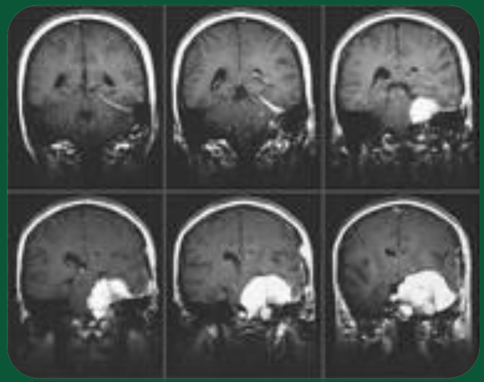


Targeted Drug Delivery

Magnetic Heating (Hyperthermia)

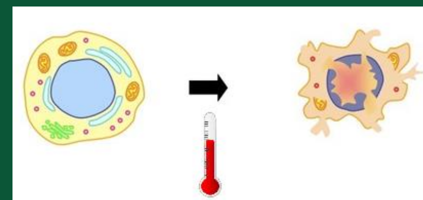


Cell Separation

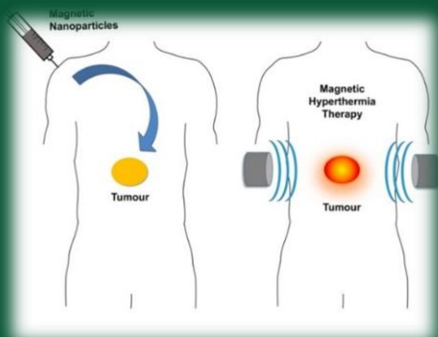


MRI Image Enhancement

Magnetic hyperthermia for cancer treatment:
Using magnetic nanoparticles under an external AC magnetic field to target, heat and destroy cancer cells.



- protein denaturation
- cell membrane restructuring
- cell deactivation
- (driven to apoptosis) around 40-45 °C

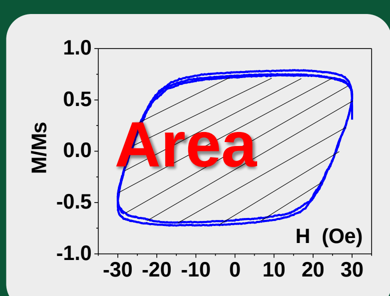


NanoTherm™ Therapy

Mag*Force AG* (Germany)

The standard measure of heating efficiency is the **Specific Absorption Rate (SAR)**:

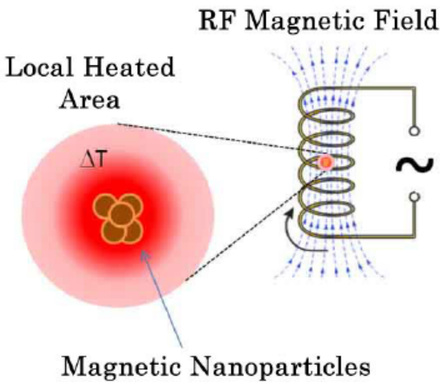
$$SAR = Area \cdot f$$



Higher SAR → fewer nanoparticles

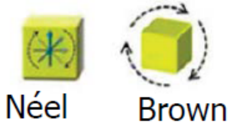
[5] D. Ortega and Q. Pankhurst, "Magnetic hyperthermia," Cambridge, Royal Society of Chemistry, 60-88 (2013).
[6] R. Ivkov et al. Int. J. Hyperthermia, 29(8), 703-851 (2013).

Introduction: magnetic fluid hyperthermia



SLP: Specific Loss Power

SLP=f(f, H_0, Relaxation Mechanism)



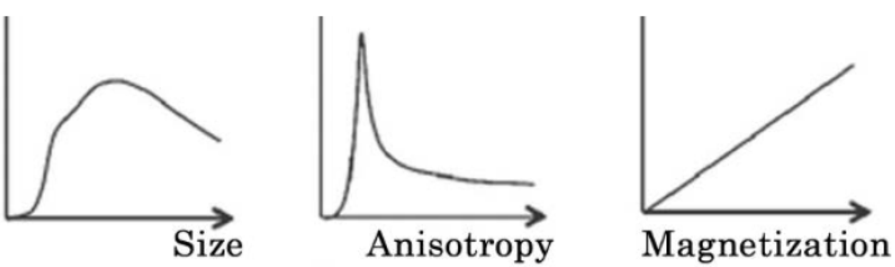
Linear Response Theory (LRT)

- non-interacting single domain particles
- Linear susceptibility ($H<<H_K$)

$$P = \pi\mu_0\chi_0 H_0^2 f \frac{2\pi f\tau}{1+(2\pi f\tau)^2}$$

$$\frac{1}{\tau} = \frac{1}{\tau_B} + \frac{1}{\tau_N} \qquad \tau_B = \frac{3\eta V_H}{k_B T} \qquad \tau_N = \tau_0 e^{K_{eff}V/k_BT}$$

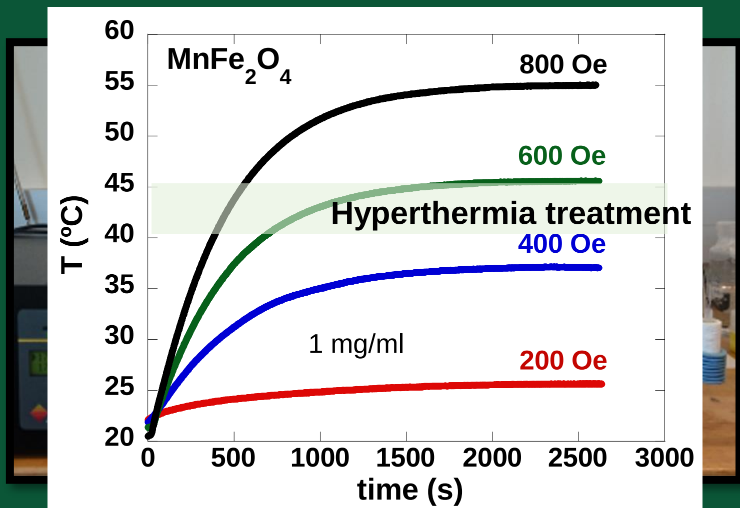
SLP



R. Rosensweig, J Magn Magn Mater, 252, 370-374 (2002).
C. Dennis, R. Ivkov, Int J Hypertherm, 29(8), 715-729 (2013).

Magnetic Hyperthermia

I. Calorimetric method

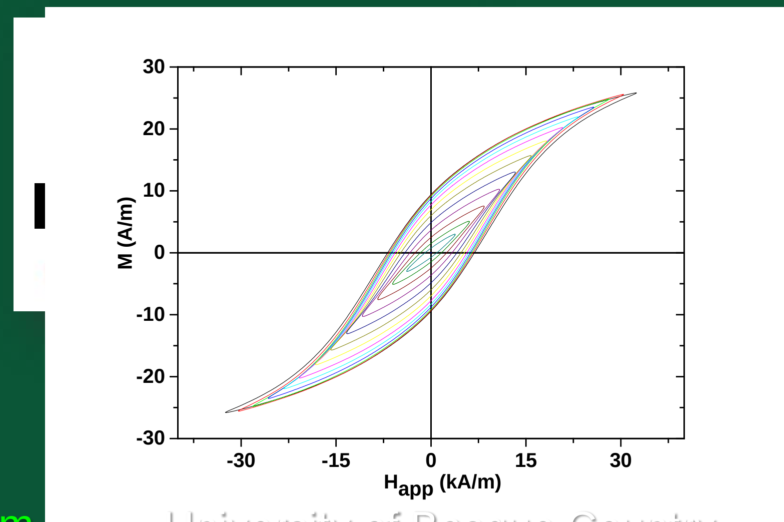


4.2 kW Ambrell Easyheat LI 3542 system

$$SAR = \frac{m_s}{m_n} C_p \frac{\Delta T}{\Delta t}$$

C_p: specific heat of the solution
m_s: mass of the solvent
m_n: mass of the nanoparticles
$\Delta T/\Delta t$: initial slope of the heating curves

II. AC Magnetometry method



University of Basque Country
Eneko Garaio, Irati Rodrigo, Jose Angel Garcia

$$SAR = Area \times frequency$$

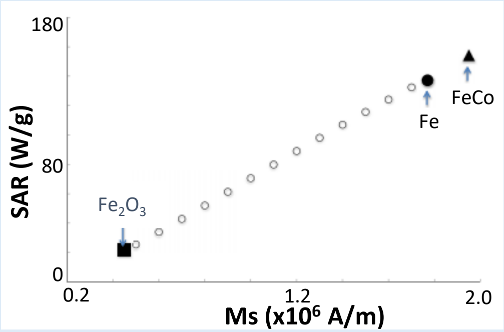
- AC magnetometry is more accurate and reproducible than other methods.

Atkinson Brezovich limit: H x f = 4.85×10^8 Am^{-1}Hz

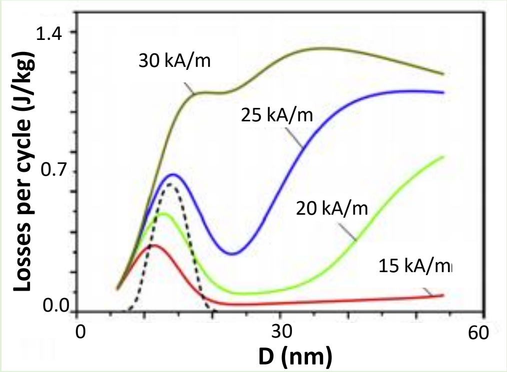
Motivation

Heating efficiency

Saturation Magnetization



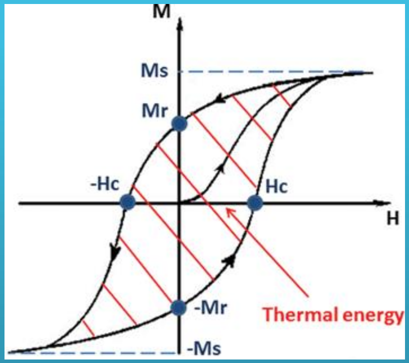
Size



Anisotropy

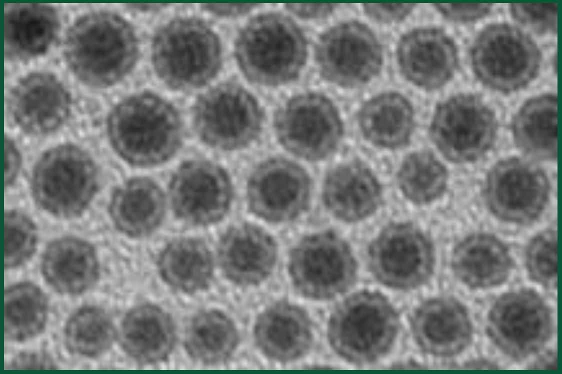
[7] C. Binns, "Magnetic Nanoparticle Hyperthermia Treatment of Tumours," Berlin, Springer-Verlag, 197-215 (2013).

How to increase M_s and retain biocompatibility?



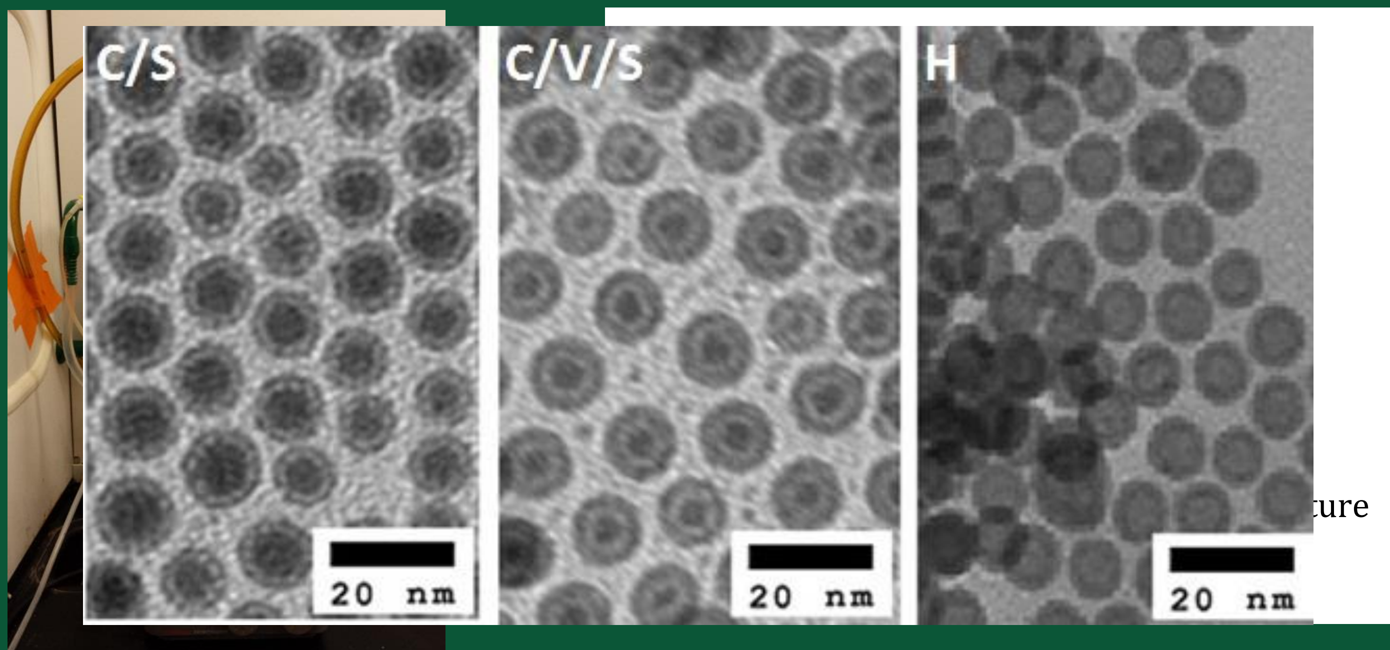
SAR = Area · f

- *Bulk saturation magnetization:*
  - ✓ Iron-oxide ----- 92 emu/g
  - ✓ Iron ----- 220 emu/g

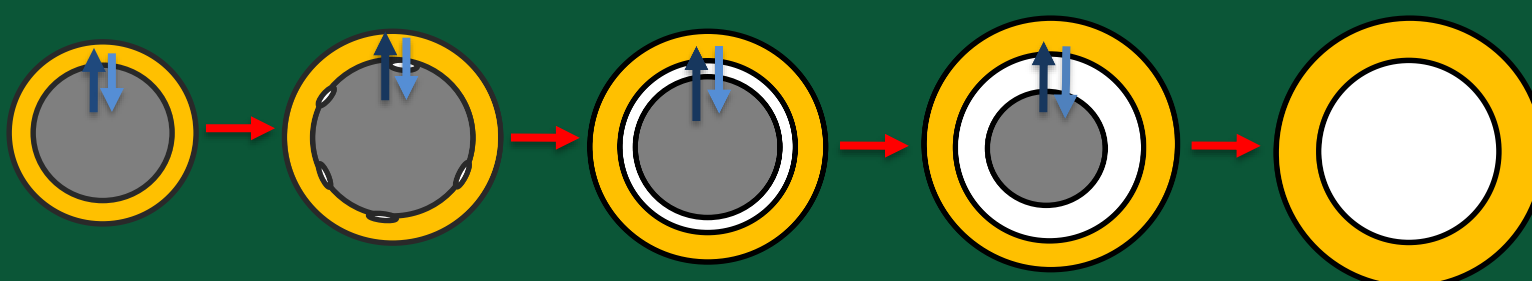


- By creating core/shell nanostructures with a metallic core and an Fe oxide shell, it is possible to achieve nanoparticles with good biocompatibility and high saturation magnetization.

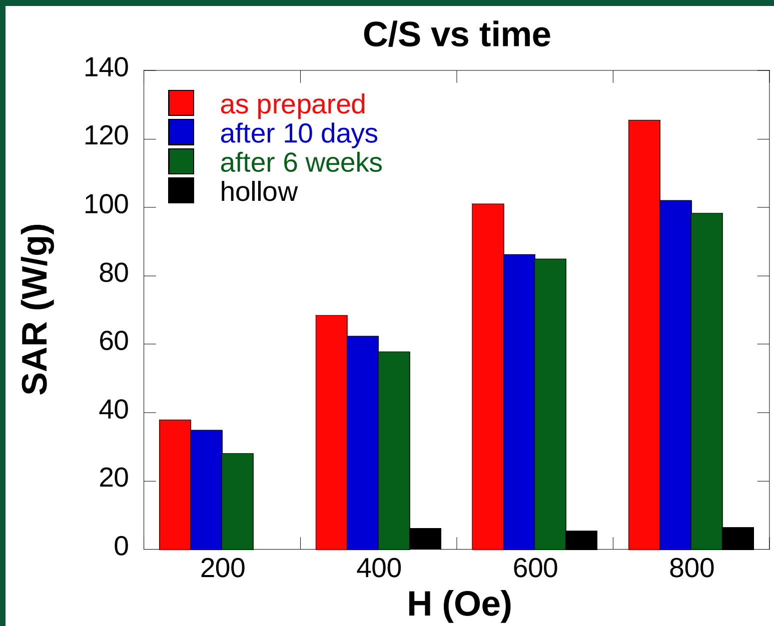
Synthesis of Core/Shell and Hollow Nanoparticles

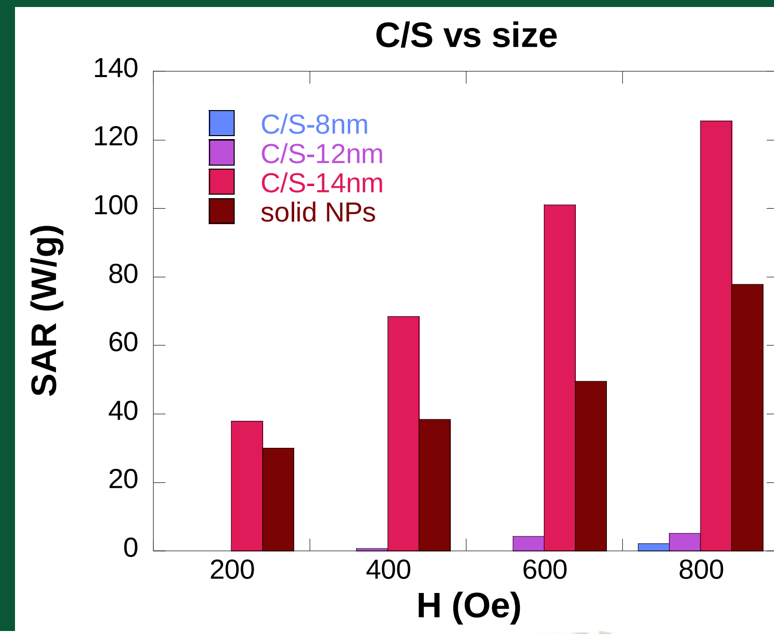


Kirkendall Effect



Magnetic Hyperthermia





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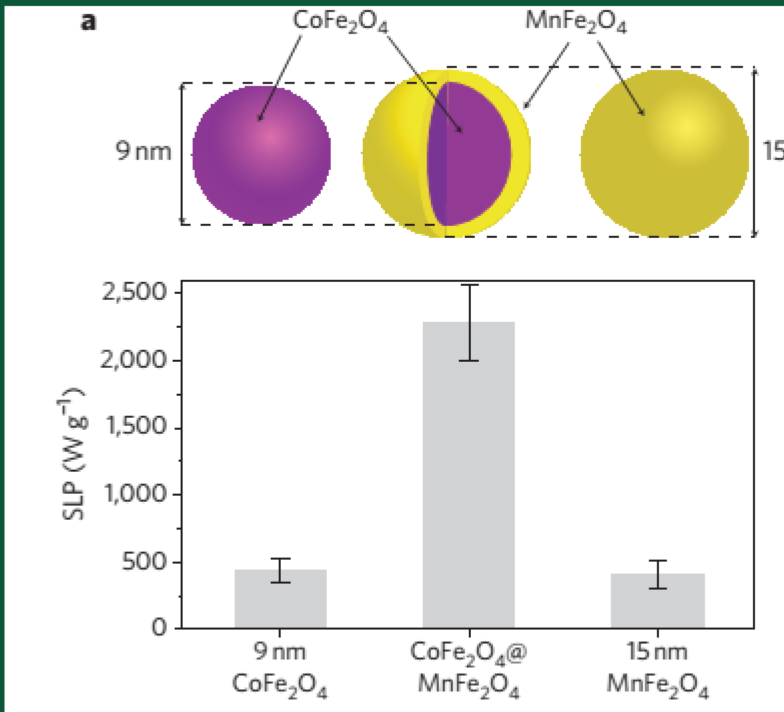
Cite this: *RSC Adv.*, 2016, 6, 38697

Core/shell iron/iron oxide nanoparticles: are they promising for magnetic hyperthermia?†

Z. Nemati,[a] J. Alonso,[ab] H. Khurshid,[a] M. H. Phan[a] and H. Srikanth*[a]

Exchange coupled nanoparticles for hyperthermia



LETTERS
PUBLISHED ONLINE: 26 JUNE 2011 | DOI: 10.1038/NNANO.2011.95
nature nanotechnology

Exchange-coupled magnetic nanoparticles for efficient heat induction

Jae-Hyun Lee[1], Jung-tak Jang[1], Jin-sil Choi[1], Seung Ho Moon[1], Seung-hyun Noh[1], Ji-wook Kim[1], Jin-Gyu Kim[2], Il-Sun Kim[3], Kook In Park[3] and Jinwoo Cheon[1]*

- ✓ A significant increase in the efficiency of magnetic thermal induction by nanoparticles taking the advantage of the exchange coupling between a magnetically hard core and magnetically soft shell to tune the magnetic properties of the nanoparticle and maximize the specific loss power.

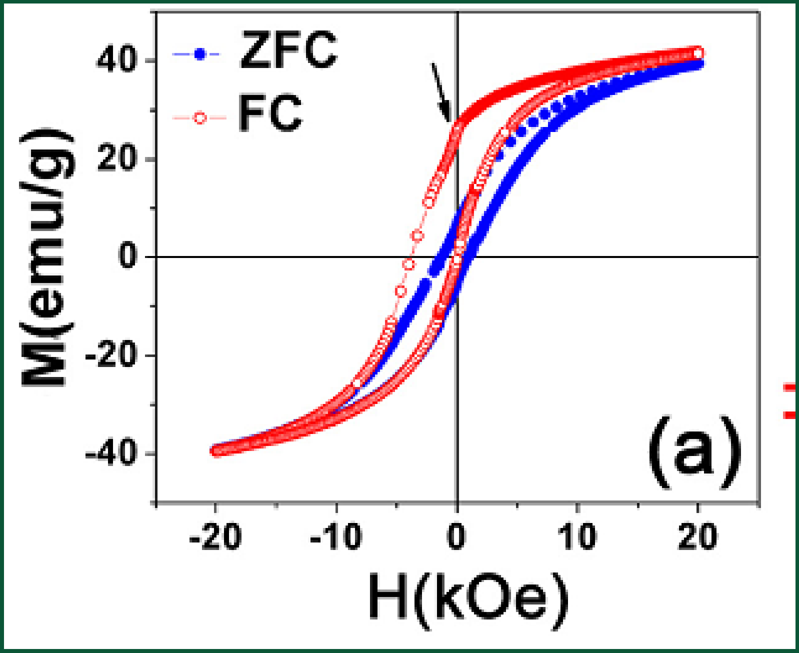
- ✓ The optimized core–shell magnetic nanoparticles have specific loss power values that are an order of magnitude larger than conventional iron-oxide nanoparticles.

Exchange coupled FeO/Fe_3O_4 nanoparticles

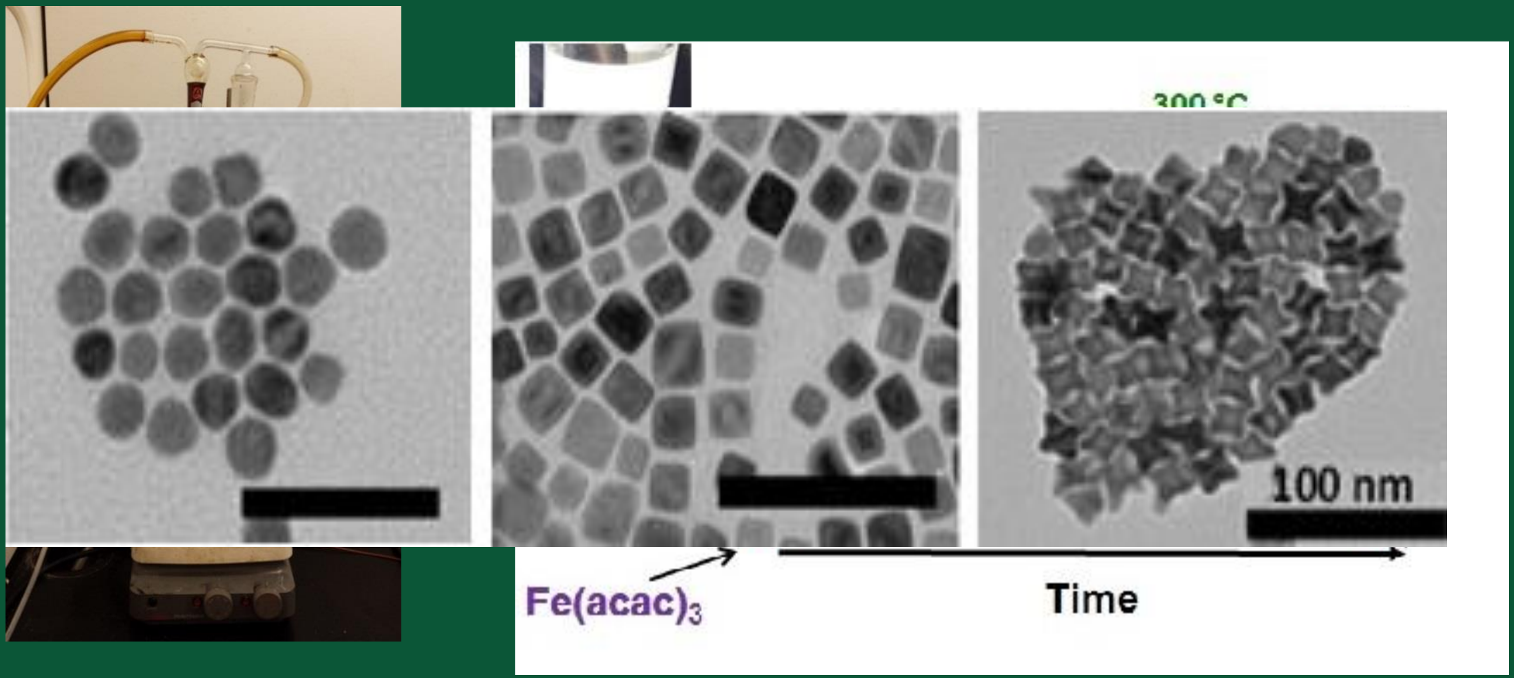
JOURNAL OF APPLIED PHYSICS 117, 17A337 (2015)

Anisotropy effects in magnetic hyperthermia: A comparison between spherical and cubic exchange-coupled FeO/Fe_3O_4 nanoparticles

H. Khurshid,[1,a)] J. Alonso,[1,2] Z. Nemati,[1] M. H. Phan,[1] P. Mukherjee,[1]
M. L. Fdez-Gubieda,[2,3] J. M. Barandiarán,[2,3] and H. Srikanth[1,a)]
[1]*Department of Physics, University of South Florida, Tampa, Florida 33620, USA*
[2]*BCMaterials Edificio No. 500, Parque Tecnológico de Vizcaya, Derio 48160, Spain*
[3]*Depto. Electricidad y Electrónica, Universidad del País Vasco, Leioa 48940, Spain*



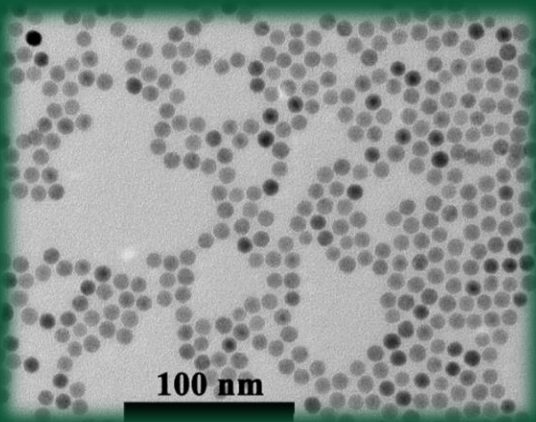
Nanoparticle legos: Playing with shapes



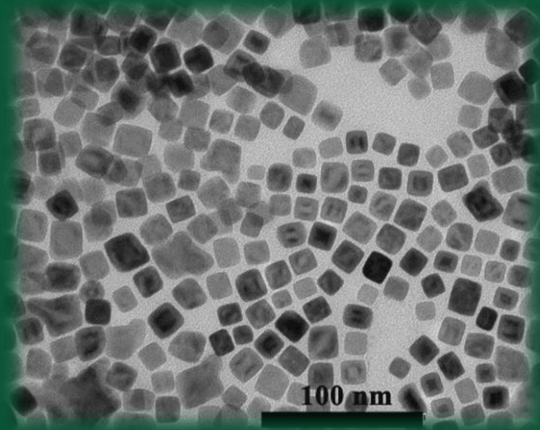
- The Fe_3O_4 nanoparticles were obtained by further annealing the as-prepared exchange coupled FeO/ Fe_3O_4.

H. Khurshid et al. Nanoscale, 5, 7942 (2013).

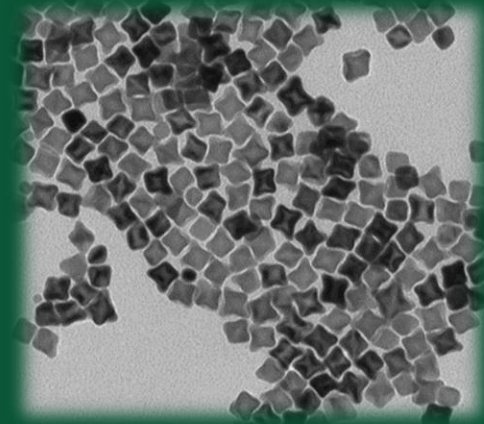
Shape dependence: Dancing with the ~~Stars~~…SARs!



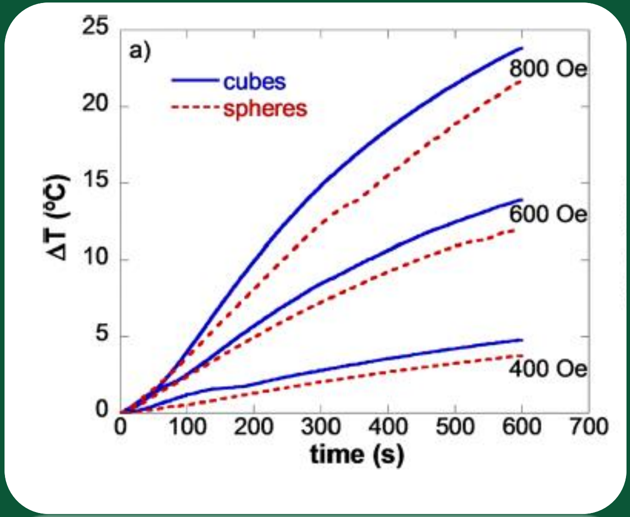
spheres

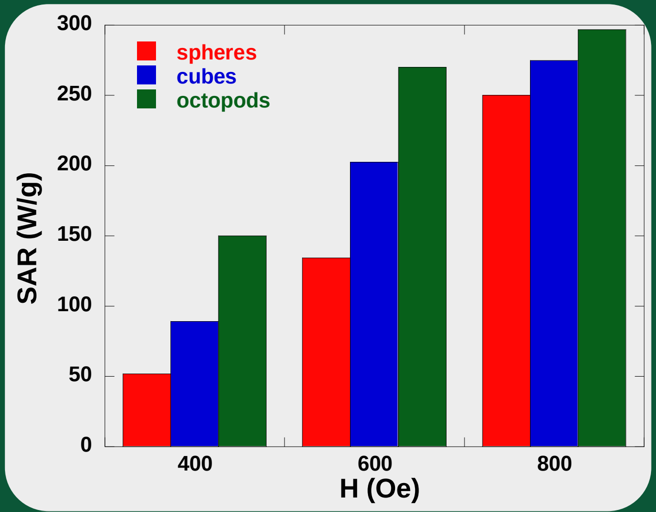


cubes



octopods

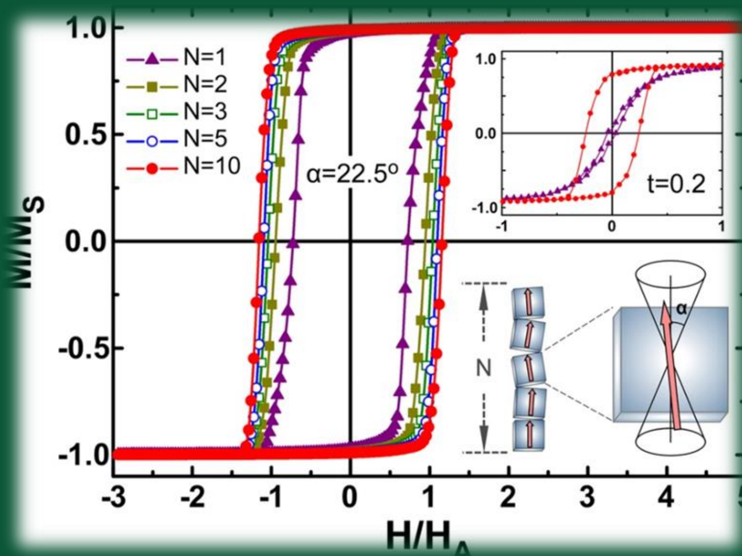




Increased shape or surface anisotropy gives rise to higher heating rates:

SAR (octopods) > SAR (cubes) > SAR (spheres)

'Chains' of improving SAR is higher in high aspect ratio nanostructures!

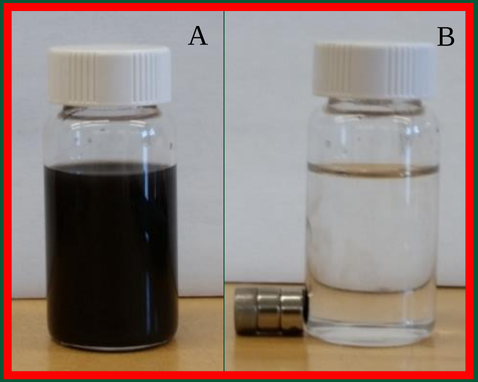


- Chains of magnetosomes (magnetic nanoparticles produced by bacteria) show higher heating efficiency than isolated magnetosomes.

- High aspect ratio nanostructures (chains, wires, rods…) can give rise to a notable increase of the SAR.

C. Martinez-Boubeta et al., *Scientific Reports* **3**, 1652 (2012); E. Alphandery et al., ACS. Nano. **3**, 1539–1547 (2009).

Fe_3O_4 nanorods with tunable aspect ratio

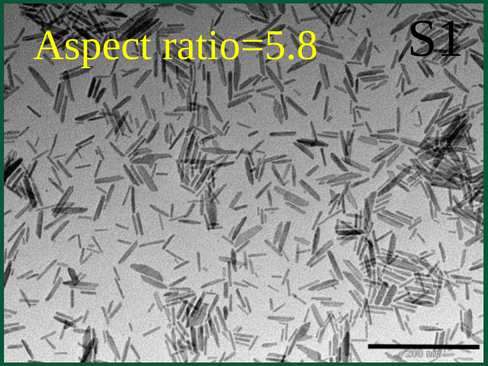


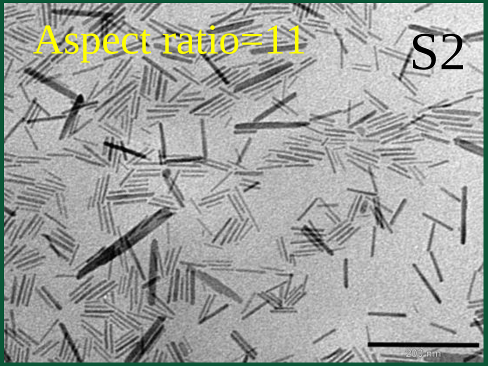
$Fe(CO)_5$ +

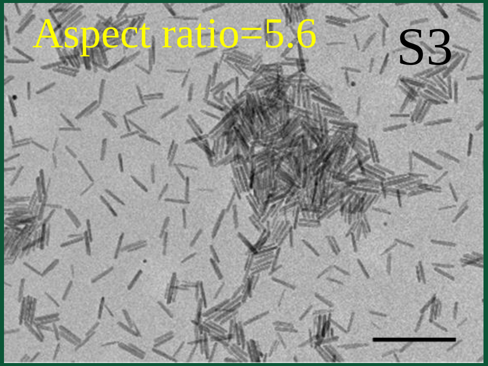
OA/HDA = 3.3

OA/HDA = 6.6

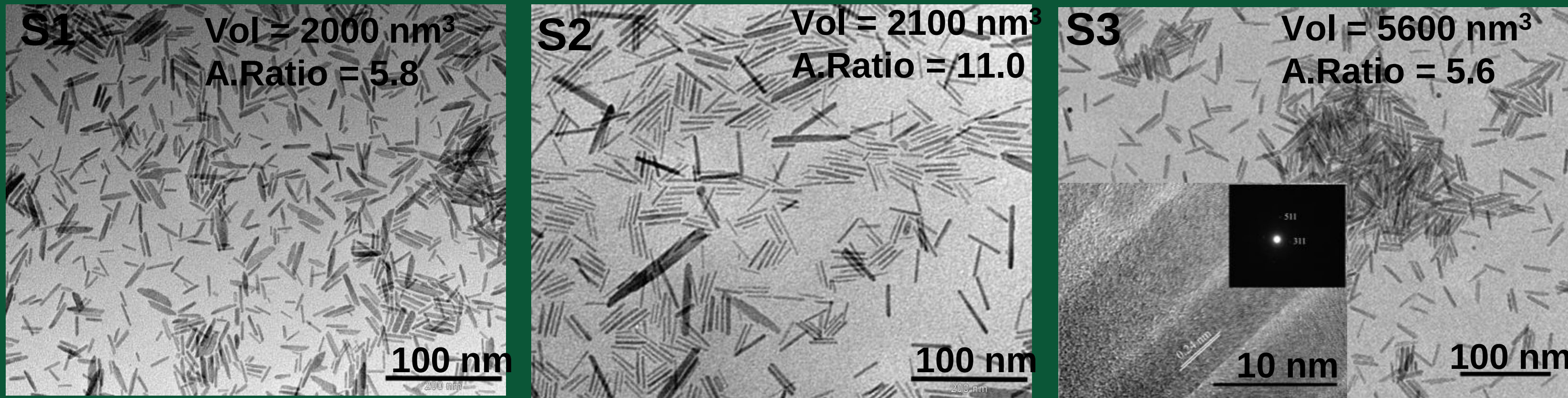
OA/HDA = 9.1





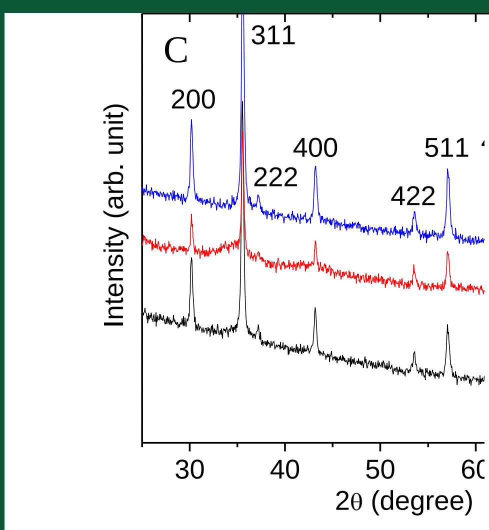


Structural Characterization



- The **aspect ratio and volume** of the nanorods were tuned.

	Length (nm)	Width (nm)	Aspect ratio
S1	41.0	7.0	**5.8**
S2	65.0	5.7	**11.0**



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Cite this: *Nanoscale*, 2017, **9**, 7858

Epitaxial magnetite nanorods with enhanced room temperature magnetic anisotropy†

Sayan Chandra,‡[a] Raja Das,‡[b] Vijaysankar Kalappattil,[b] Tatiana Eggers,[b] Catalin Harnagea,[a] Riad Nechache,[c] Manh-Huong Phan,*[b] Federico Rosei *[a] and Hariharan Srikanth *[b]

University of South Florida

IEEE MAGNETICS

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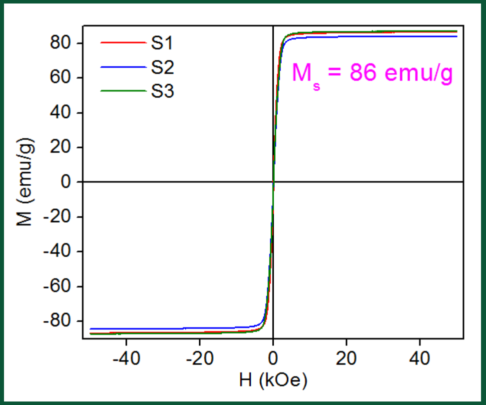
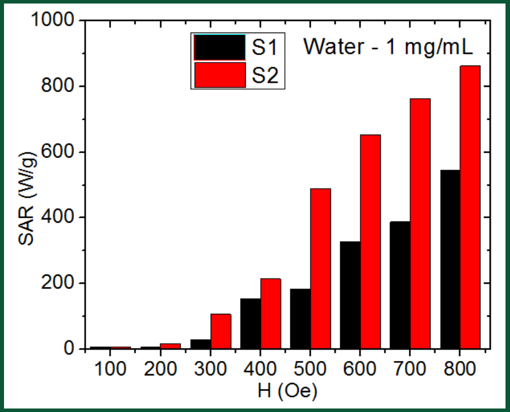
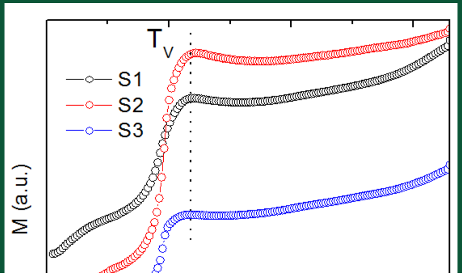
Inductive heating properties of Fe_3O_4 nanorods

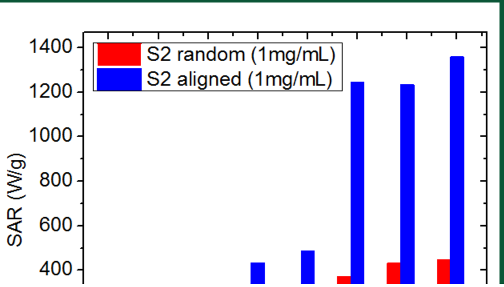


M-H loops @ 300 K



SAR for S1 and S2





tions

- *The s*
- *M(T)* *rystalline.*

THE JOURNAL OF PHYSICAL CHEMISTRY C

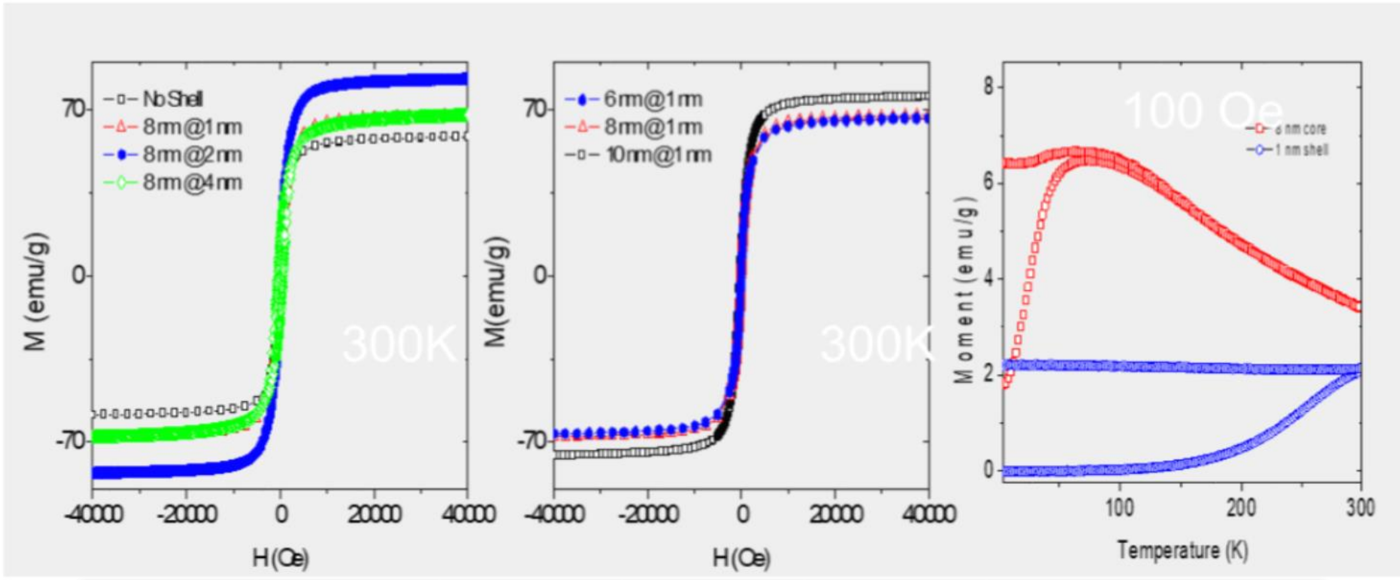
Article

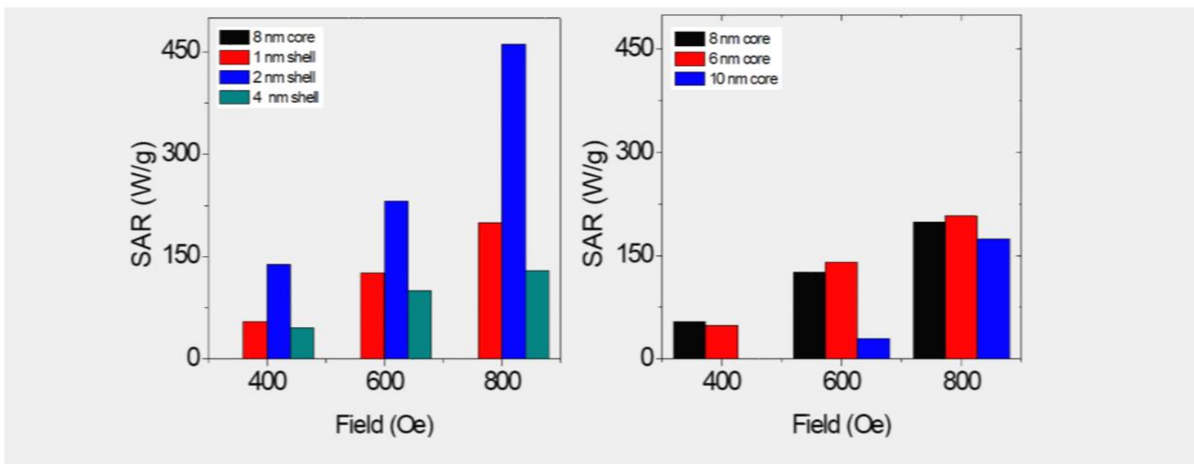
pubs.acs.org/JPCC

Tunable High Aspect Ratio Iron Oxide Nanorods for Enhanced Hyperthermia

Raja Das,[*,†] Javier Alonso,[†,‡] Zohreh Nemati Porshokouh,[†] Vijaysankar Kalappattil,[†] David Torres,[†] Manh-Huong Phan,[*,†] Eneko Garaio,[§] José Ángel García,[‡,∥] Jose Luis Sanchez Llamazares,[⊥] and Hariharan Srikanth[*,†]

$Fe_3O_4/CoFe_2O_4$ Core/Shell Nanoparticles

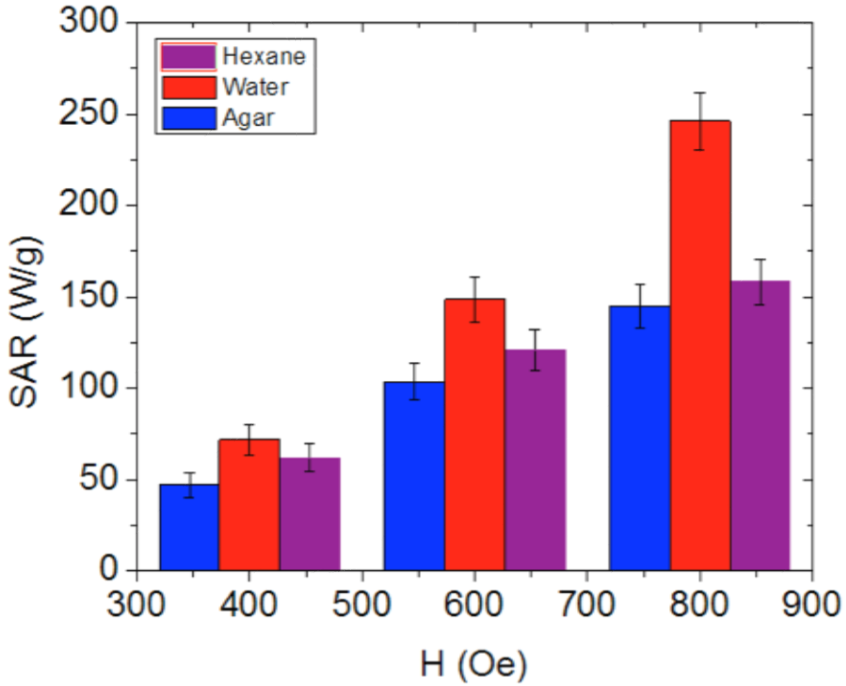




- SAR increases with increment in shell thickness and core diameter
- SAR value is much higher for the variation of the shell thickness than the variation in the core size

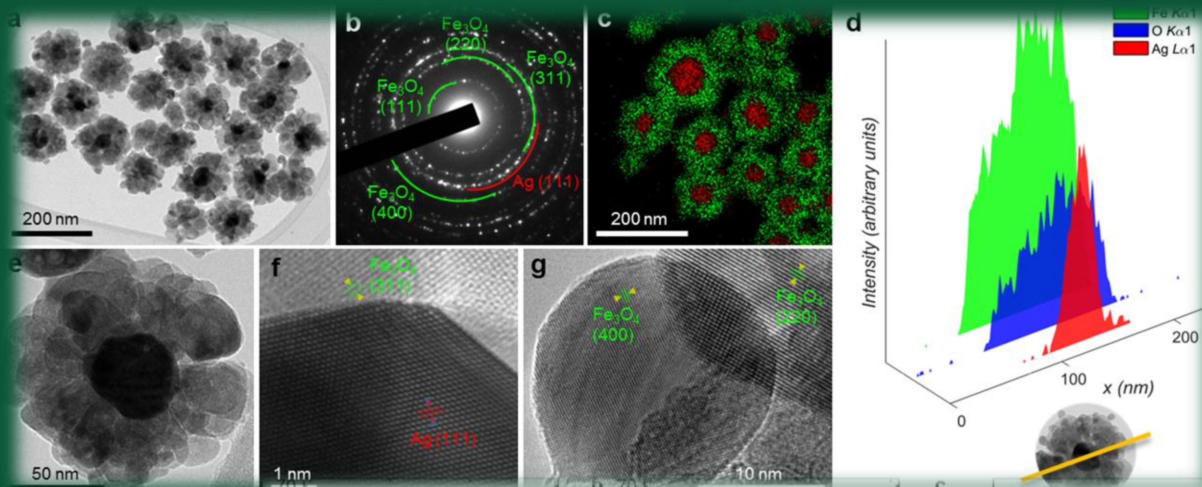
SAR in different viscous environments

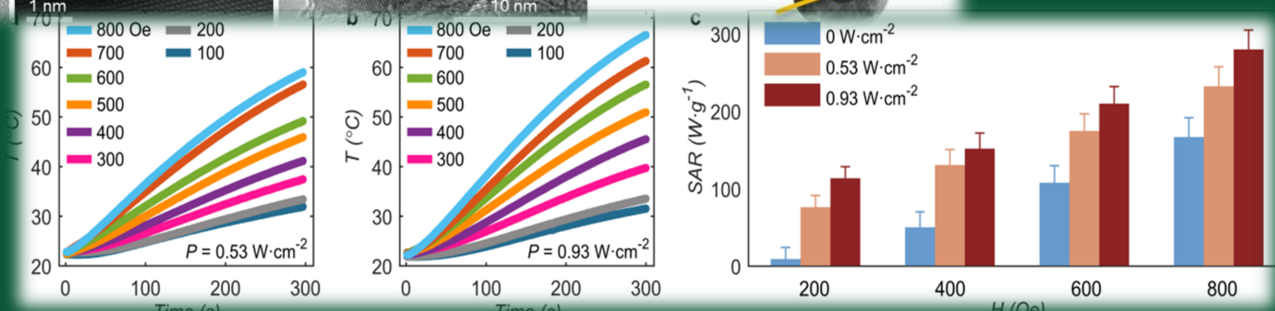
SAR Data: 10nm $CoFe_2O_4$ @ Fe_3O_4

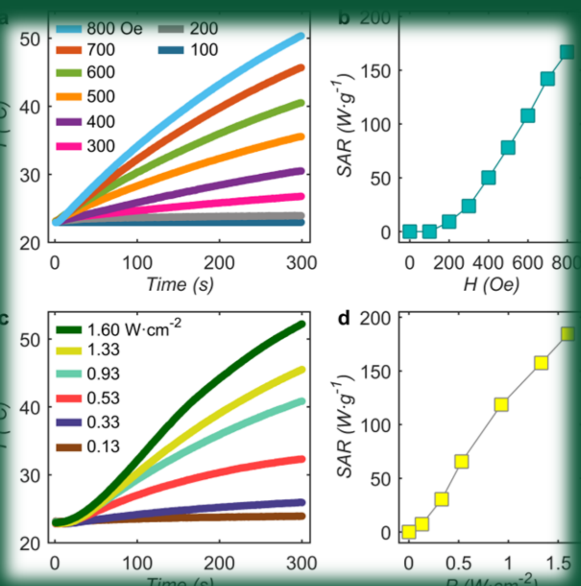


H (Oe)	Hexane	Water	Agar
400	61.990	83.837	47.125
600	121.01	148.447	103.63
800	158.97	246.18	144.51

$Ag@Fe_3O_4$ Nanohybrids as Highly Efficient Agents for Photothermal and Magnetic Hyperthermia







Magnetic and photothermal hyperthermia. (a-b) Heating curves … ac magne… ency, f = 300 … at two differe… olution of the … fferent laser powers.

ACS APPLIED MATERIALS & INTERFACES
Research Article
www.acsami.org

Boosted Hyperthermia Therapy by Combined AC Magnetic and Photothermal Exposures in Ag/Fe_3O_4 Nanoflowers

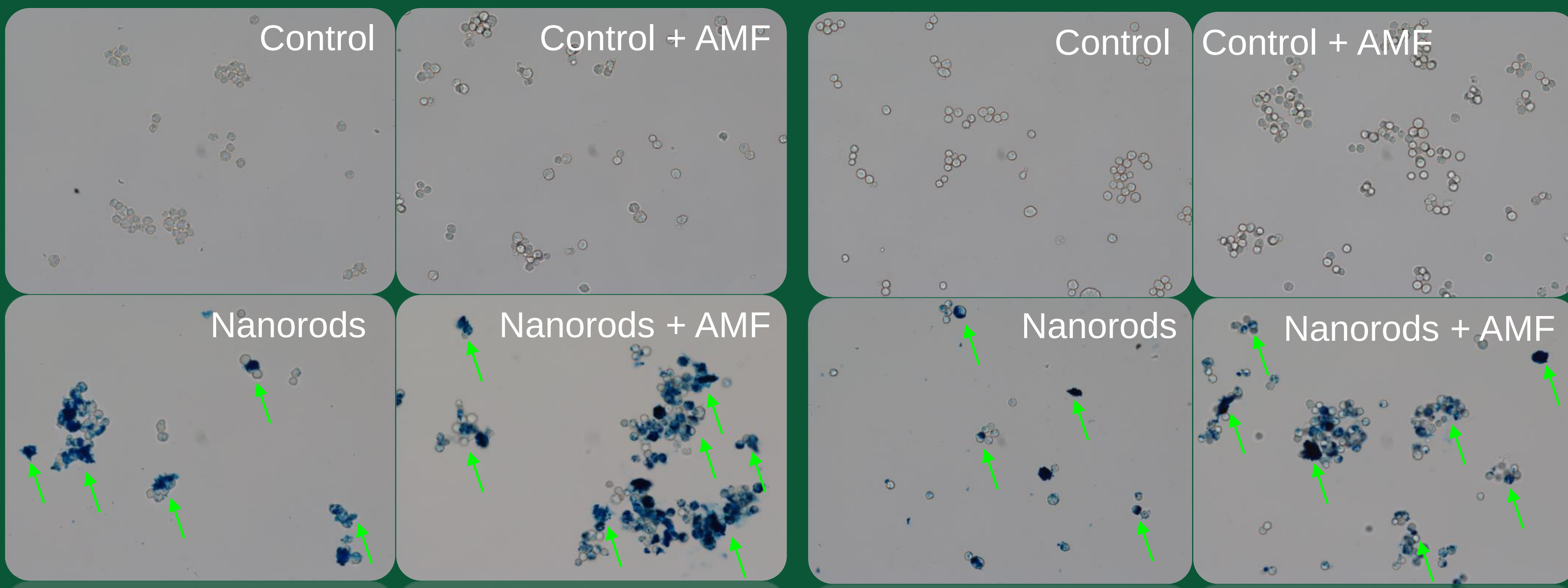
R. Das,[†,¶] N. Rinaldi-Montes,[†,‡,¶] J. Alonso,[†,§] Z. Amghouz,[‖] E. Garaio,[⊥] J. A. García,[§,#] P. Gorria,[◆] J.A. Blanco,[‡] M.H. Phan,[†] and H. Srikanth[*,†]

Internalization of Fe_3O_4 nanorods in the macrophages

Cells were kept at 37 ºC, 5% CO_2
Total volume: 3.5 ml/well
5×10^5 cells/ml
30 µg nanorods /ml

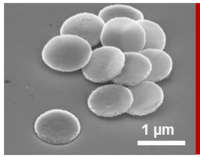
After 2 h

After 24 h



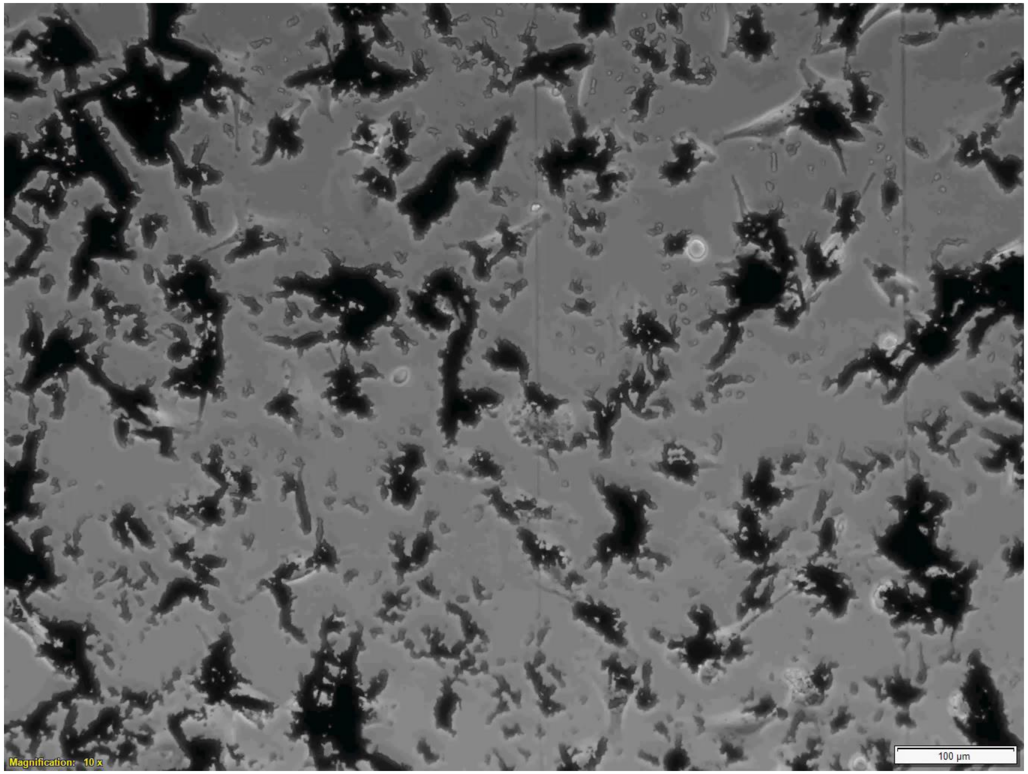
In vitro experiments were carried out by Rosa Martínez, David Muñoz and Eneko Garaio at the University of Basque Country (UPV/EHU)

Magneto-mechanical cancer cells destruction



U87 Glioma cells with gold-plated vortex Au/NiFe/Au

1 image / 10 min – total 48h



This video was taken during a toxicity test for the particles, without applied field. Here, the amount of particles is maximum. Viability of the cells is assessed after 48h incubation with the particles. Cells death would be achieved by applying a 20 Hz rotating field.

Credits for the video:

Cécile Naud,
Thèse de Doctorat (Univ. Grenoble Alpes, 2019)

If one paper cited:

"Triggering the apoptosis of targeted human renal cancer cells by the vibration of anisotropic magnetic particles attached to the cell membrane"
Selma Leulmi, Xavier Chauchet, Mélissa Morcrette, Guillermo Ortiz, Hélène Joisten, Philippe Sabon, Thierry Livache, Yanxia Hou, Marie Carrière, Stéphane Lequien, and Bernard Dieny,
Nanoscale 7, 15904 (2015). doi 10.1039/c5nr03518j

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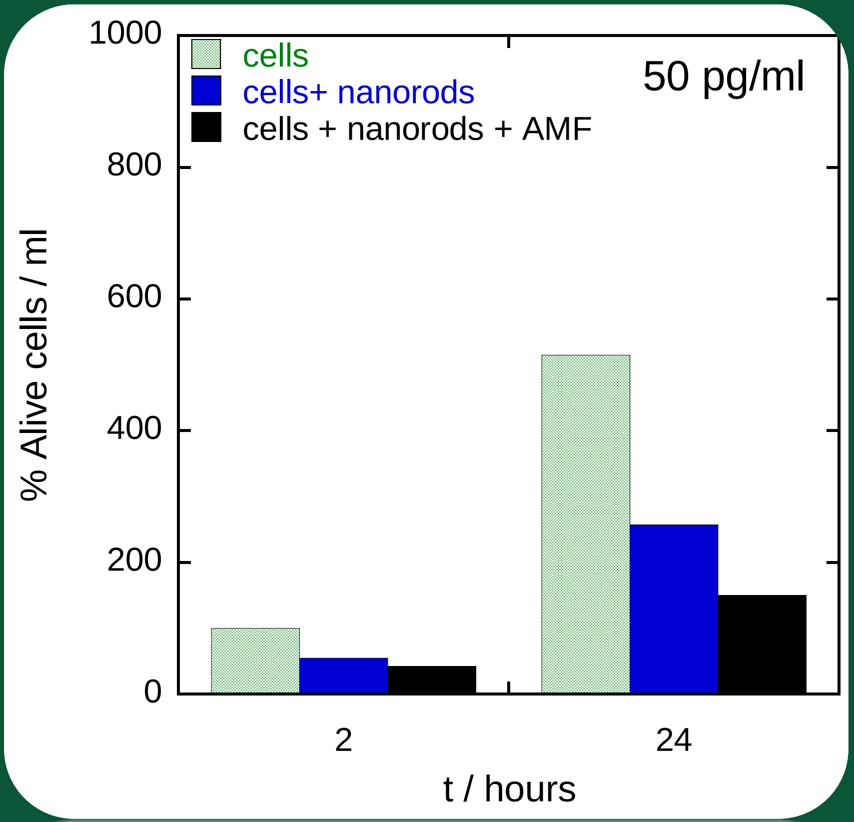
Effect of Hyperthermia



- The incorporation of nanorods into cells slows down their growth.
- Application of AMF generates a 40% decrease in their population after 24 h.
- These results are very promising for magnetic hyperthermia treatment of cancer.

Magneto-mechanical destruction of cancer cells

Kim et al. Nature Materials 9, 165 (2010) Argonne group (Ryzkhova, Novosad)

Mansell et al. Scientific Reports 7, 4257 (2017)
Vemulkar et al. APL 110, 042402 (2017)
Cambridge group (Russell Cowburn)

- Microdiscs with vortex states
- Synthetic antiferromagnetic discs
- Low field/frequency actuation induced torque

FLASH NEWS!

MagForce AG Receives FDA Investigational Device Exemption Approval to Conduct a Clinical Trial with NanoTherm Therapy as Focal Ablation Treatment for Intermediate Risk Prostate Cancer

February 10, 2018 05:55 AM Eastern Standard Time

BERLIN & CARSON CITY, Nev.--(BUSINESS WIRE)--MagForce AG (Frankfurt, Scale, XETRA: MF6, ISIN: DE000A0HGQF5), a leading medical device company in the field of nanomedicine focused on oncology, together with its subsidiary MagForce USA, Inc., announces that it has received U.S. Food and Drug Administration (FDA) Investigational Device Exemption (IDE) approval to conduct a clinical trial with NanoTherm therapy as focal ablation treatment for intermediate risk prostate cancer.

Source: www.businesswire.com

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Journal of Physics D: Applied Physics
J. Phys. D: Appl. Phys. **50** (2017) 363001 (33pp)
https://doi.org/10.1088/1361-6463/aa81a1

Topical Review

The 2017 Magnetism Roadmap

D Sander[1], S O Valenzuela[2,3], D Makarov[4], C H Marrows[5], E E Fullerton[6], P Fischer[7,8], J McCord[9], P Vavassori[10,11], S Mangin[12], P Pirro[13], B Hillebrands[13], A D Kent[14], T Jungwirth[15,16], O Gutfleisch[17], C G Kim[18] and A Berger[10]

[1] Max Planck Institute of Microstructure Physics, Halle, Germany
[2] ICN2 Catalan Institute of Nanoscience and Nanotechnology, CSIC and The Barcelona Institute of Science and Technology (BIST), Campus UAB, Bellaterra, 08193 Barcelona, Spain
[3] ICREA Institució Catalana de Recerca i Estudis Avançats, 08070 Barcelona, Spain
[4] Helmholtz-Zentrum Dresden-Rossendorf e.V., Institute of Ion Beam Physics and Materials Research, Bautzner Landstrasse 400, 01328 Dresden, Germany
[5] School of Physics and Astronomy, University of Leeds, Leeds LS2 9JT, United Kingdom
[6] Center for Memory and Recording Research, University of California, San Diego, La Jolla, CA 92093-0401, United States of America
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[10] CIC nanoGUNE, E-20018 Donostia-San Sebastian, Spain
[11] IKERBASQUE, The Basque Foundation for Science, E-48013 Bilbao, Spain
[12] Institut Jean Lamour, UMR 7198 CNRS-Université de Lorraine, France
[13] Fachbereich Physik and Landesforschungszentrum OPTIMAS, Technische Universität Kaiserslautern, 67663 Kaiserslautern, Germany
[14] Department of Physics, New York University, New York 10003, United States of America
[15] Institute of Physics, Czech Academy of Sciences, Czech Republic
[16] University of Nottingham, Nottingham, United Kingdom
[17] Material Science, TU Darmstadt, Darmstadt, Germany
[18] Department of Emerging Materials Science, DGIST, Daegu, 42988, Republic of Korea

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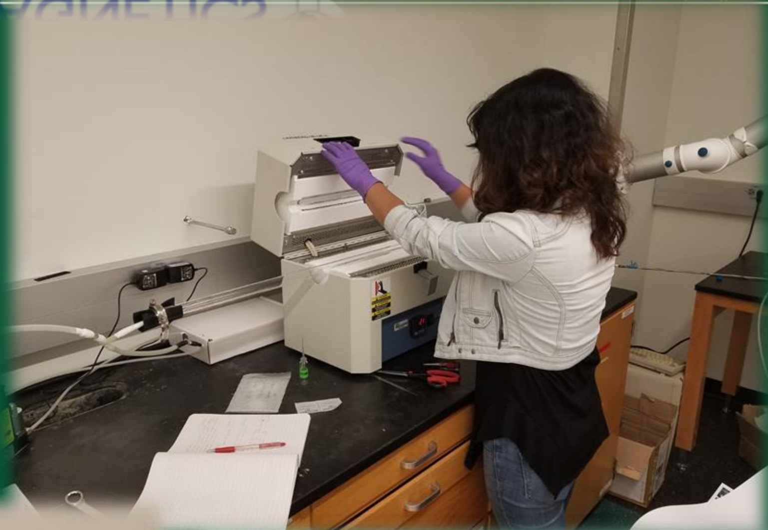
Summary

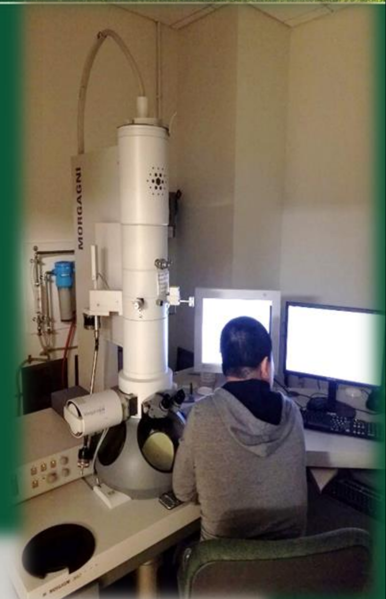
Functionalized magnetic nanoparticles with variable size and shapes for nanomedicine applications

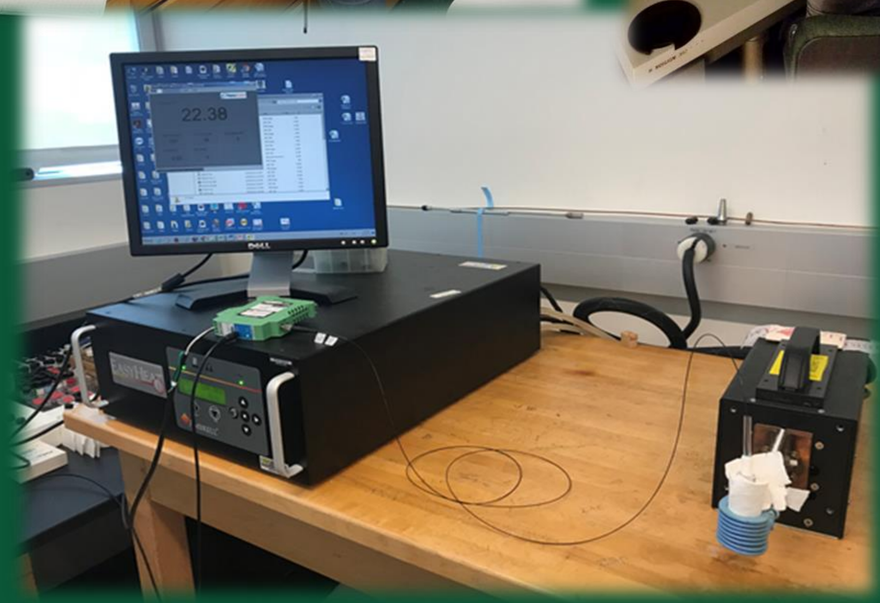
The importance of anisotropy and its influence on functional response in hyperthermia and tunable RF device applications

SIZE DOES MATTER

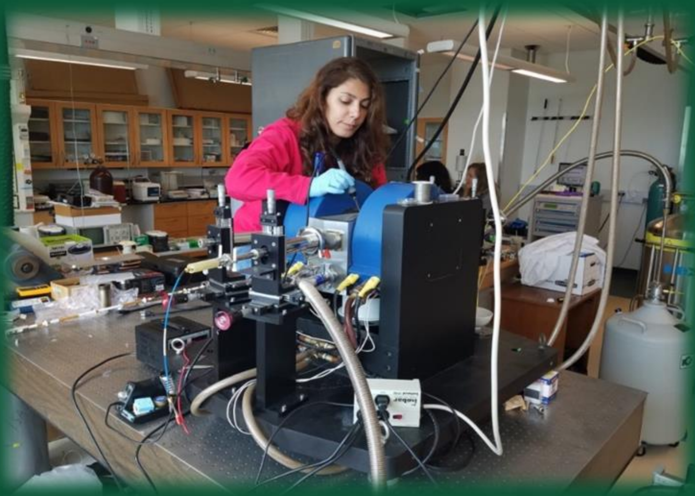
Nano size that is….and shapes, surfaces and interfaces







Some sample fabrication and characterization facilities at USF Functional Materials Laboratory



Advanced DC, AC, RF magnetization, transport and thermal measurements @USF Functional Materials Laboratory

The USF FML group and IEEE Magnetics Society thanks you for your attention…

FML group seen here doing what we love the most…discussing research in bars and coffee shops…

Yep…we put the ‘fun’ in dysfunctional ☺

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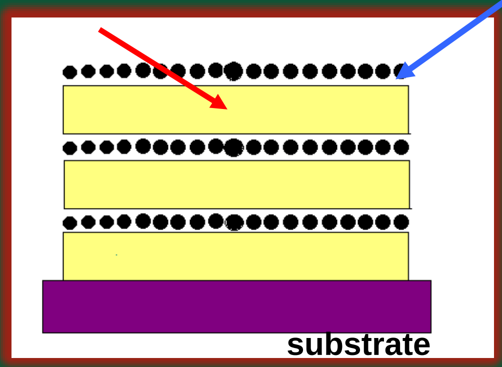
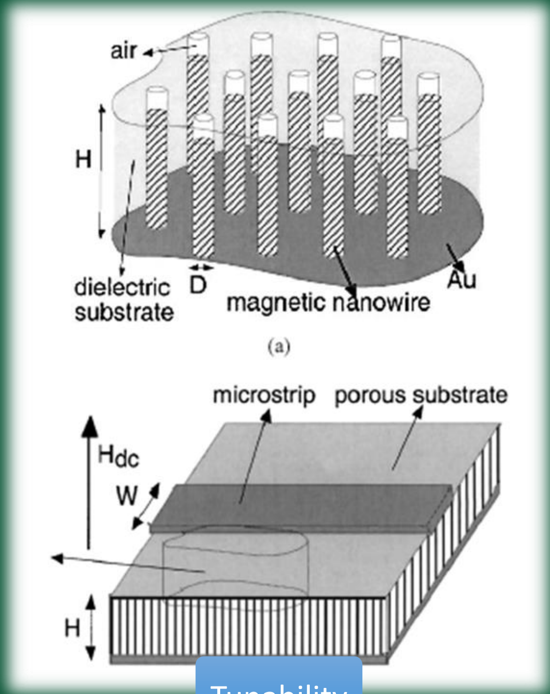
Schemes for functional material structures for tunable EM applications

(Magnetoelectric, multiferroic, meta-materials…)

Magnetic Nanoparticles

Ferroelectric polymer





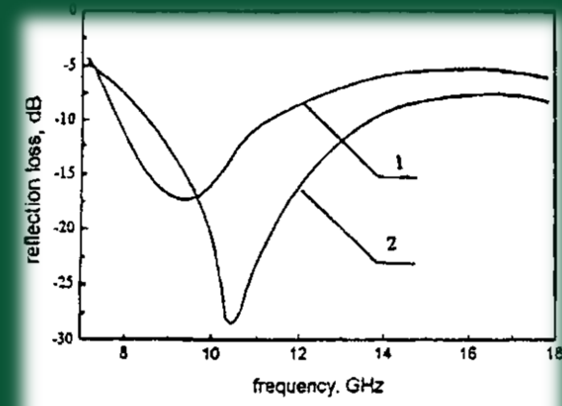
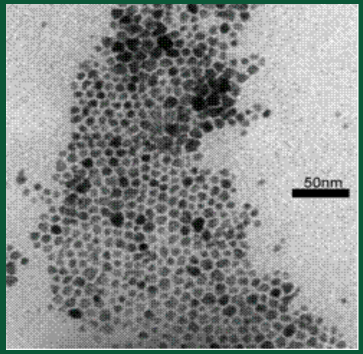
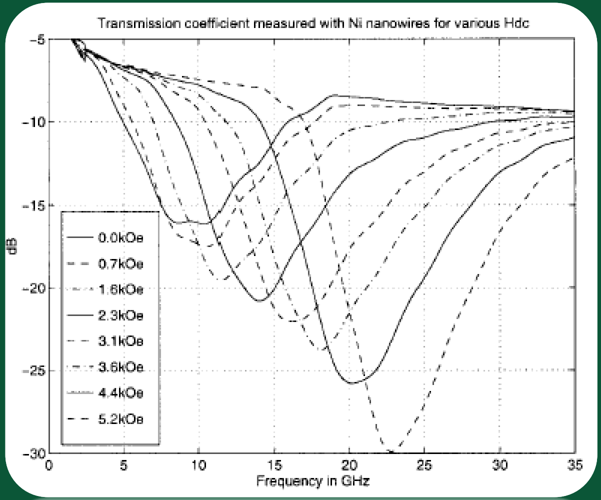


Fig. 2. Influence of the particle size on the microwave absorption: (1) 5 μm, (2) 65 nm.



$$Z = \sqrt{\frac{\mu}{\varepsilon}}$$



Tunability

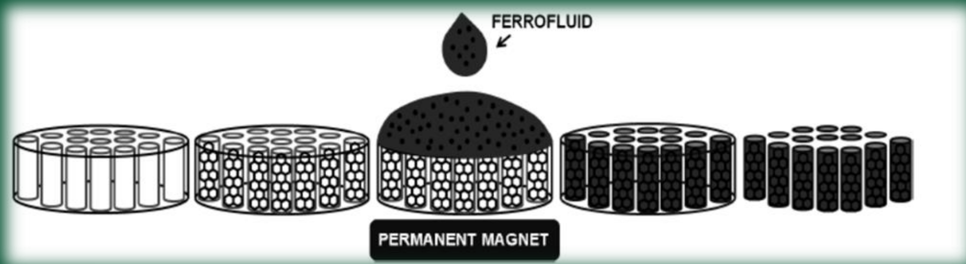
Dielectric ↔ Magnetic

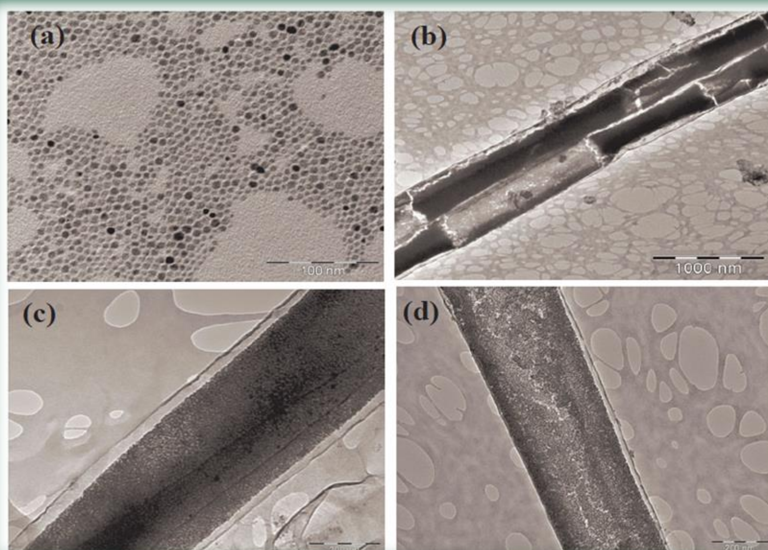
$$K = \frac{\Delta\varepsilon}{\varepsilon \tan\delta_\varepsilon}$$

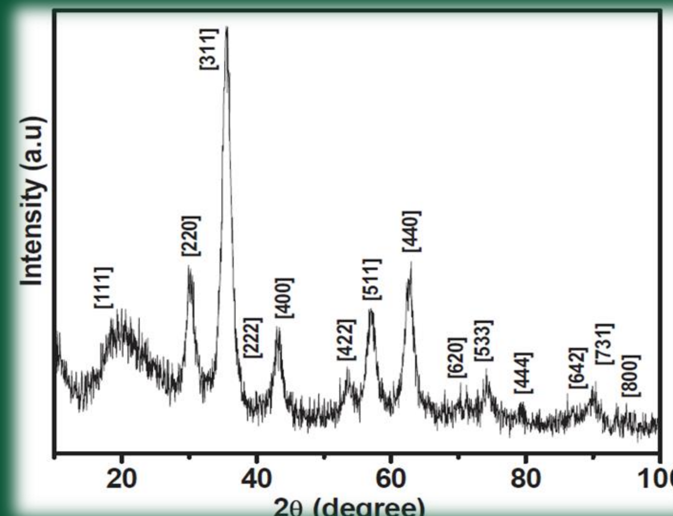
$$K = \frac{\Delta\mu}{\mu \tan\delta_\mu}$$

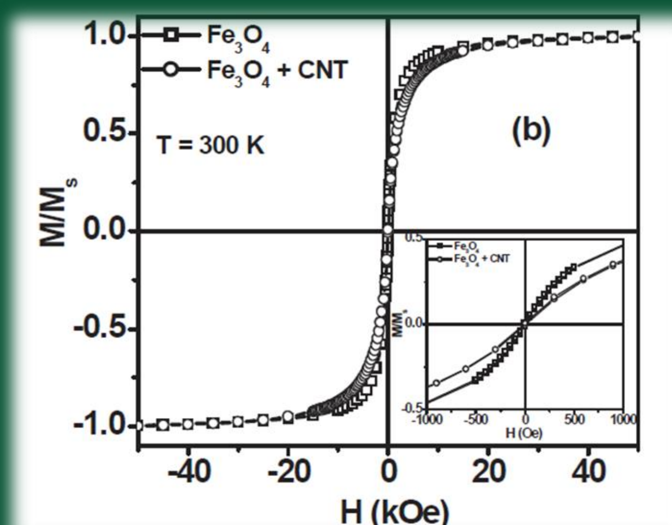
Candidate host matrix systems can range from ceramics to polymers

'Suck-cessful' synthesis of nano popsicles









IOP Publishing Nanotechnology
Nanotechnology **20** (2009) 485604 (7pp) doi:10.1088/0957-4484/20/48/485604

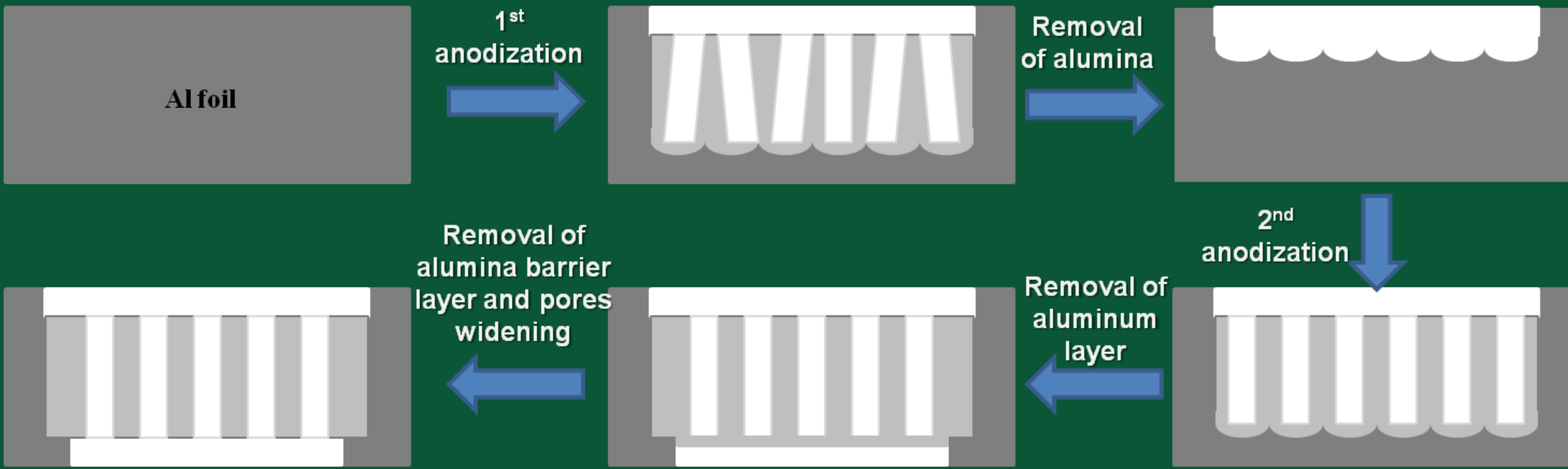
Carbon nanostraws: nanotubes filled with superparamagnetic nanoparticles

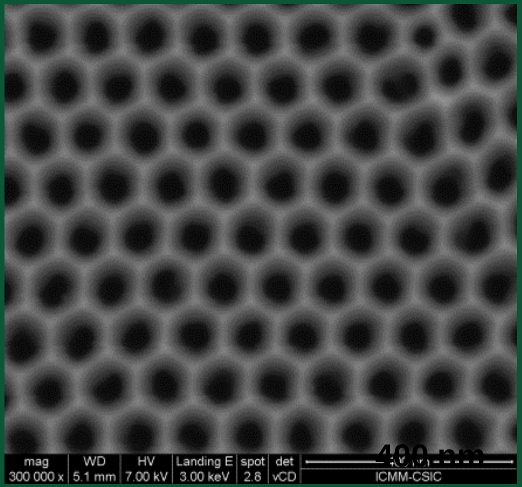
Susmita Pal, Sayan Chandra, Manh-Huong Phan, Pritish Mukherjee and Hariharan Srikanth[1]

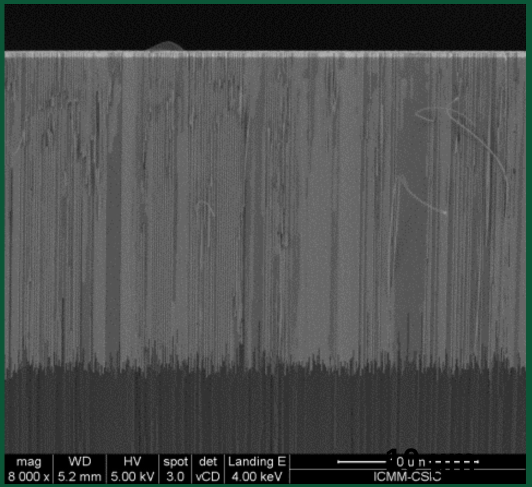
Integrated Functional Materials Group, Department of Physics, University of South Florida, Tampa, FL 33620, USA

Two-Step Anodization Process

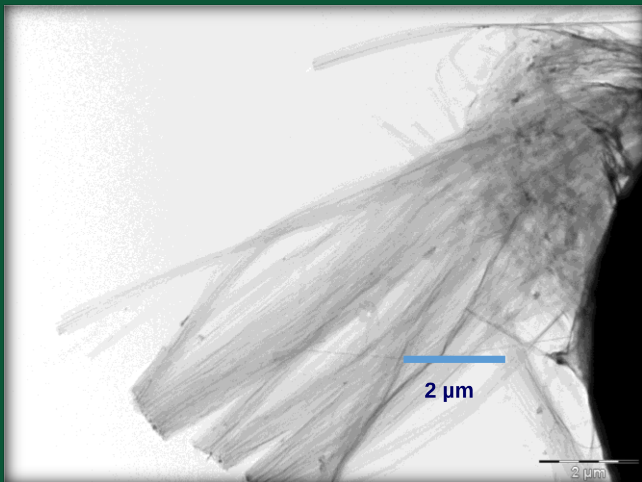
Ester Palmero and Manuel Vazquez (ICM-CSIC, Madrid)



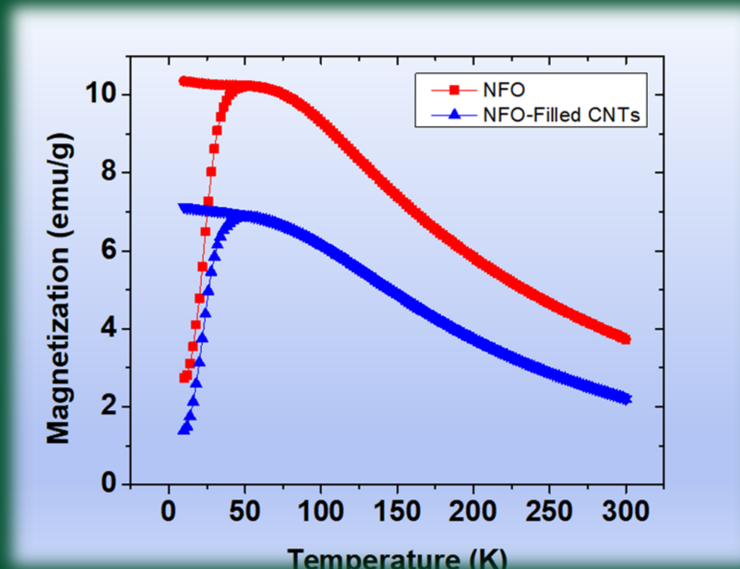




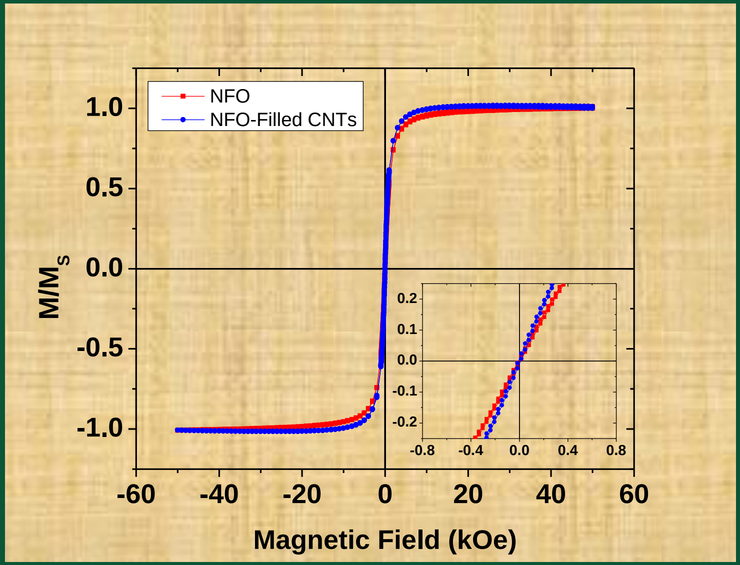
XRD and TEM for NFO and NFO-Filled CNTs from custom templates



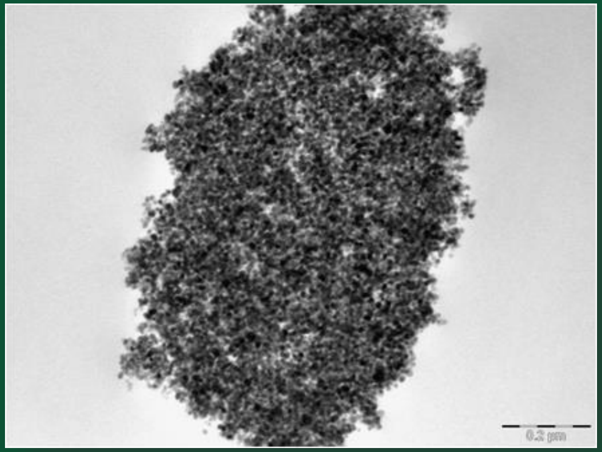
~80 nm diameter mulit-walled CNTs

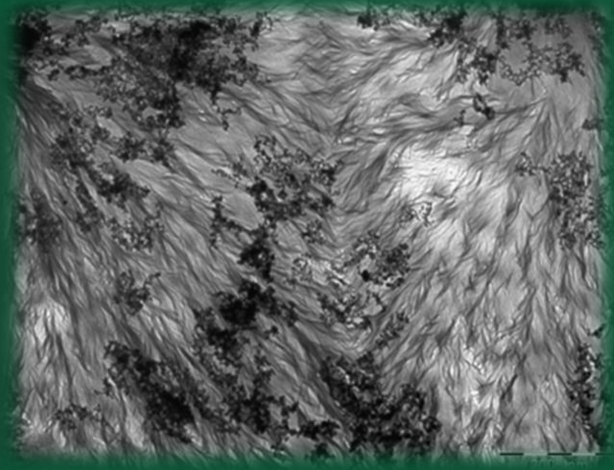


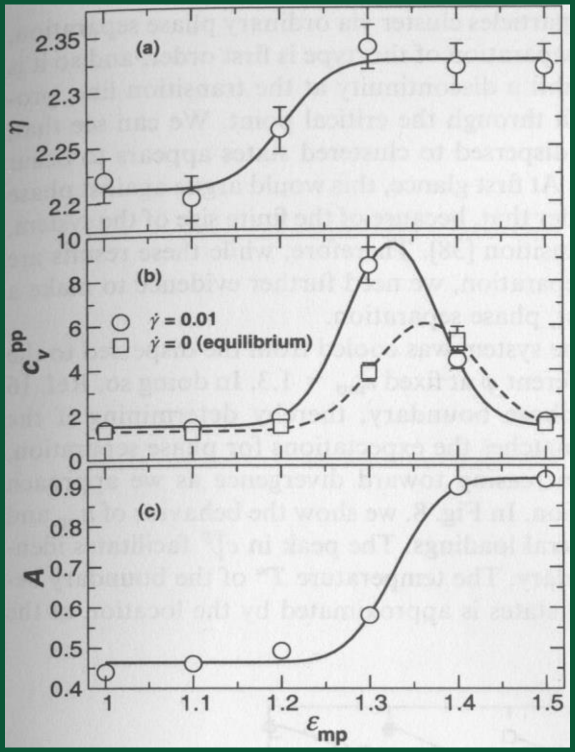
7 nm $NiFe_2O_4$–Filled CNTs



The aggravation of agglomeration….







Soft Materials Structure and Dynamics, ed J. Dutcher and A. Marangoni (Marcel Decker, New York NY, 2005)

Controlled dispersion and assembly of nanoparticles within a polymer matrix is a challenge in materials processing and manufacturing

- Clustering is a common problem in polymer composites
- Molecular dynamics simulations predict interaction conditions favoring uniform dispersion or formation of larger clusters

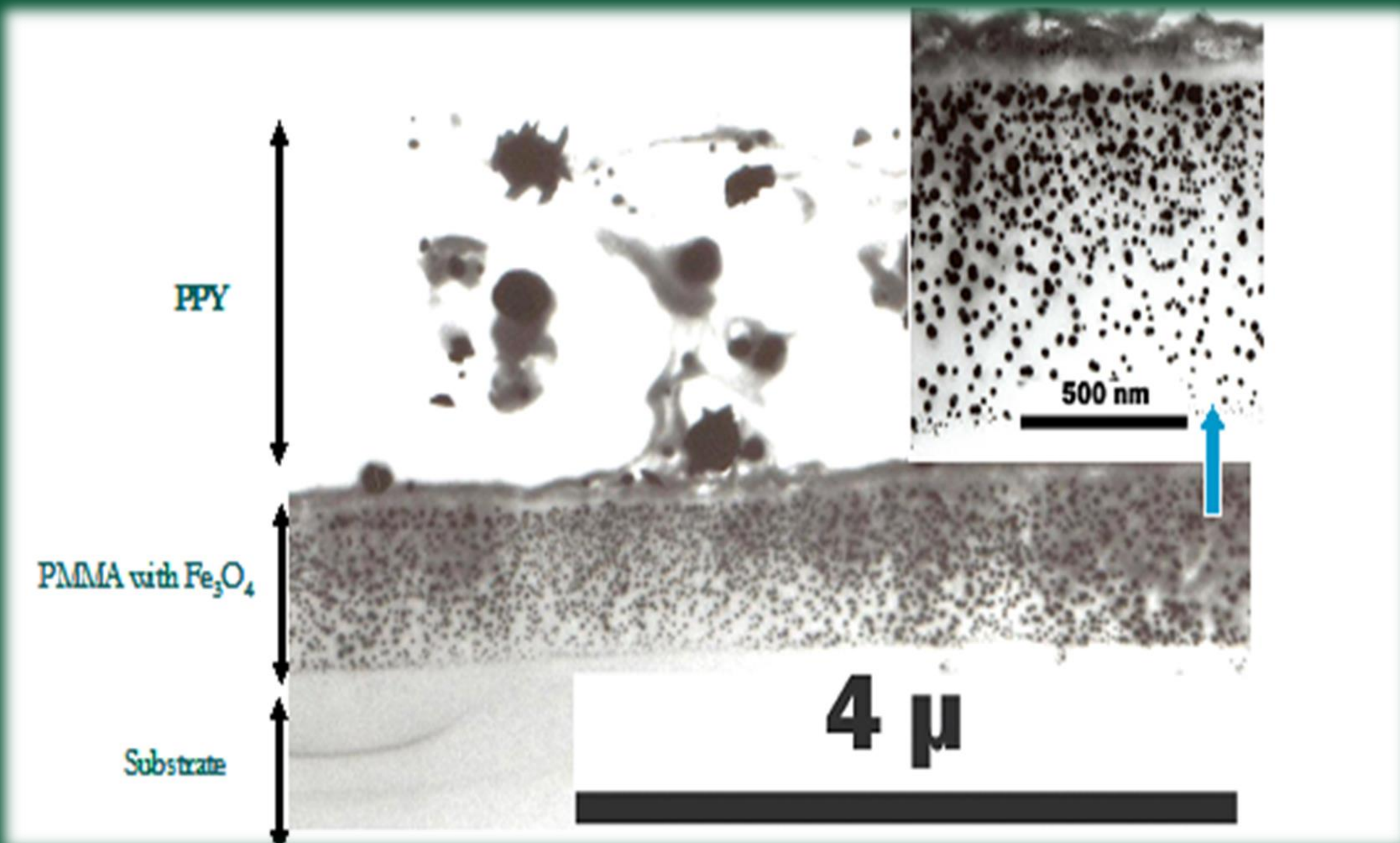
Can we control this process?

A. Heilmann, *Polymer Films with Embedded Metal Nanoparticles*, Springer, New York **2003**.

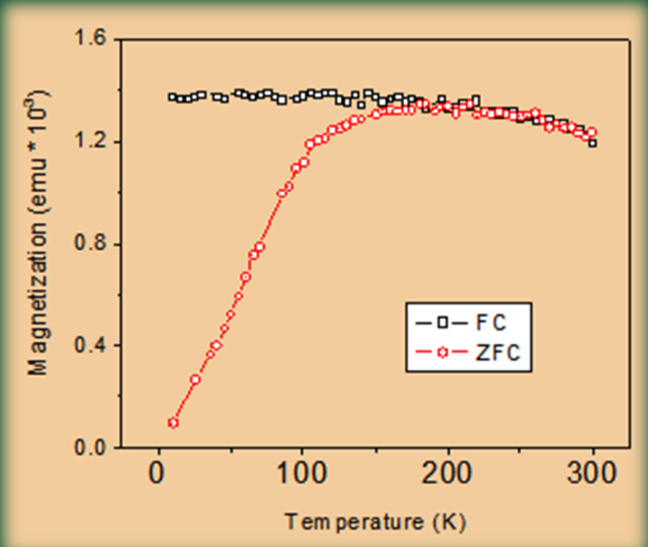
T. Desai, P. Keblinski, S. K. Kumar, *J. Chem. Phys.* **2005**, *122*, 134 910.

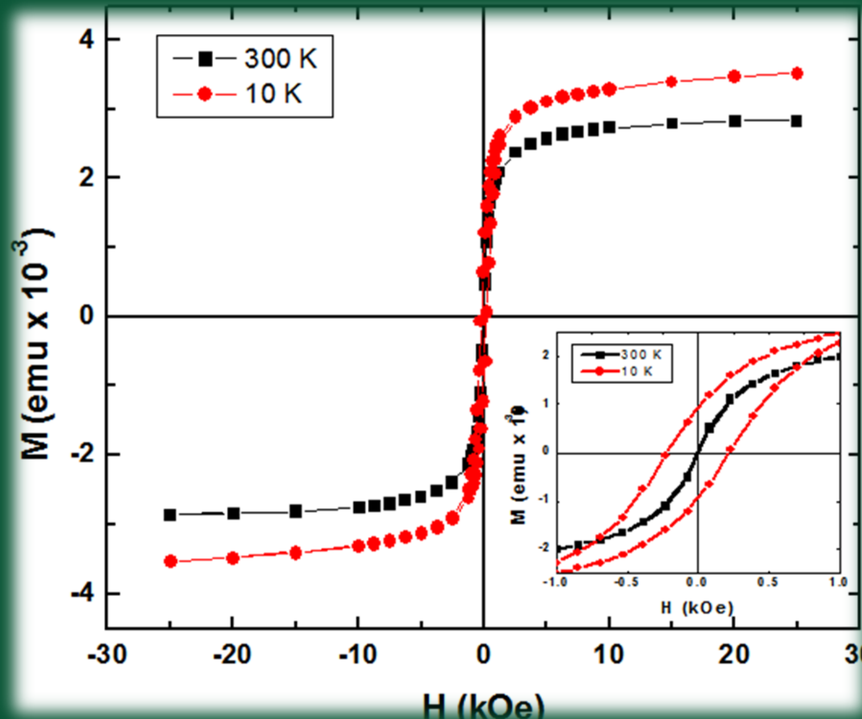
Yes! Countering steric forces with surface charges on nanoparticles

Cross-sectional TEM of Bilayer

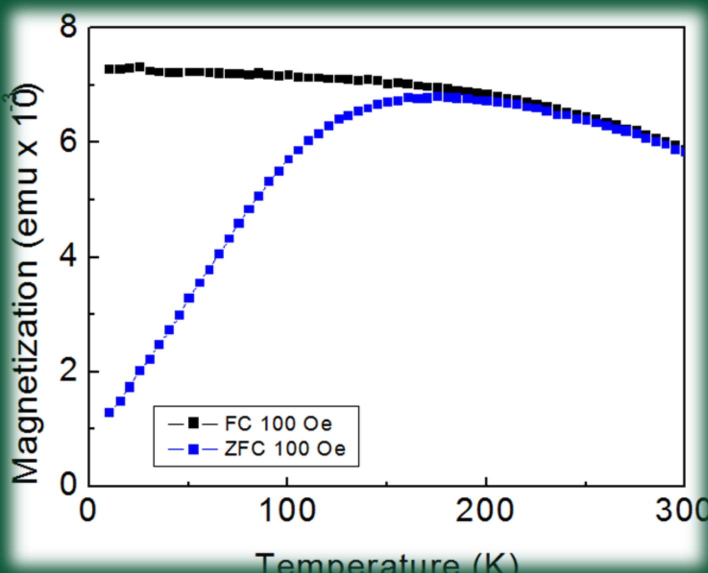


ZFC and FC curves of Fe_3O_4 nanoparticles





ZFC and FC curves of particles in PMMA



First demonstration of superparamagnetic polymer nanocomposite films

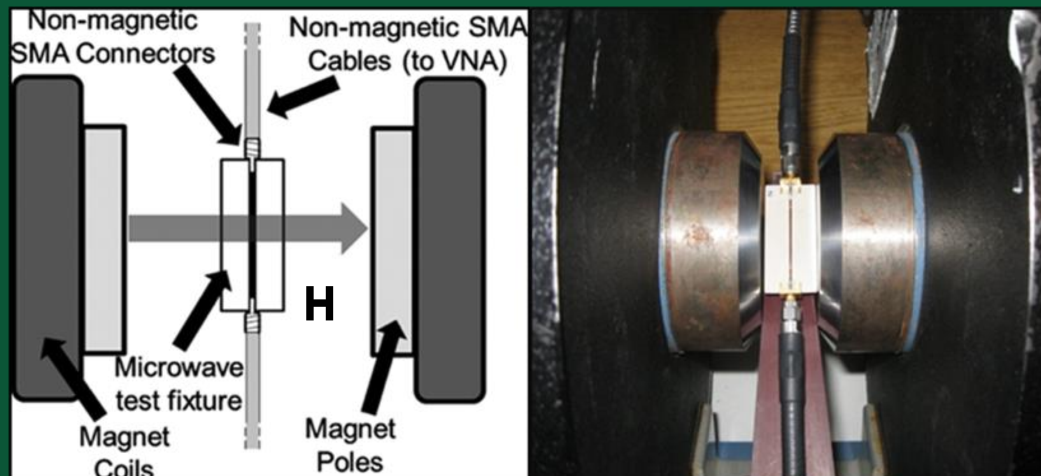
Superparamagnetic Polymer Nanocomposites with Uniform Fe_3O_4 Nanoparticle Dispersions**

By *James Gass*, *Pankaj Poddar*, *James Almand*, *Sanyadanam Srinath*, and *Hariharan Srikanth**

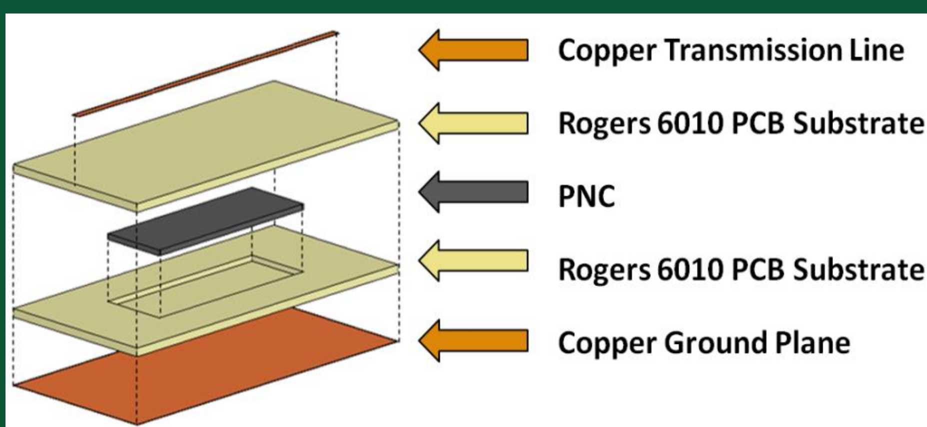
Adv. Funct. Mater. **2006**, *16*, 71–75

Microwave Tunability

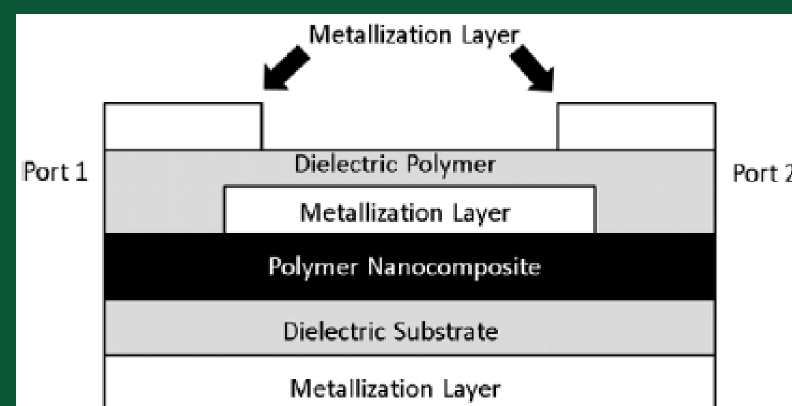
In collaboration with microwave gurus Jing Wang and Tom Weller (EE, USF)



Resonator in Electromagnet

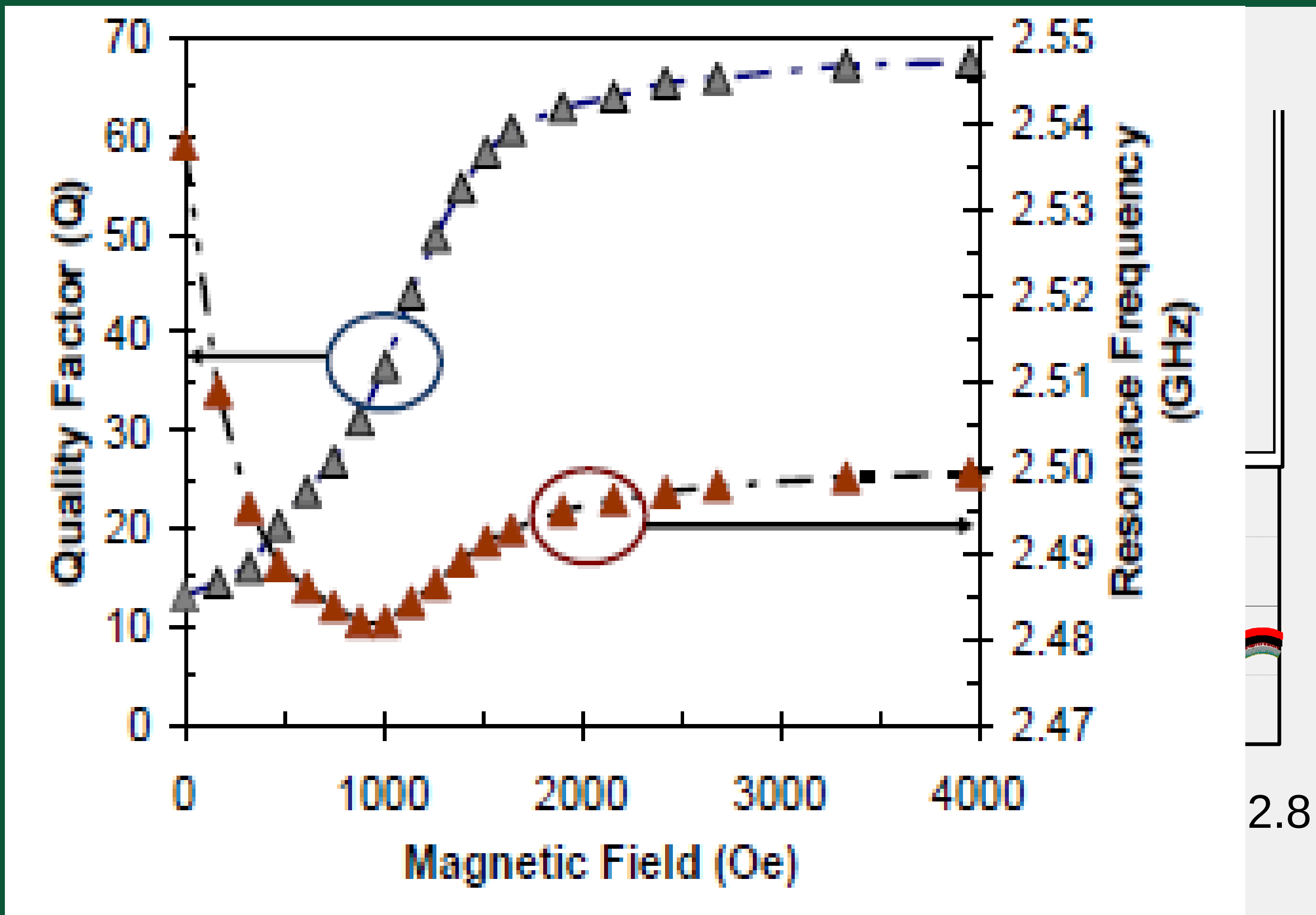


Cavity Resonator



Microstrip Linear Resonator

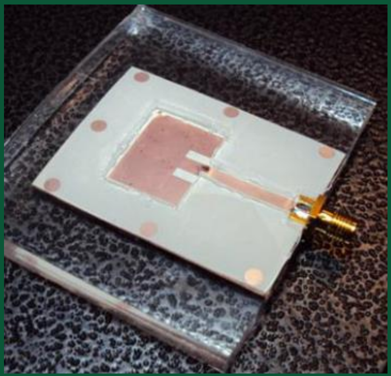
Q-factor, Power loss and Resonance Frequency

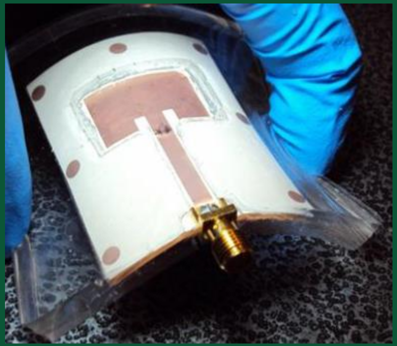


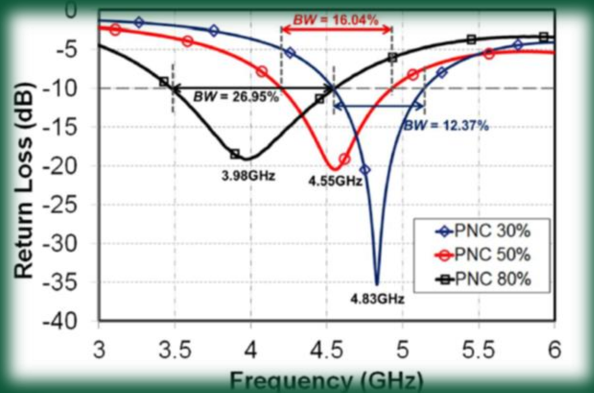
- **Q-Factor increases 5.4 times**
- **Power loss decreases by 13.7 dB**
- **Resonance Frequency varies by 57MHz**

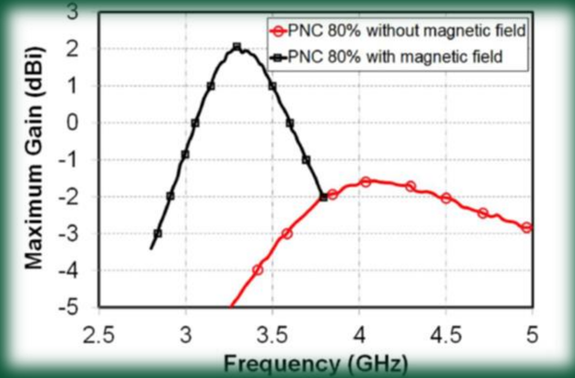
Morales, C., et al., *Tunable Magneto-Dielectric Polymer Nanocomposites for Microwave Applications*. Ieee Transactions on Microwave Theory and Techniques, 2011. **59**(2): p. 302-310.

Microstrip patch antenna fabrication and performance

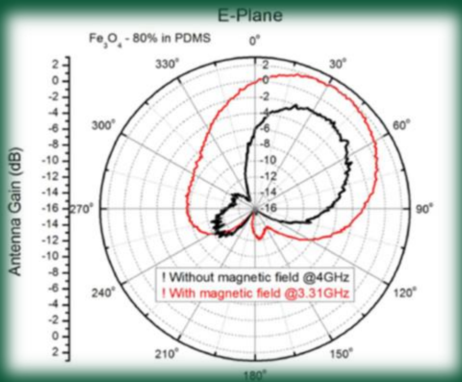








Antenna Design	Resonance Frequency (GHz)	Bandwidth (MHz)	Maximum Gain (dBi)	Efficiency	Area (mm^2)	Miniaturization % /Factor
PDMS	3.931	185 (4.7%)	5.095	50.74%	594.05 (27.25x21.8)	---
PDMS-Fe_3O_4 80% PNC	3.298	245 (7.45%)	2.12	31.28%	312.05 (19.75x15.8)	» 57% / 2.3
PDMS-Fe_3O_4 50% PNC	3.986	244 (6.12%)	4.063	44.10%	312.05 (19.75x15.8)	» 47.5% / 1.9
PDMS-Fe_3O_4 30% PNC	4.585	230 (5.02%)	5.085	40.49%	312.05 (19.75x15.8)	» 39.5 / 1.65



$$\lambda_g = \frac{c}{f\sqrt{\mu_r \varepsilon_r}}$$