Highlights

2014

Energy efficiency oriented

Mag-MEMS: Magnetic Microsystems

Foreword

Magnetic MicroSystems: Mag-MEMS

The Mag-MEMS trans-disciplinary research group develops magnetic microsystems, to address two global areas of strategic importance: micro-energy and bio-medical applications.

Our work explores the fertile grounds at the interface between various scientific fields. This approach is thus intrinsically collaborative, and we have systematically established partnerships involving researchers from local teams and laboratories with complementary skills and expertise.

Innovative devices which have recently emerged from our research exploit the beneficial advantages of scale reduction laws on magnetic interactions, including stable passive levitation of microscopic solids and fluid droplets over micro-magnets, or the efficient capture of biological entities tagged with superparamagnetic nanoparticles. Composite energy transducers based on the hybridization of complementary active materials exploit the coupling of their multiphysics properties.

The results offer potential applications within the socio-economic world:

- *The start-up EnerBee was created in 2014 to produce autonomous sensors based on contactless energy harvesters.*
- *The project Magia is currently entering its maturation phase within the technological incubator GATE1, with a view to produce simple, fast and robust magnetic immunoassays for diagnostics.*

Contents

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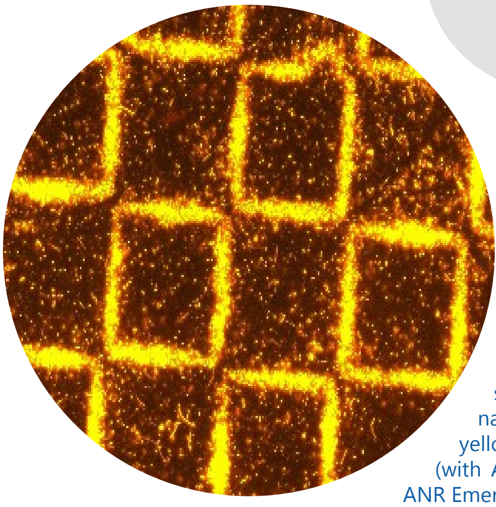
Bio-Mag-MEMS: interactions between cells and micro-magnets

Thesis prize, Grenoble INP (Paul Kaufman)

Integrated arrays of micro-magnets are used for attracting, guiding, and matrixing cells. Scale reduction laws are very advantageous to most magnetic forces, which can be inversely proportional to the dimensions of the magnets: integrating micro magnets into microsystems leads to innovative applications in biology and other fields. Two main effects can be exploited :

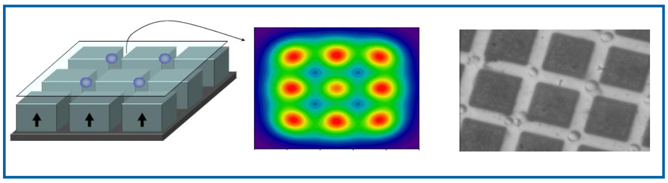
- diamagnetic repulsion: the vast majority of biological entities (cells, bacteria, viruses...) are naturally diamagnetic, they can thus be repelled by the strong magnetic gradients generated around micro-magnets. As they are usually immersed in water which is also diamagnetic, the fluid's susceptibility can be artificially boosted by the addition of paramagnetic salts (typically gadolinium, which is biocompatible and widely used as a contrast agent for MRI). This enhances the susceptibility difference between fluid and particles, leading to a diamagnetic Archimedes repulsion or levitation force.
- magnetic attraction: biological bodies can be marked magnetically, either on their surface, or by internalization. This is usually achieved using superparamagnetic nanoparticles, which are chemically functionalized.



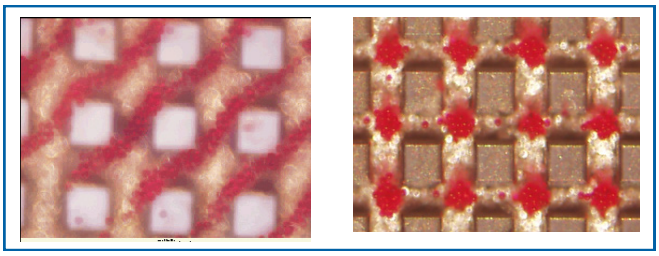
Magnetically-tagged bacteria trapped above an array of micro-magnets. Flat 50x50 µm magnetic grid obtained by thermo-patterning. Bacteria having internalized superparamagnetic nanoparticles. Detection by yellow fluorescence. (with Ampère/ECL, Institut Néel - ANR Emergent)

A multidisciplinary group of academic teams from Rhone-Alpes have pooled their complementary areas of expertise:

- State of the art integration and patterning of micro-magnets – Institut Néel
- Magnetic MEMS for microfluidics, in PTA cleanroom & CIME-Nanotec platform– G2Elab, LMGP, I.Néel,
- Microfluidics biological tests : LMGP, Biopuces/CEA, Ampère/Lyon (ANR Emergent)
- Immunoassays, electrochemical & fluorescence detection in microfluidics: LMGP
- Immunology: Institut Albert Bonniot (IAB)



Matrix of microparticles in diamagnetic levitation / confinement in a paramagnetic buffer solution. Left: Principle, Centre: Simulated magnetic traps, Right: Matrixed yeast cells (with LETI/CEA, Ampère/ECL)



Diamagnetic latex beads (red) guided and matrixed above topographically patterned micro-magnet arrays (with Néel, Biopuces, LMGP)

Contact

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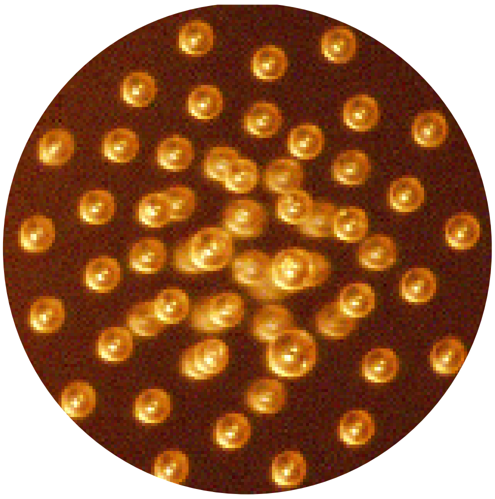
Further reading

Diamagnetic trapping of arrays of living cells above micromagnets
Kauffmann P., Ith A., O'Brien D., Gaude V., Boué F., Combe S., Schaack B., Bruckert F., Dempsey N., Haguet V. et al
Lab on a Chip 11,18 (2011) 3153-3161 [hal-00648664- version 1]

Hybrid Bio-Mag-MEMS combining magnetophoresis and dielectrophoresis
Blaire G., Masse A., Zanini L.-F., Gaude V., Delshadi S., Honegger T., Peyrade D., Weidenhaupt M., Dumas-Bouchiat F., Bruckert F. et al
European Physical Journal B: Condensed Matter and Complex Systems 86, 4 (2013) 165 [hal-00850011 - version 1]

μ SYSTEMS

Diamagnetic levitation of micro droplets above miniature magnets

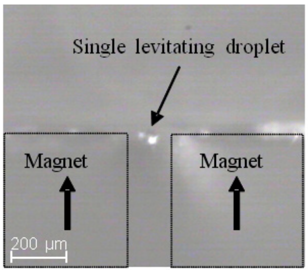


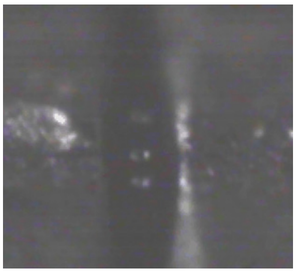
Top : Diamagnetic levitation of micro-droplets of water, mutually repulsed by their electrostatic charges.

Magnetic microsystems Mag-MEMS can offer original applications in digital micro-fluidics. Water is very slightly diamagnetic, as are most biological entities. This very discreet property is mainly observable as repulsion forces from magnetic sources and gradients. Repulsion is quite exceptional in the natural world, and can be exploited for the stable levitation of diamagnetic objects above simple magnets, passively, without the need for power supply, and at room temperature. Scale reduction laws are favorable to this effect, which scales up with miniaturization. Levitation becomes easily observable when dimensions are reduced beneath the millimeter range. This offers fascinating opportunities for integrated magnetic microsystems.

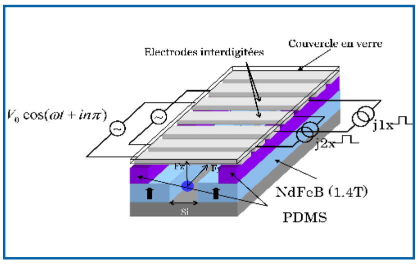
Research teams from G2Elab, Institut Néel, Biopuces/CEA and LETI in Grenoble have jointly developed such applications, where passively levitated micro-droplets may be used as biological reactors. Reactions can happen in micro-gravity conditions. Cross-contamination between samples can be virtually eliminated, as well as unwelcome adhesion of cells on the channel walls. The absence of mechanical contact allows micro-droplets to be moved with minute forces, thus acting as extremely sensitive micro-sensors, for the detection of acceleration or electrostatic forces for example.

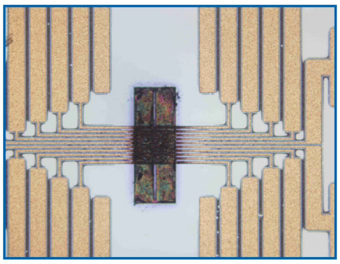
Such innovative functions should contribute to the development of Lab-on-Chip and μTAS (micro-Total Analysis Systems) devices. Biological entities may be manipulated and analyzed, using reduced volumes of molecules and reactive agents, without the need for complex fluidic pumps and valves.





Levitation of 30 μm water micro-droplets over millimetre-sized NdFeB magnets
Left: side view, 1 droplet. Right: top view, 3 droplets





MEMS combining diamagnetic levitation and dielectrophoretic manipulation
Left : principle. Right : integrated device (with LMGP, Néel, LTM LETI)

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FURTHER READING

P. Kauffmann, H. Chetouani, G. Pham, V. Haguet and G. Reyne
Magnetophoretic and Dielectrophoretic Actuations Coupled with Diamagnetic Trapping in Air and Liquids
Sensor Letters Vol. 7, NO. 3, pp.1-5, 2009

Stable, natural diamagnetic levitation of micron-sized solids

Many materials are naturally diamagnetic, and are thus repelled by magnetic field sources such as permanent magnets. These forces are extremely weak, and are usually negligible to the naked eye. However, this effect benefits from scale reductions: in the range of about 10 µm, the weight of micro-particles can be compensated and levitation then becomes possible using smart arrangements of permanent magnets of similar size.
This levitation is stable, achieved in air or vacuum at room temperature, and does not require the use of any external energy supply, electronics control, nor superconductors.
Thus we were able to levitate and manipulate Bismuth particles (size 10-15 µm) above permanent magnet strips (Fig. 1). The Si-integrated, 30 µm thick strips of NdFeB were made in Institut Néel using PVD combined with micro-technology.

The repulsion between permanent magnets and diamagnetic materials was then used to levitate a double-dipole miniature magnet 15 µm above a polished graphite plate (Fig. 2). Highly Oriented Pyrolytic Graphite (HOPG) is today the material exhibiting the highest known diamagnetic properties.
This experimental world premiere was achieved during H. Chetouani's & Ch. Pigot's PhDs and H. Profijt's Masters, under the supervision of G. Reyne & O. Cugat. The work was carried out within the C²µ Microsystems / FMNT facility at MINATEC.
These innovative results herald many applications in the fields of µ-conveyors, ultra-sensitive accelerometers and gyrometers, and frictionless µ-actuators.

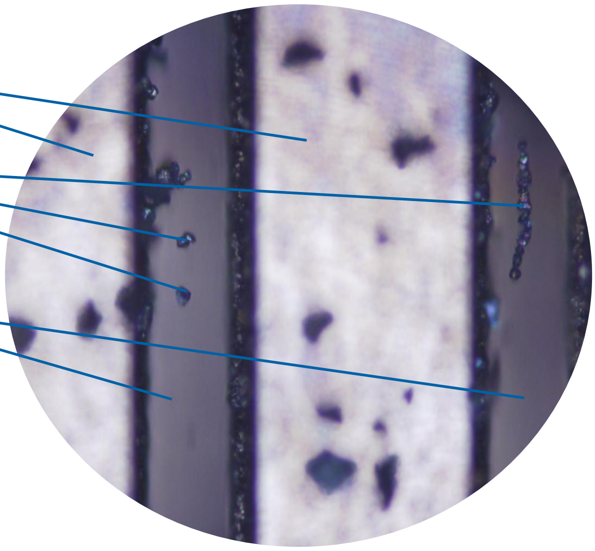

Fig.1 : Bi particules in stable levitation above permanent magnet strips.
- left: two particles kept 20 µm apart by induced dipolar repulsion.
- right: 16 particules stuck together by Van der Waals forces.

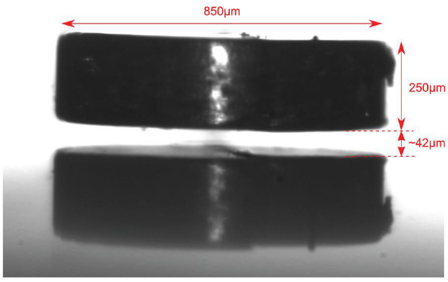

Fig.2 : double-dipole miniature magnet (phi 850 µm) in stable levitation 15 µm above polished graphite.
The twin-magnet structure is visible in the reflection.

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«Stable diamagnetic self-levitation of a micro-magnet by improvement of its magnetic gradients»
Journal of Magnetism and Magnetic Materials, 321, 4 (2009)

Kokorian Jaap, Profijt Harald, Kustov Mikhail, Abelmann Leon, Reyne Gilbert, Dempsey Nora M., Cugat Orphée
«Diamagnetic levitation of NdFeB films above Highly Oriented Pyrolytic Graphite: towards micromachined flying carpets»
EUROMAT 2009 (European Congress and Exhibition on Advanced Materials and Processes), 10/07/2009, Glasgow, Royaume-Uni

Multiferroic composites for integrated magnetoelectric devices

PhD Gor LEBEDEV (Dec. 2012) - Collaboration: LETI/CEA (Bernard Viala)
Thesis first prize (SEEDS - Club EEA)

This research focuses on multilayered magnetoelectric composites, within the framework of multifunctional materials. These novel materials exhibit coupled physical properties (magnetic, electric, optical, mechanical...) which can be controlled by an external stimulus of a different nature (stress, temperature, magnetic or electric field, light...). Currently, the most sought-after multifunctional materials include magnetoelectric materials, the magnetic properties of which (permeability, magnetization, coercivity, anisotropy) can be controlled with a simple electric field. This is easily understandable, since the staggering range of potential industrial innovations includes smart RF components (antennas, oscillators, filters), magnetic sensors (magnetometers, current sensors), transducers (voltage controlled actuators), and micro-generators (energy harvesting, autonomous sensors...).

Until recently, the literature has mainly reported on natural multiferroics, which exhibit several ferroïc orders, theoretically offering the intrinsic capability of controlling magnetic properties via electric fields. Early research was mainly theoretical, but the first experiments were hampered by the scarcity of natural multiferroic materias, and by their weak magnetoelectric coupling.

Recent years have brought dramatic improvements, thanks to two advances. The first one was the rapid evolution of fabrication techniques which made possible the deposition of multilayered materials in thin films. Second, novel magnetoelectric composite materials coupling magnetostrictive and piezoelectric materials are being intensively explored. Within these artificial multiferroics, the coupling between the ferroic orders was increased by several orders of magnitude. This conjunction enables the development of novel integrated devices with direct practical applications, and which now guide fundamental research.

Our work yielded three important results:

- a phenomenological approach based on energy analysis, to describe the panorama of effects expected in laminated multilayered composites, was used to determine the key properties of materials ($\lambda s/Ms$ ratio) requested for a high magnetoelectric effect. Macroscopic composites based on FeCoB thin films deposited onto piezoelectric substrates (macro fibre composite) were developed, exhibiting record magnetoelectric coefficients of 250 V/cm.Oe.
- novel concepts of magnetoelectric composites based on antiferromagnetically coupled magnetic materials were introduced. Their study produced spectacular results on the voltage control of the direction of magnetization, and the electrical control of several stable states of magnetization (2 patents).
- one of the first multiferroic devices for microelectronics was designed and built : an innovative tunable RF inductor, based on our novel magnetoelectric composites.

Only a handful of teams have worked on such composite multiferroic devices, based on bulk magnetostrictives, and the planar approach is very recent. We are currently the only team to have introduced the continuous magnetic drive of the angular position by voltage-control of the easy axis, which opens very promising perspectives with minimal power consumption and Joule losses.

This pluridisciplinary research results from our fruitful collaboration with CEA/DCOS/LCRF and several other local labs. This partnership on composite multiferroics is now consolidated with several joint PhDs, including an innovative energy harvesting technology which is currently being industrialized (start-up EnerBee, 2014).

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Further reading

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Journal of Applied Physics, vol 111, n°7, 07C725

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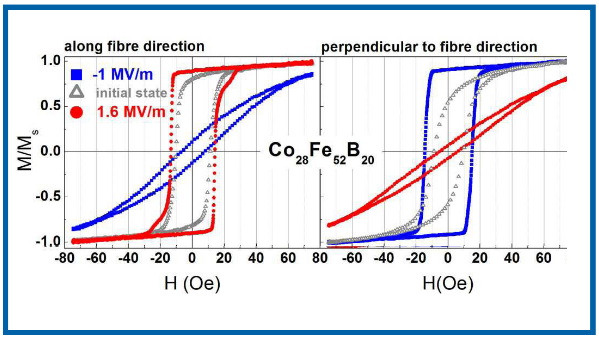
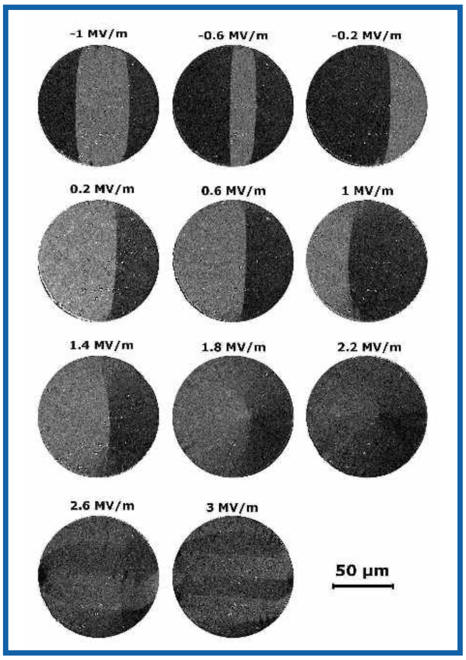
«Electric field controlled magnetization rotation in exchange biased antiferromagnetic/ferromagnetic/piezoelectric composites»
Applied Physics Letters, 99-23 (2011) 232502-232502-3

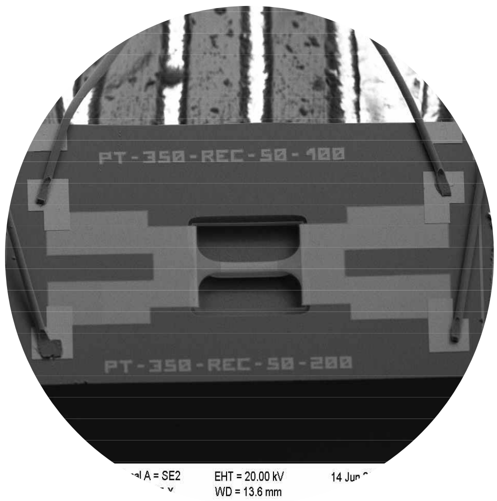


Normalized magnetic hysteresis cycles switched by applying opposite electrical fields, and measured along the fibres (easy axis) and perpendicular to the fibres (hard axis).



Direct magneto-optical Kerr observation of the rotation of the easy axis in 100 µm circular pods, for increasing values of the electric field applied to the demagnetized composite.

a



b

Integrated devices Si (~1 mm^2):
Piezoelectric / magnetostrictive multilayers (100 nm PZT + FeCo 100 nm)
a) 3-phased transducer for 360° easy axis rotation.
b) single beam RF tunable antenna (tested, functional)