# MEMS : an overview

- What ? – why ? – how ?
- Magnetic MEMS

# Micro-magnets for MEMS

- Candidate Hard Magnetic Materials
- Preparation routes
-Micro-fabrication
-Beyond magnets

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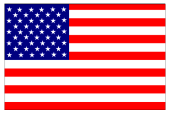
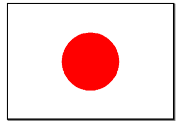
ESM2007 - September 9-18th 2007, Cluj-Napoca, Romania

# What are MEMS ?

MEMS : “Micro-Electro-Mechanical Systems” 

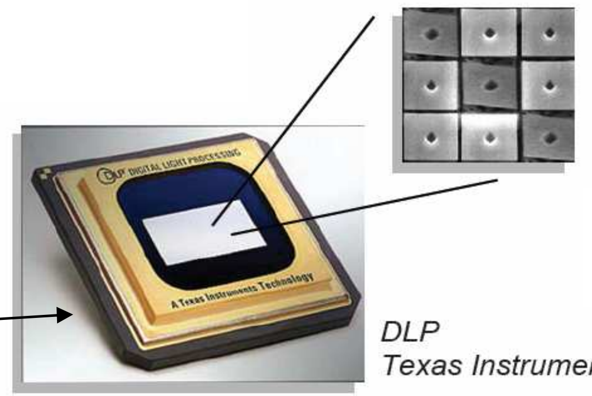
“Microsystems Technology” (MST)  “Mecatronics” 

machines which range in size from µm to mm
e.g. actuators, motors, generators, switches, sensors….

**electrostatic, thermal, piezoelectric, piezoresistive, capacitive, magnetic…**

***Common examples***

- inkjet printer heads (ink ejection)
- accelerometers ( airbag deployment…)
- gyroscopes ( trigger dynamic stability control…)
- pressure sensors (car tires, blood…)
- displays (DLP video projectors…)
- optical switching technology (telecommunications)



*DLP*
*Texas Instruments*

# Domains of application

## Telecommunications

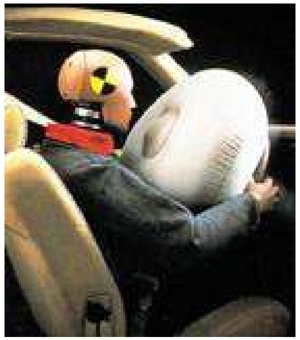

µ-switch for mobile phones
commutators for optic fibre networks

## Data storage

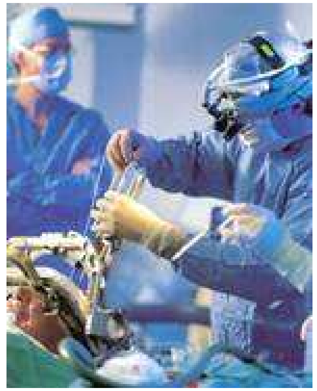
µ-positionner for HDD heads
motorisation for HDD

## Bio-technologies

less-invasive surgery, µ-injections,
lab-on-chip, ophtalmology…



## Automotive
## Aeronautics (Glass-cockpit…)
## Space (1 kg = 20 k$!)



## Consumer electronics

media players, gaming devices, footpods..

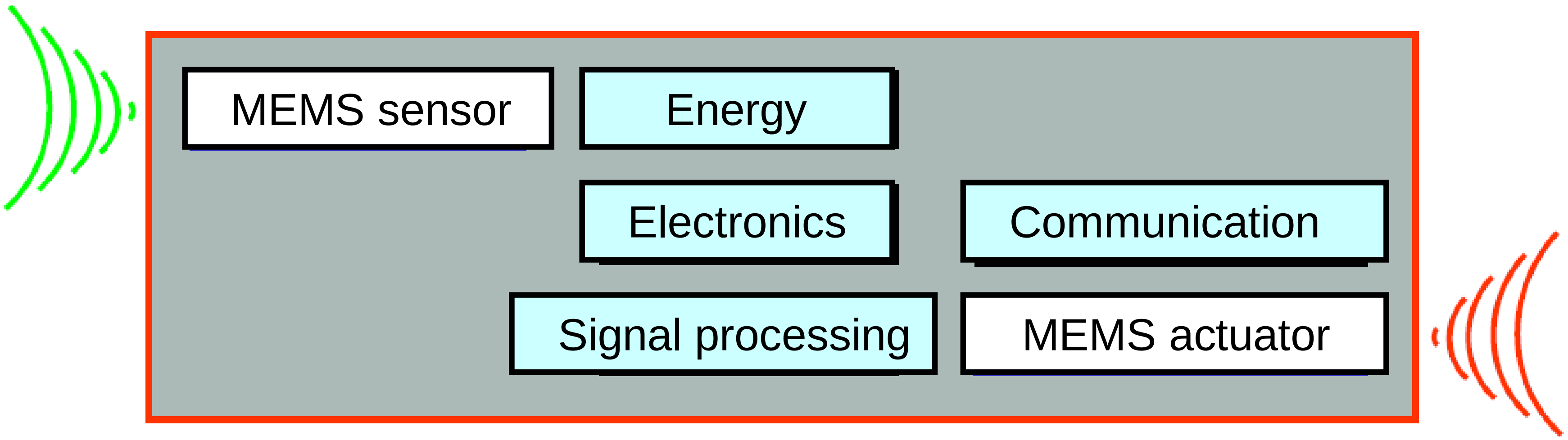
# Why are MEMS of interest ?

***SIZE*** : small and light !
portable applications - mobile phones, aerospace devices …
limited space applications - implantable devices, micro-surgery…..

***COST*** : batch processing ⇒ cheap

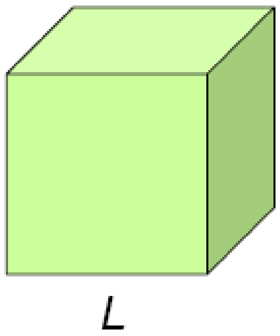
***ENERGY EFFICIENCY*** : they use little power themselves,
+ they can be used to improve efficiency in bigger systems (cars, houses..).

***INTELLIGENT SYSTEMS***: MEMS (eyes + arms + legs) + ELECTRONICS (brain)



# Why size matters…..

effects not exploitable at the macro-scale can become of interest at the micron-scale



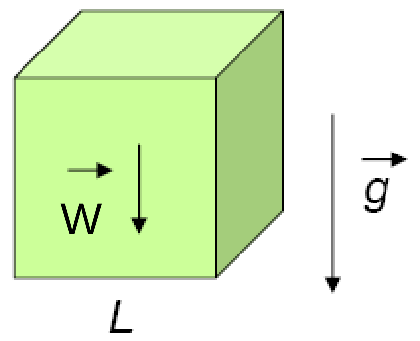

Volume $V = L^3$
Surface $S = 6L^2$

: Surface / Volume = $\frac{6}{L}$

Surfaces effects dominate at small scales

# Scaling laws

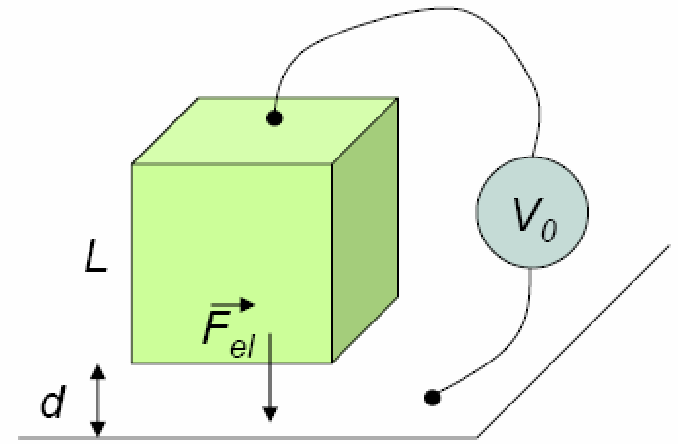
Gravitational force (weight)




$$W = mg = \rho\, V g = \rho\, L^3 g$$

$\propto L^3$

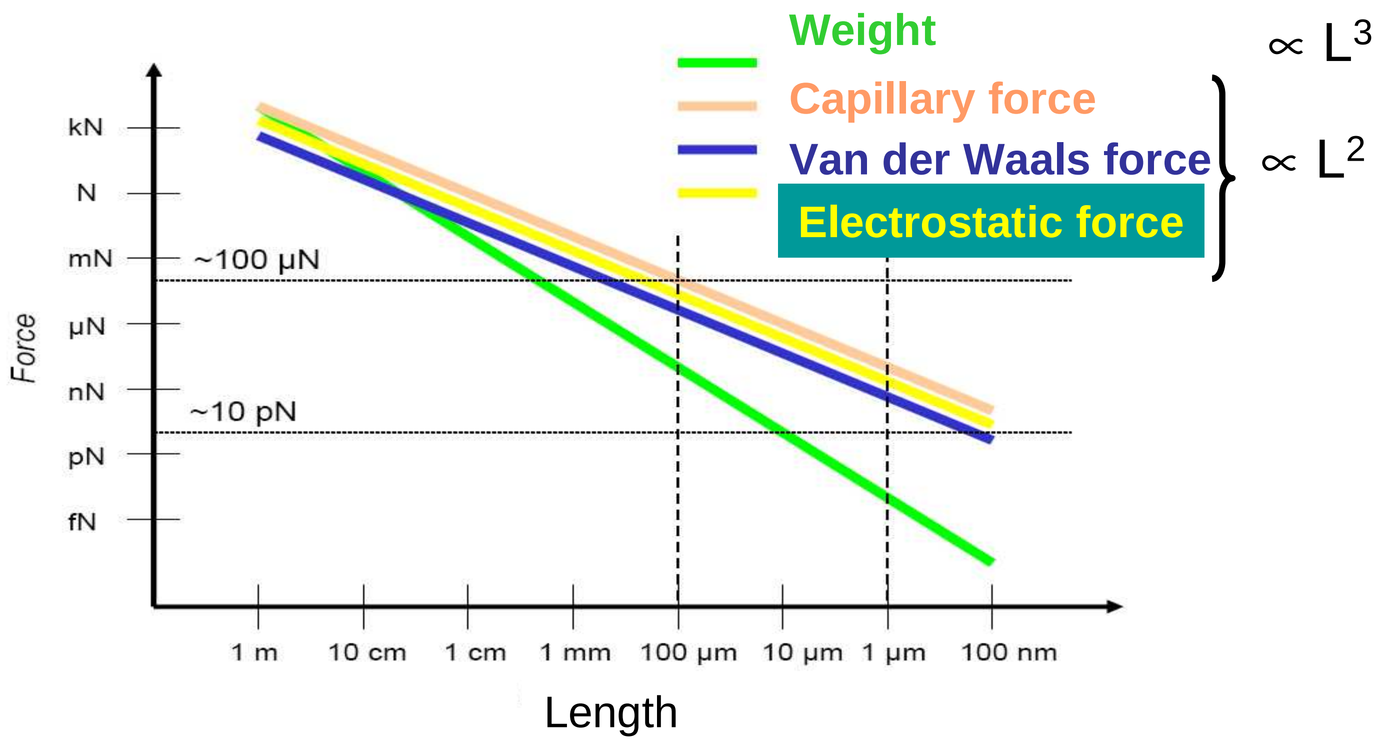
Electrostatic force




$$F_{el} = \frac{\varepsilon_0 S V_0^2}{2d^2} = \frac{\varepsilon_0 L^2 V_0^2}{2d^2}$$

$\propto L^2$

# Scaling laws for different forces




For MEMS, **weight is negligible,**

**surface forces** may cause **movement or deformation**:

electrostatic force can be used for actuation (controlable)

capillary force can lead to MEMS failure (during fabrication or use)

Van der Waals force can lead to stiction

# Scaling laws

**size reduction**

increases -resonance frequency

$\propto 1/L$

decreases -response time

(e.g. thermal exchange)

-stiffness

-power consumption

# How are MEMS made ?

MEMS are made with techniques originally developed for the microelectronics industry

Building block for MEMS fabrication :

I – Deposition

II - Lithography

III – Etching

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# Deposition

## **chemical** reaction:

- **C**hemical **V**apor **D**eposition (CVD)
- Electrodeposition
- Thermal oxidation

## **physical** reaction:

- **P**hysical **V**apor **D**eposition (PVD)
- Casting

# Chemical deposition

## Chemical Vapor Deposition

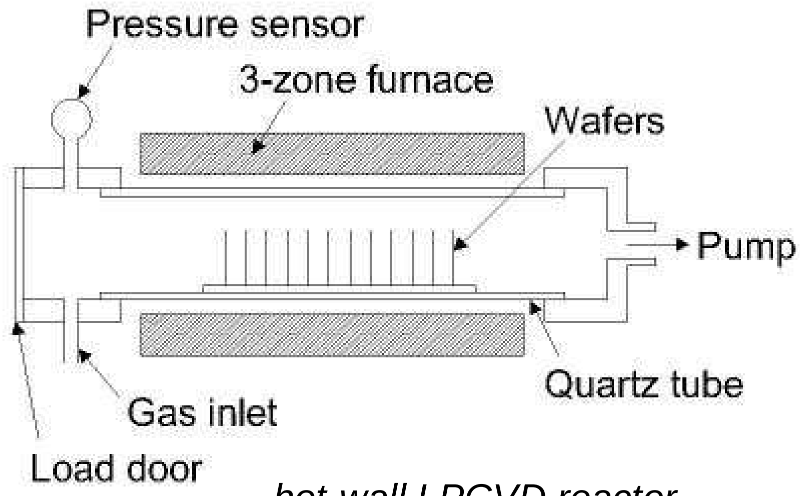
-**L**ow **P**ressure CVD (LPCVD)

deposition on both sides of wafer

-**P**lasma **E**nhanced CVD (PECVD)

deposition on one side of wafer

!!! hazardous byproducts !!!



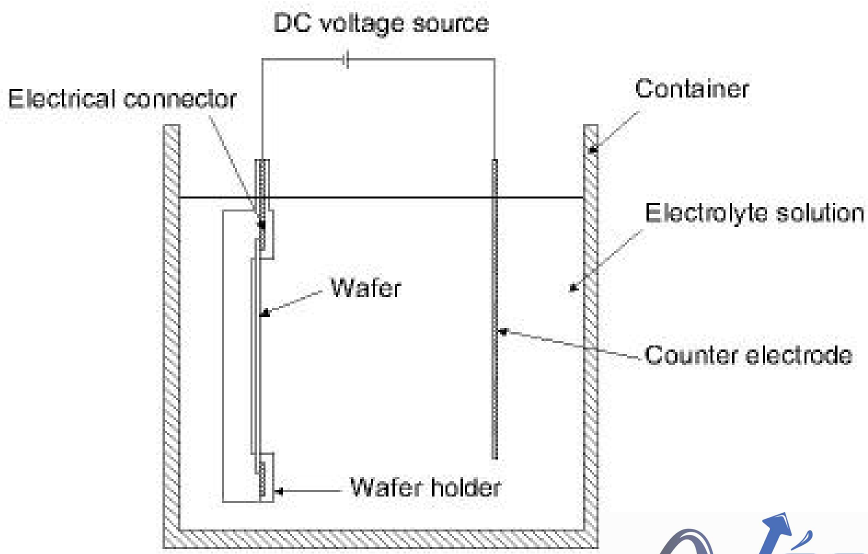

*hot-wall LPCVD reactor*

## Electrodeposition

restricted to electrically conductive materials

Well suited to Cu, Au, Ni

1µm to >100µm

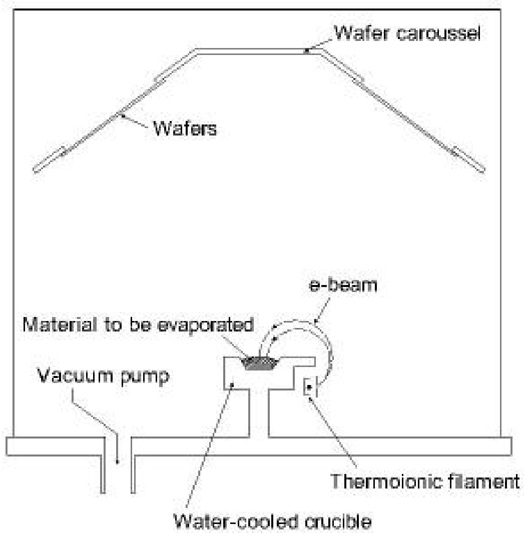


# Physical Vapor Deposition (PVD)

far more common than CVD for metals (lower process risk, cheaper material costs)

## Evaporation

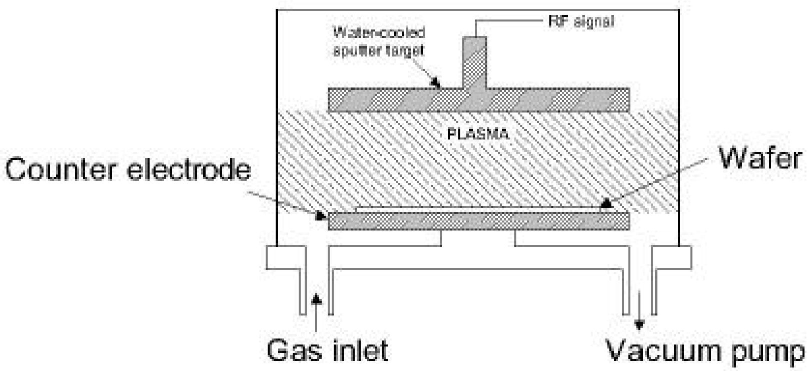
heating : e-beam or resistive - material specific




## Sputtering

ion bombardment ($Ar^+$) of target

material released at much
lower T than evaporation
Well suited to alloys

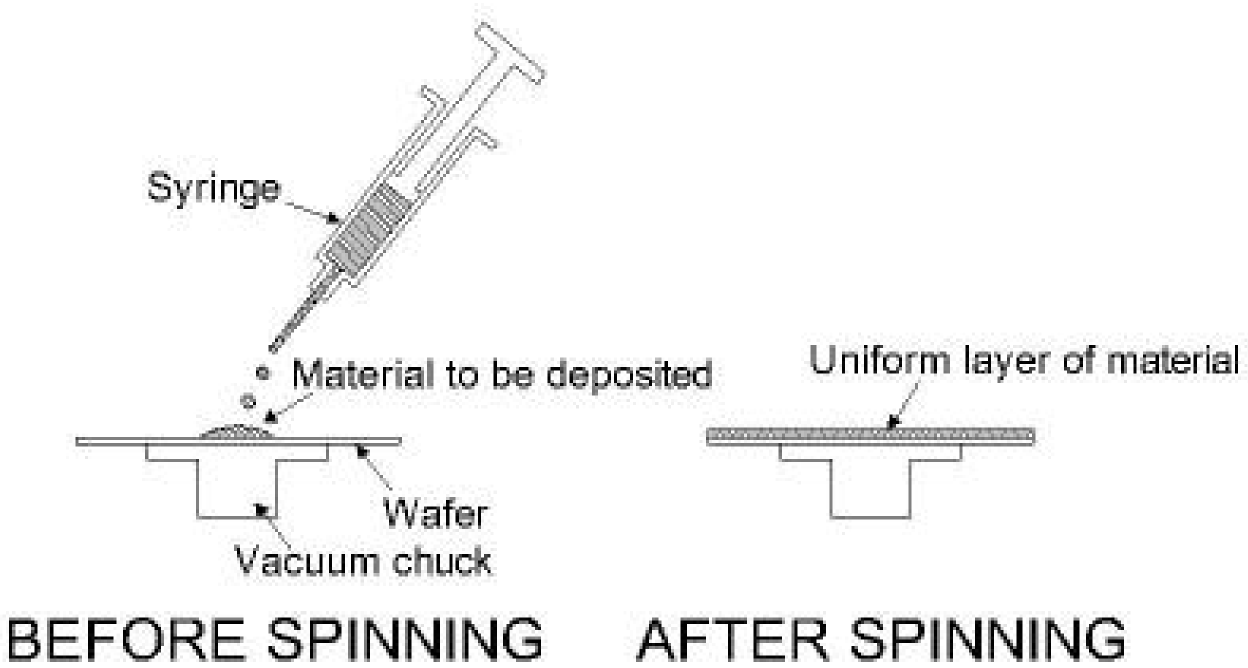


# Casting

-material dissolved in a solvent and applied to the substrate by spraying or spinning

- used for polymers, photoresist, glass

- thicknesses: from a single monolayer of molecules to tens of µm



# How are MEMS made ?

MEMS are made with techniques originally developed for the microelectronics industry

Building block for MEMS fabrication :

I – Deposition

II - Lithography

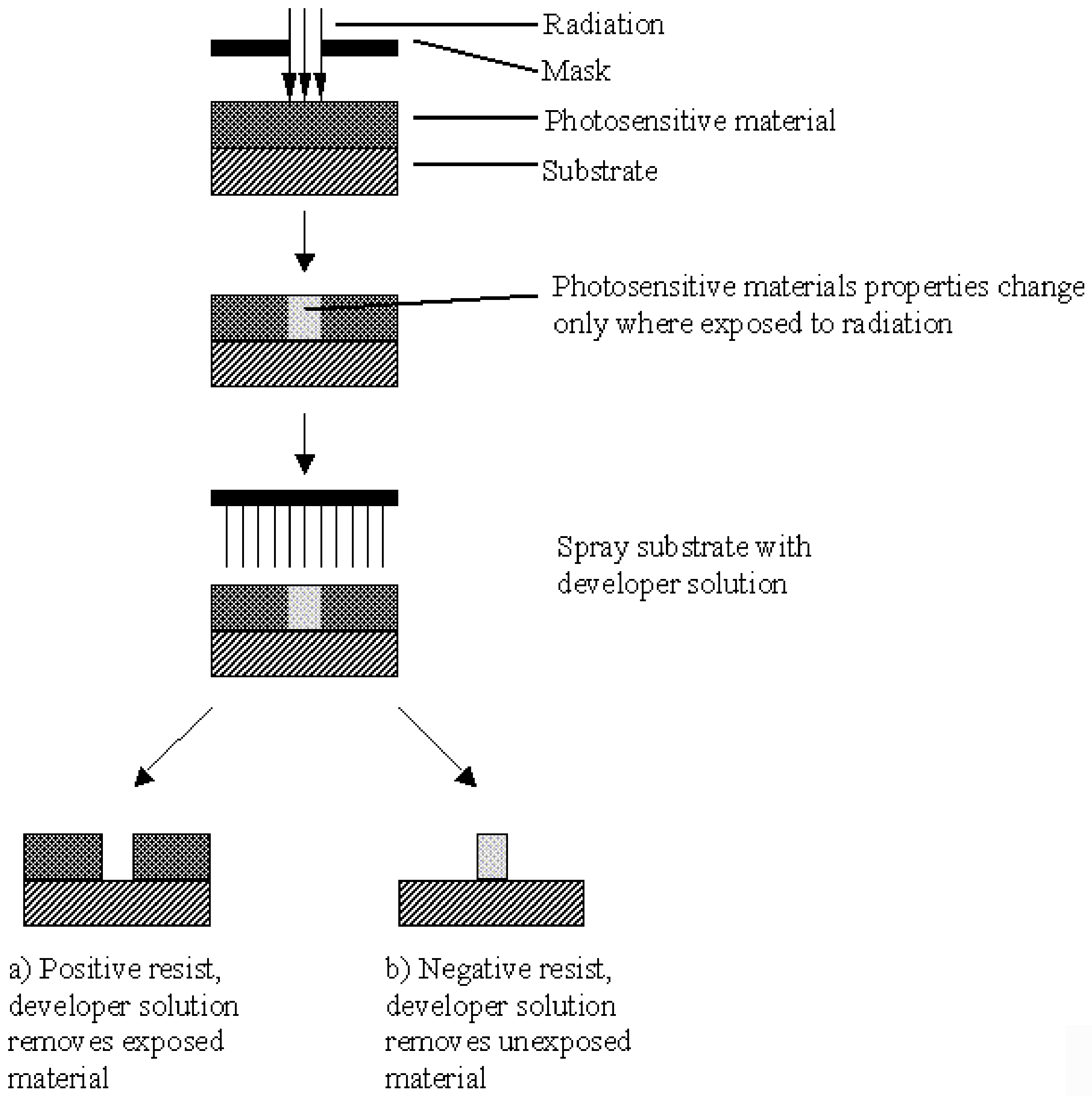
III – Etching

# Lithography

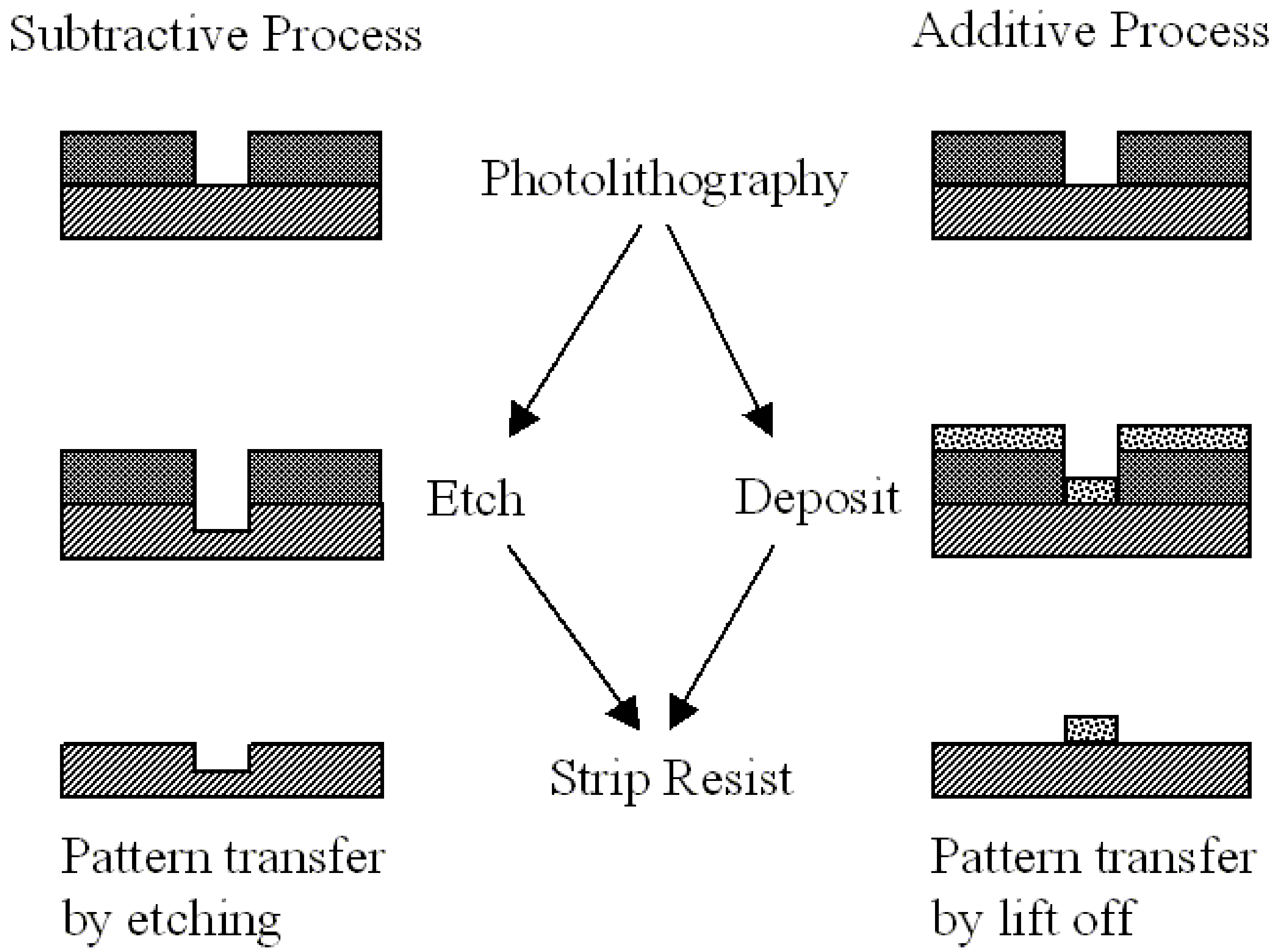
**Resolution:**

Optical
UV ≈ 0.5 µm
Deep UV ≈ 0.3 µm

E-beam < 100 nm



# *Pattern transfer*




lift-off approach less common because resist is incompatible with most MEMS deposition processes (high temperatures + contamination)

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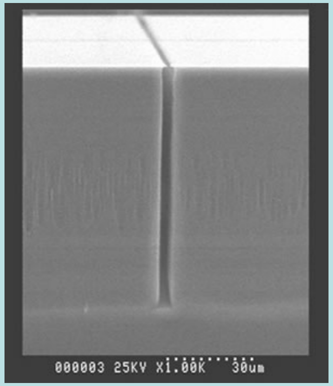
# Dry etching

**1) Sputter etching** - similar to sputtering deposition

**2) Reactive ion etching (RIE)**
accelerated ions react at surface – have both chemical and physical etching

**deep-RIE** → hundreds of microns + almost vertical sidewalls, aspect ratios ≤ 50 : 1

"Bosch process"
alternates repeatedly between two gases:
gas # 1: deposition of a chemically inert passivation layer (polymer)
gas # 2: etches, polymer on horizontal surfaces is immediately
physically sputtered while sidewalls not sputtered

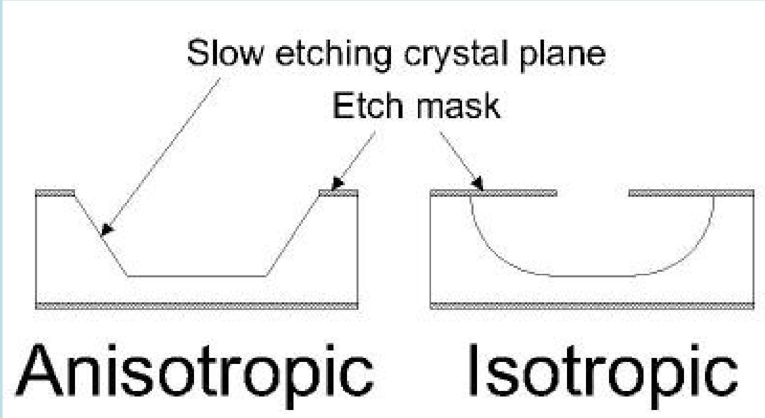


**3) Vapor phase etching**
material is dissolved at the surface in a chemical reaction with gas molecules
e.g. HF for etching $Si0_2$
$XeF_2$ for etching Si

# Etching

## Wet etching

material is dissolved in a chemical solution




**wet etching**
simple and cheap

vs

**dry etching**
expensive
much higher resolution
High aspect ratio (≤ 50 : 1)

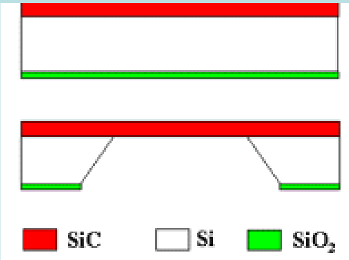
# MEMS technologies

**Bulk micromachining**

- defines structures by selectively etching inside a substrate,

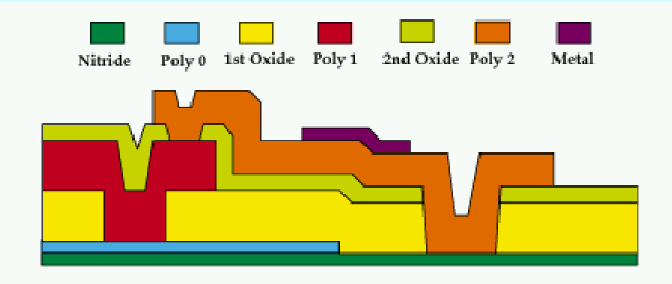
  typically Si is used and wet etched with KOH or TMAH

- relatively simple and inexpensive




**Surface micromachining**

- deposition / etching of different layers on a substrate
- many fabrication steps (expensive)
- can produce complicated devices

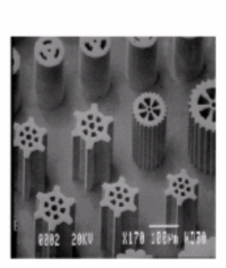


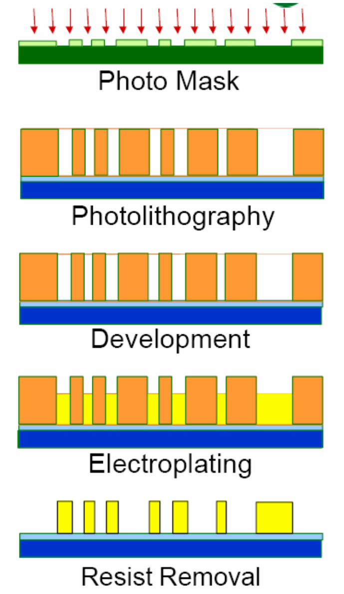

**LIGA** : x-ray **Li**thographie-**G**alvanoformung-**A**bformung
(x-ray Lithography-Electrodeposition-Moulding)

x-ray litho. of PMMA to produce template for electro-dep. (e.g. Ni)

the electrodeposited structure may be used as a mould for replication from another material ( plastic, ceramic)

- small, but relatively high aspect ratio devices





# Why is magnetism of interest for MEMS ?

# Remarkable features of magnetic interactions



Large forces

Magnetic pressure = 4 bar / Tesla² = 400 mN/mm² / T²

Large energy densities

Magnetic: $\frac{1}{2}B^2/\mu_0$ => 400 000 J/m³ @ 1 T

Electrostatic : $\frac{1}{2}\varepsilon_0 E^2$ => 40 J/m³ @ 3 MV/m

*(elect. breakdown in air)*

Long range

Several 10 to 100 µm or more

Contactless actuation

Remote / Wireless actuation → Medical implantable

Action through sealed membranes / vaccuum / skin

Suspension / Levitation

(Bi)stability

Magnets : permanent forces without power waste

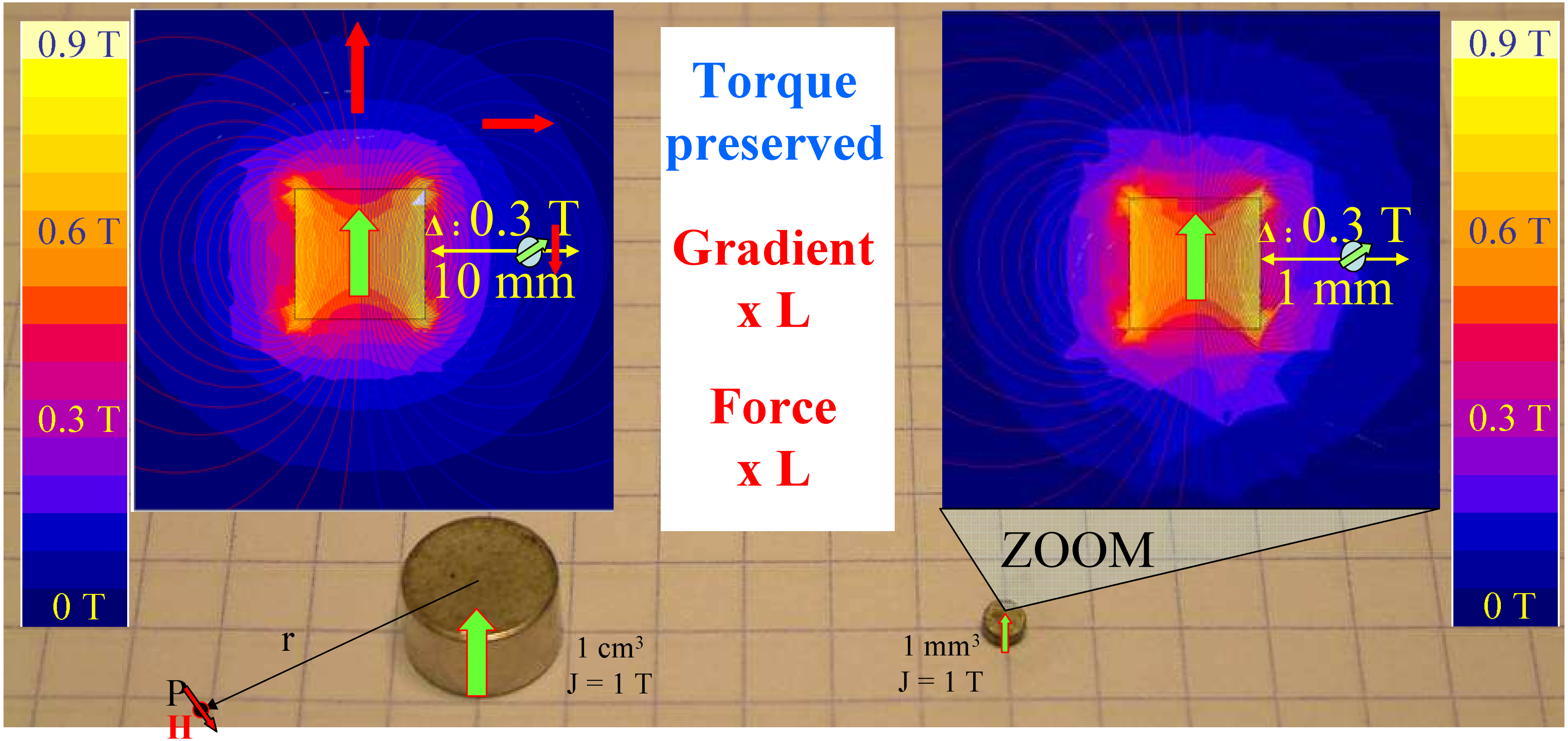
Long term forces - Safety

Bidirectionality

Repulsion / Attraction

# Homothetical scale reduction :

# Field gradients & forces between magnets = increased




**Magnitude and topology of field preserved:**

$$\overrightarrow{H1(P)} := \frac{v1}{4 \cdot \pi \cdot \mu o \cdot r^{3}} \cdot \overrightarrow{\left( 3 \cdot \frac{\overrightarrow{(J1 \cdot r)}}{r^{2}} \cdot \vec{r} - J1 \right)}$$

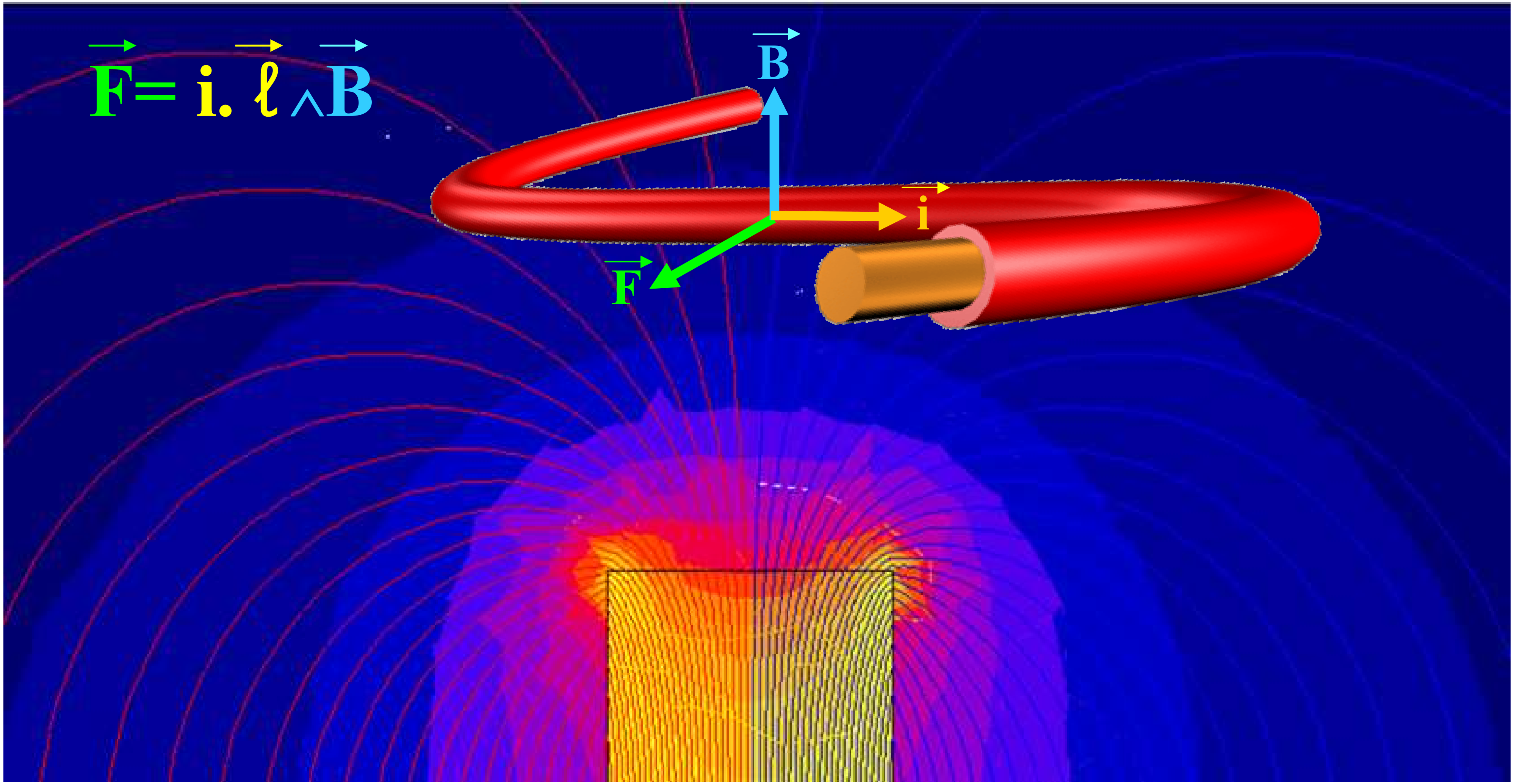
**Δ(Field) / Distance = Gradient**

=    */10*    *x10*    =    *x10*

**Gradient x Moment = Force**

# Laplace/Lorentz forces by a magnet onto a current

**same current density** x same field = same force density



# Effects of a scale reduction 1 / L on conductor / conductor interactions (volumic, massic)

*(at constant current density)*

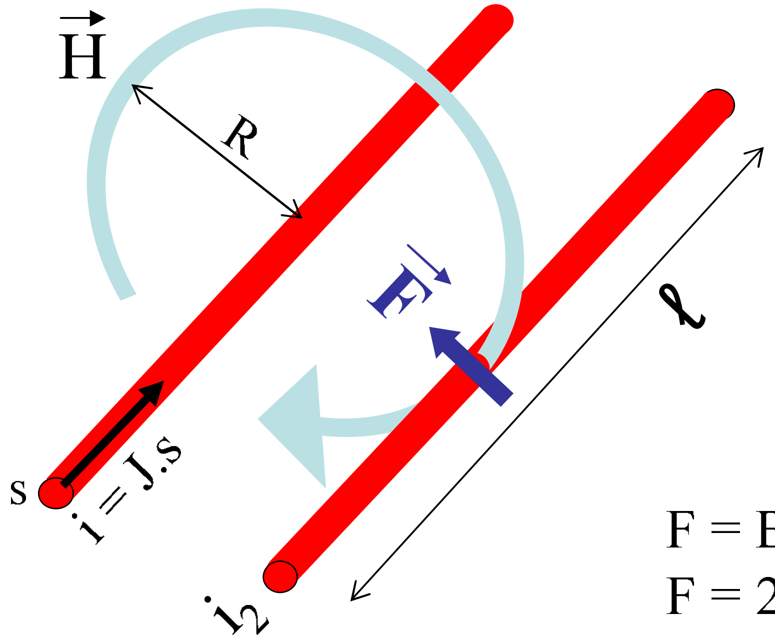
*(infinite wire)* $H = i / 2\pi R$

$B = \mu_0 H = 4\pi 10^{-7} \cdot J.s / 2\pi R$

$\propto J.d^2/d$

$\propto 1/L$

**reduced**




$F = B.\, i.\, \ell$

$F = 2.10^{-7}.i_1.i_2.\, \ell / R$

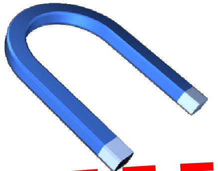
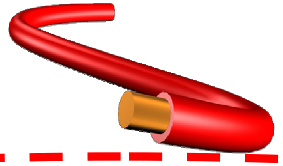
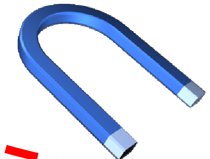
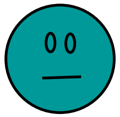
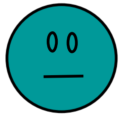
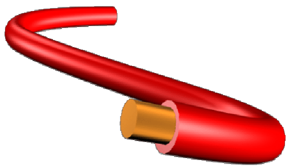
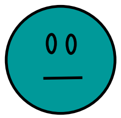
$\Rightarrow F_{/volume} \propto J^2.s.s.\, \ell / R\, .d^3$

$\propto 1/L$

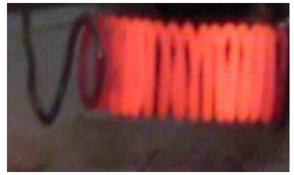
**reduced**

# Effects of a scale reduction 1 / L on magnetic interactions (volumic, massic)

*(at constant current density)*

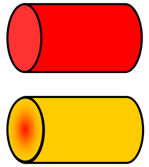
| *Scale reduction 1 / L* | magnet  | current  | iron  | induction $e = -d\Phi / dt$ |
|---|---|---|---|---|
| magnet  | $\times$ L  |  | $\times$ L  | / L $\times$ frequency  |
| current  |  | / L  | / L  | / $L^2$ $\times$ frequency  |

# μ-coils can withstand gigantic current densities
thanks to better cooling



Heat generation $RI^2$ = volume = $d^3$

Heat dissipation = surface = $d^2$

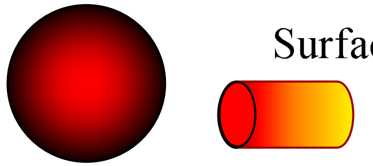


=> S/V ratio = $d^2/d^3 = 1/d$ : improves with scale reduction factor L

Distance between thermal sources = d

$\Rightarrow$ Thermal gradient = x L

$\Rightarrow$ heat flow through surface = x L

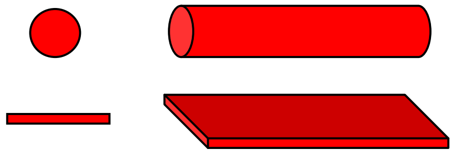


Surface thermal flow

$\Phi/s = \lambda.\Delta T/e$

Cylindrical wire = S/V min

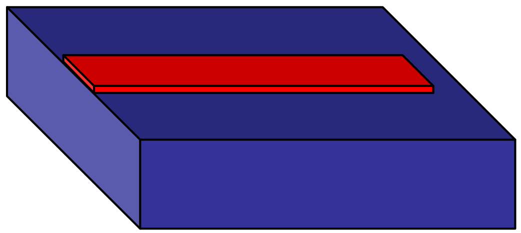
Planar conductor = S/V max



=> S/V ratio increases also

Conductor = metallic thin film

Si substrate = excellent heat conductor/absorber

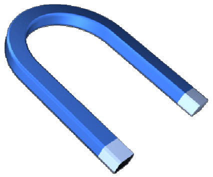
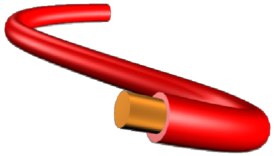
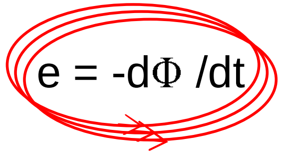


Short time constants = current pulses = μs

**Classical electrotechnics : 5 A/mm² DC…**

**Integrated μ-coils : up to 1 Million A/mm² in pulses!**

# Effects of a scale reduction 1 / L
# on magnetic interactions (volumic, massic)
## *with increased current density* $\times L_i$

| *Scale reduction* *1 / L* | magnet  | current  | iron  | induction  |
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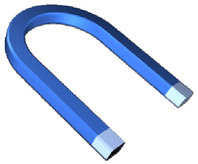
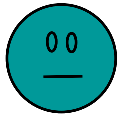
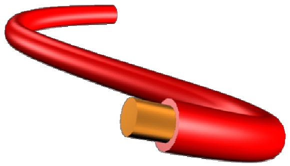
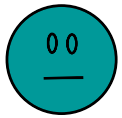
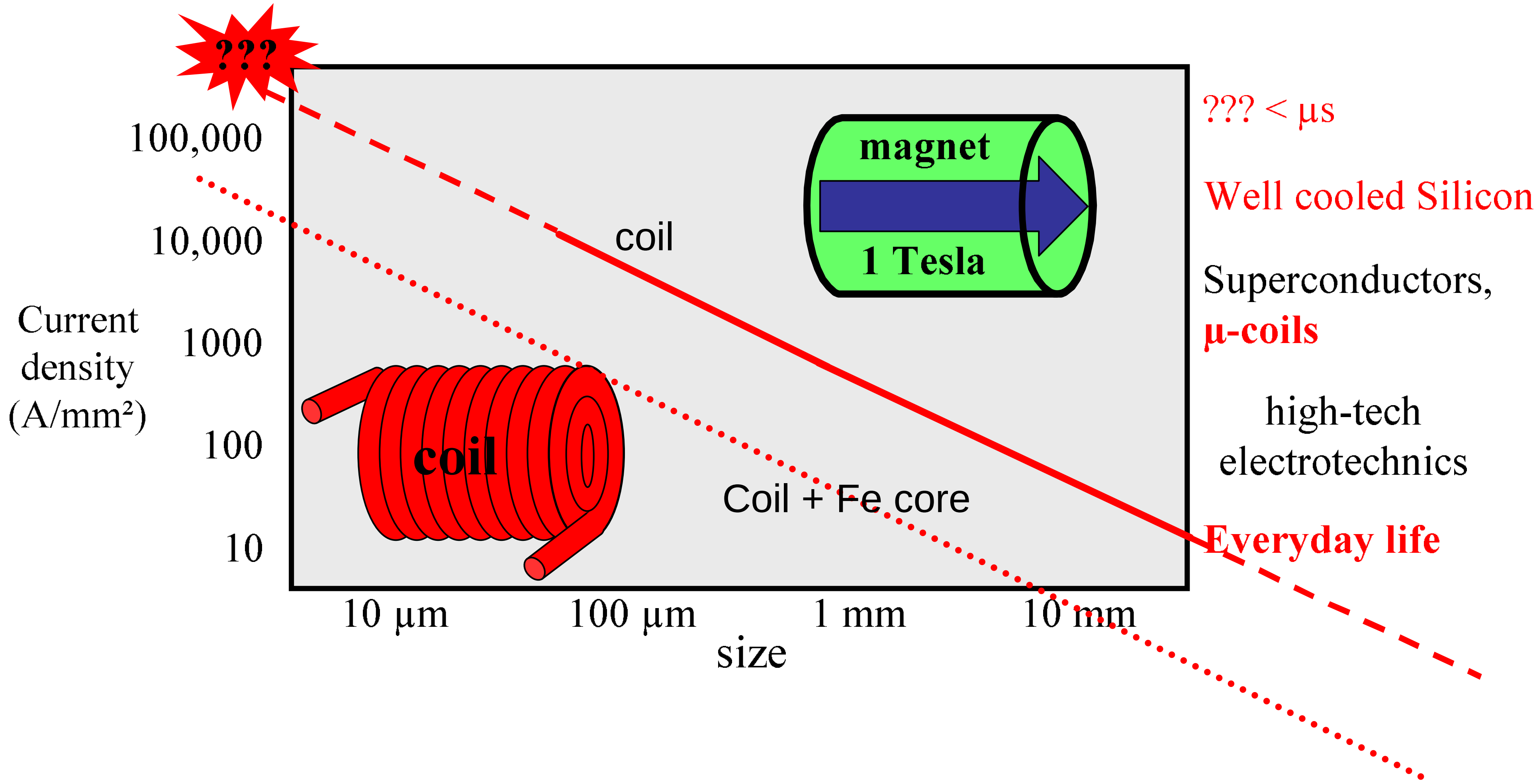
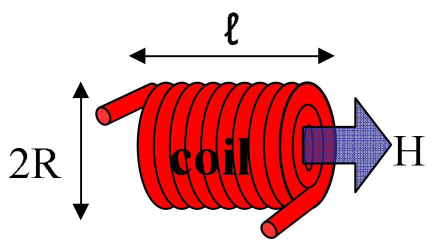
| magnet  | $\times L$  | $\times L_i$  | $\times L$  | $/ L$ $\times$ frequency  |
| current  | $\times L_i$  | $\times L^2_i / L$  | $\times L^2_i / L$  | $\times L^2_i / L^2$ $\times$ frequency  |

# The importance of µ-magnets




$H = N.i / \ell$ (A/m)

$i = J.s = J.\pi R^2$

$H = N.J.\pi R^2 / \ell$

**A µ-magnet is much more interesting than a µ-coil/µ-electromagnet of same size**

Some examples of magnetic MEMS…..

# Deformable mirror for adaptive optics



(astronomy, ophtalmology…)

Image from star distorted by atmosphere

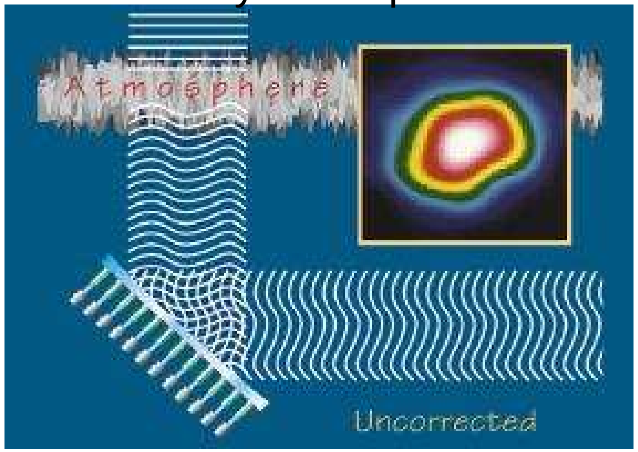
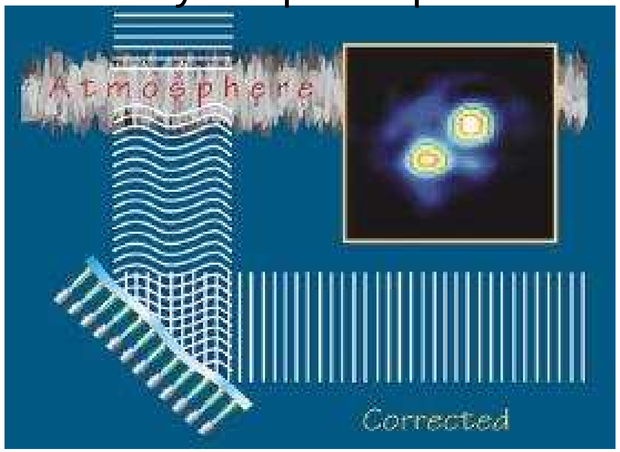
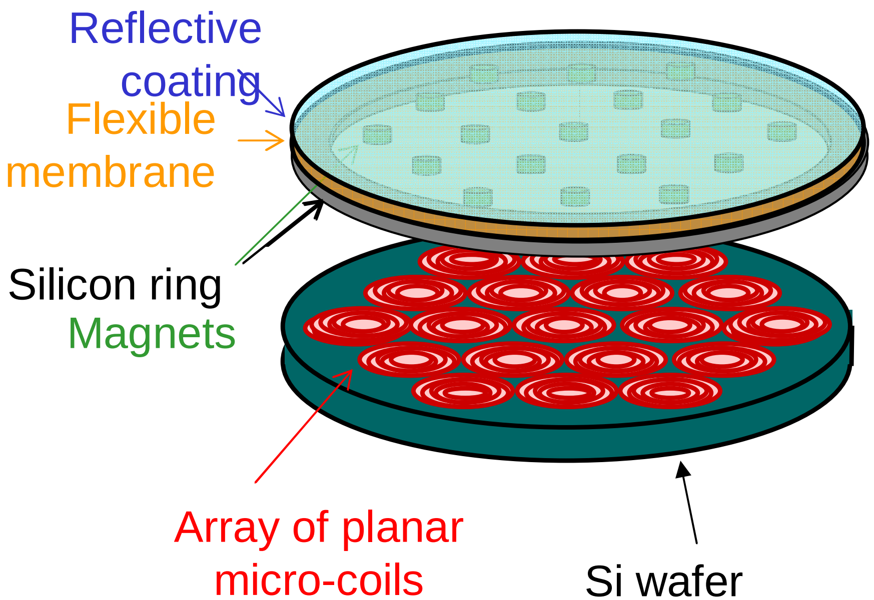
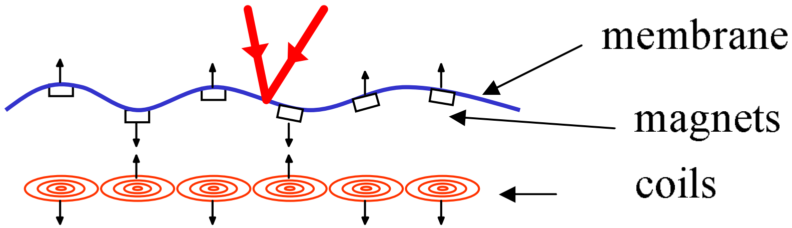



Image corrected by adaptive optics



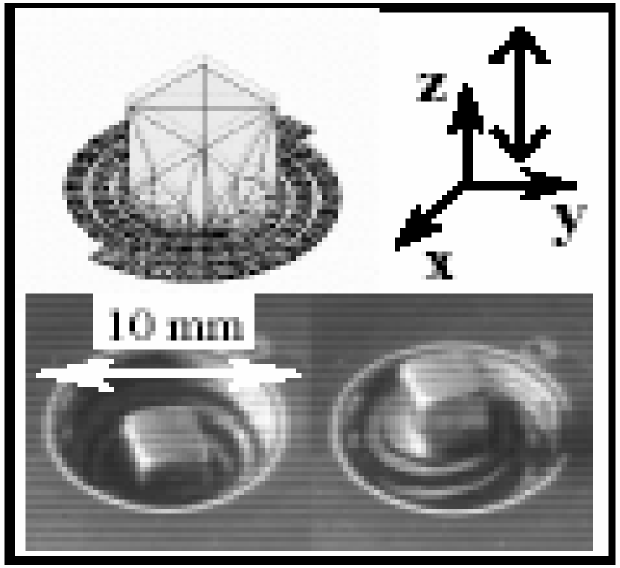

*LEG - LAOG - LPMO - IEMN*

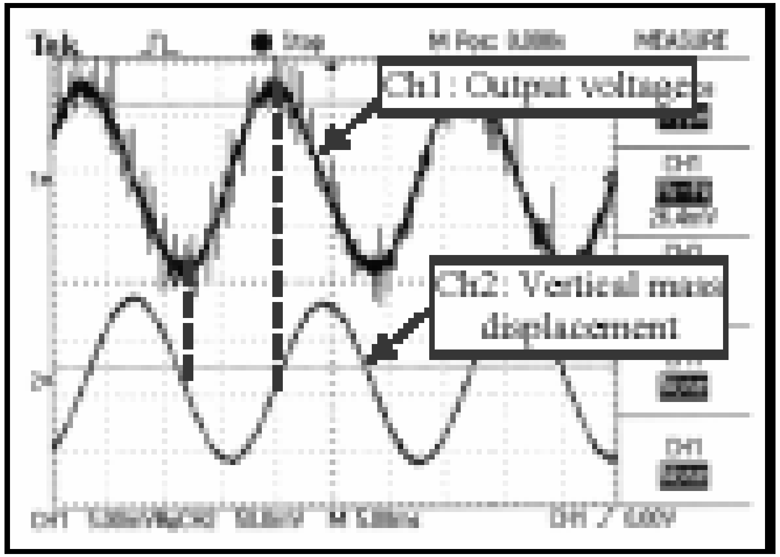


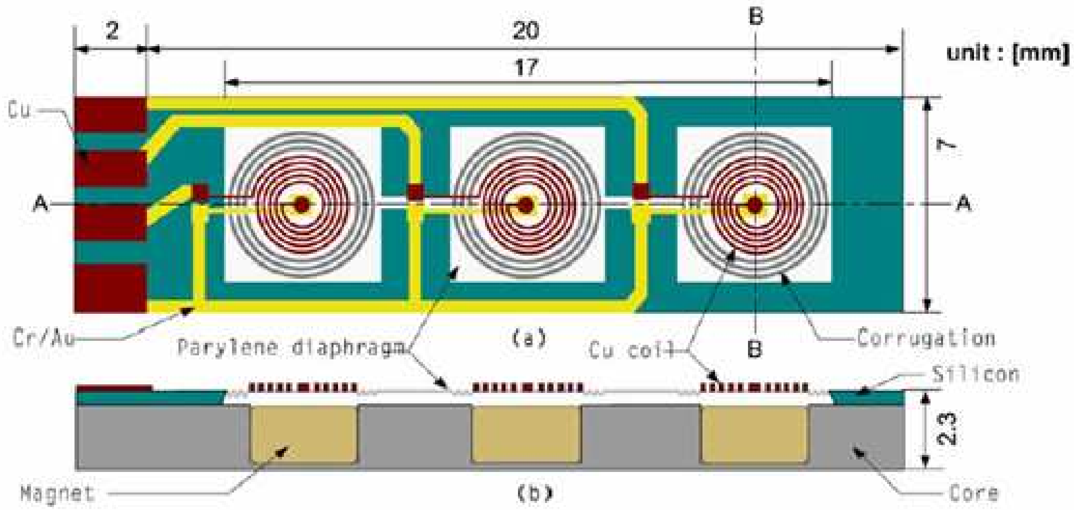

SmCo Ø 0.85 x 0.25 mm *(COMADUR)*

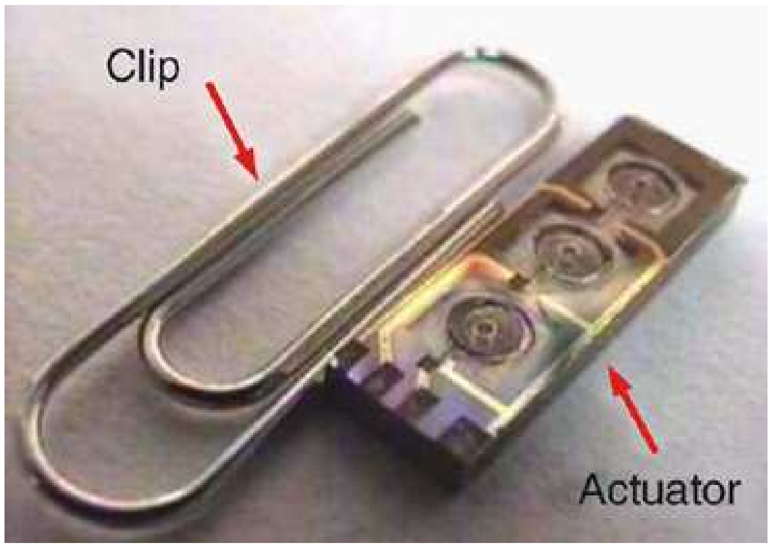
## Energy harvesting (vibrations) : µ-generator *(Univ. Hong Kong)*




## Membrane pump for µ-fluidics (Suwon, Korea)

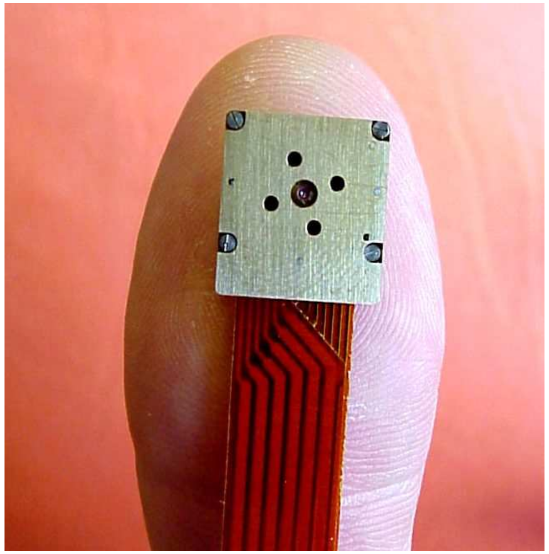


# MAGNETIC MICRO-ACTUATOR prototypes

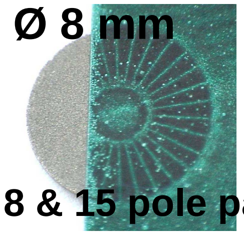
Collab. G2ELab + CEA/LETI (Grenoble, France)

**Planar µ-motor**



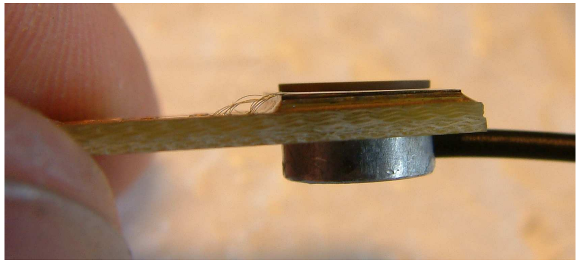
**2 x 3 phases brushless**
**275,000 rpm on magnet / air bearings**

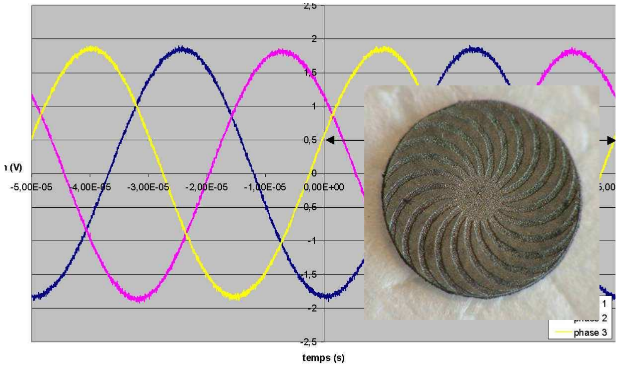
**Ø 8 mm**



**8 & 15 pole pairs**

**Planar µ-turbo-generator**

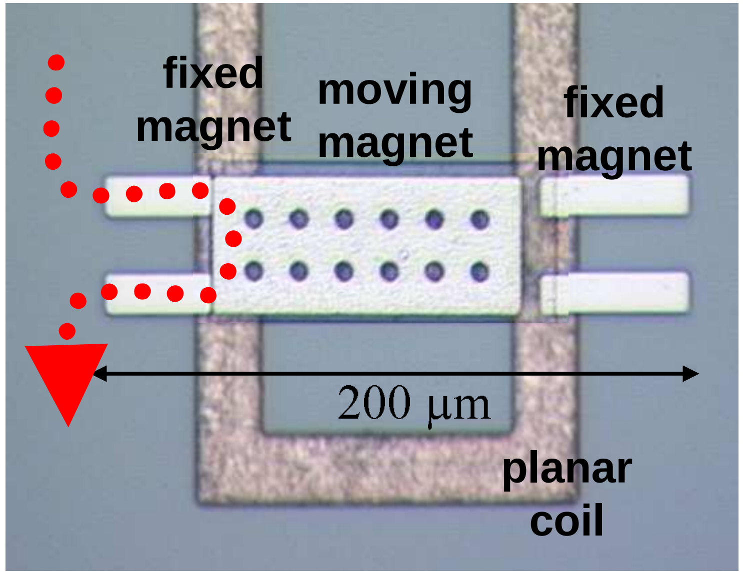





**Voltages measured at 80,000 rpm**
**Output ~ 1 W @ 100,000 rpm**

µ-machined bulk NdFeB

**Bistable ultra-fast levitating µ-switch**




**Commutation 5 µm/30 µs/30 µJ/pulse**

**1st fully integrated prototype**

Electrodep. $Co_{85}Pt_{15}$

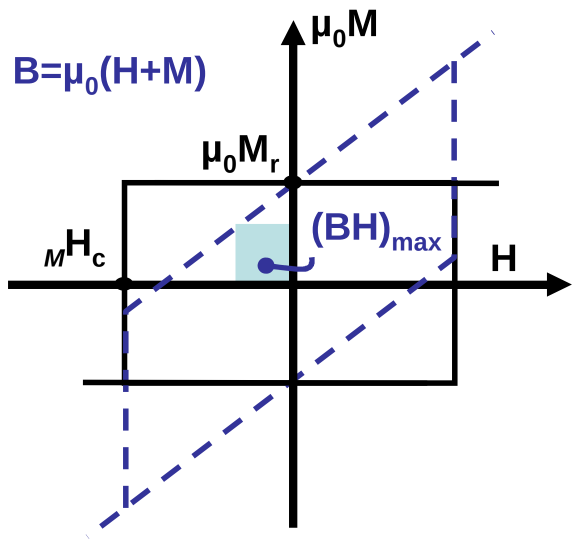
**Need for high quality integrated thick film magnets for MEMS !**

# Micro-magnets for MEMS

- Candidate materials
- Integration issues
- Preparation of high performance materials in thick film form by sputtering
- Film patterning
- Beyond magnets

**Nora M. Dempsey**
**Institut Néel, CNRS/UJF, Grenoble, France**

# High performance permanent magnet materials




$M_r \leq M_S$
$H_c \leq H_A$

$M_r$, $H_c$ determined by microstructure

↑$(BH)_{max}$ → ↓ magnet volume

| Material | $\mu_0 M_S$ (T) | $\mu H_A$ (T) | $(BH)_{max,th}$ kJ/m³ | $T_C$ (K) |
|---|---|---|---|---|
| **RE-TM** | | | | |
| $Nd_2Fe_{14}B$ | 1.61 | 7.6 | 514 | 585 |
| $SmCo_5$ | 1.05 | 40 | 220 | 1000 |
| $Sm_2Co_{17}$ | 1.30 | 6.4 | 333 | 1173 |
| **$L1_0$** | | | | |
| FePt | 1.43 | 11.6 | 407 | 750 |
| CoPt | 1.00 | 4.9 | 200 | 840 |

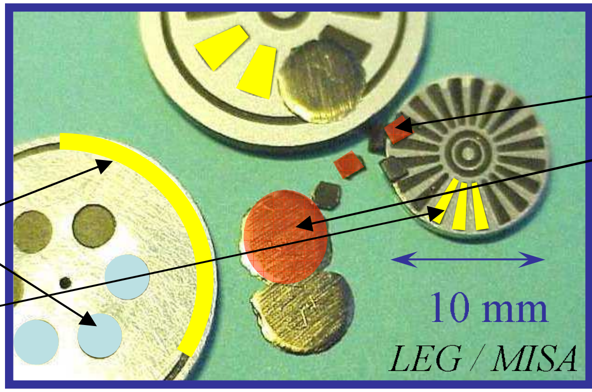
# Routes to prepare thick film magnets

**Top-down routes**

**Bottom-up routes**

**Micro-machining of bulk magnets**

**Screen printing**

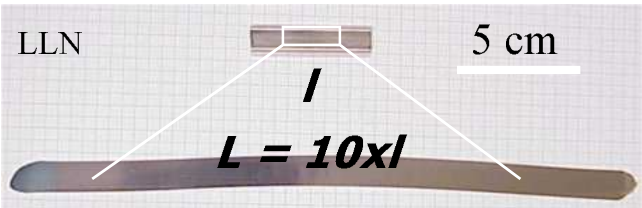



**Sputtering**

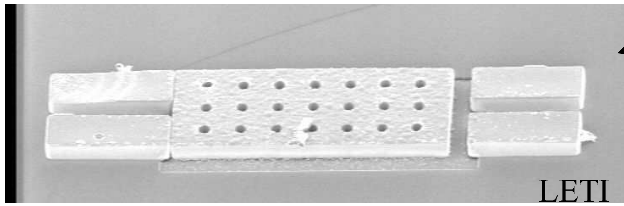
**Pulsed Laser Deposition (PLD)**


Plasma spraying

**Deformation (e.g. rolling)**




**Electro-deposition**




t = 5 µm
l = 200 µm

# Routes to prepare thick film magnets

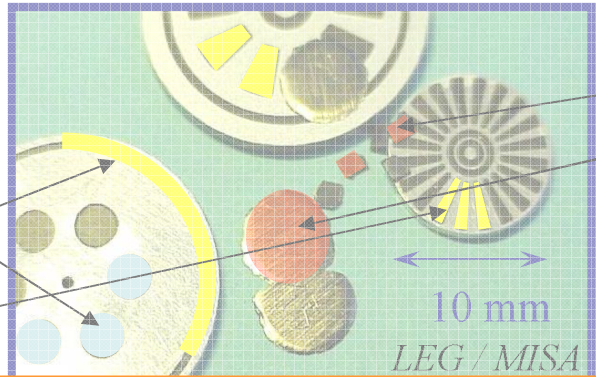
**Top-down routes**

**Bottom-up routes**

**Micro-machining of bulk magnets**

**Screen printing**

**Deformation (e.g. rolling)**




**Sputtering**

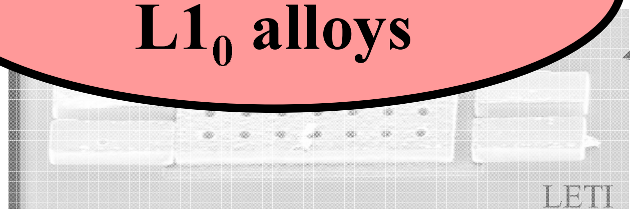
**Pulsed Laser Deposition (PLD)**

Material specific !

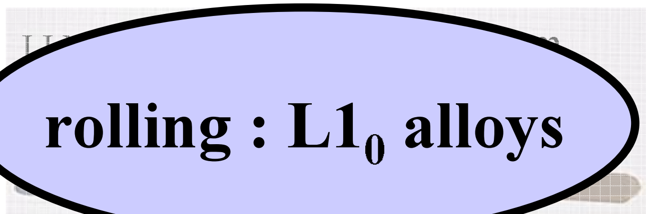
**Plasma spraying**


**Electro-deposition**

**electro-deposition: $L1_0$ alloys**




t = 5 µm
l = 200 µm



**rolling : $L1_0$ alloys**

# Micro-magnets for MEMS

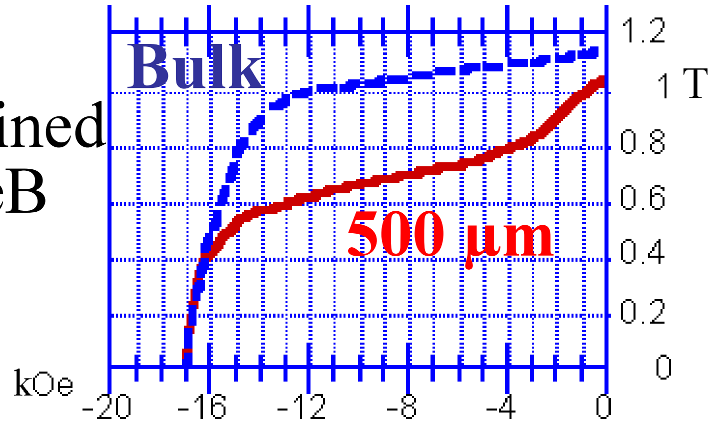
- Candidate materials
- Integration issues
- Preparation of high performance materials in thick film form by sputtering
- Film patterning

# Influence of processing on magnetic properties

- **Sample degradation**

e.g. **drop in coercivity**:
μ-machining,
screen printing

μ-machined NdFeB

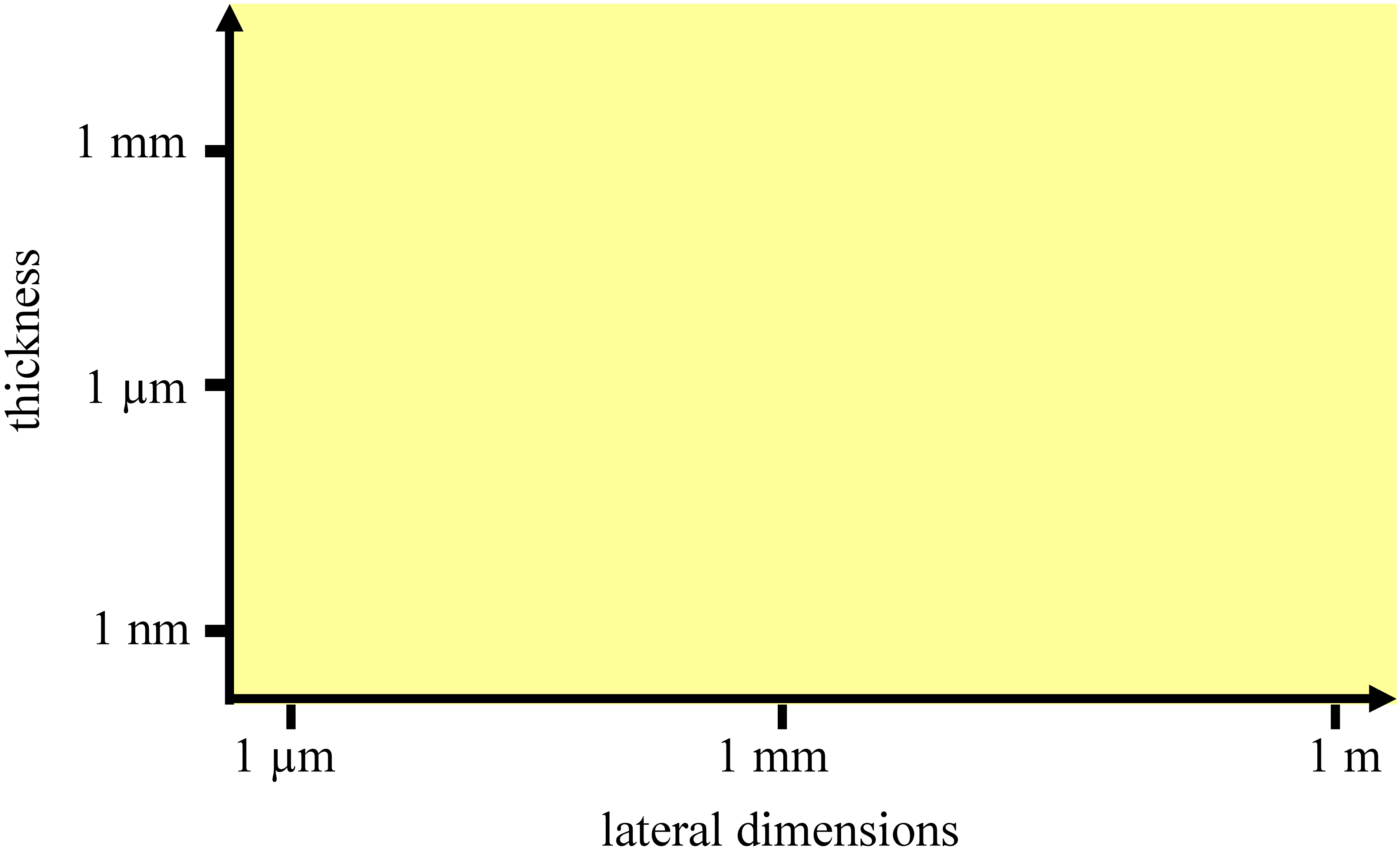



- **Dilution of magnetic phase** → **reduction of remanent magnetisation**:
screen printing (vol. fraction of binder)
plasma spray (porosity);

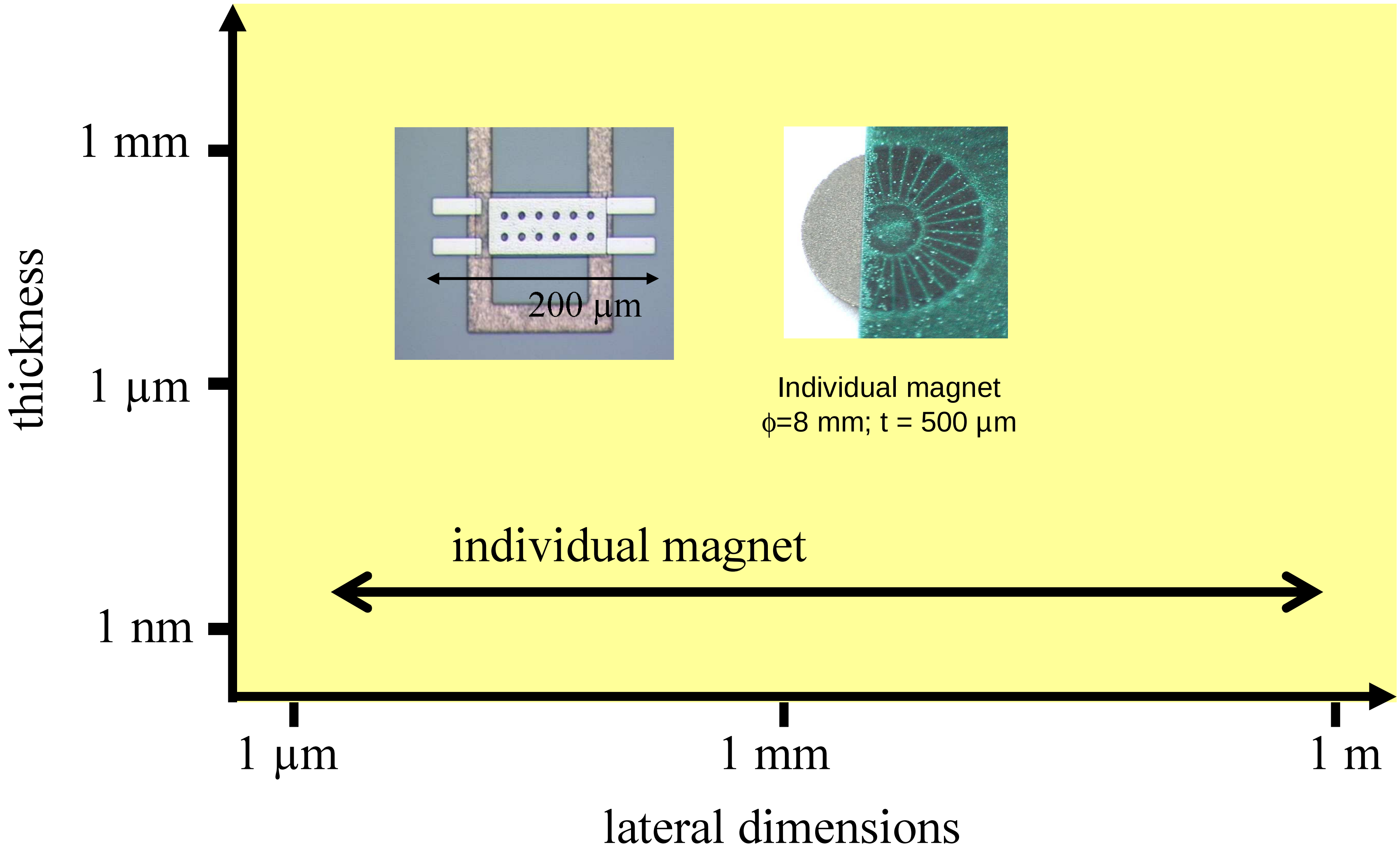
- **Magnet texture** : choice of process + process parameters
will determine ability to produce a textured magnet

For now Isotropic : screen printing, plasma spraying, rolling…..

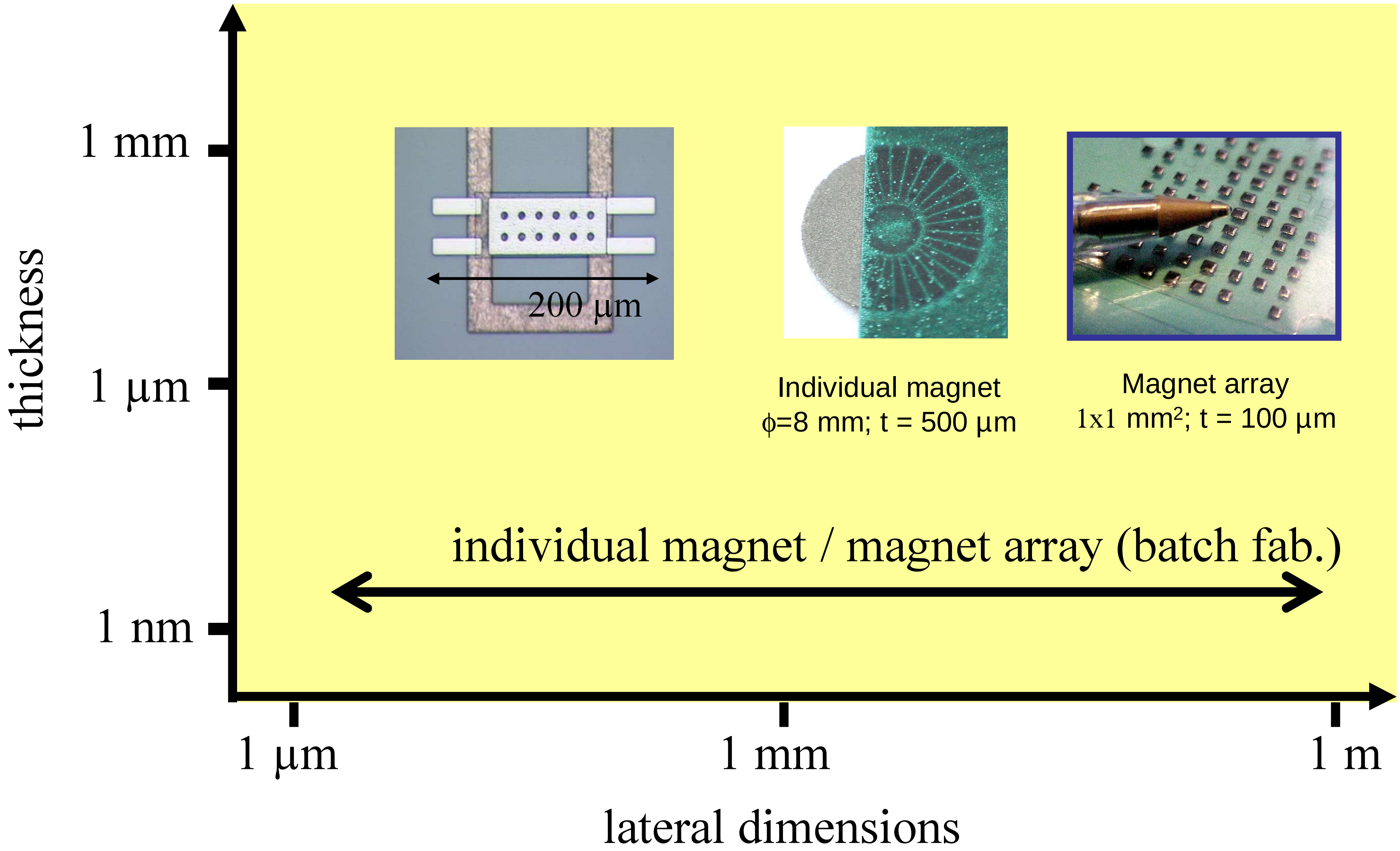
# Magnet Dimensions



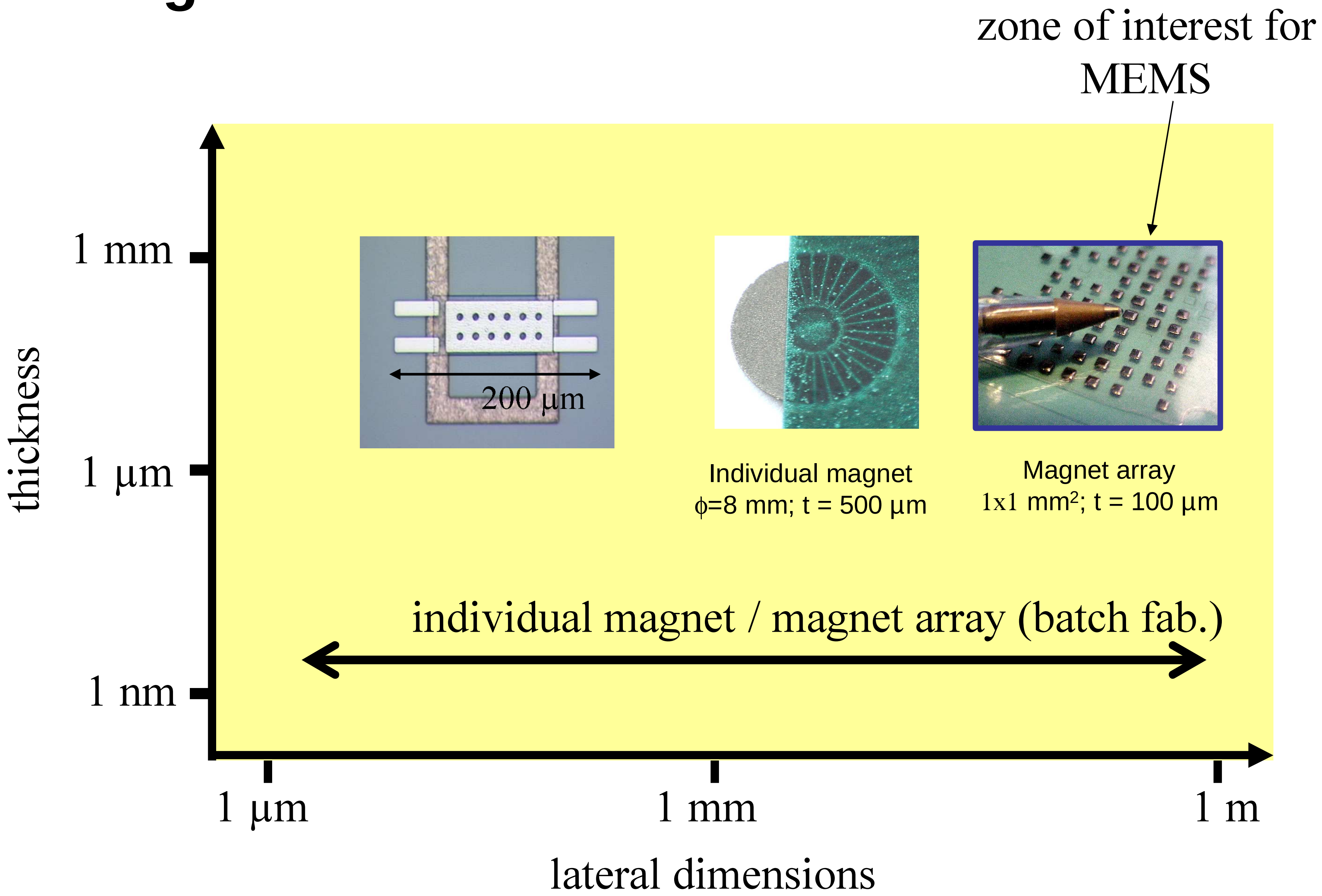
# Magnet Dimensions



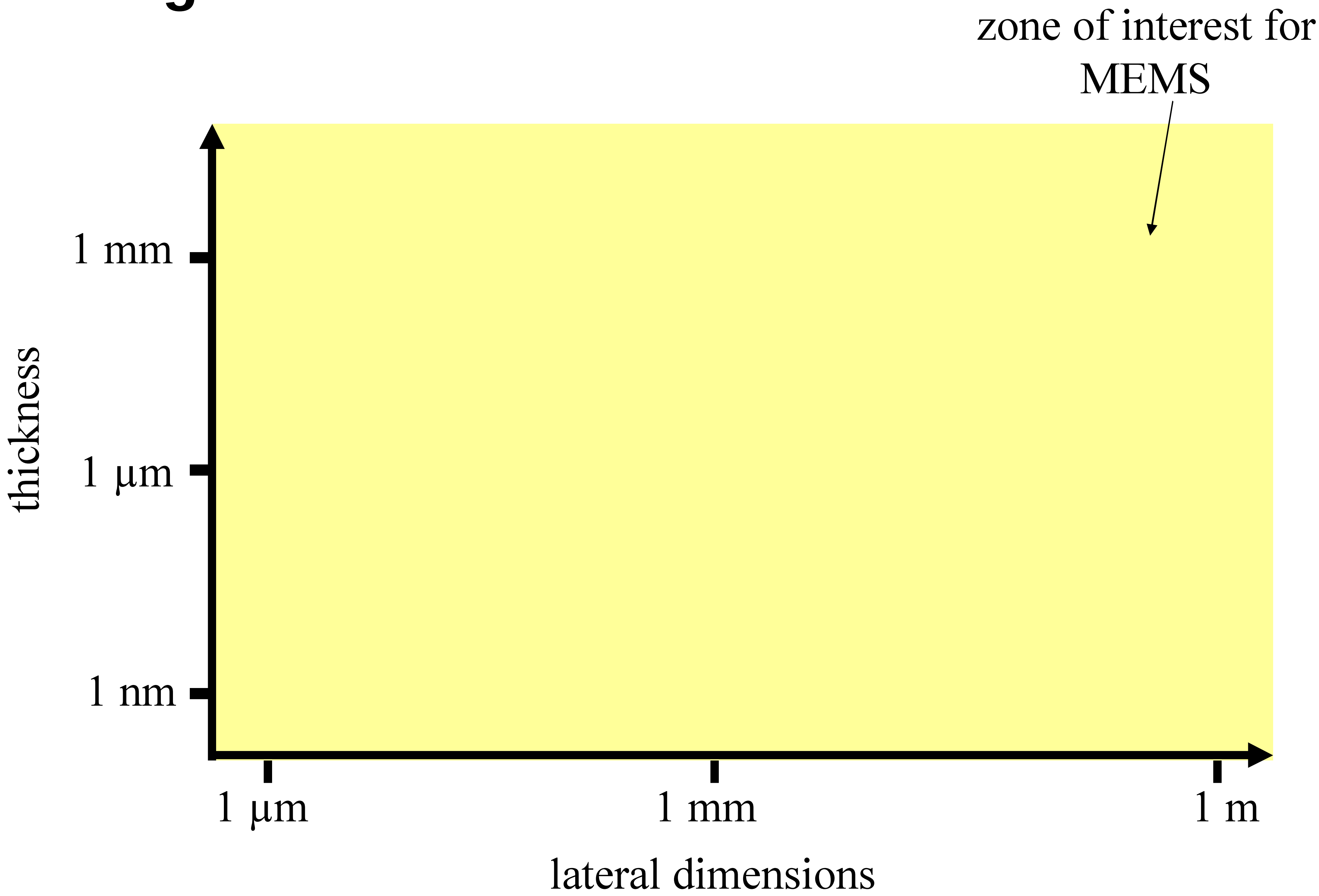
# Magnet Dimensions



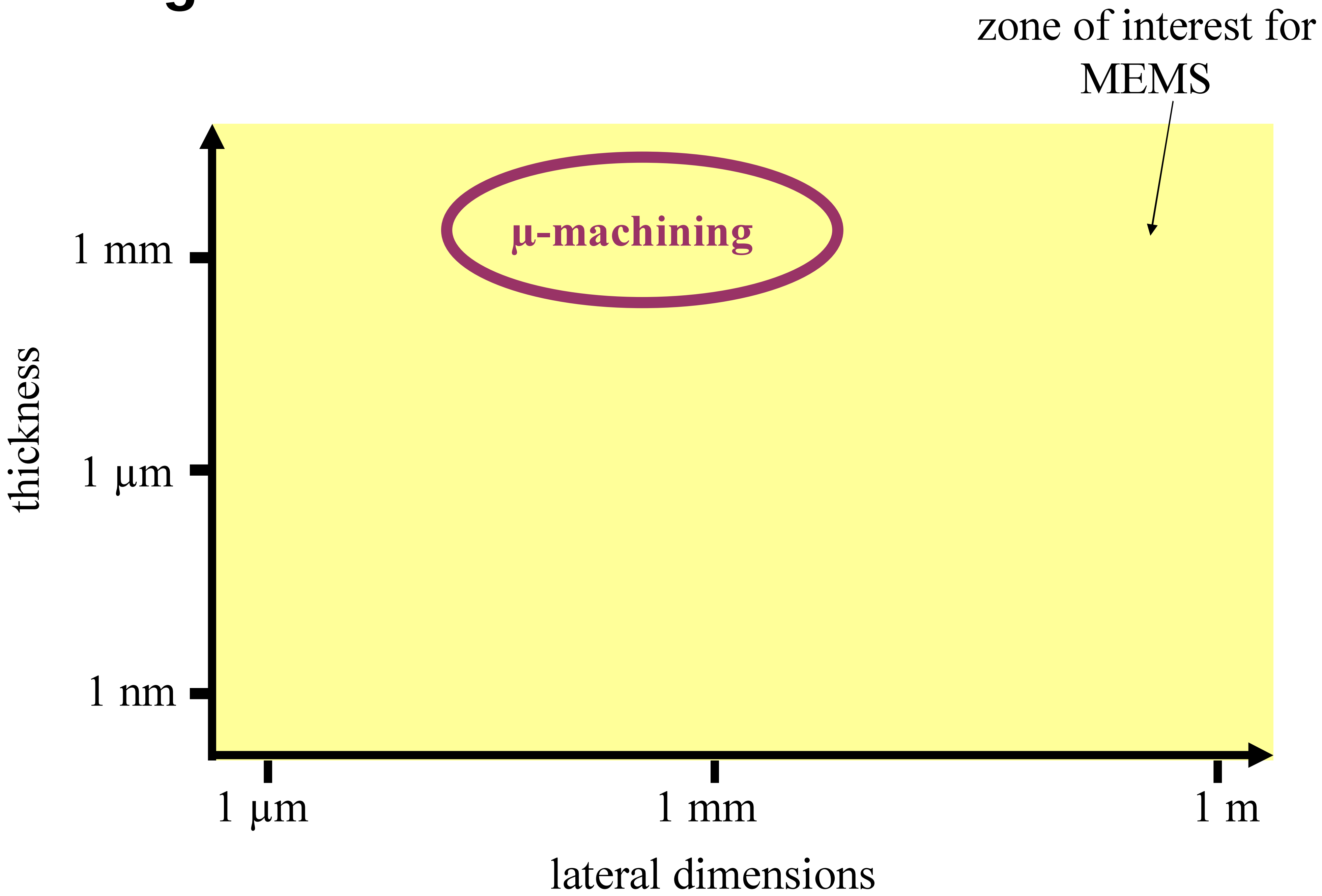
# Magnet Dimensions



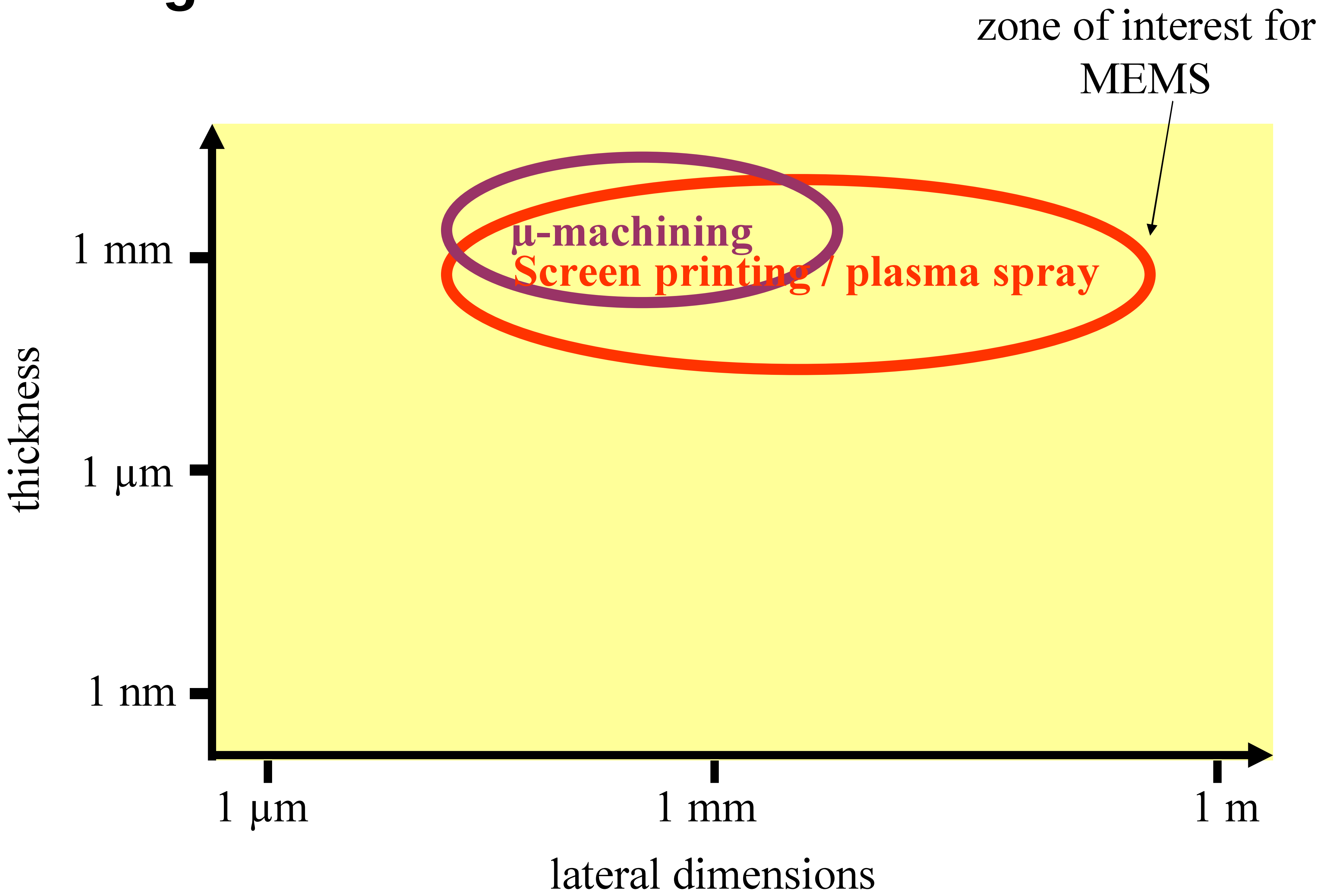
# Magnet Dimensions



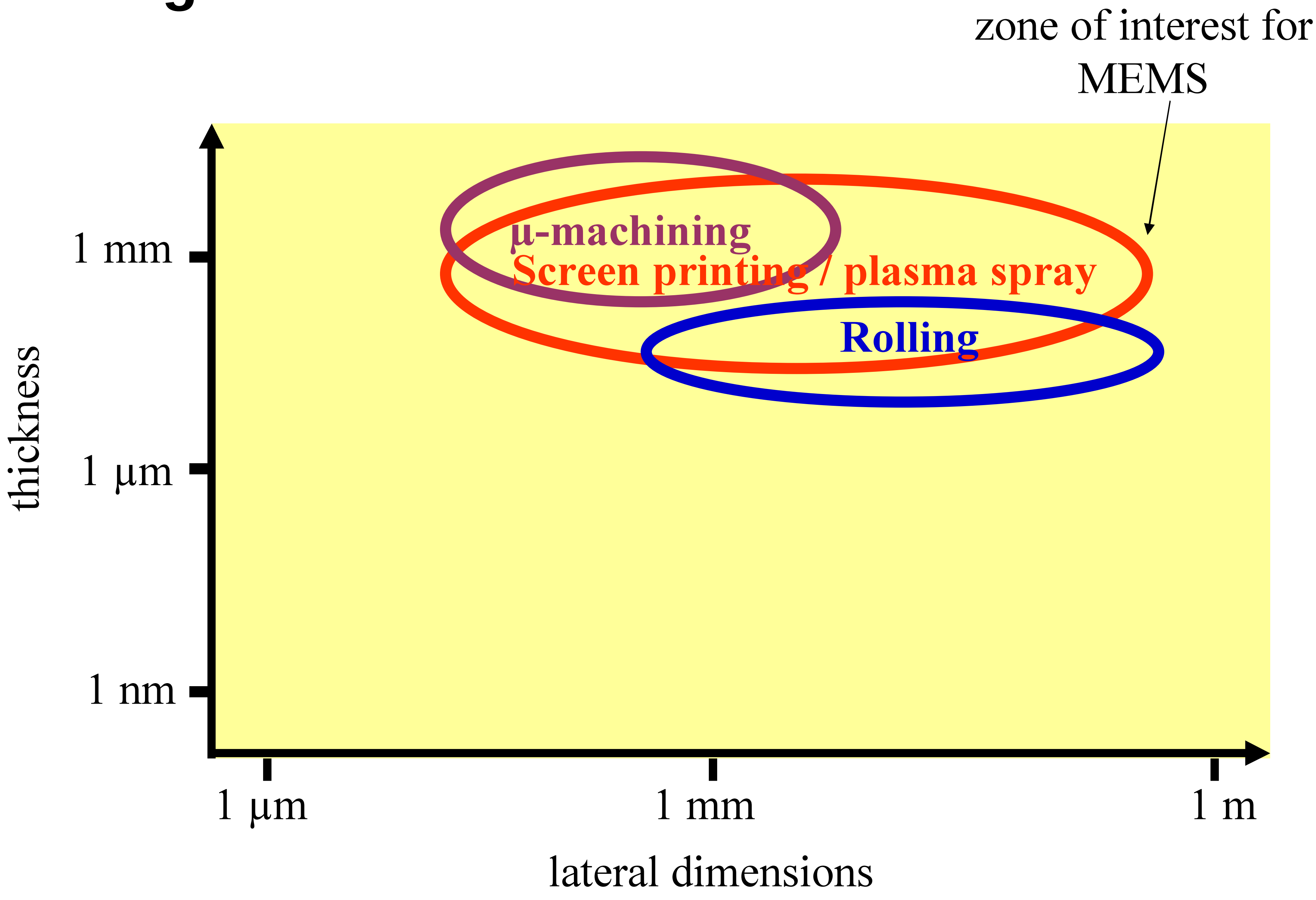
# Magnet Dimensions



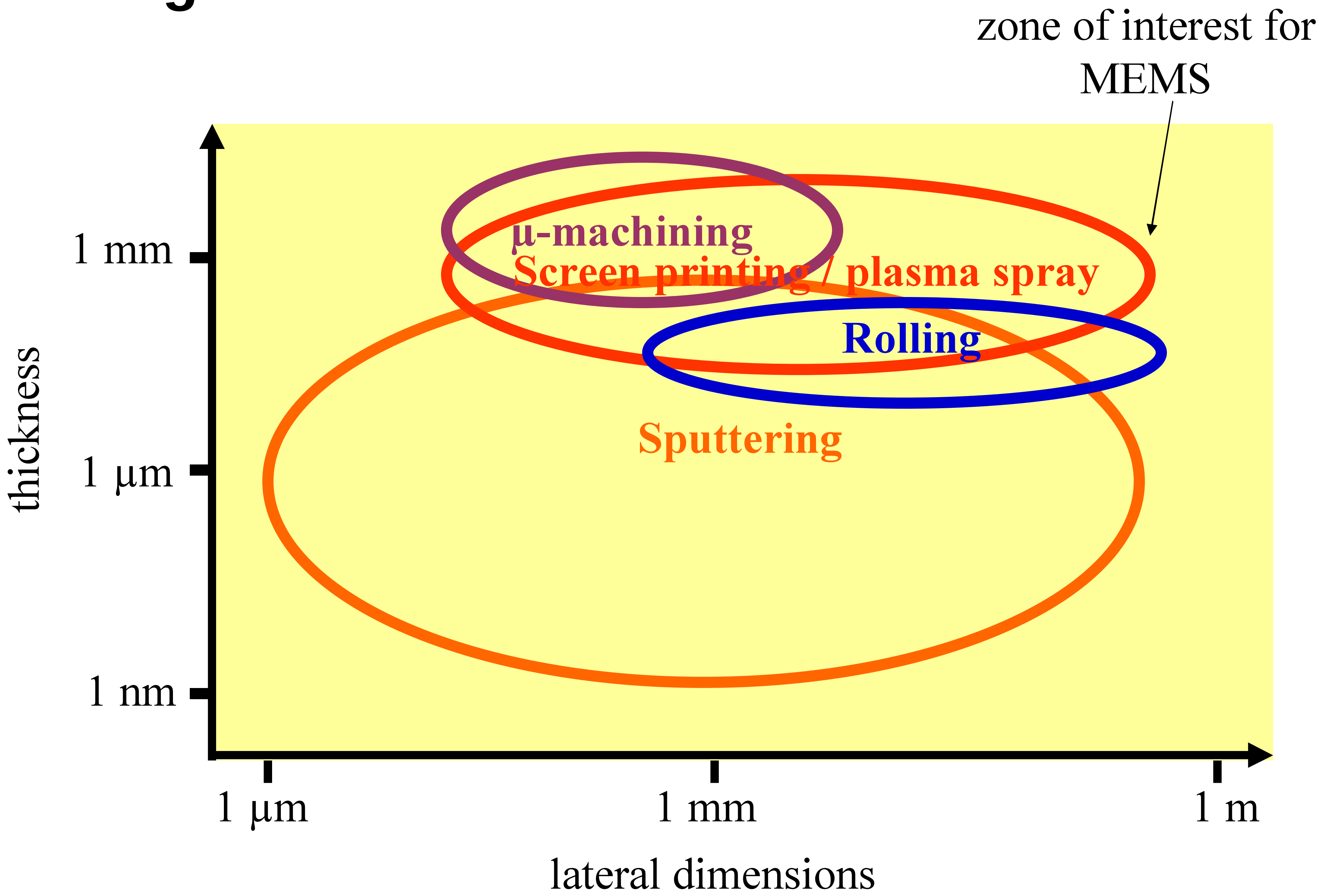
# Magnet Dimensions



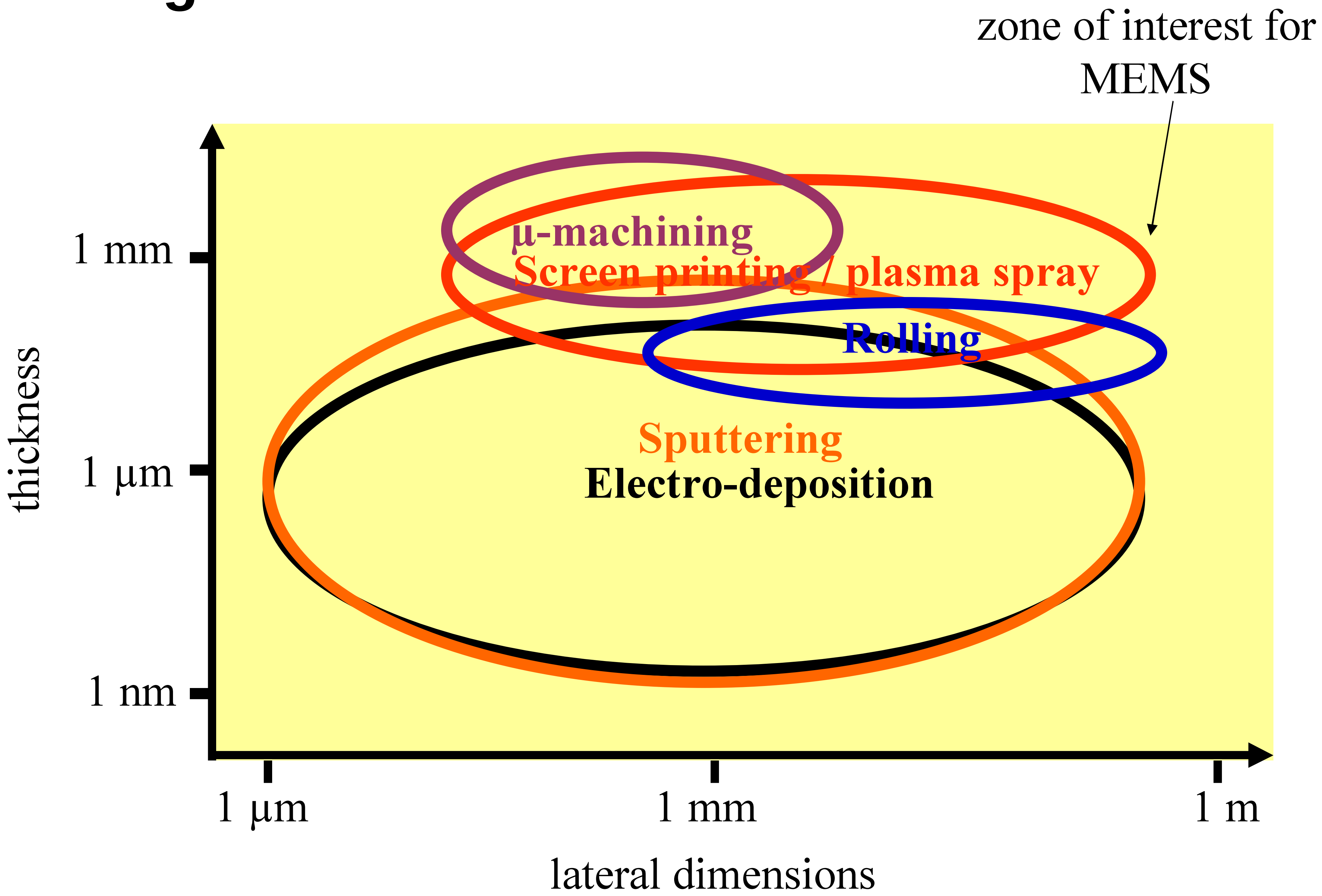
# Magnet Dimensions



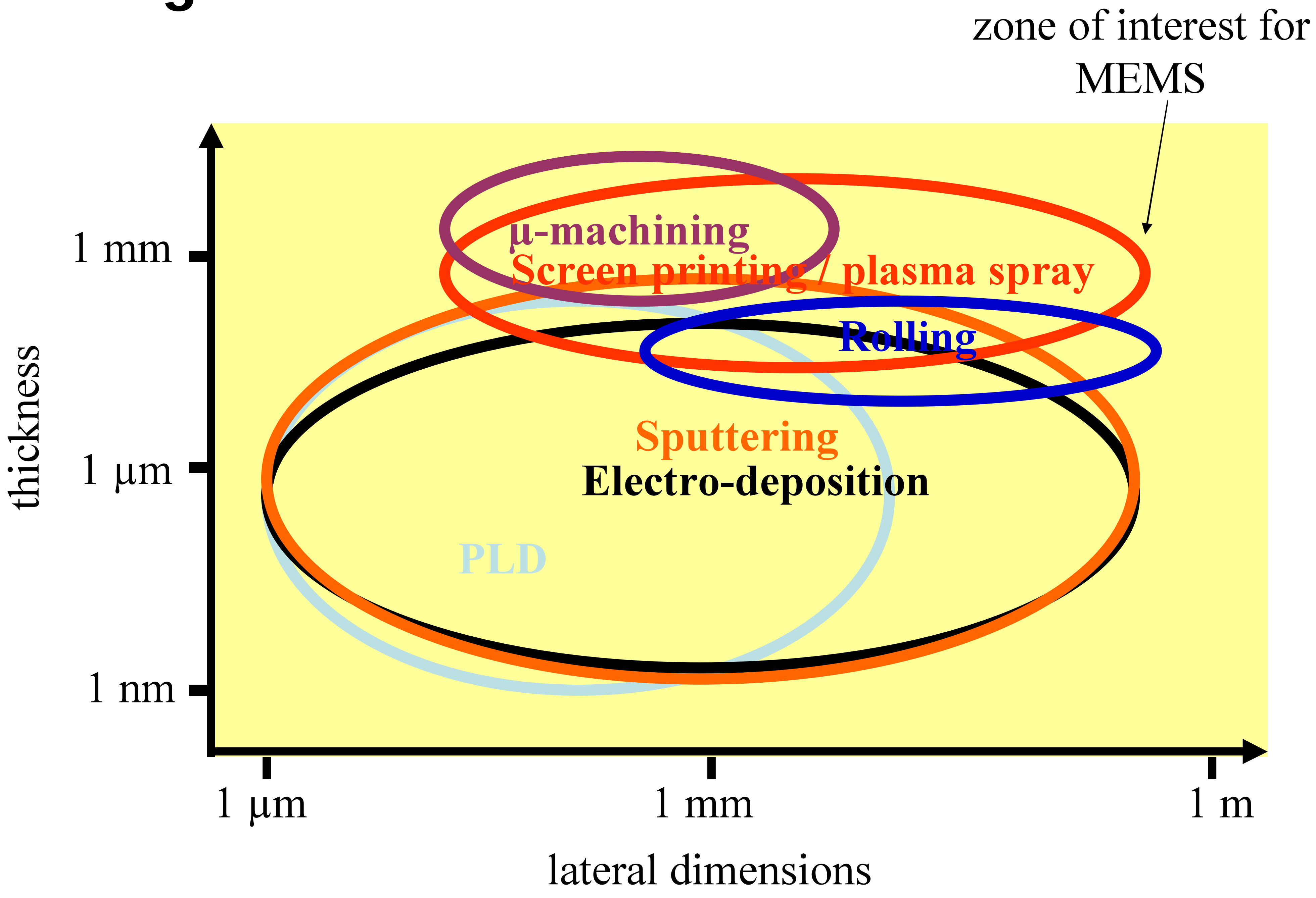
# Magnet Dimensions



# Magnet Dimensions



# Magnet Dimensions

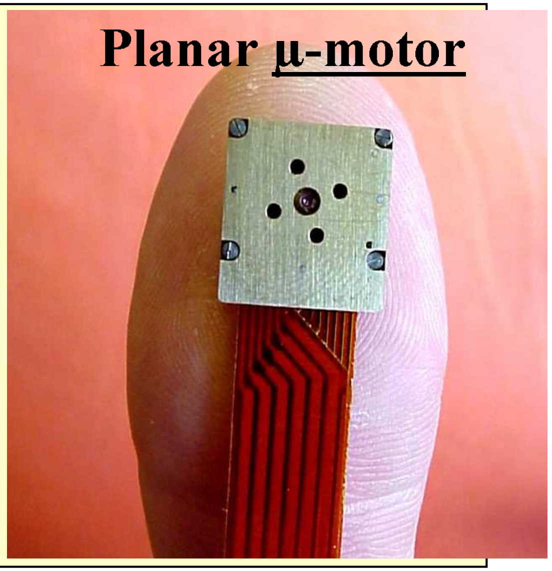


# Integration issues : magnet insertion

**Simple milli-systems**

1) produce many individual magnets
2) "pick & place" magnet into μ-system

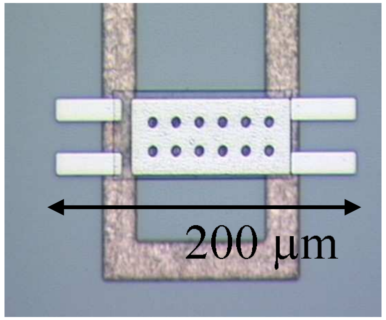
c.f. wrist-watches,
surface mounted μ-electronic circuits




**Complex micro-systems**

produce and insert magnet in same step
full integration, on-chip processing

Bi-stable μ-switch




LEG/LETI

# Integration issues for film magnets

• **Choice of substrate / buffer / capping layers:**

will determine magnetic and mechanical properties,
could influence cost of system

must consider **compatibility** with - other μ-system components
- microfabrication techniques

e.g. Si vs MgO

• **Film patterning**

pre-patterned substrates
deposition through masks
post-deposition patterning

• **Thermal compatibility**

for high anisotropy phases*, need elevated processing temperatures
($Nd_2Fe_{14}B$ > 580°C, $SmCo_5$ > 350°C, FePt > 450°C)
-Wafer bonding allows full processing of magnet before integration of other system components

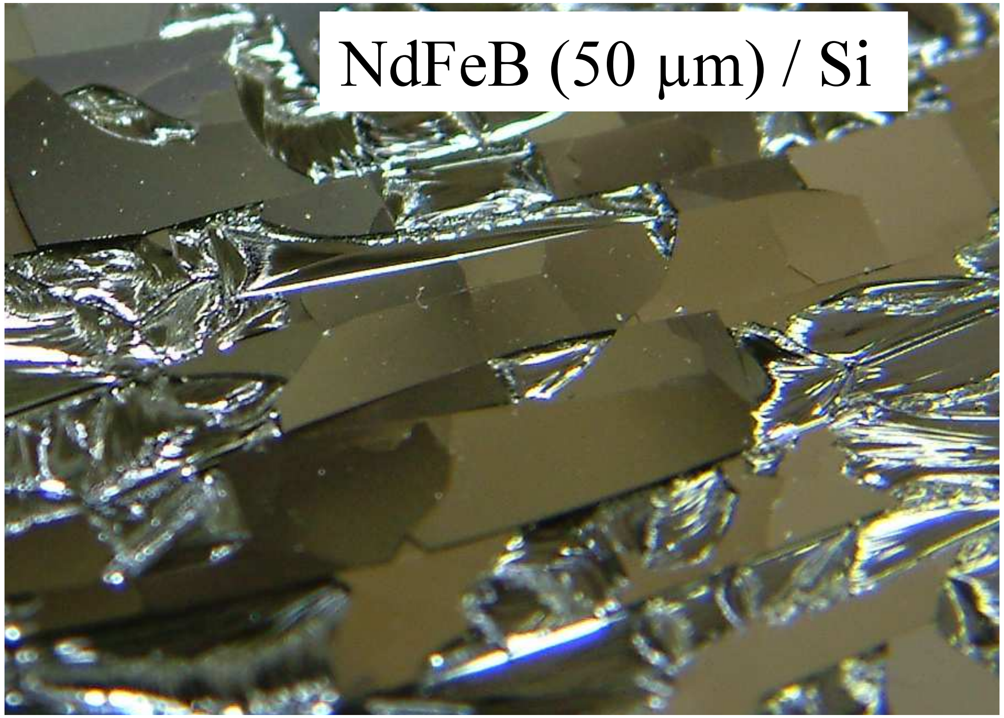
*non-$L1_0$ $Co_{80}Pt_{20}$ may be produced by electro-deposition at low processing temp.

# Integration issues for film magnets

**• Mechanical compatibility**

will have a build up of stress in thick films

mechanical stress ∝ difference in thermal expansion coefficients of susbstrate /buffer layer /magnetic layer




Minimise strain :

choice of substrate / buffer

reduced surface area of magnet

**• Chemical compatibility**

pollution of - other system components

- microtechnology equipment (clean room environment !!)

# Micro-magnets for MEMS

- Candidate materials

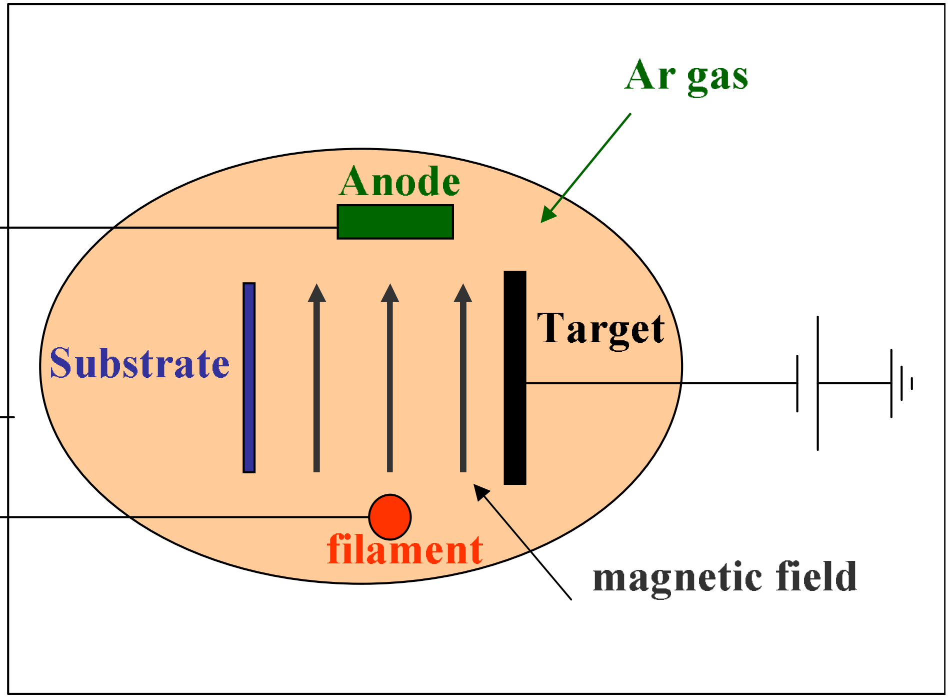
- Integration issues

- Preparation of high performance materials in thick film form by sputtering

- Film patterning

- Beyond magnets

# Preparation of thick film magnets by sputtering

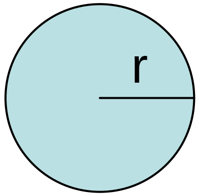



## Triode sputtering machine

- Base pressure : $10^{-6}$ mbar
- Sputtering pressure : $10^{-3}$ mbar
- Target ≤ 10x10 cm²
- Deposition rate ≤ 20 μm/h
- Substrate ≤ 100 mm

Tsub ≤ 750℃

-adapter for 200 mm substrates




| r(cm) | t (μm) |
|---|---|
| 0 | 5 |
| 5 | 4 |
| 10 | 2 |

# Film preparation parameters

**• Target:**

Composition

Target potential

(kinetic energy of impinging ions)

**• Substrate:**

distance to target (thickness+homogeneity)

material (Si, $Al_2O_3$..)

bias

temperature during deposition

**• Deposition conditions**

Ar pressure

**• Post-deposition annealing**

**Film:**

composition

μ-structure

crystal structure

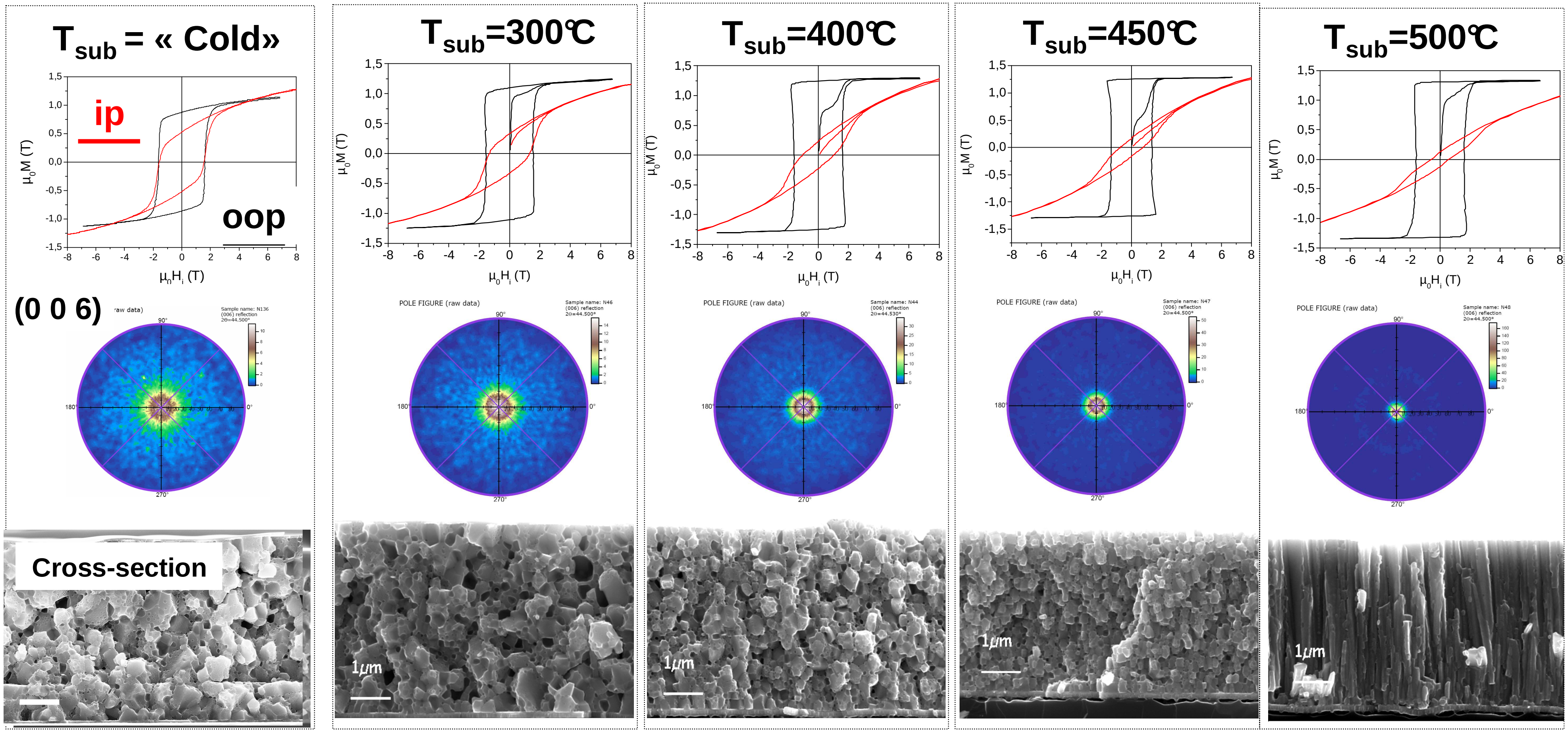
crystal texture

# NdFeB thick films

## - influence of deposition temperature

{**Si** / Ta (100 nm) / **NdFeB (5µm)** / Ta (100 nm) }

**2-step process: deposition at $T_{sub}$ = X ℃ + annealed in situ at 750℃ for 10 min.**



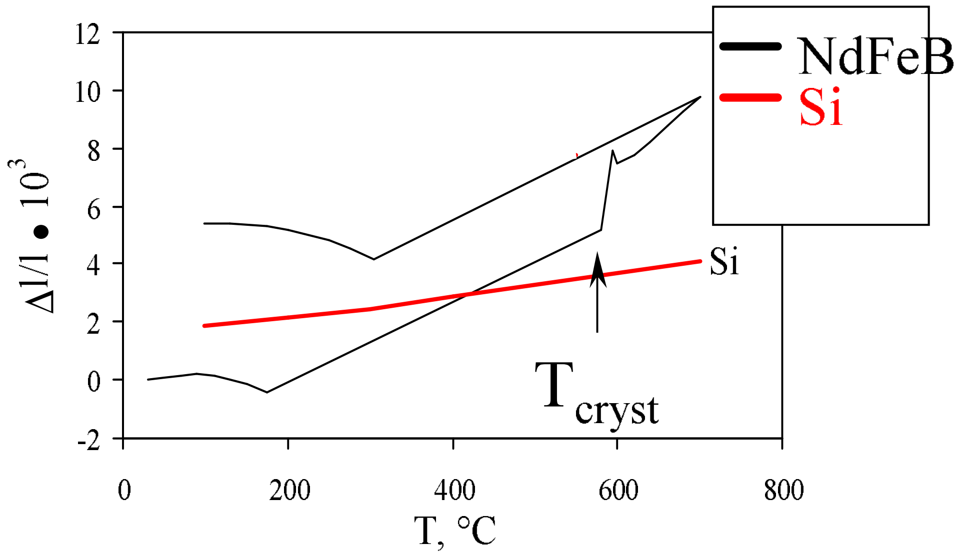

Equiaxed grains ⟶ Columnar grains

Grain size ↓ as $T_{sub}$ ↑ => ↑ of the density of nucleation sites during deposition

# Mechanical issues

have mechanical problems with continuous films….
on 100 mm wafer, central area ($\phi \approx 3$ cm) peels off when film annealed

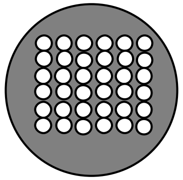
Attributed to
differential thermal expansion (NdFeB vs Si)
+ volume change during crystallisation



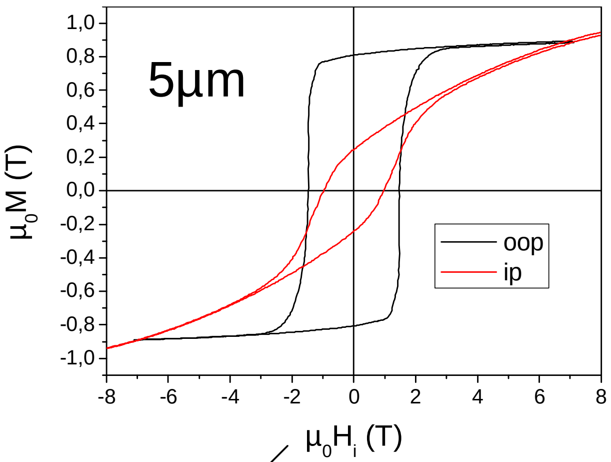

B.A. Kapitanov et al., J. Magn. Magn. Mater. **127**, 289 (1993).

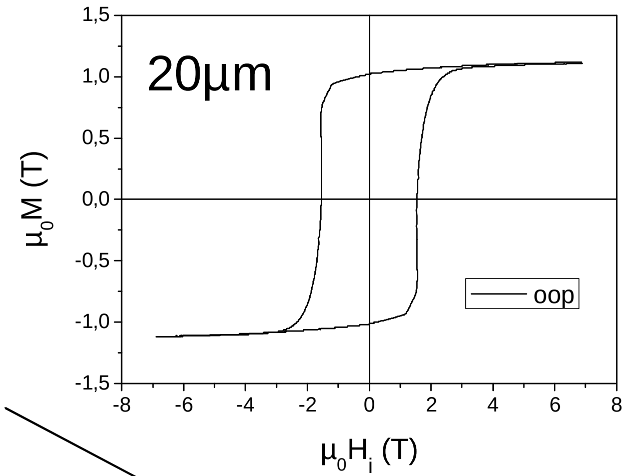
# Mechanically intact thick NdFeB films
## (deposit crystallised ($T_{dep}$ = 550°C) + through mask)

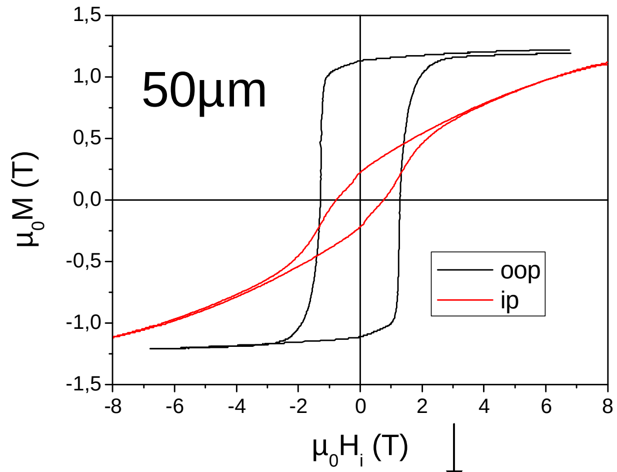
Steel mask, $\phi$ = 5 mm

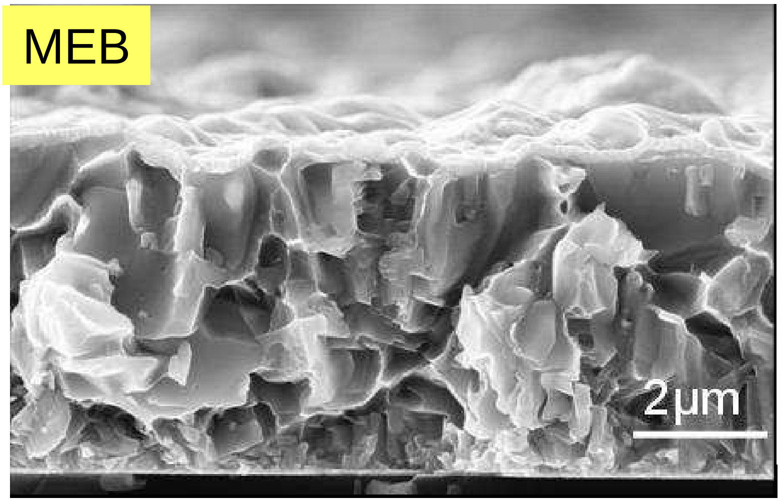


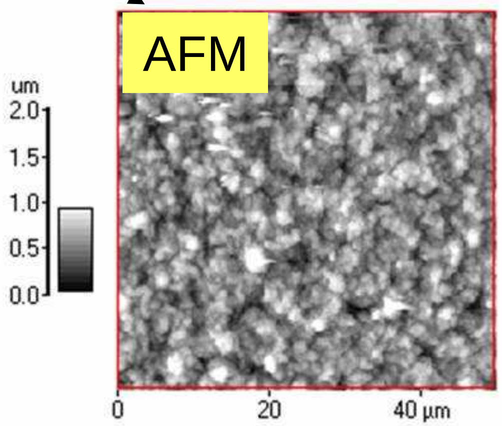
Surface roughness !!!



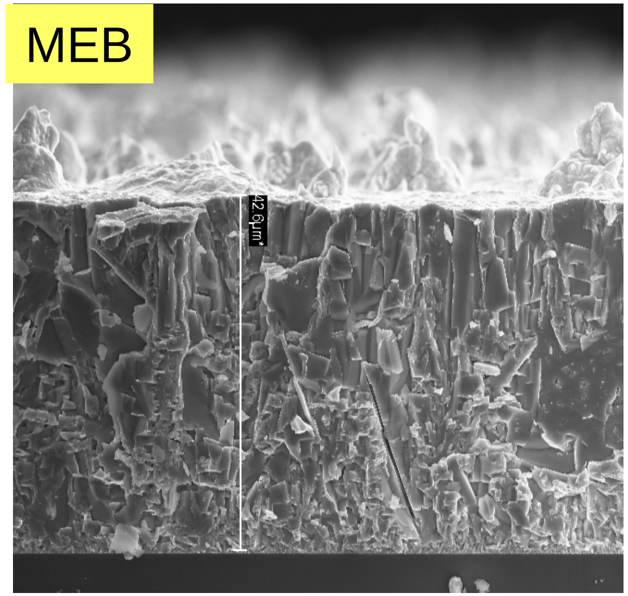



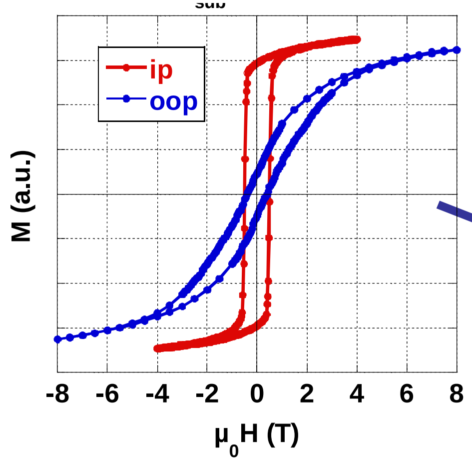




rms=161nm

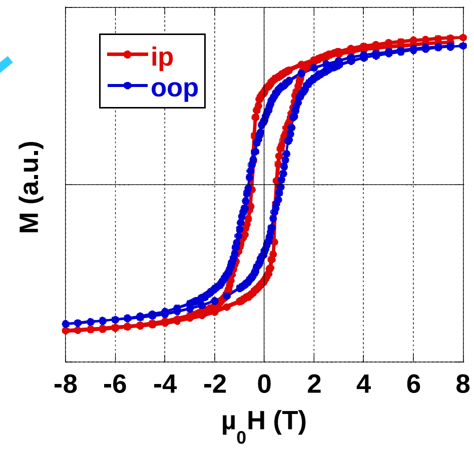


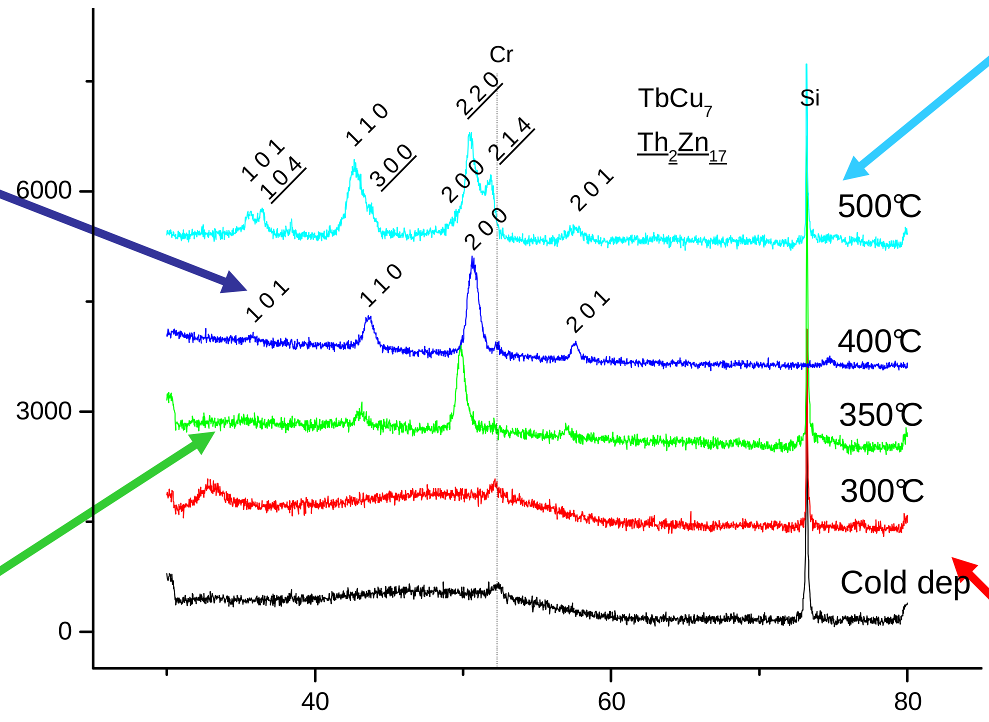
# SmCo thick films
## -infleunce of deposition temperature

$T_{sub}$ = 400℃

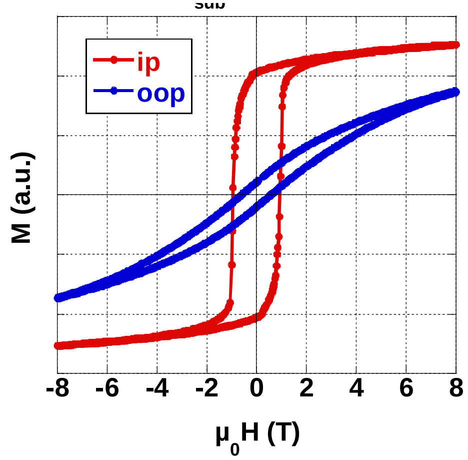


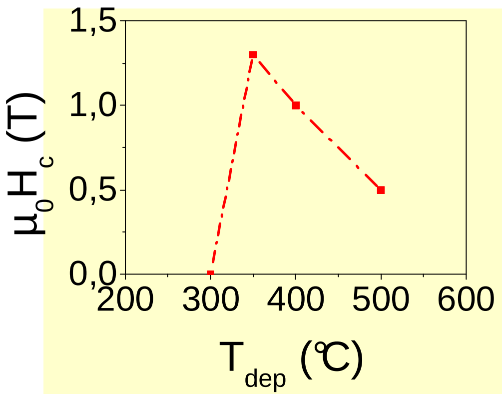

$T_{sub}$ = 500℃



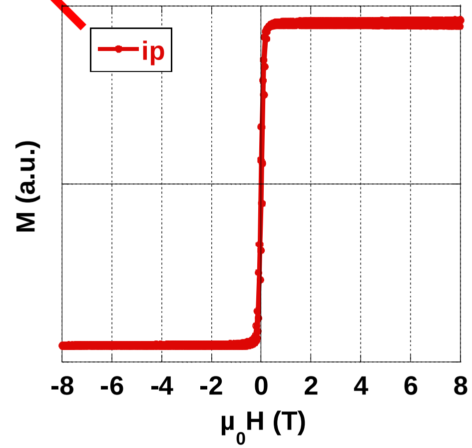

$T_{sub}$ = 350℃



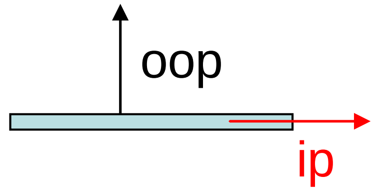




For $T_{sub}$
= 350-400℃
$\mu_0 M_r \approx 0.8$ T

$T_{sub}$ = 300℃



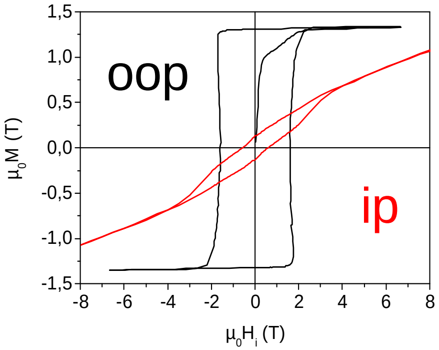
# Thick hard magnetic films (5 µm) on Si

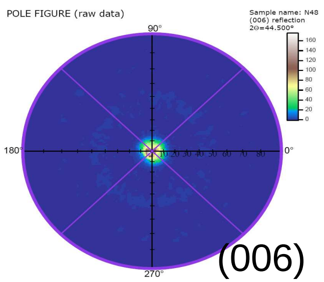



NdFeB
out-of-plane texture

**$T_{dep}$: 450℃ + $T_{ann}$ : 750℃**

**or $T_{dep}$ = 550℃**

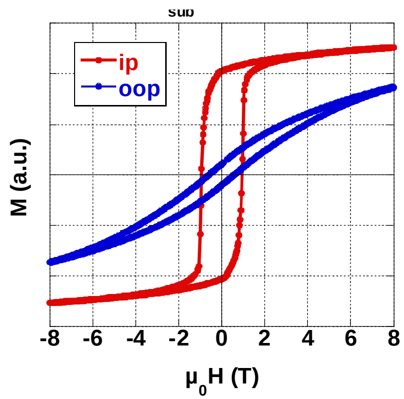


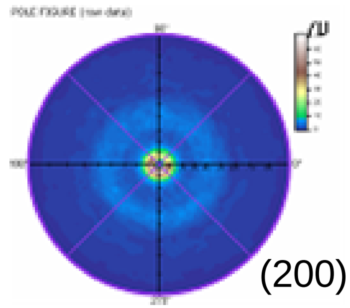




**$(BH)_{max}$=400 kJ/m³**

SmCo
in-plane texture

**$T_{dep}$: 350℃**

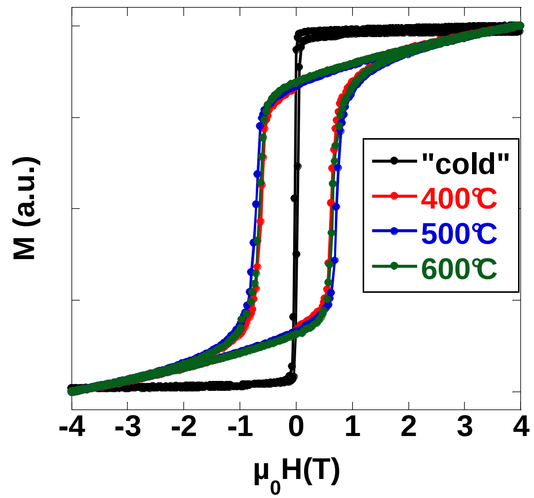



**$(BH)_{max}$=140 kJ/m³**

FePt
isotropic

**$T_{dep}$: ≥ 400℃**




**$\mu_0 H_c$ > 1 T**
**Corrosion resistive**

# Micro-magnets for MEMS

- Candidate materials

- Integration issues

- Preparation of high performance materials
  in thick film form by sputtering

-Film patterning

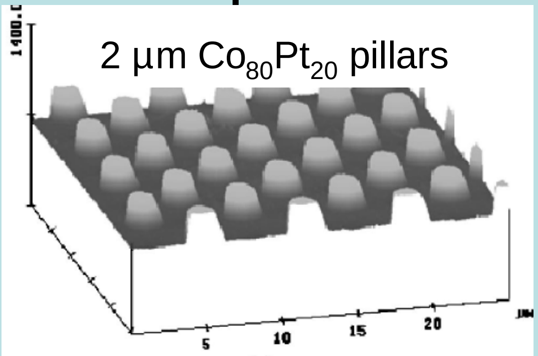
-Beyond magnets



NÉEL institut

# Micro-structured Magnets

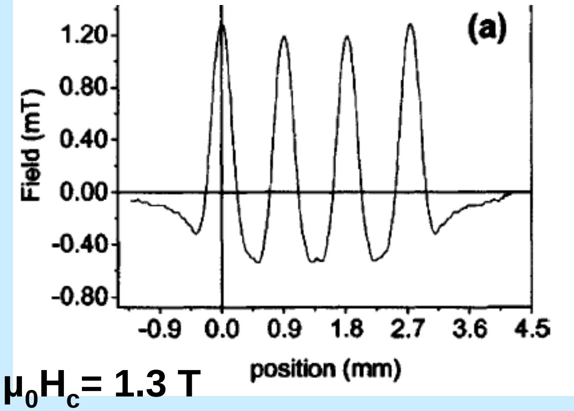
**Electro-deposited**




**$\mu_0H_c$= 0.4 T, $(BH)_{max}$= 34 kJ/m$^3$**

**2002 Zana_JAP_91_7320**

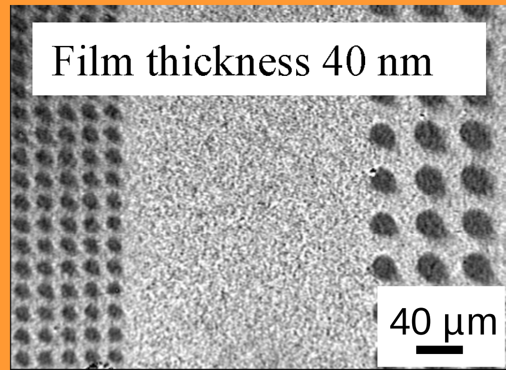
**Electro-deposited** $Co_{50}Pt_{50}$
in nanoporous membranes
450 µm pole pitch




**$\mu_0H_c$= 1.3 T**

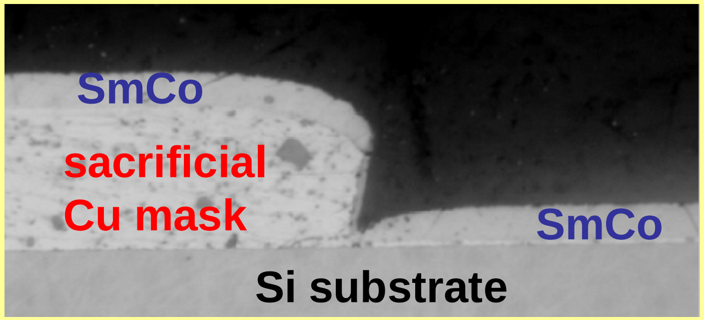
2005 Rhen_JAP_97_113908

**PLD of FePt ($L1_0$)**
**Local laser annealing**
**→ disordering**



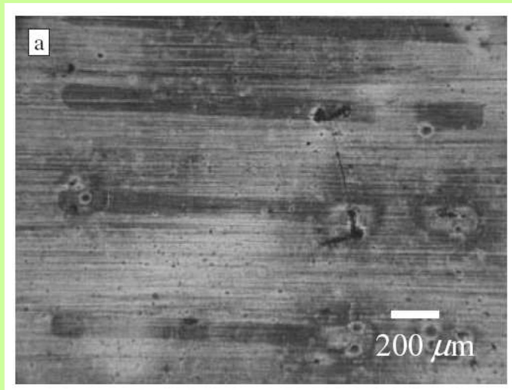

**2006 J. Buschbeck_JAP (IFW)**

**Sputtered SmCo**
**Lift-off of Cu mask by wet etch**




**2002 Budde JMMM242_1146**

**Sputtering of amorphous NdFeB**
**Local laser annealing → crystallisation**




**2003 Okuda_JJAP_42_6859**

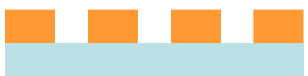
# Proposed routes for the structuration of magnetic films

## 1) Topographic

**Deposition on prepatterned subst.**

+ polishing

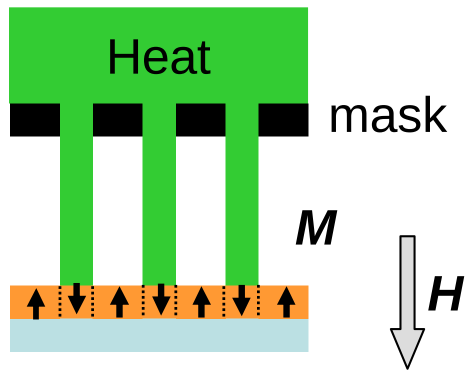
**Etching of magnetic layer**



*irreversible*

## 2) Magnetic

**Thermomagnetic patterning**




cf: thermomagnetic writing for recording media

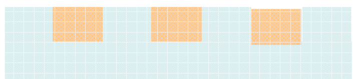
*reversible*

# Proposed routes for the structuration of magnetic films

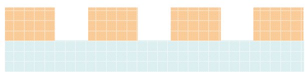
## 1) Topographic

**Deposition on prepatterned subst.**

+ polishing



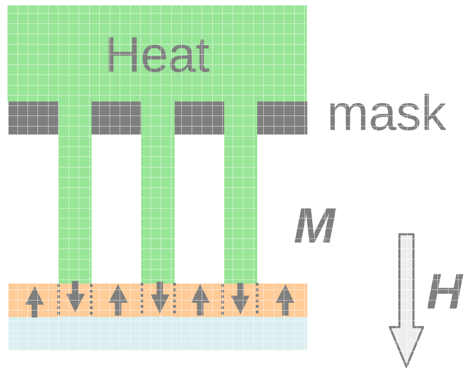
**Etching of magnetic layer**



*irreversible*

## 2) Magnetic

**Thermomagnetic patterning**

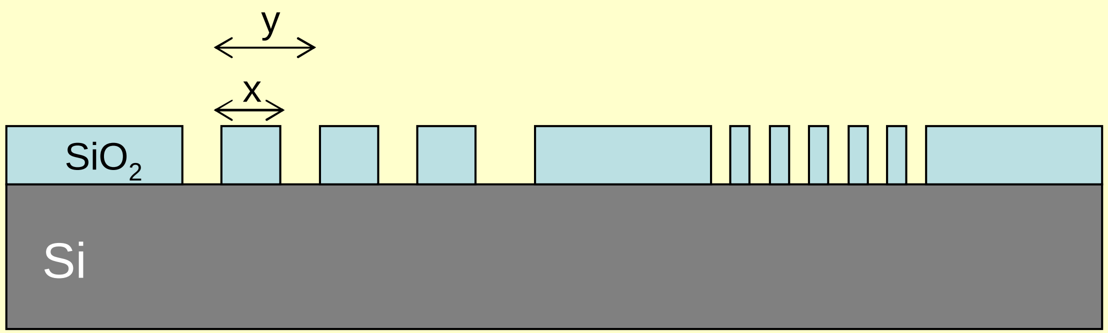



cf: thermomagnetic writing for recording media

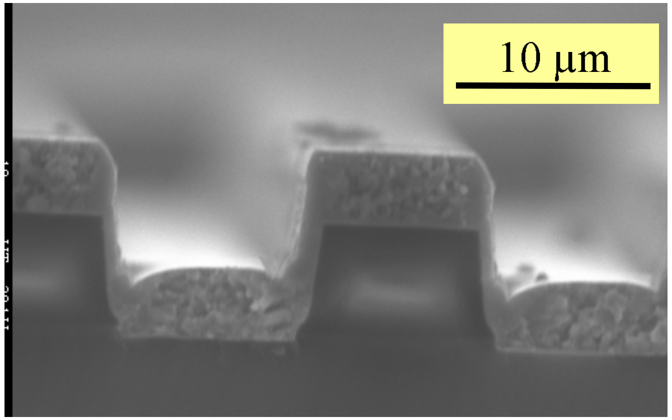
*reversible*

# Topographically patterned films

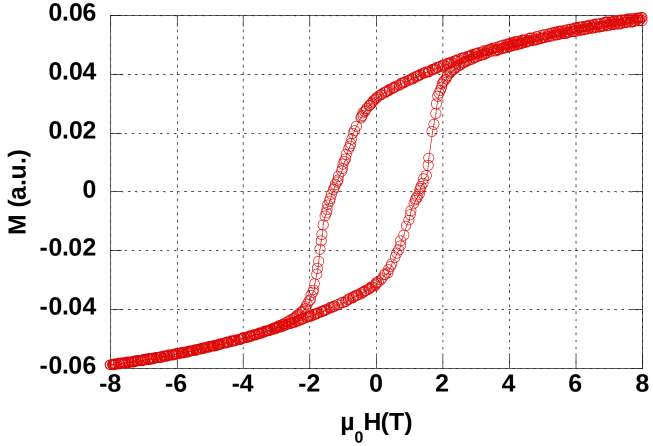
**Use of pre-patterned Si/$SiO_2$ substrate with sets of trenches of different lateral dimensions**




« cold » deposition of Ta(100nm) / **NdFeB (5 µm)** /Ta (100 nm) + in-situ anneal (750℃/10 min)

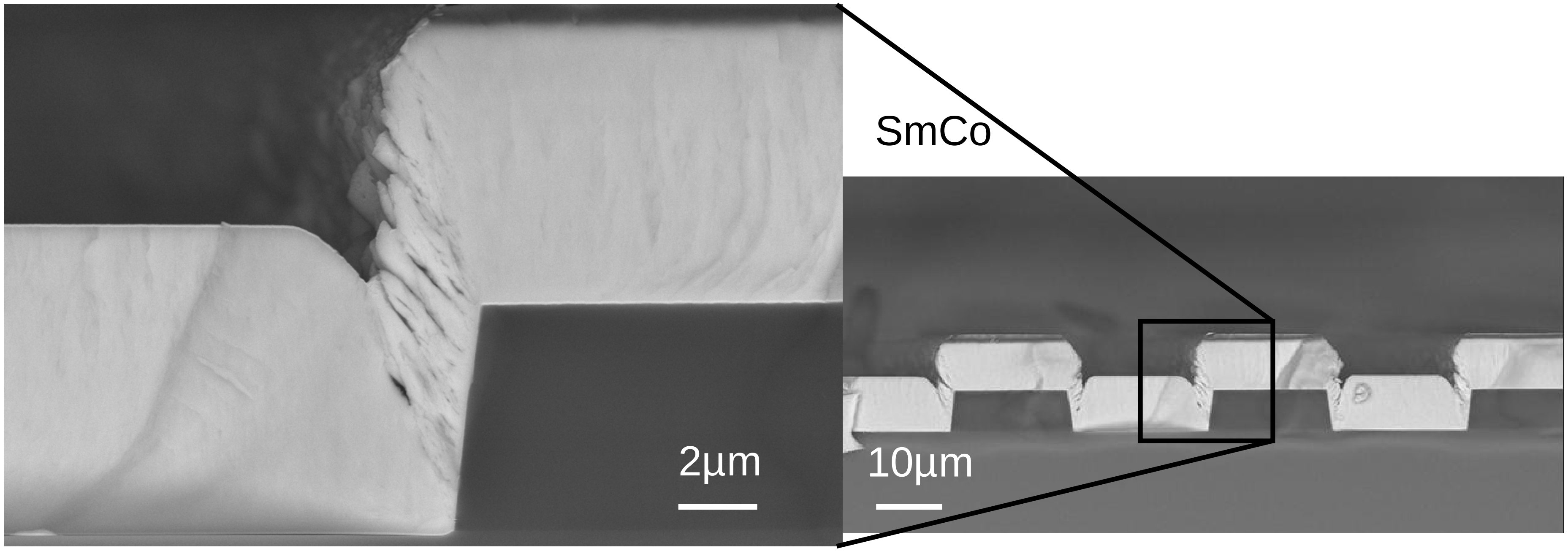


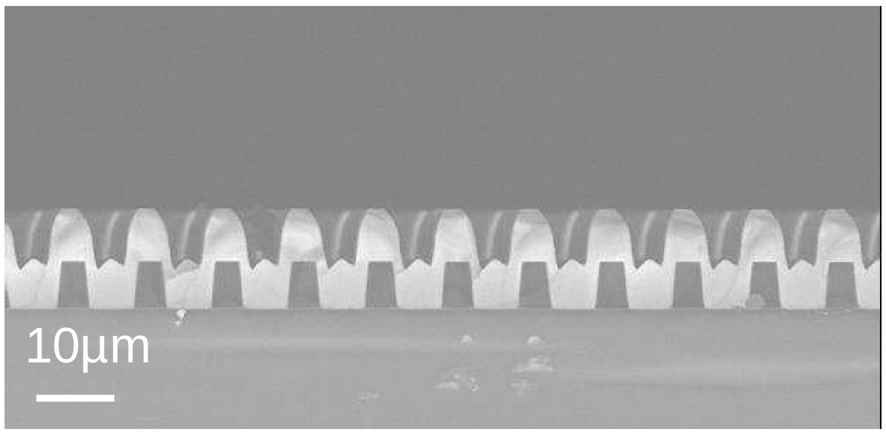

**in-plane loop of a piece containing 3 sets of trenches (widths 5, 10 and 20 µm)**

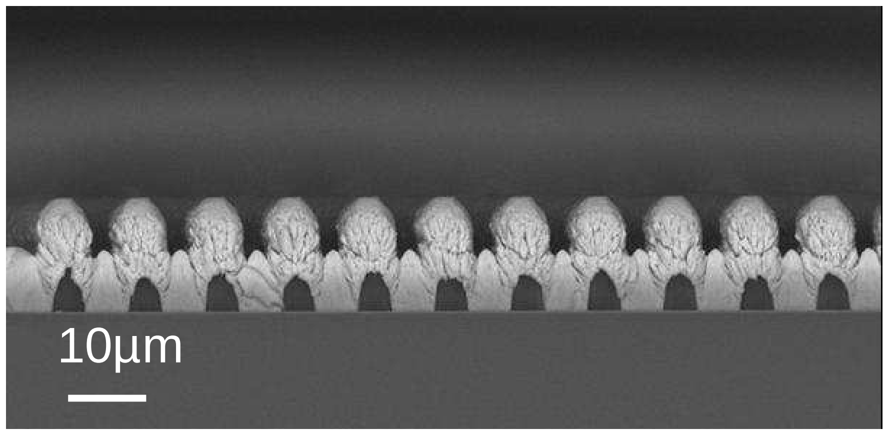



Need local magnetic characterisation !

# Trench filling on pre-patterned wafers



# Local magnetic characterisation for MEMS

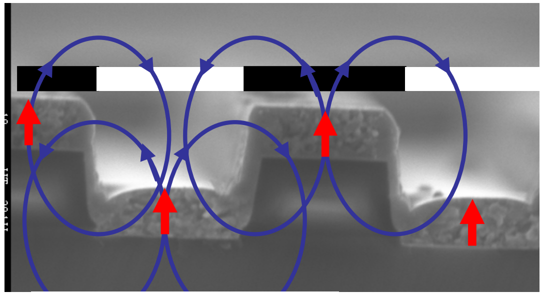
Need to measure stray fields produced by μ-magnets :

- to characterise inhomogeneities
  (process optimisation)

- to calculate forces at work in the μ-system
  (simulation/design optimisation)

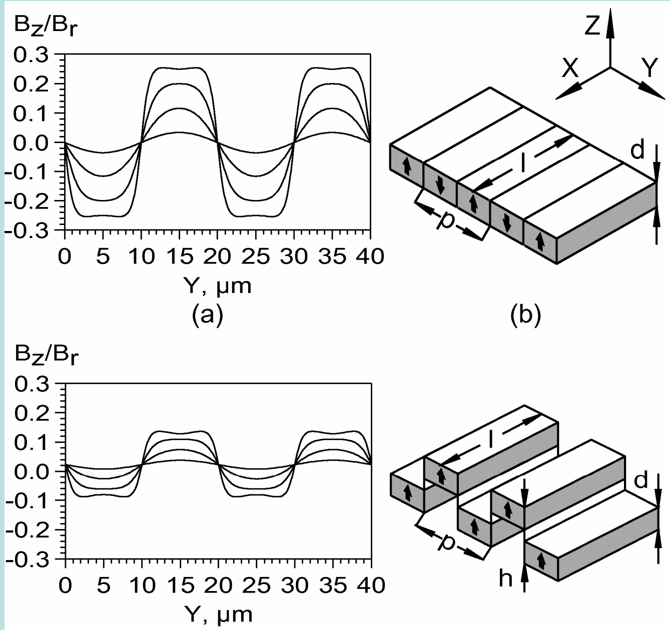
Tools :
Scanning Hall probes (sensititvity + scan param. adapted to MEMS)
Kerr microscope + MOIF

# MOIF* imaging of topographically patterned films




•Magneto Optic Imaging Film (e.g. ferrite garnet)

sample saturated out-of-plane




multipole

**Theoretically calculated $B_z/B_r$ at**

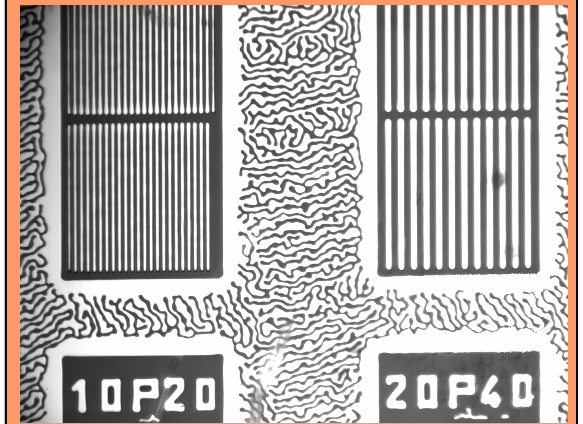
1, 2, 4 and 8 µm from film surface

**($t_{film}$ = 3.5 µm, p = 20 µm**

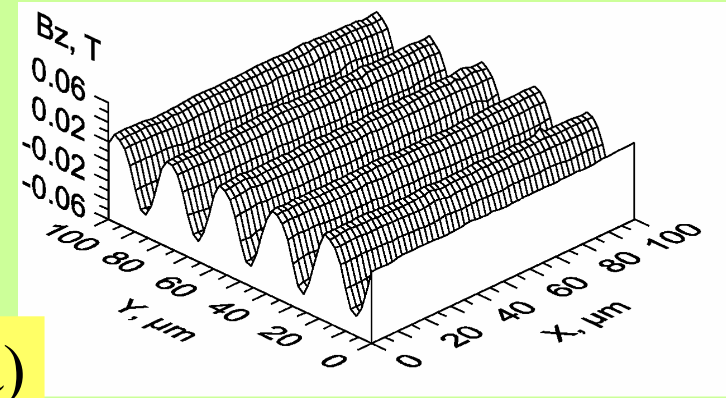
**h = 10 µm l = 100 µm)**

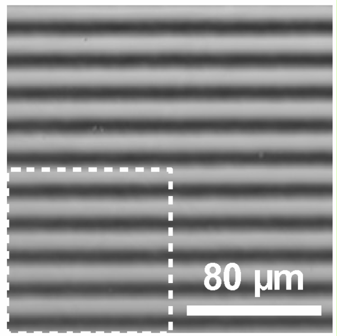
unidirectional

**uniaxial MOIF**




***$B_z$* distribution reconstructed from halftone planar MOIF images at a distance of 4 µm**

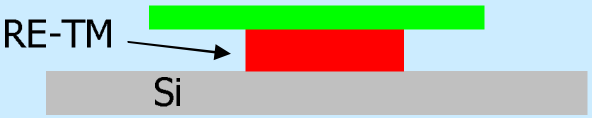



Tver State University (Russia)

# Wet etching/planarisation of RE-TM films

## Wet etching



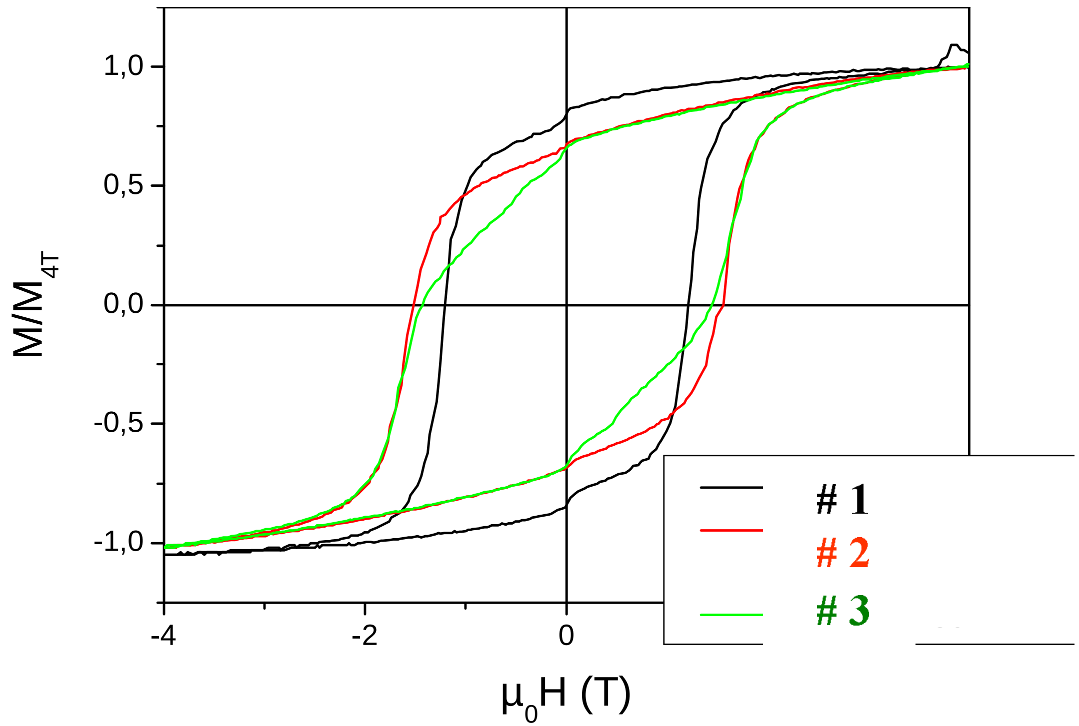


lateral over-etching

≈ 15 µm

Films etched in amorphous state

Hystersis loops
of wet etched /planarised
and annealed NdFeB




#1: capped with Ta + annealed

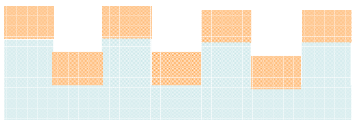
#2: ion etched + capped with Ta + annealed

#3: annealed

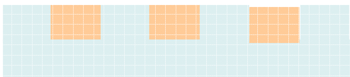
# Proposed routes for the structuration of films

## 1) Topographic

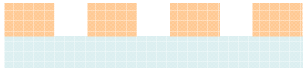
Deposition on prepatterned subst.



+ polishing



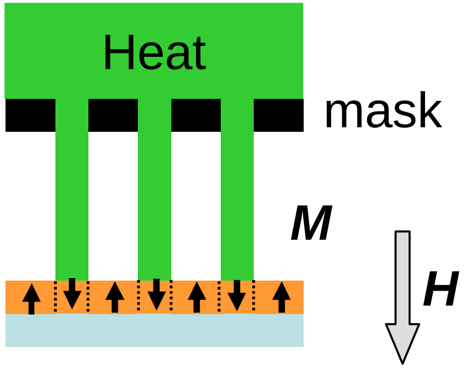
Etching of magnetic layer



*irreversible*

## 2) Magnetic

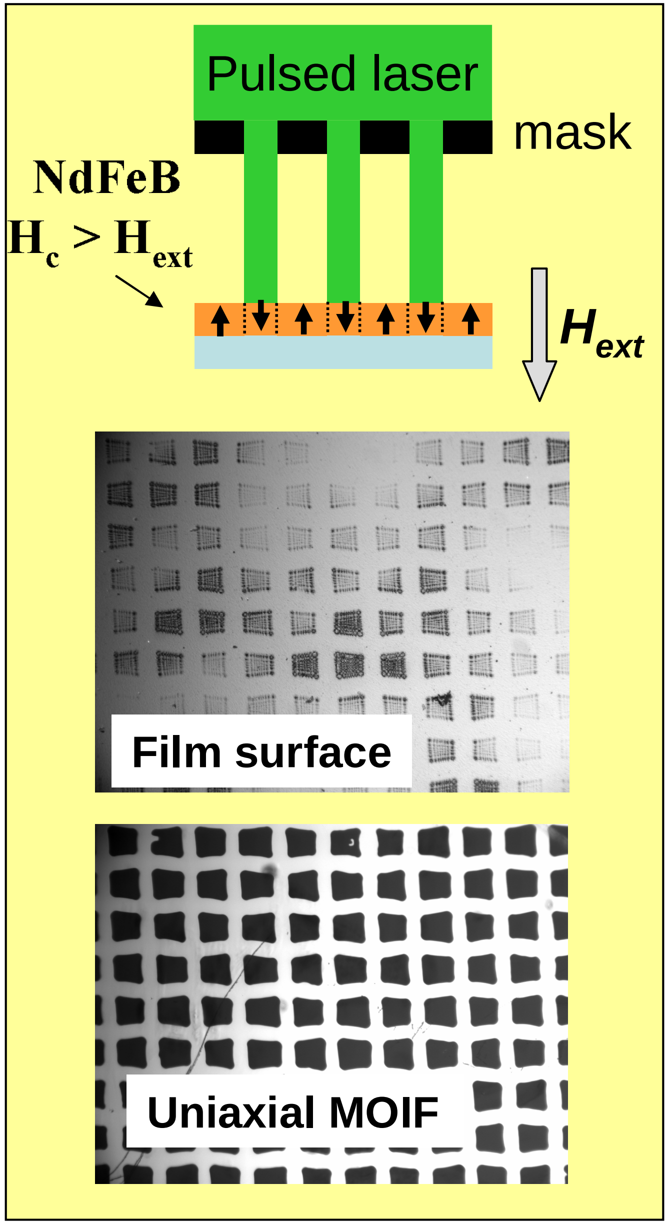
**Thermomagnetic patterning**



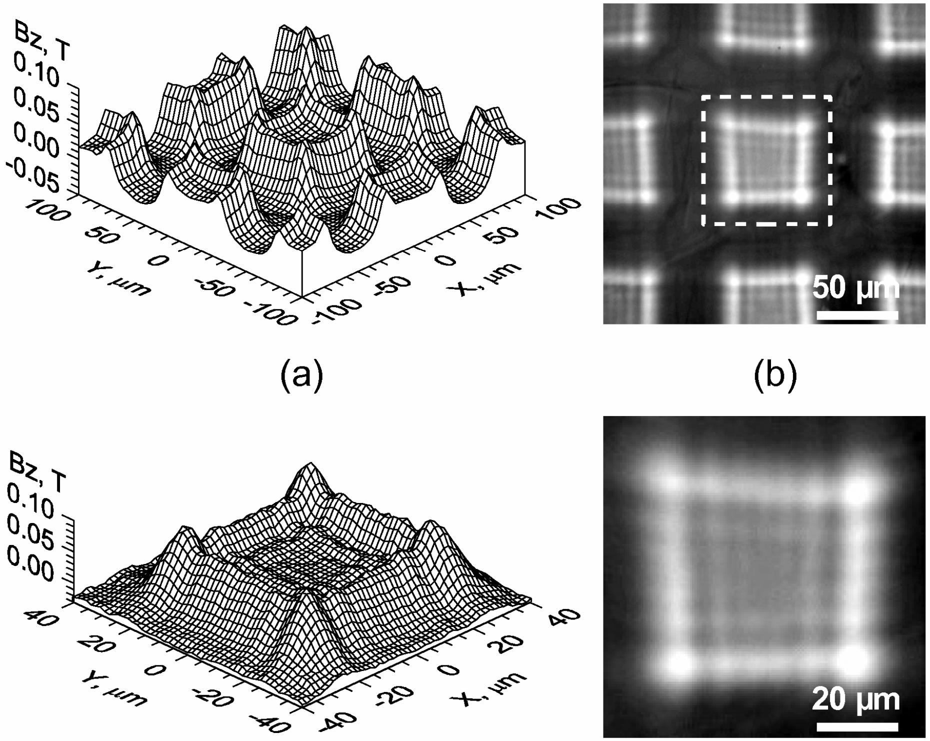

cf: thermomagnetic writing for recording media

*reversible*

# Thermo-Magnetic patterning of NdFeB films




planar MOIF




(a) (b)

**Magnetisation modulation due to Fresnel diffraction at mask**

**Pitch (~12 μm) determined by $\lambda_{laser}$ and distance from mask to sample.**

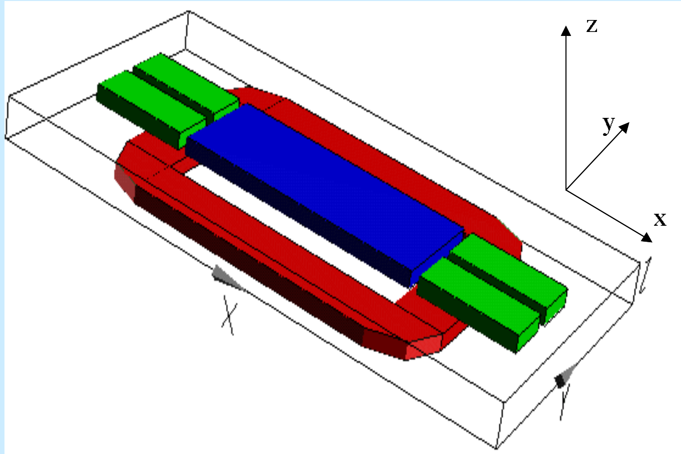
**Demonstrates the perspective for optical interference thermomagnetic writing**

# Applications of µ-magnets

## RF µ-switches

Collaboration:
G2ELab : **µ-system designer**
LETI : **µ-fab platform**
Institut Néel : **magnet films**
Alcatel Space : **end user**

Funding: ANR “Nanomag2“




58 process steps (including 9 litho.)

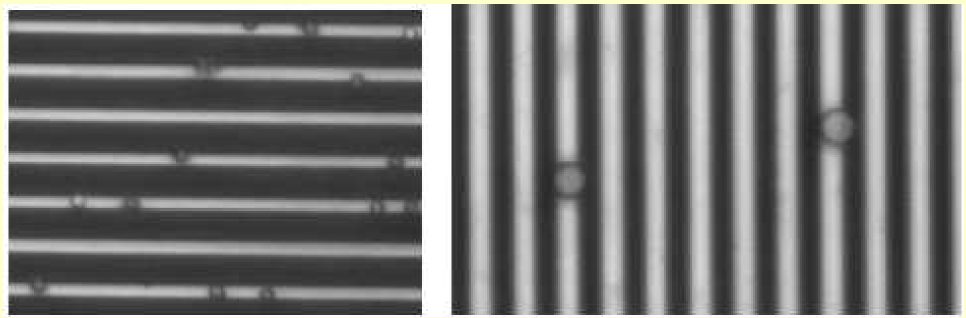
## Diamagnetic levitation

LEG and CEA (Biochips Laboratory, SMOC/LETI)

« clip » C. Pigot

H. Chetouani et al., Transducers ‘07

Contactless containment of 3µm latex microbeads with linear magnetic traps



# Micro-magnets for MEMS

- Candidate materials

- Integration issues

- Preparation of high performance materials in thick film form by sputtering

-Film patterning

-Beyond magnets

# Beyond hard magnets: switchable materials

**Why go beyond hard magnets?**
They are driven by currents in coils
⇒ Joule heating losses
⇒ Complex design

**Switchable magnetic materials:**
Reversible change of magnetic properties ($M_S$, $H_A$) by an external parameter.

## Thermo-switchable

New functionality
(e.g. laterally resolved modifications by controlled laser heating)

Contactless !

## E-field switchable

Novel concept
Unexplored potential

e.g. FePt, FeRh

## Strain switchable

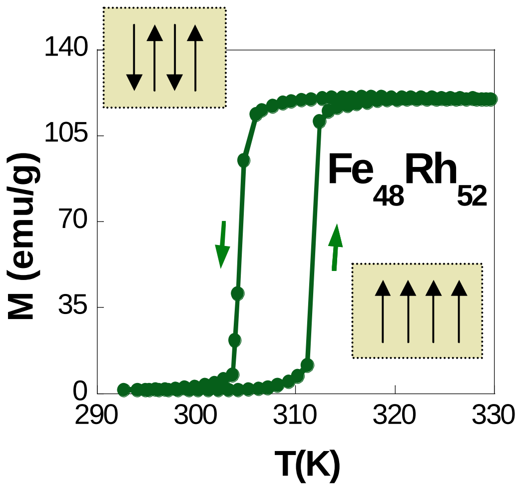
Magnetostrictive

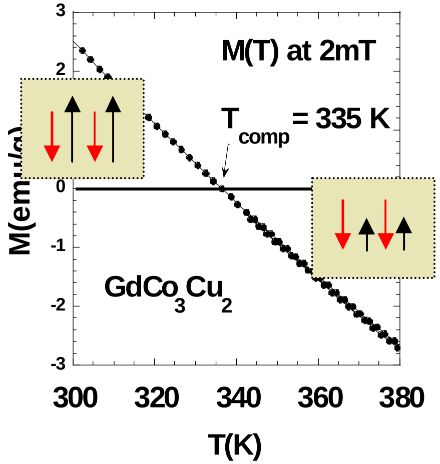
Multiferroics

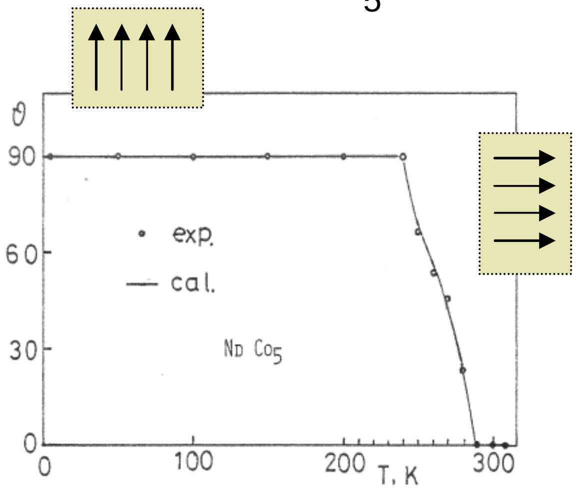
magnetic shape memory

# Thermo-switchable materials

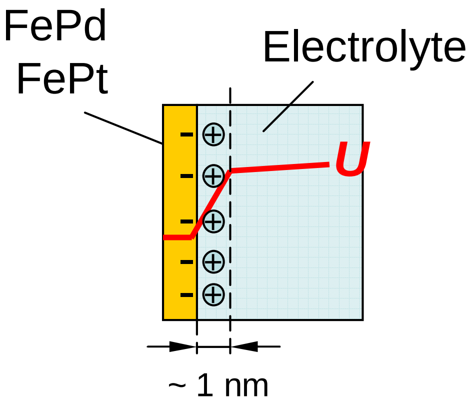
| Antiferro ⇔ ferro | Ferrimagnetic Compensation | In-plane ⇔ out-of-plane |
|---|---|---|
| **on / off switching** | **up / down switching** | **90° switching** |
| e.g. FeRh | $GdCo_3Cu_2$ | $NdCo_5$ |



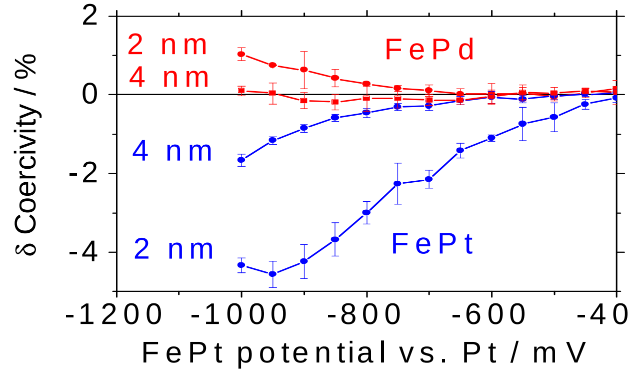



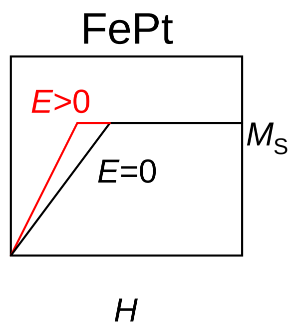
# E-field switchable materials

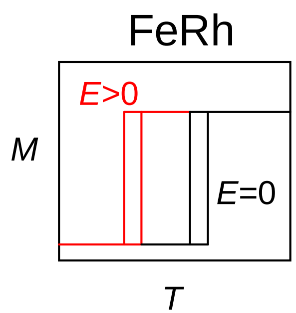



reversible modification of magnetic properties in itinerant electron systems

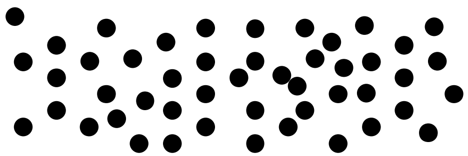



**Surface effect:** High surface-to-volume ratio needed




**Nanocrystalline powder**



- Compaction
- Sintering

**nanoporous**

**Alloy film**

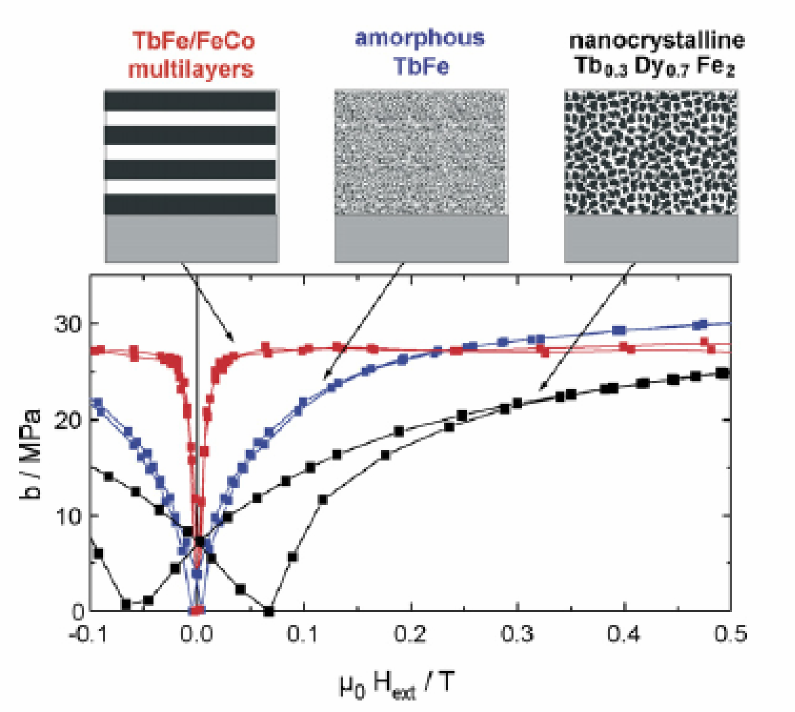
Selective dissolution of sacrificial component

**nanoporous**

Prospect for **NEMS**

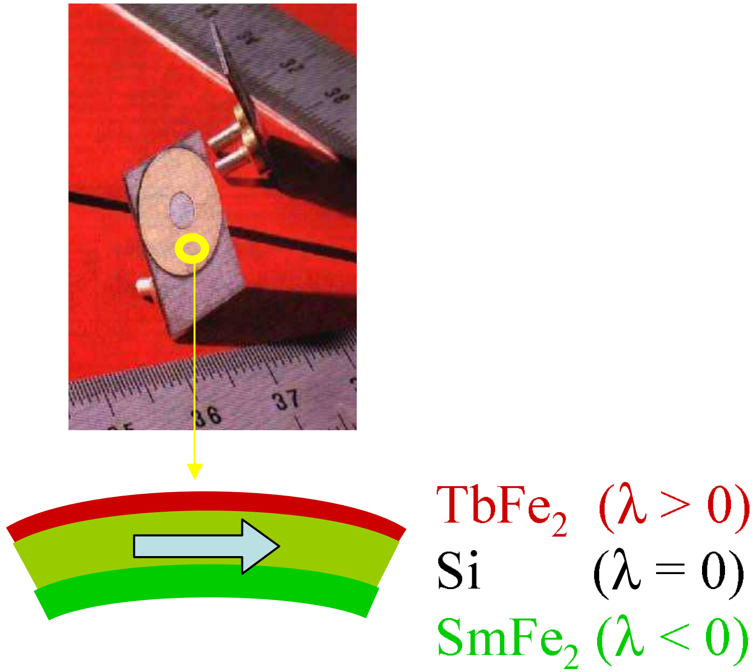
# Other Magnetic Materials for MEMS

## - Magnetostrictive




bimorph membranes (μ-pump)

Planar micropump




## - Magnetic Shape Memory Alloy

See **K. Dörr** (talk)
\+ **M. Thomas** (poster)

# Acknowledgments

**Institut Néel :**
A. Walther (PhD), C. N’dao (PhD) and D. Givord

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**LETI/CEA**
C. Marcoux, B. Desloges, C. Dieppedale

**TVER STATE UNIVERSITY**
R. Grechishkin, M. Kustov (PhD)

WEB:

Bernard Legrand (IEMN) « Ecole Nanosciences et Nanotech. – Autrans 2006 »

http://www.mems-exchange.org

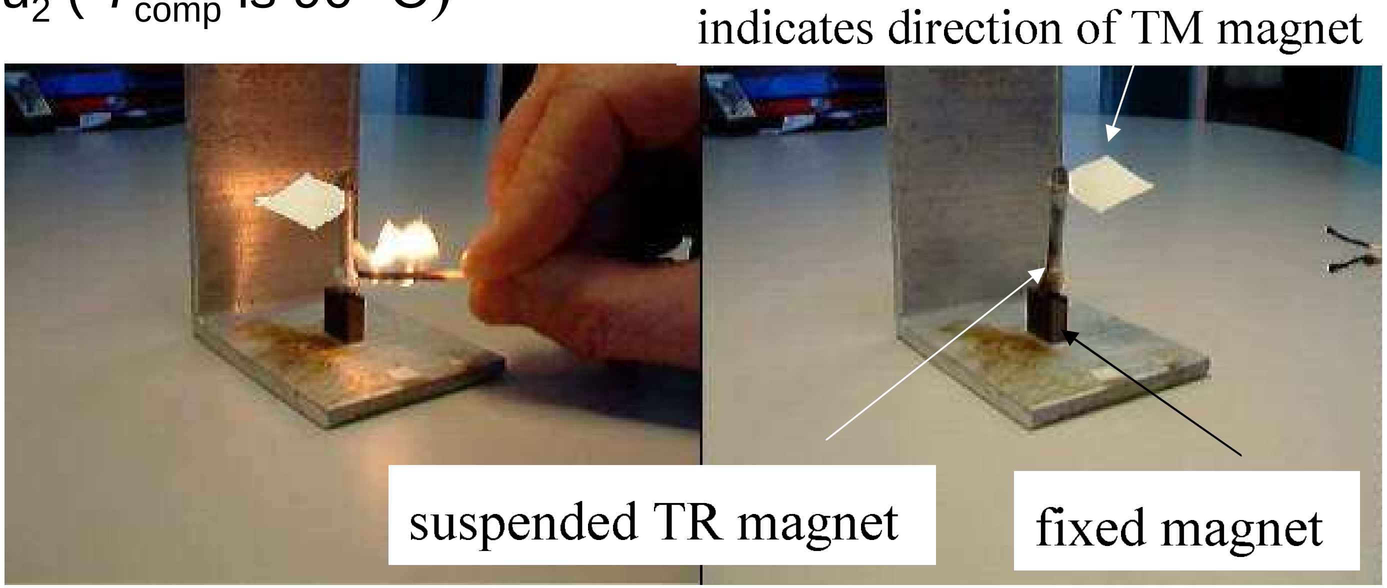
http://www.memx.com

# Applications of THERMO-REVERSIBLE Permanent Magnet

$GdCo_3Cu_2$ ( $T_{comp}$ is 90 °C)

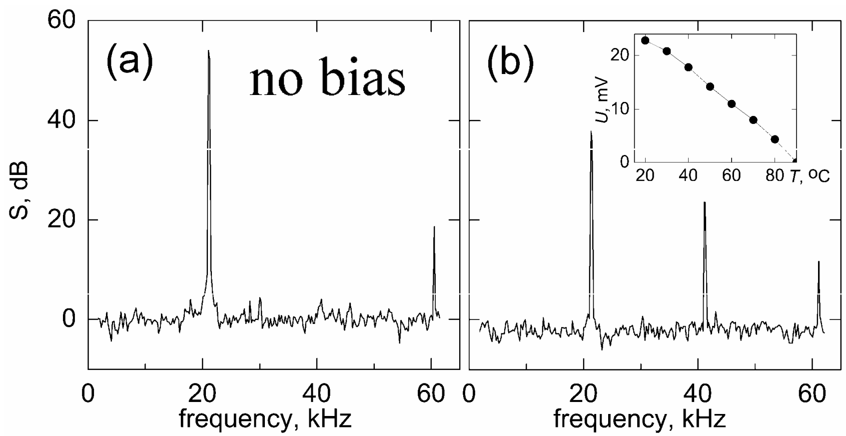
**thermally controlled Actuator:**

suspended TR magnet rotates by 180° when heated above $T_{comp}$




**remotely interrogated temperature sensor :**

*signal element* square loop soft magnetic tape (nc $Fe_{81}B_{13.5}Si_{3.5}C_2$) producing detectable harmonics.
Bias with magnet → appearance of even harmonics




Grechishkin et al. APL **89**, 122505 (2006); D. Mavrudieva et al, SENSOR LETTERS **5**, 1 (2007)