Magnetic Microsystems

Tiny Magnets Solving Big Problems

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October 4, 2017

Interdisciplinary Microsystems Group

- **Founded in 1998**


Toshi Nishida
ECE 1998
Low power devices
and sensors


Mark Sheplak
MAE/ECE1998
Acoustic/flow sensors


Huikai Xie
ECE 2002
Inertial sensors,
microoptics


Hugh Fan
MAE 2003
Microfluidics


David Arnold
ECE 2005
Micromagnetics,
PowerMEMS


Saeed Moghaddam
MAE 2010
Microheat exchange,
energy storage


Y.K.Yoon
ECE 2010
RF wireless MEMS
and antennas


Jack Judy
ECE 2013
Neural interfaces


Roozbeh Tabrizian
ECE 2015
Microresonators


Alexandra Garraud
ECE 2015
Wireless power,
BioMEMS

Alumni: L. Cattafesta (1999-2012), H. Sodano (2008-2015)

Multi-functional Integrated System Technology Center

MIST CENTER

Multi-functional Integrated System Technology

"Innovating More than Moore technologies for smart systems in the IoT era"

- *40 faculty at 3 universities*
- *~50 students/postdocs*
- *~$1.5M/yr research expenditures*

www.mist-center.org

UF UNIVERSITY of FLORIDA

UCF

UNIVERSITY of VIRGINIA

Allegro MicroSystems, LLC

BOEING

bridg
Bridging the Innovation Development Gap

CORNING

intersil

imec

Honeywell

IC² Interdisciplinary Consulting Corp

JABIL

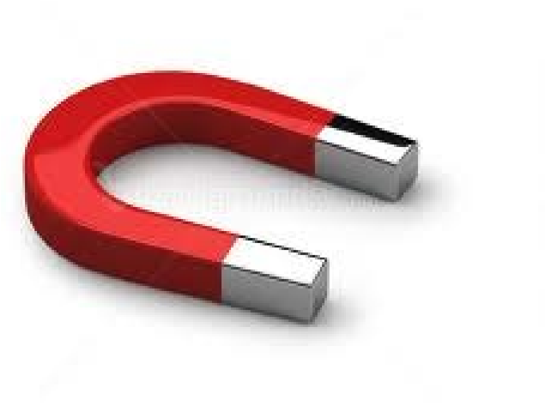
Namjeong Foundation

Prioria

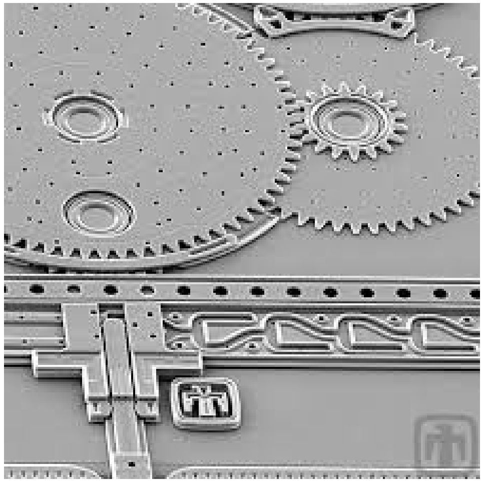
U.S. ARMY RDECOM
TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.

Outline

- **Motivations**



- **Technology Development**
  - Magnetic Materials
  - Magnetic Patterning
  - Characterization



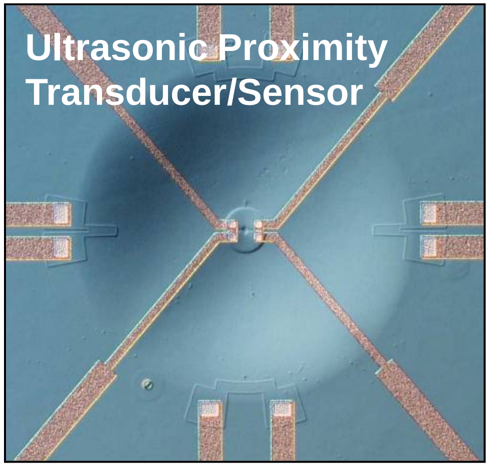
- **Applications**
  - Microactuators
  - Magnetic nanomanufacturing
  - Magnetic microrobots

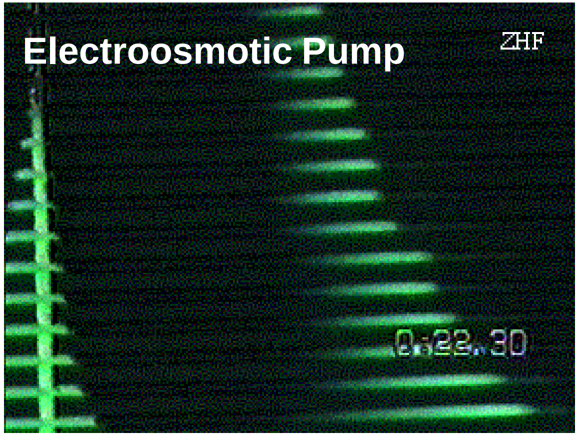
https://www.youtube.com/watch?v=uL6e3co4Qqc

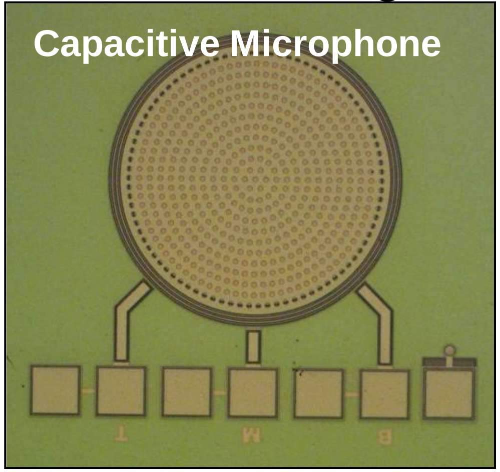
ding end effectors (as simple as metal wires) the micro-robots can perform useful tasks.

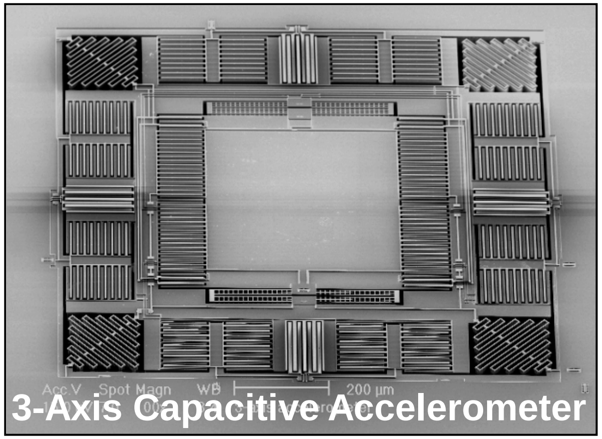
MEMS Overview

- Microelectromechanical Systems (MEMS) - integration of mechanical elements, sensors, actuators, and/or electronics on a common silicon substrate through microfabrication technologies

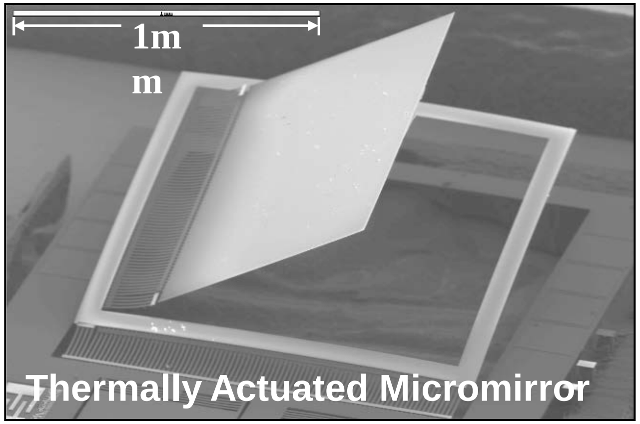

Ultrasonic Proximity Transducer/Sensor


Electroosmotic Pump


Capacitive Microphone


3-Axis Capacitive Accelerometer

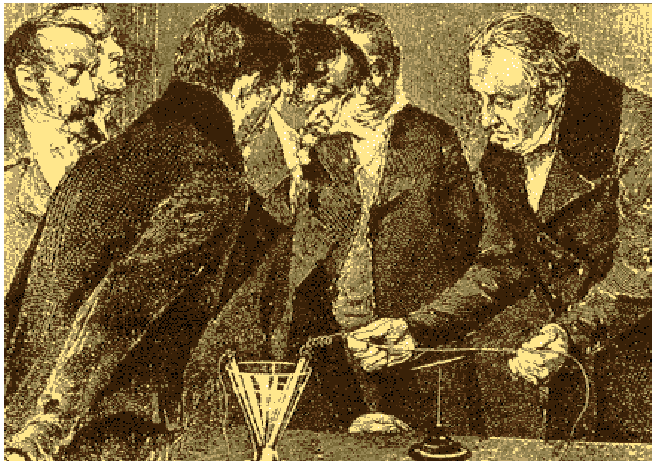

Piezoresistive Microphone


Thermally Actuated Micromirror

Magnetic Transducers

Magnetic transducers have been around for almost 200 years

- **Benefits**
  - High stroke
  - Moderate force
  - High energy density
  - Direct, fully linear transduction (electrodynamic)
  - Contactless
  - Bi-directional
  - Low voltage
  - Wide temperature range
  - Robust

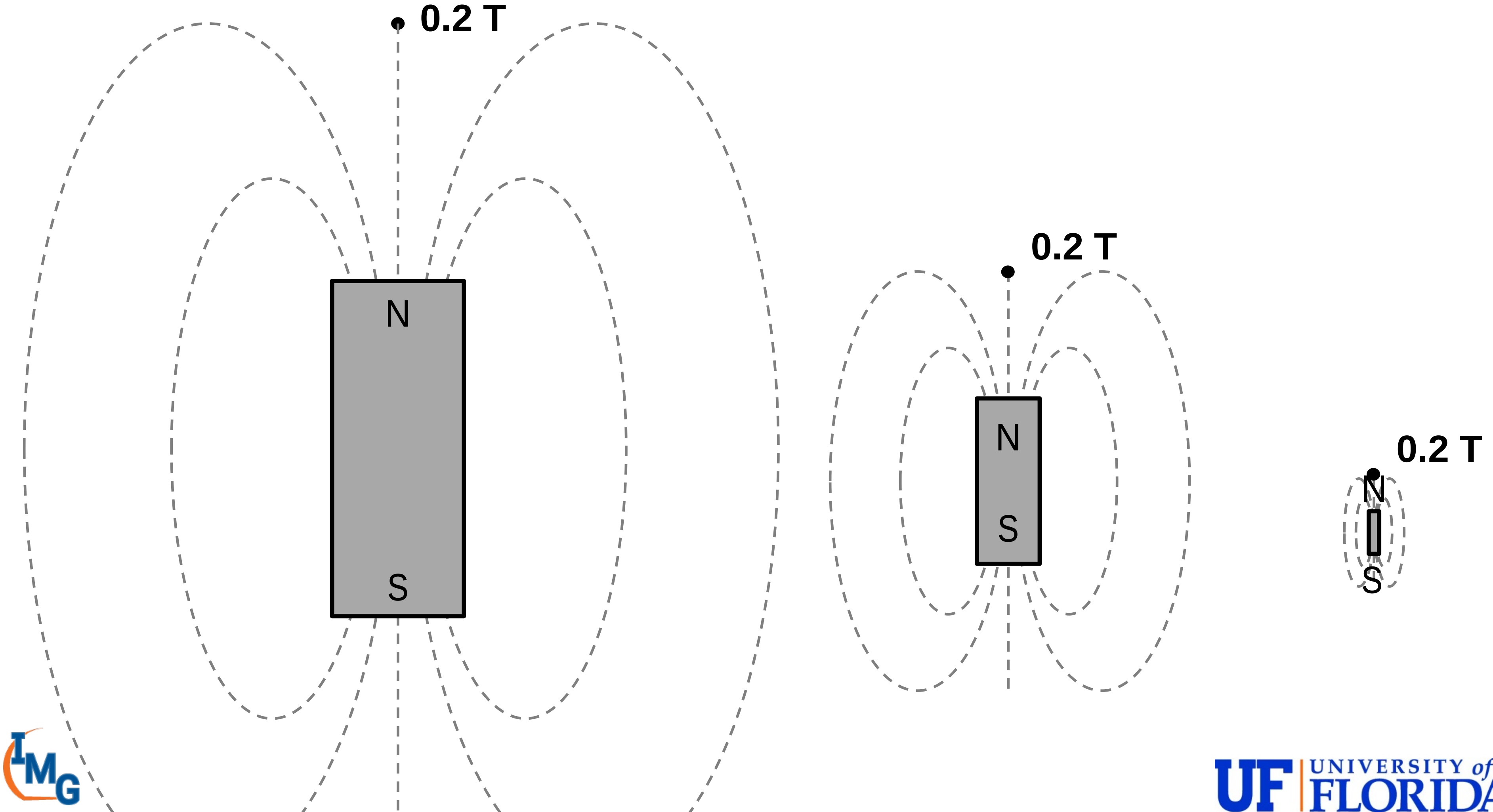


H. C. Oersted, 1819

Magnetic MEMS are still emerging!

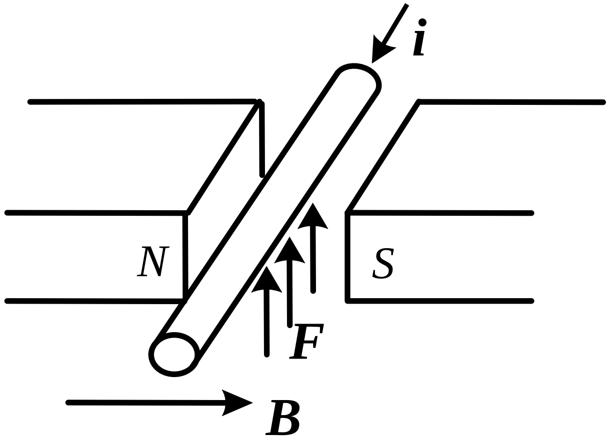
Magnetic Field Scaling

- **Magnetic fields from PM's are scale-independent**
  (down to µm length scales)

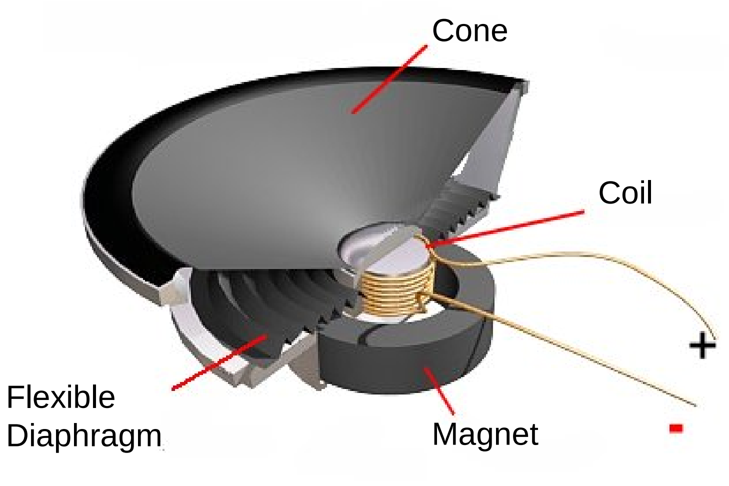


Electrodynamic Transduction

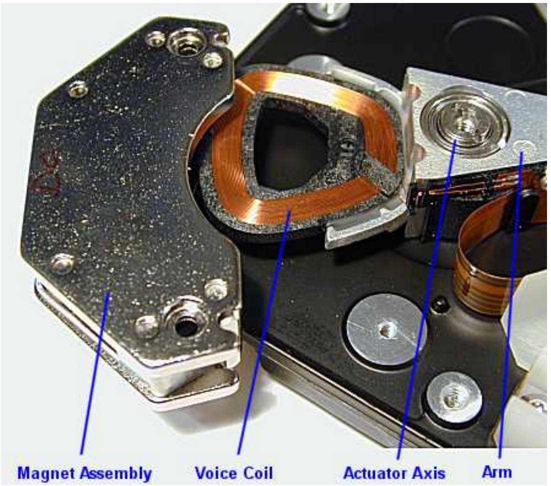
1. **Electrodynamic Transduction:** motor action produced by the current in an electric conductor located in a fixed transverse magnetic field



$$\boxed{F = Bli}$$



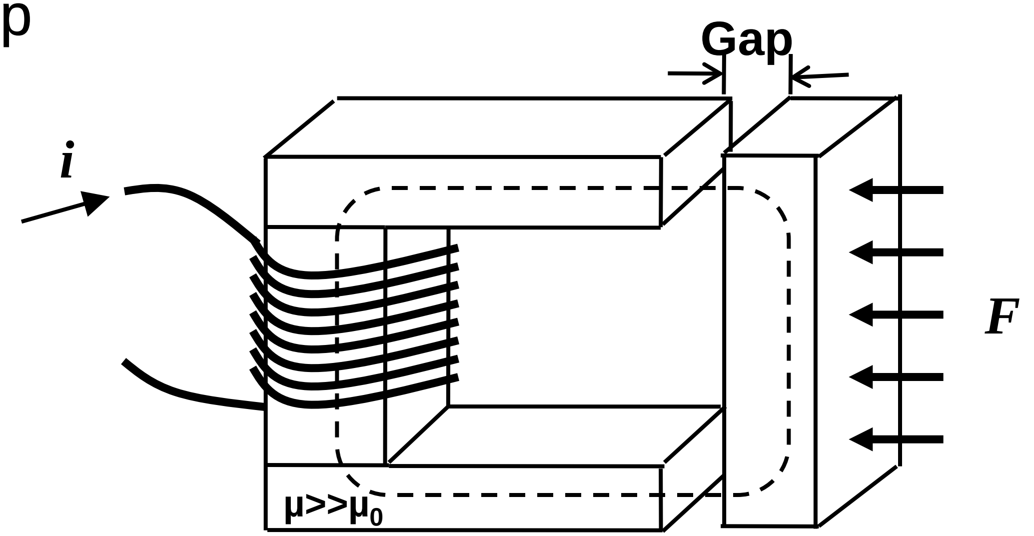
Voice Coil Speaker



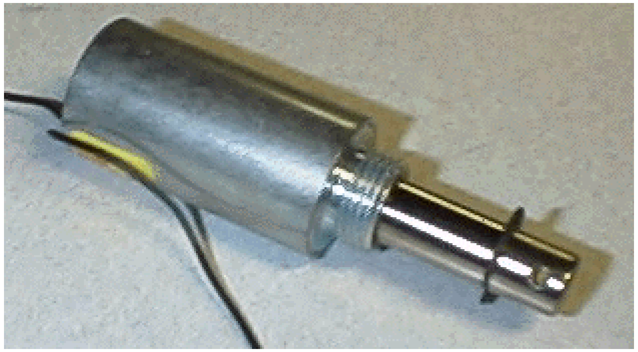
Hard Disk Drive Actuator

Magnetic Transduction

2. **Magnetic Transduction:** motor action produced by the tendency for magnetic moments to align and/or close a magnetic air gap



$$F = \frac{\mu_0 N^2 i^2 A_g}{2g^2}$$

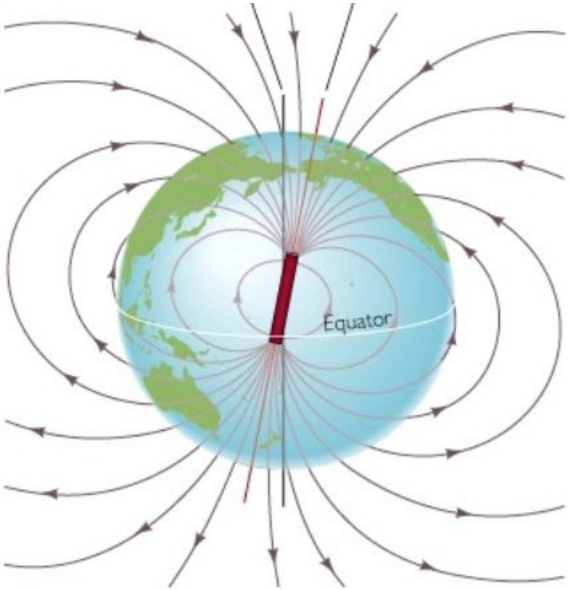

Solenoid


Telegraph Receiver

Magnetic Latching

3. **Magnetic Latching:** bistable latches, bonding, constant mechanical force

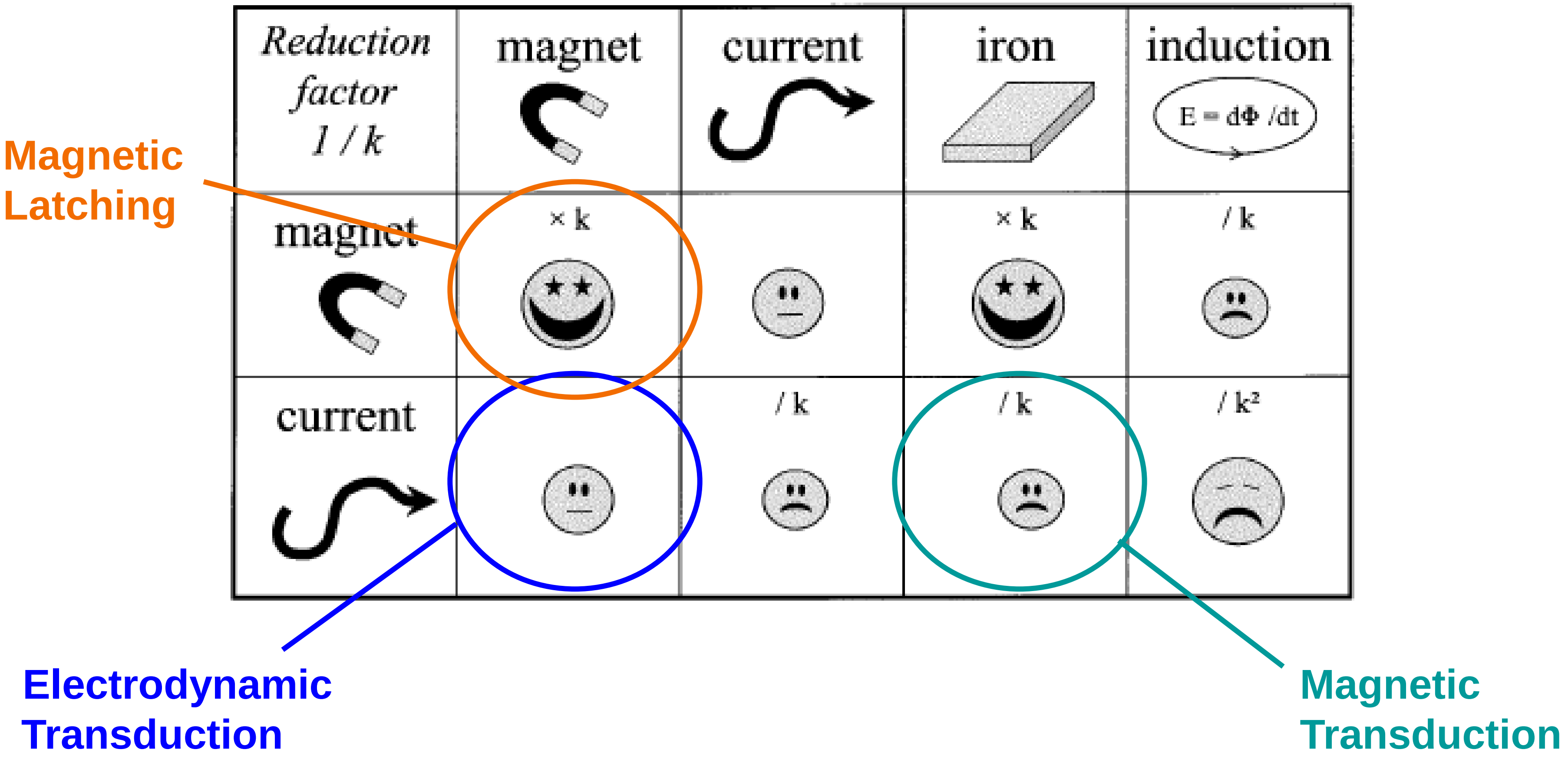
$$\vec{F} = \mu_0 \int_V \nabla(\vec{H} \cdot \vec{M})\, dV$$



Magnetic Scaling Laws

Force-to-Volume (Force-to-Mass) Scaling

***k* = scale reduction factor**



Reduction factor 1 / k	magnet	current	iron	induction E = dΦ /dt
magnet	× k 😁	😐	× k 😁	/ k ☹
current	😐	/ k ☹	/ k ☹	/ k² ☹

Magnetic Latching

Electrodynamic Transduction

Magnetic Transduction

O. Cugat, J. Delamare, and G. Reyne, “Magnetic Micro-Actuators and Systems (MAGMAS),” *IEEE Trans. Magn.*, vol. 39, no. 5, Nov. 2003.

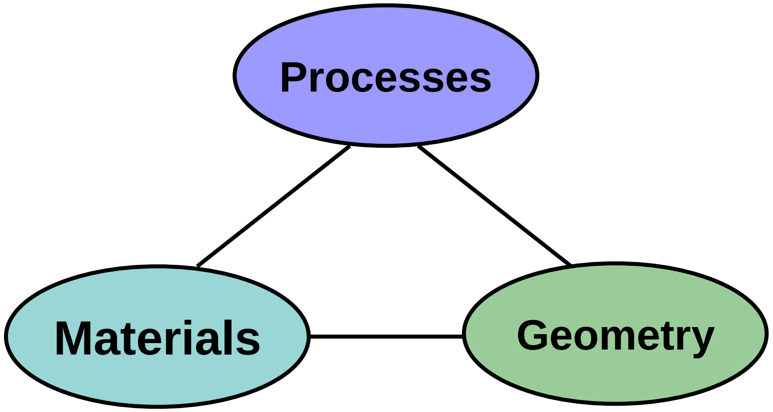
Microscale Magnetics

"*Permanent magnets are vital to magnetic actuation, but that unfortunately their <u>integration</u> still needs to be mastered.*"— H. Guckel, 1996

"*The need for both good magnetic properties and an <u>integrated</u> magnet fabrication process has not yet been concurrently fulfilled.*" — N. M. Dempsey, et. al. 2004

Microscale Magnetics

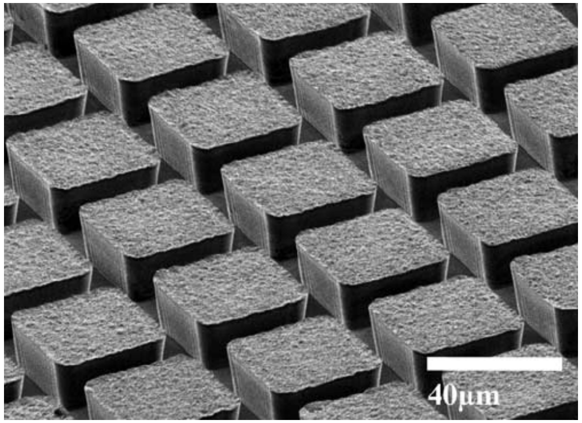
- **Trilemma for Microscale Magnetic Systems**



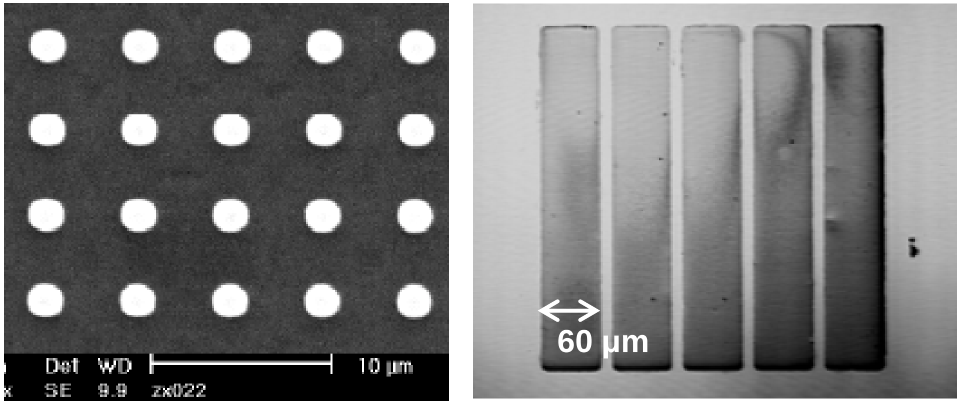
1. Process Limitations
   - Vapor Deposition
   - Electrochemical Deposition
2. Material Limitations
   - Material selection limited by deposition processes
   - Limitations for "advanced processing" (quenching, rolling, sintering, annealing, etc.)
3. Difficult Geometries
   - "Thick" magnetic films (10's or 100's of microns)
   - Three-dimensional solenoidal coils

Magnetic Thick-Films

- **Magnetic “Thick” Films**
  - Soft Magnets:
    - Plated NiFe, NiFeMo, CoFe, etc.
  - Hard Magnets:
    - Plated CoNi, CoPt, FePt (underexplored)
    - Sputtered/PLD SmCo, NdFeB (complex/oxidation)
    - Powders (largely unexplored)



Electroplated CoNiP [*Guan & Nelson., 2005*]



Electroplated CoPt magnets [*Zana et al., 2004-5*]

Electroplated NiFe core and Cu windings in a planar induction motor [*Cros et al., 2004*]

Technology Development

- Materials
- Magnetic Patterning
- Characterization

Magnetic Thick-Films

- **Ideal Hard Magnet for MEMS**

Performance

Good magnetic properties

Thick (2 µm – 100+ µm)

Low stress

Low cost

Integrability

Fast/simple process

Low temperature

Patternable

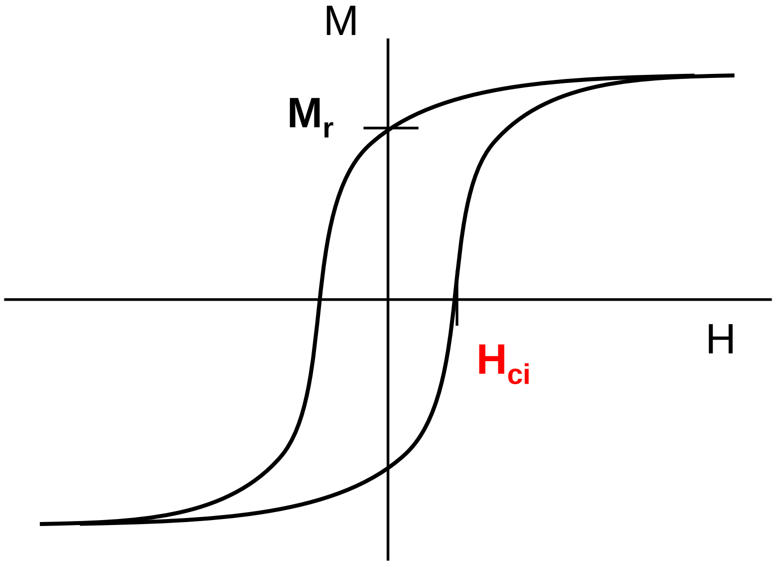
Chemically stable

Thermally stable

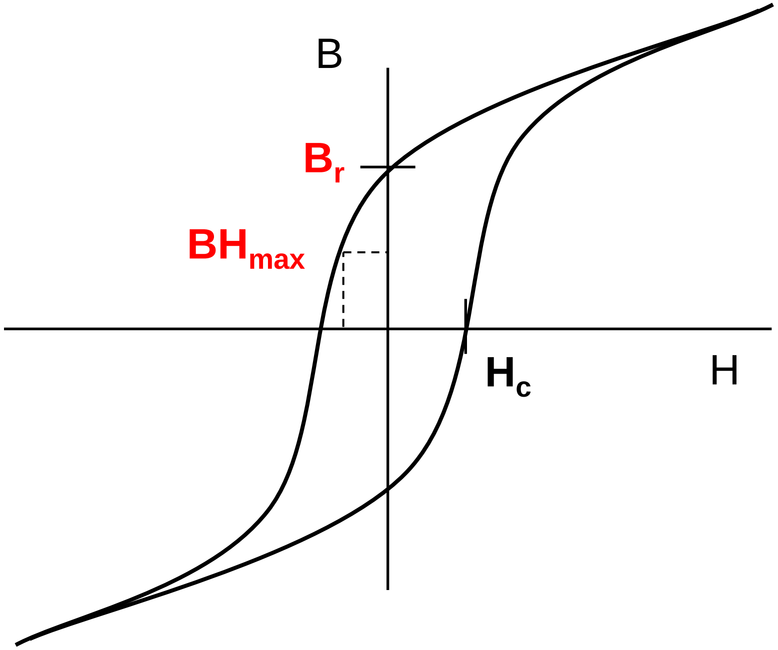
Magnetic Hysteresis Loop

- **Hysteresis Loop**
  - Magnetization **(M)** in A/m (emu/cm^3)
  - Magnetic Field **(H)** in A/m (Oersted)
  - Magnetic Flux Density **(B)** in Tesla (Gauss)

$$\boxed{B = \mu_0 (H + M)}$$

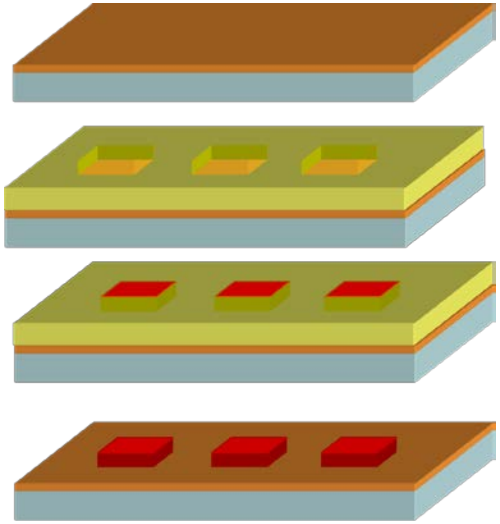


M-H Loop



B-H Loop

Electroplated CoPt Alloys

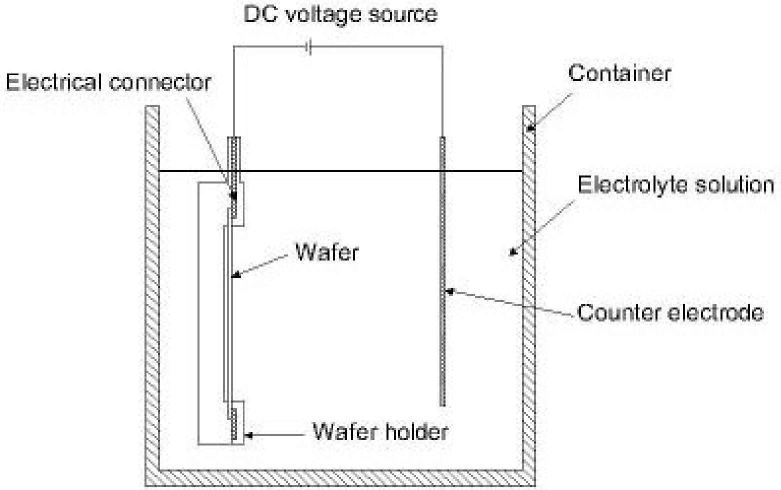


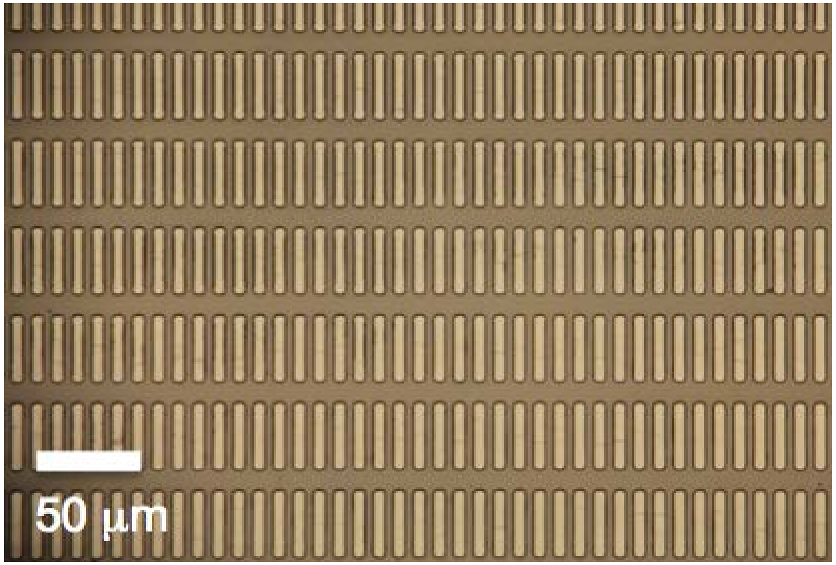
Deposit seed layer

Pattern photoresist molds

Electroplate CoPt alloy

Remove molds





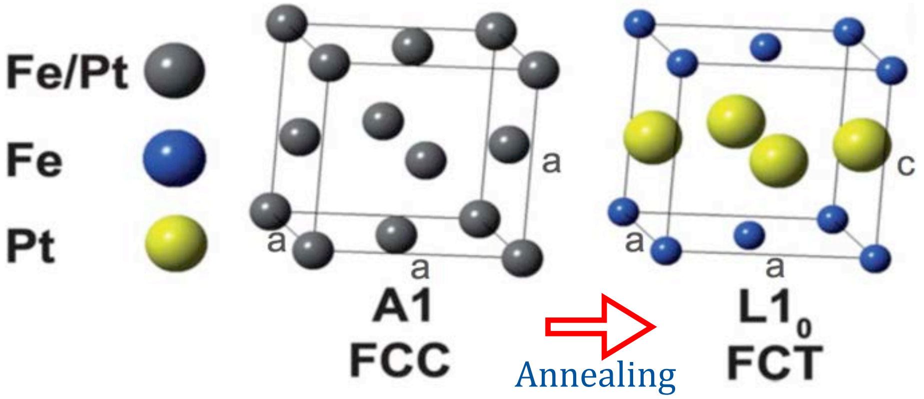
2 µm x 10 µm x 3 µm thick

Example Recipe:

Compound	Concentration (M)
Diammine-dinitro platinum $[Pt(NH_3)_2(NO_2)_2]$	0.025
Cobaltous sulfamate, $[Co(NH_2)_2(SO_3)_2]$	0.1
Ammonium citrate, $[(NH_4)_2C_6H_6O_7]$	0.1
Deposition Parameters	Temperature: 25°C Time: 1 hour pH: 5.0 Current Density.: 70 mA/cm^2:

Electroplated $L1_0$ CoPt Alloys

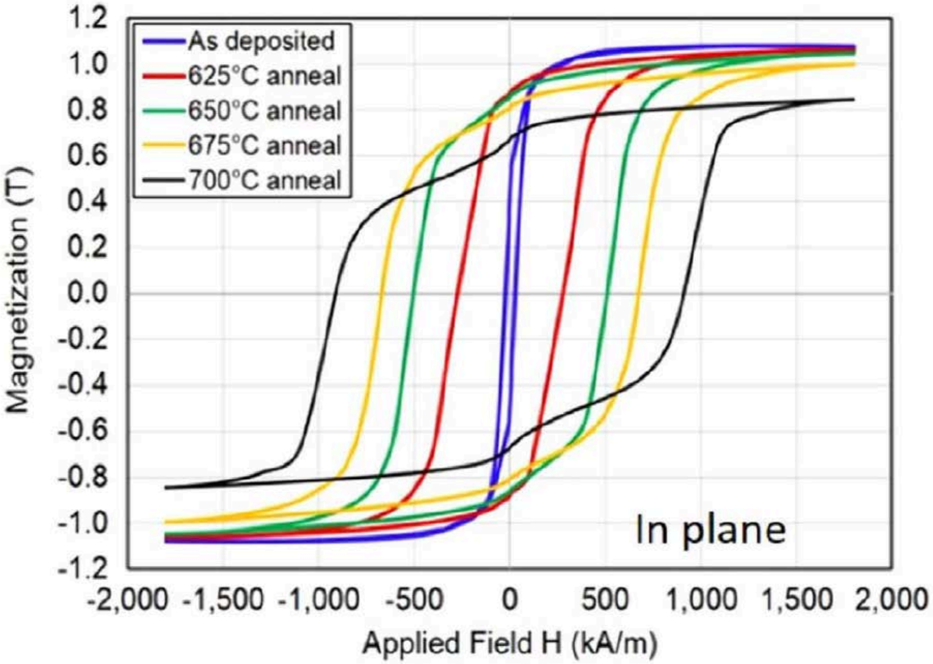
- Require annealing to induce crystalline order and consequently large magnetocrystalline anisotropy

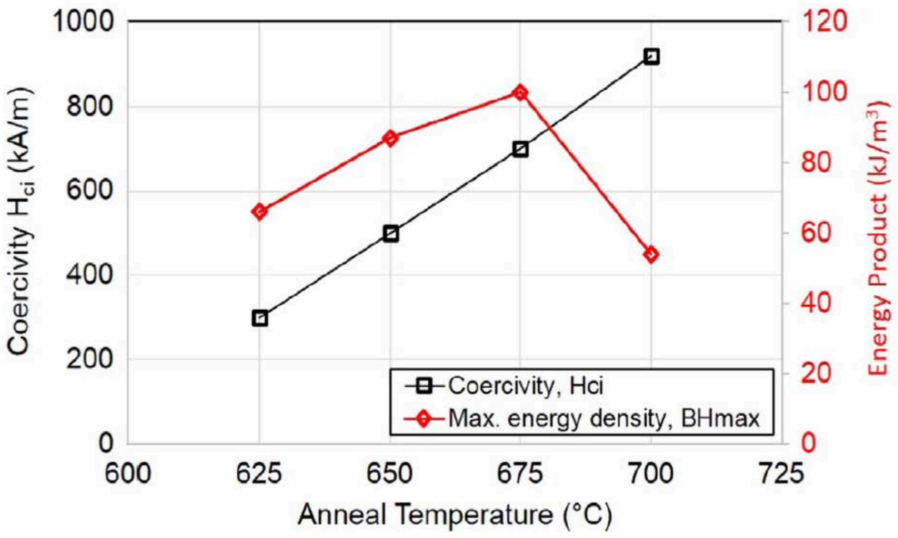


Annealing

Disordered

Ordered

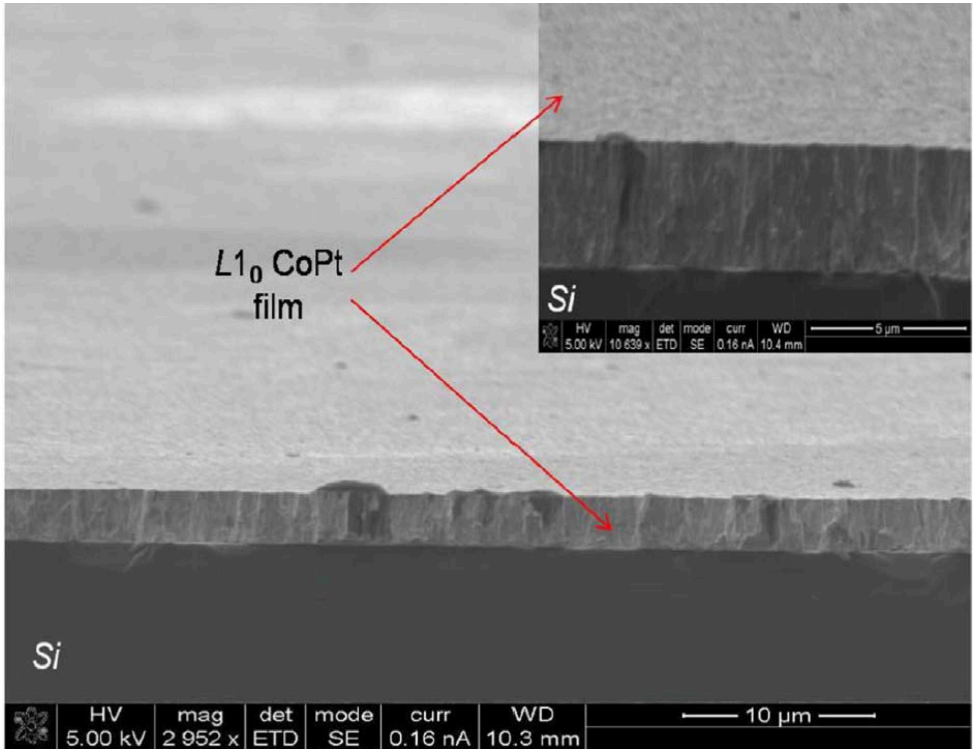


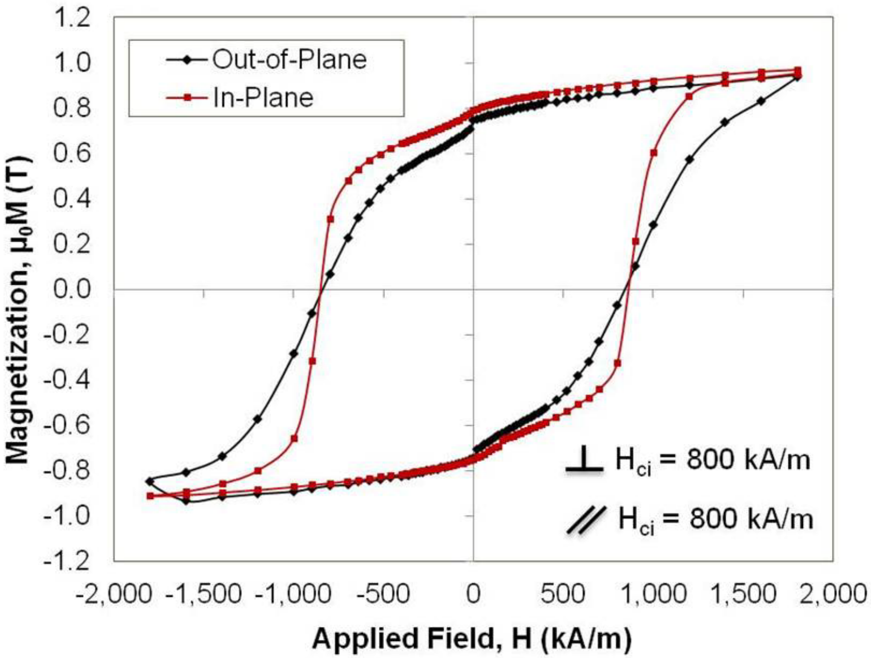


OD Oniku et al, *J. Magnet. Mag. Mat., 2016*

Electroplated $L1_0$ CoPt

- **Superior magnetic performance**
  - but requires thermal annealing (675 C)





In-Plane Properties:

H_{ci} = **800 kA/m** (10 kOe)

B_r = **0.8 T**

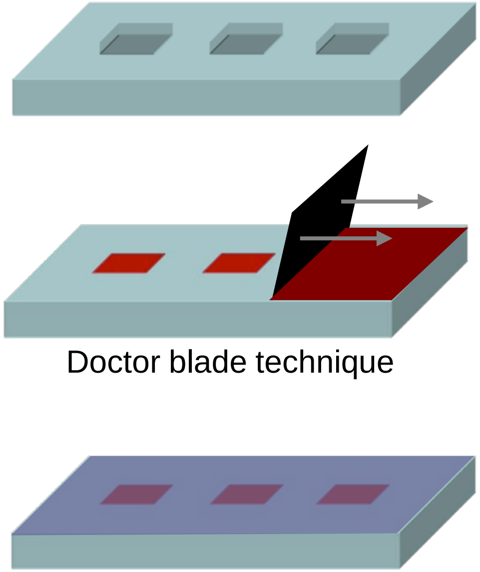
BH_{max} = **150 kJ/m^3** (19 MGOe)

OD Oniku et al, *J. Appl. Phys. 2014*
OD Oniku et al, *J. Magnet. Mag. Mat., 2016*

Bonded-Powder Magnets

- Use magnetic powders to create “thick” magnets (10 µm – 1 mm)
  - NdFeB: 5-50 µm
  - SmCo: 2-25 µm
  - Ferrites: <2 µm

Affect minimum and maximum magnet size

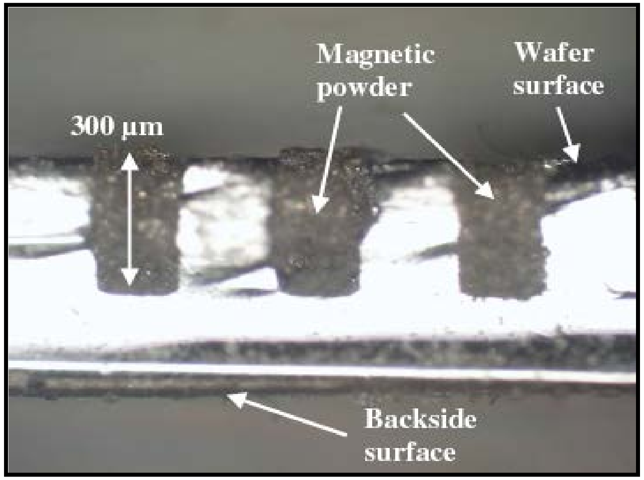


Create cavities in substrate

Pack magnetic powder

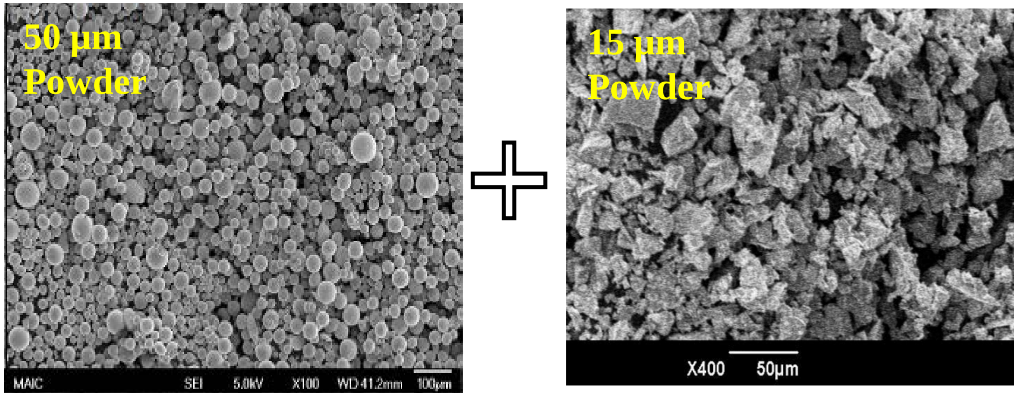
Doctor blade technique

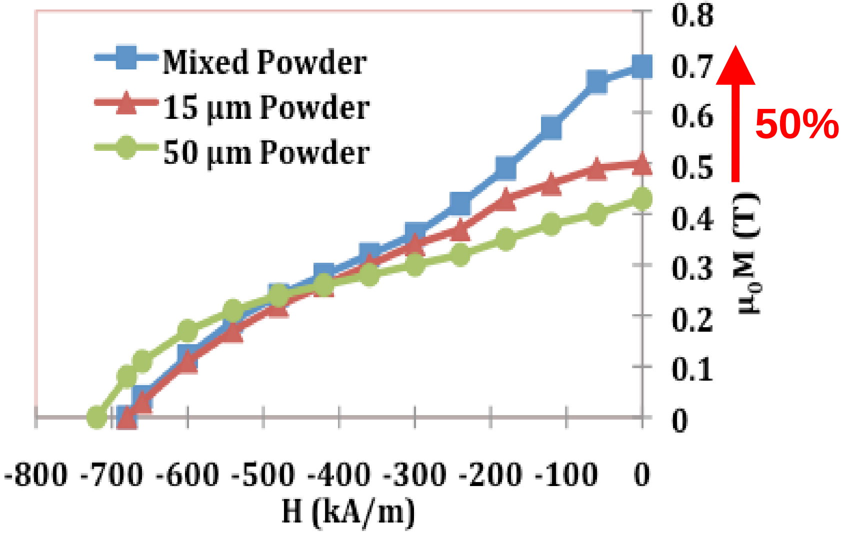
Vapor-coat Parylene-C



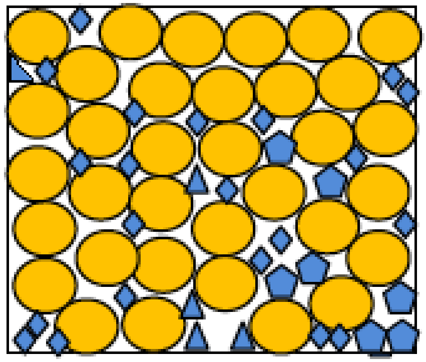
**All low-temperature processes*

Parylene-Bonded NdFeB Micromagnets





250 µm x 250 µm x 320 µm thick



Increase Volume Fraction

Isotropic Properties:

H_{ci} = **680 kA/m** (8.5 kOe)

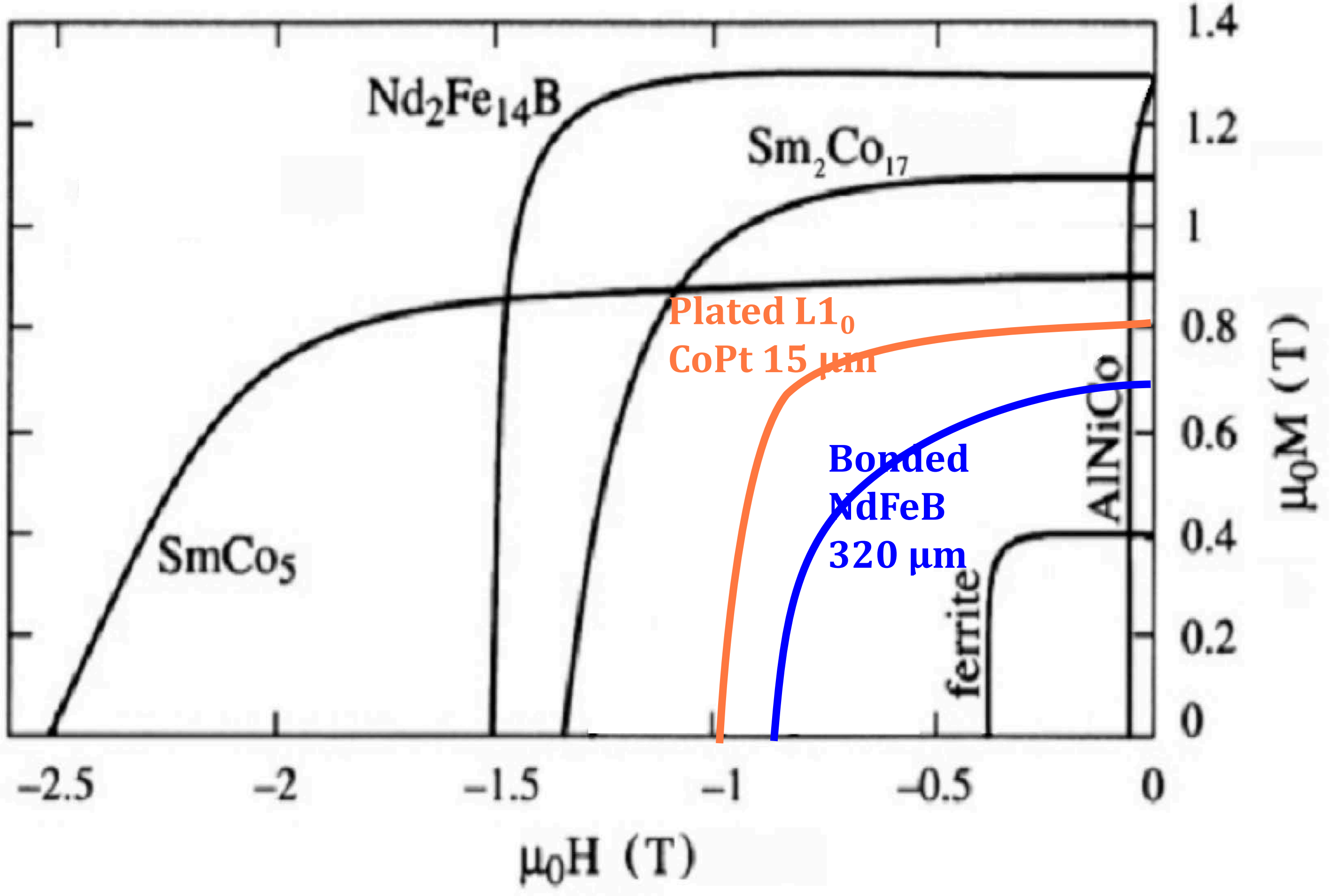
B_r = **0.7 T**

BH_{max} = **45 kJ/m³** (5.6 MGOe)

O. Oniku, et al., MEMS 2012

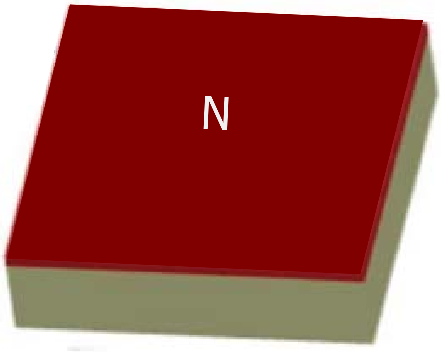
Magnetic Properties

- **Micromagnets compared to bulk magnets**



Patterned Layers

- **We want complex magnetization patterns for device applications**
- **Similar in concept to a hard disk, but we seek**
  - Thicker layers
  - Higher performance magnetic materials
  - Larger poles ("bits")
  - Batch-fabrication (high speed, low cost)

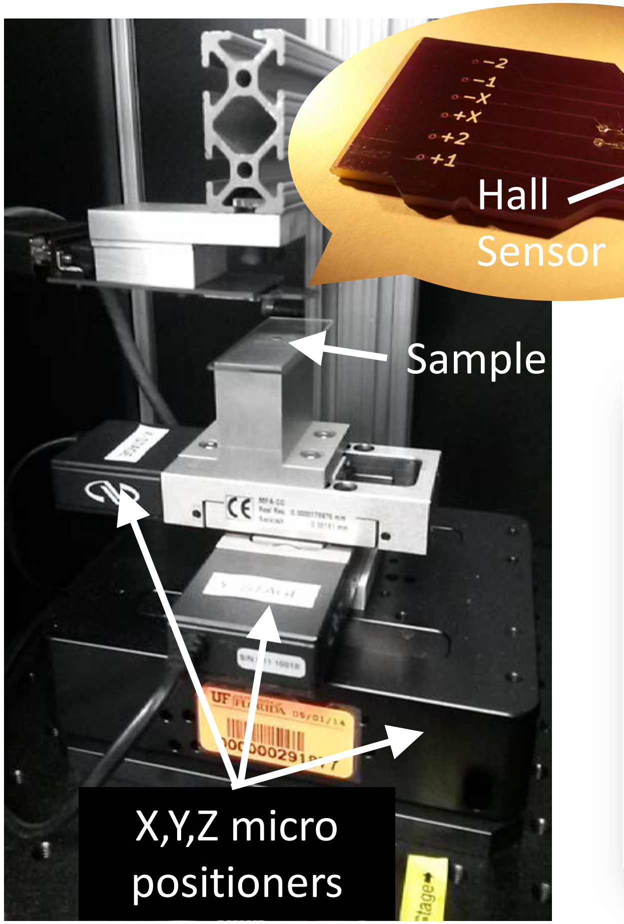


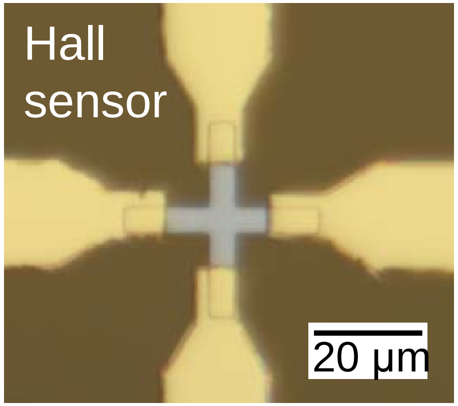
Uniform magnetization

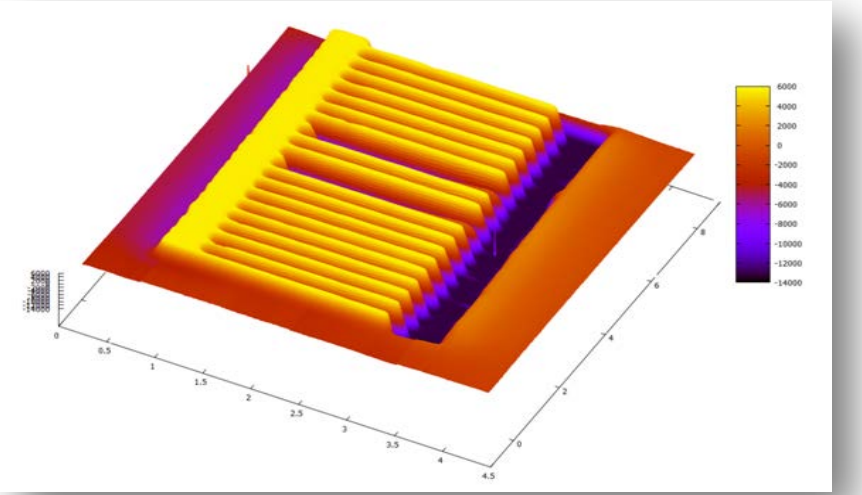
Alternating (N-S) pole pattern

High-Resolution Field Mapping

- **High-resolution Hall effect sensor (down to 1 μm²)**
- **3-axis stage with 100 nm step size (x, y axes)**
- **Automatic scan height control**



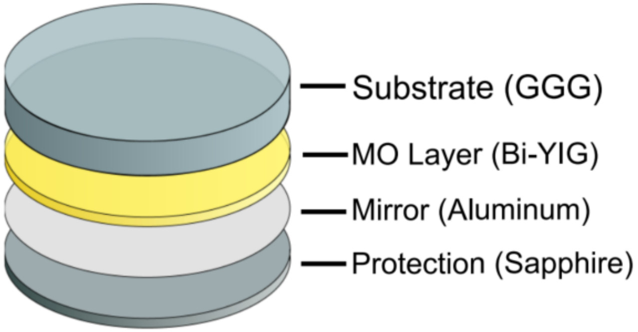




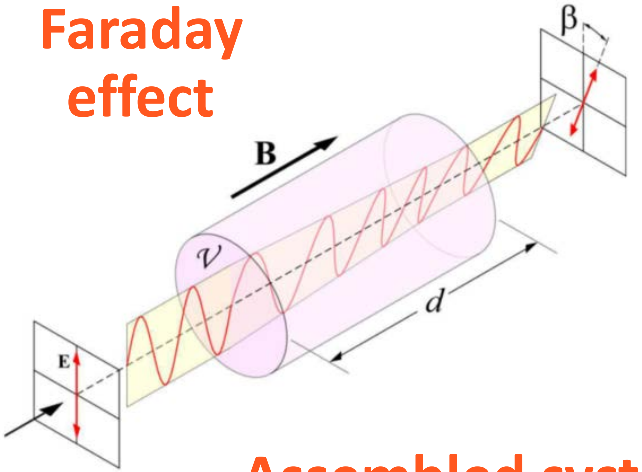
Magneto-Optical Imaging

- **Quantitative, non-intrusive stray field measurement**

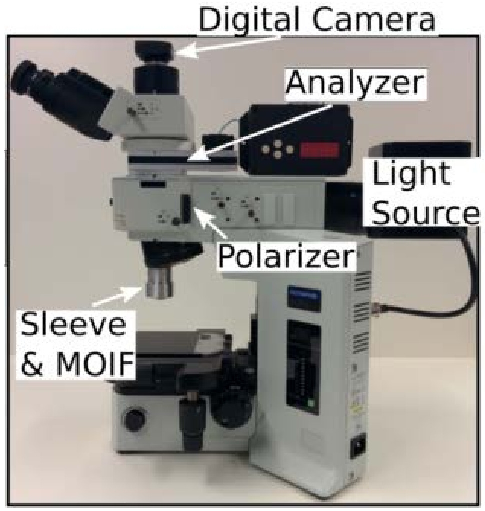
Exploded MOI film

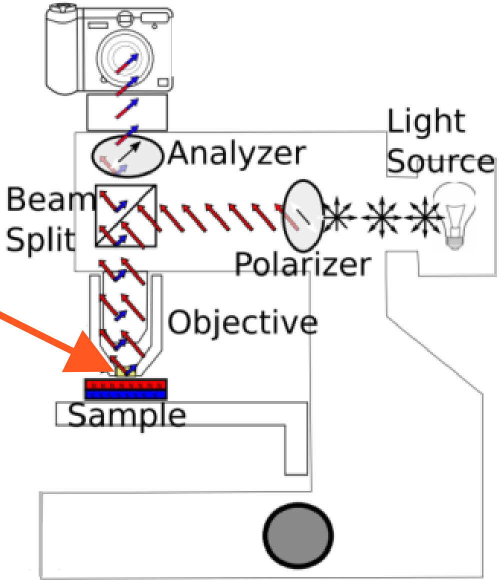


Faraday effect



Assembled system





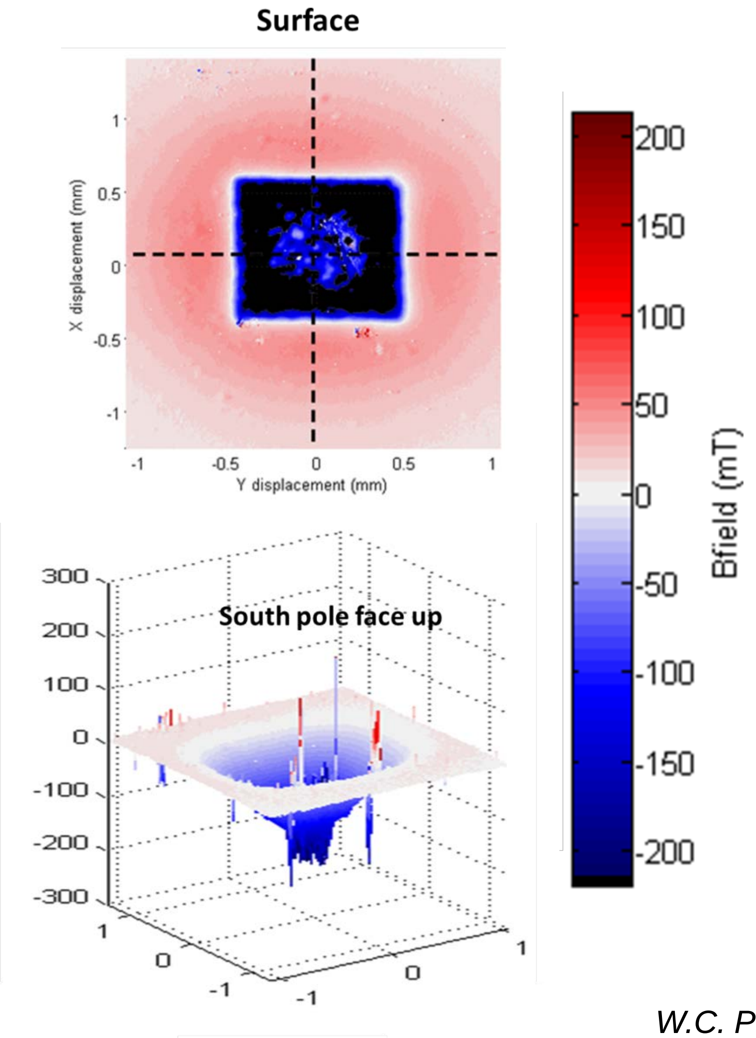
Schematic

W.C. Patterson, et al., Rev. Scientific Instrum. 2015

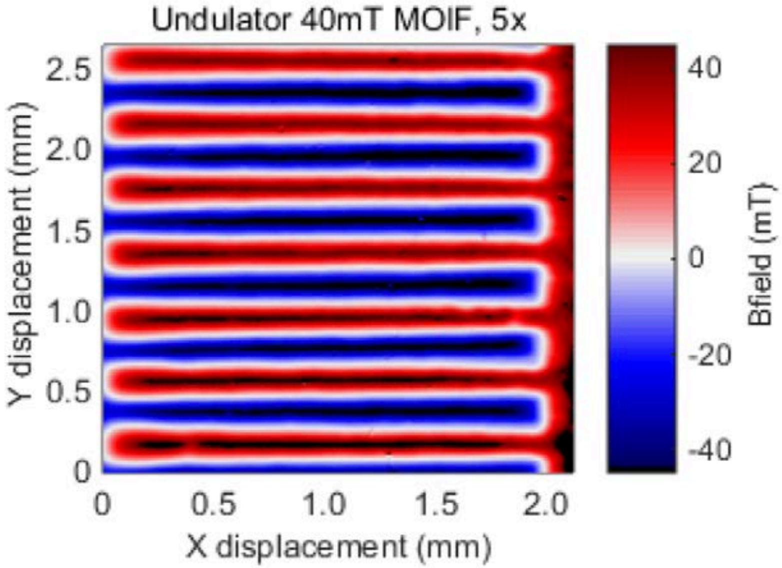
Magneto Optical Imaging

- **Example Images**

Single 1 mm NdFeB magnet



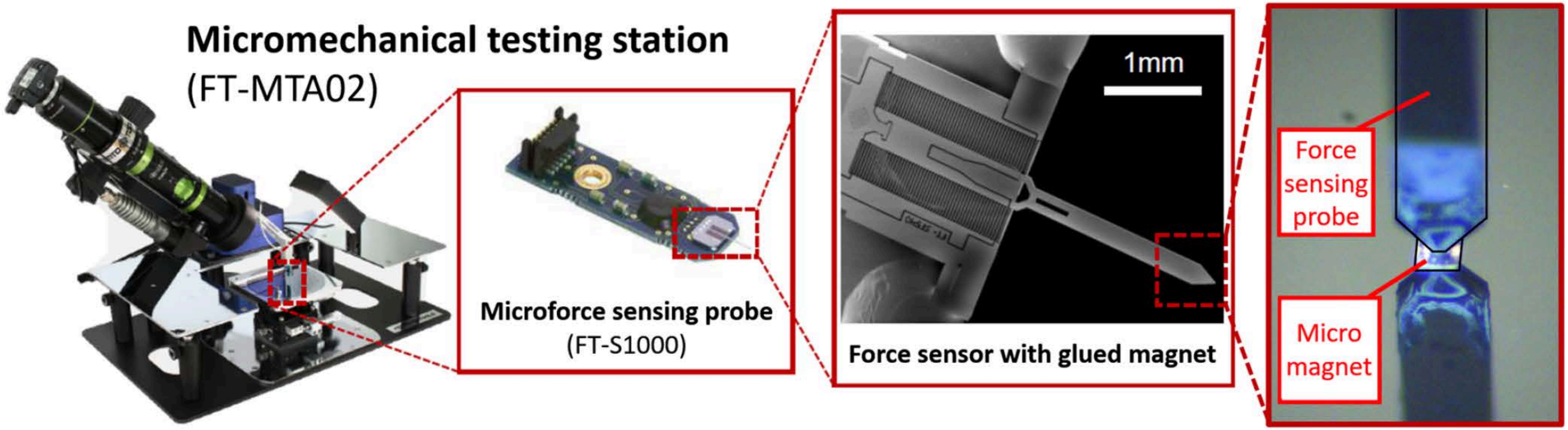
Complex field patterns

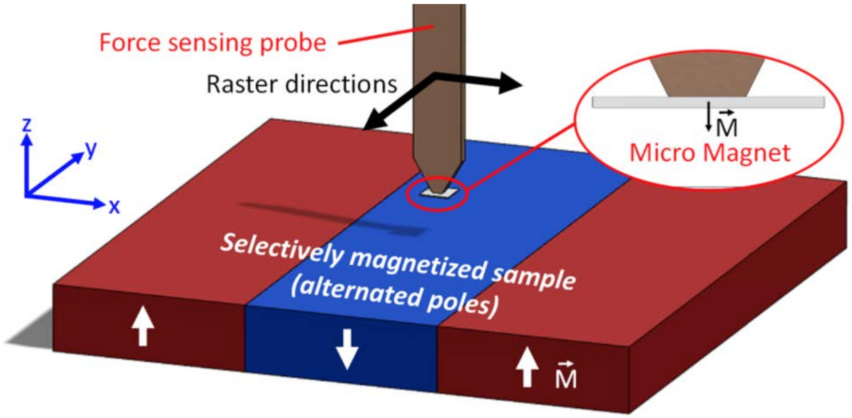


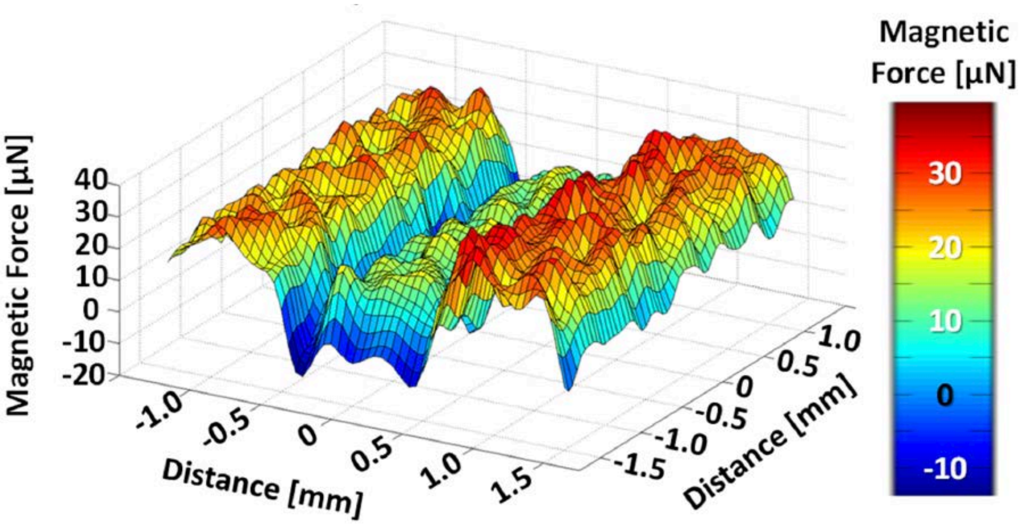
MOIF type (mT)	Magnetic range (mT)	Magnetic resolution	Spatial resolution (μm)
5	±5	±50 μT	4.2
45	±45	±0.5 mT	6.2
230	±230	±1 mT	20.1

W.C. Patterson, et al., Rev. Scientific Instrum. 2015

Microscale Magnetic Force Mapping

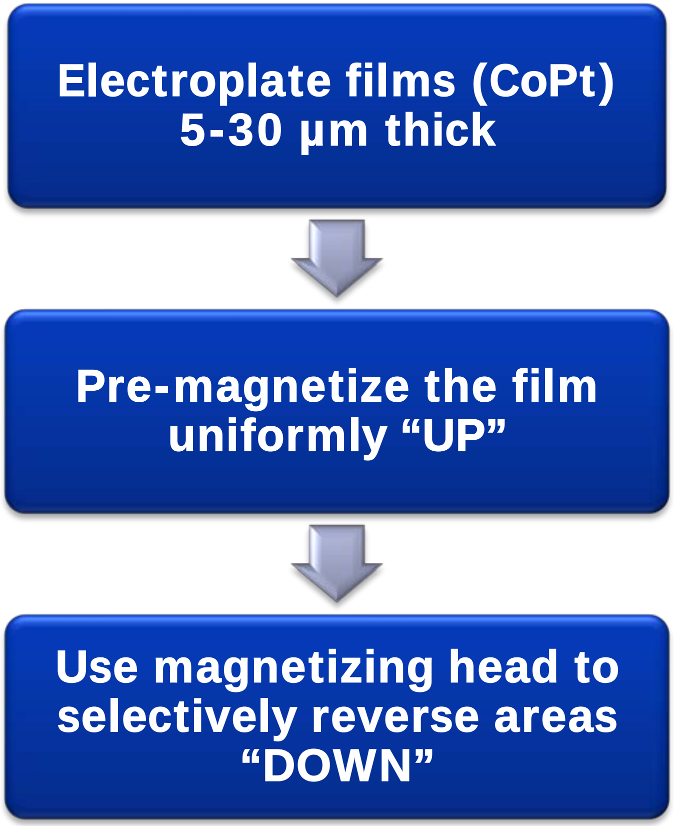






C. Velez, R.E. Carroll, D.P. Arnold, AIP Advances 2017

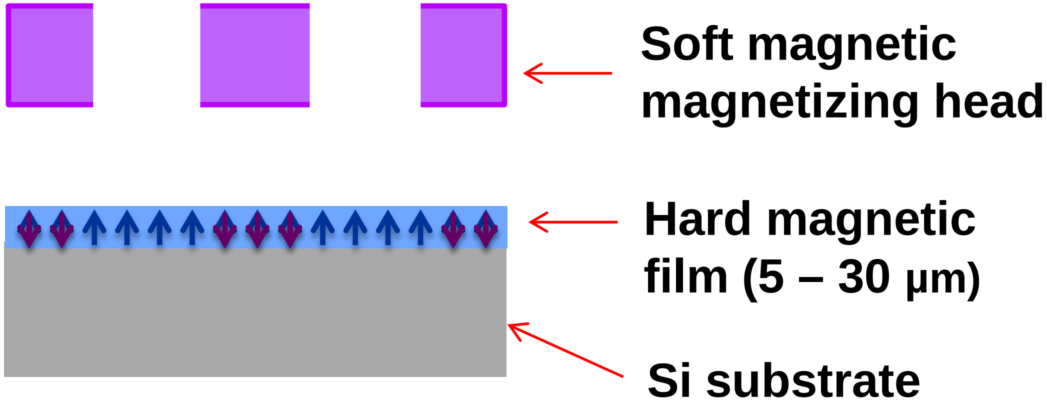
Selective Magnetization Overview



Electroplate films (CoPt) 5-30 µm thick

Pre-magnetize the film uniformly "UP"

Use magnetizing head to selectively reverse areas "DOWN"



Soft magnetic magnetizing head

Hard magnetic film (5 – 30 µm)

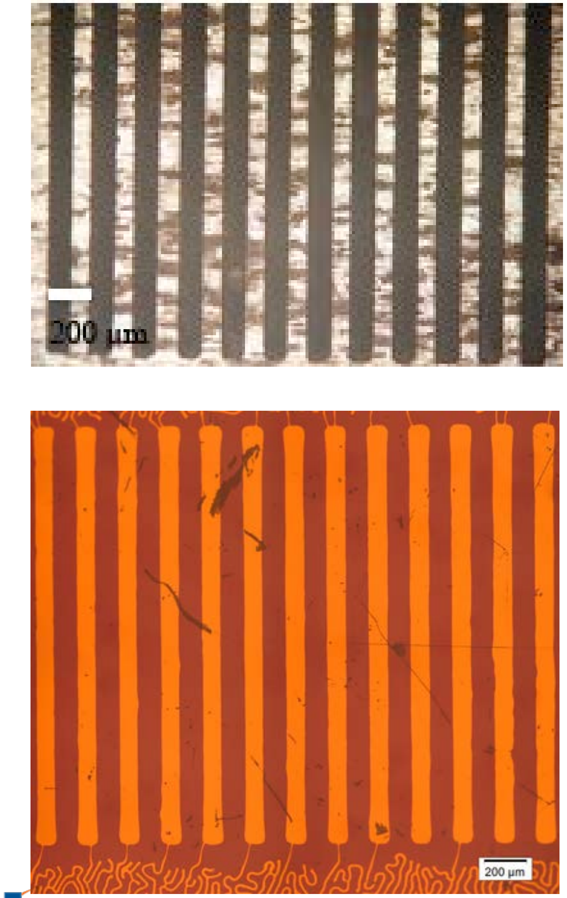
Si substrate

Selective magnetic patterning using magnetizing heads

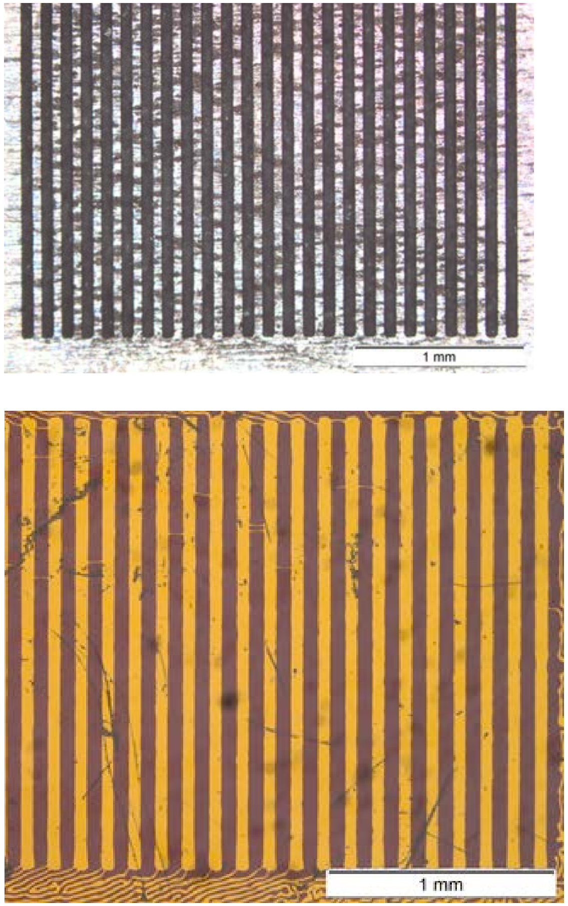
Magnetic Patterning

- **Laser-machined iron (Fe) foils (~125 µm thick)**

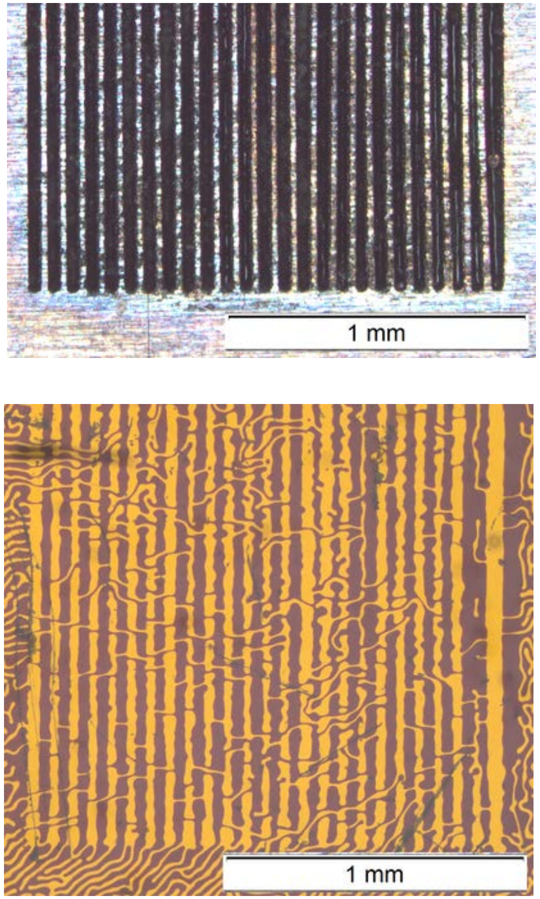
200 µm period



120 µm period



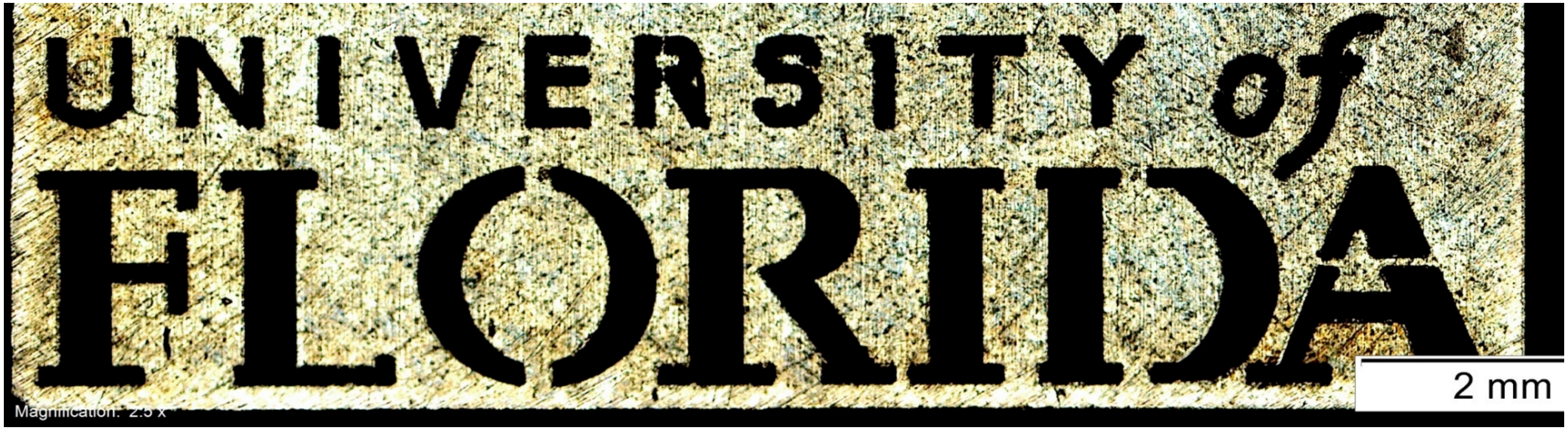
65 µm period



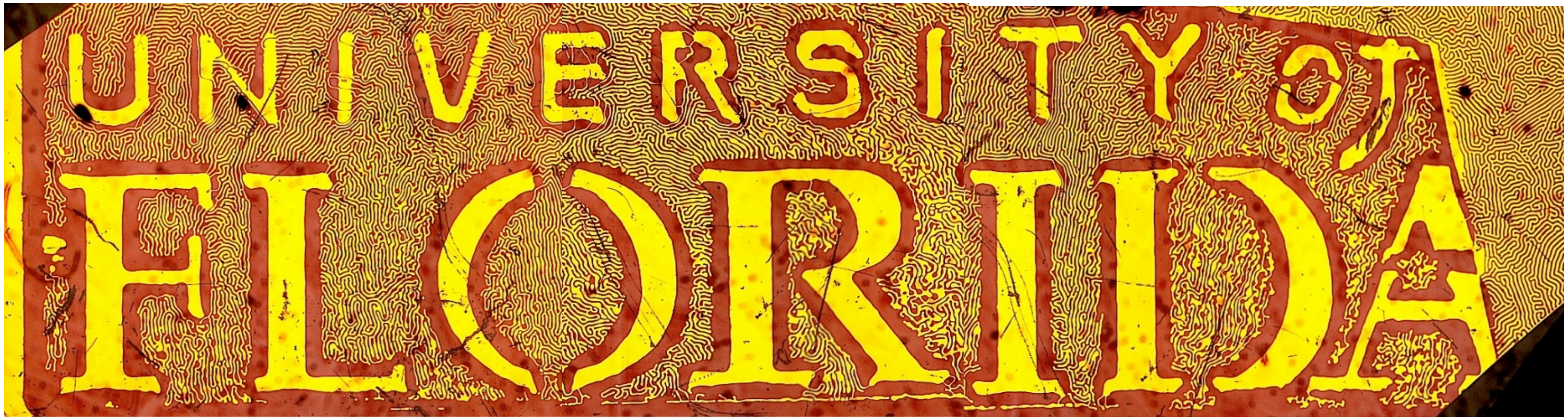
Magnetic Patterning

- **Arbitrary Patterns**

Magnetizing mask (Fe sheet)

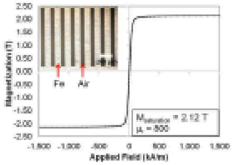


Magnetic pattern

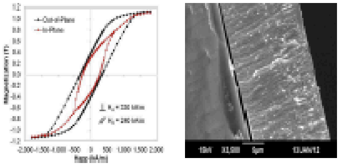


Modeling – Magnetic Patterning

Stage I

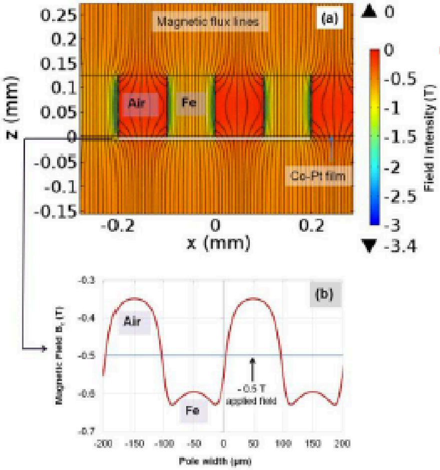


Soft magnetic mask

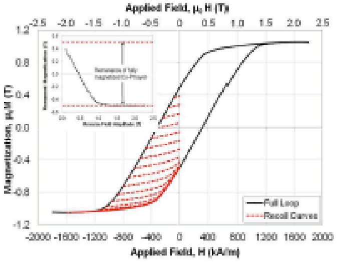


Hard magnetic layer

Field During Reversal Pulse

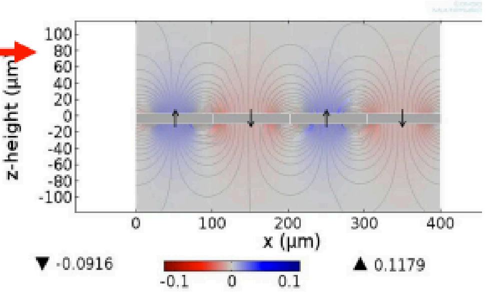


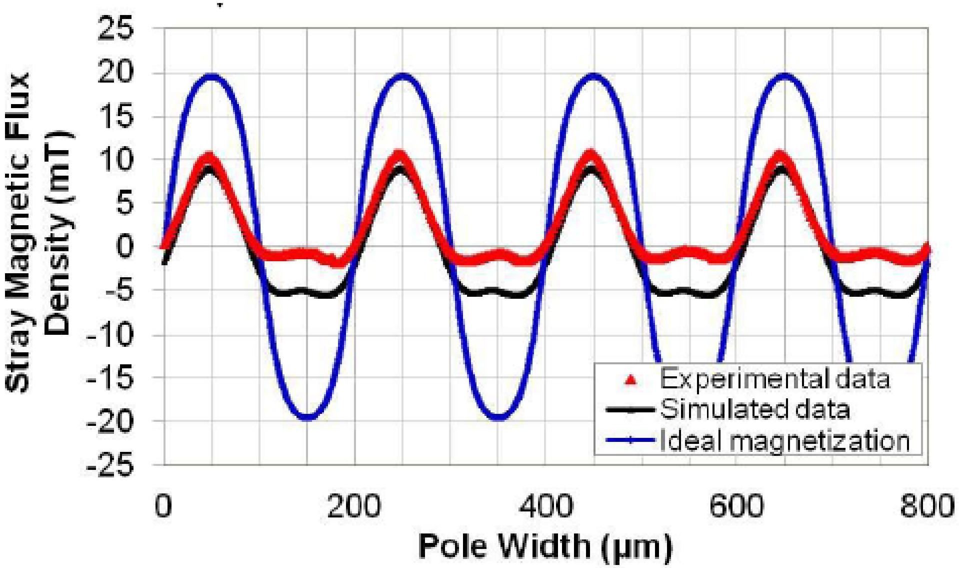
Stage II



Hard magnetic layer recoil curves

Field After Reversal Pulse



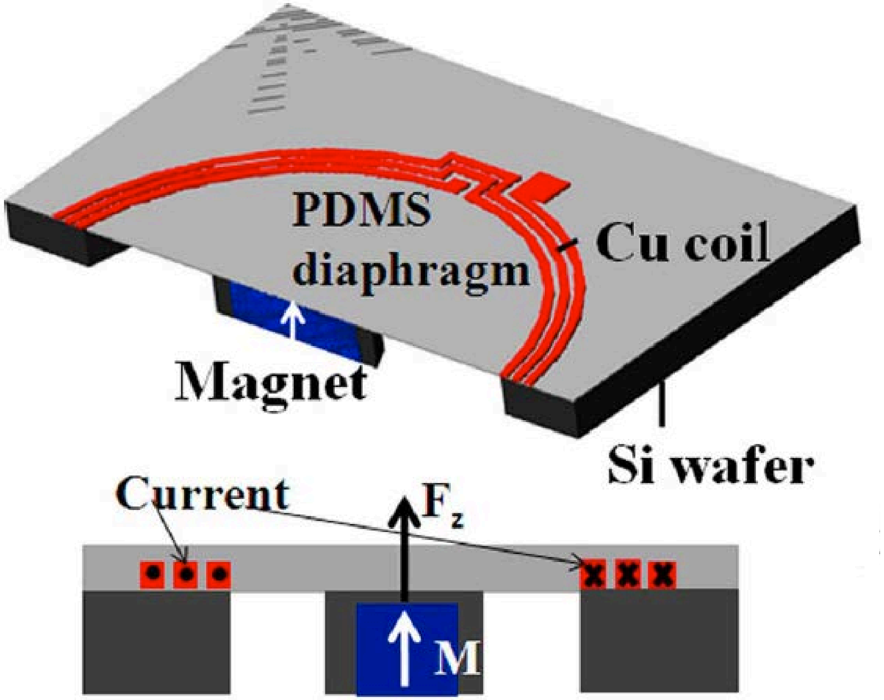


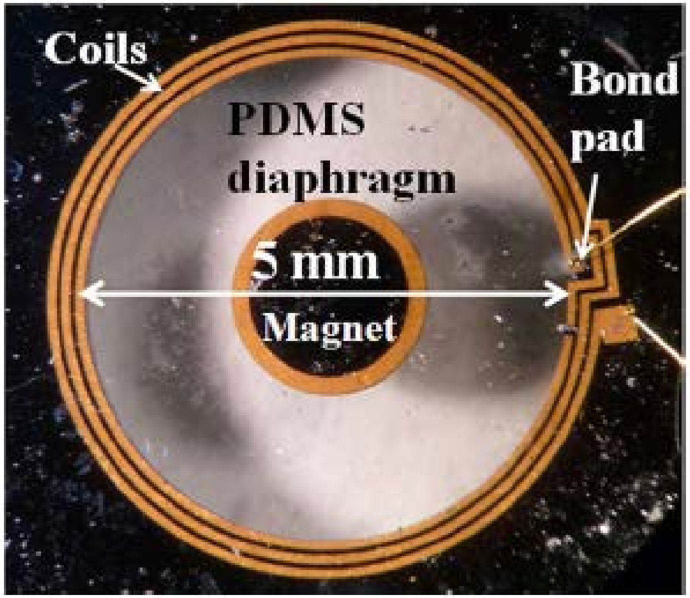
Applications (Selected Examples)

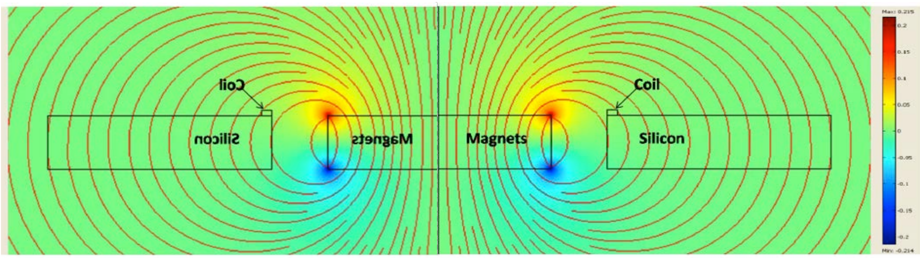
- Microactuators
- Magnetic nanomanufacturing/self-assembly
- Magnetic microrobots

Microscale Transducers

- Out-of-plane "piston"-type actuators
  - Fully Batch-Fabricated
  - PDMS membrane
  - NdFeB micromagnets



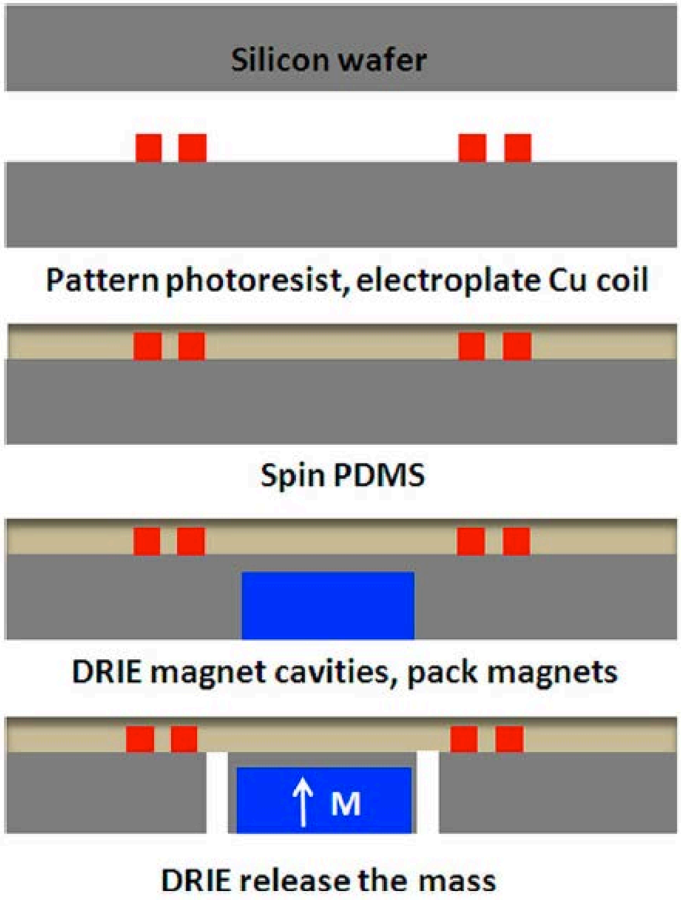




N. Wang, D.P. Arnold, IEEE Trans. Magnetics 2010.

Microscale Transducers

- Low-Temperature, 3-Mask Process



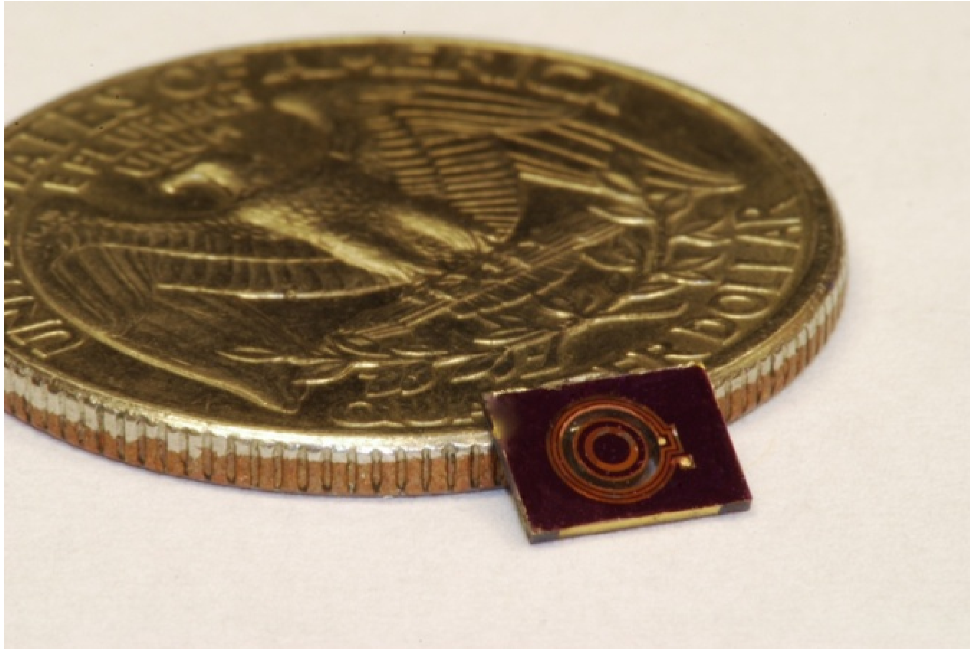
Silicon wafer

Pattern photoresist, electroplate Cu coil

Spin PDMS

DRIE magnet cavities, pack magnets

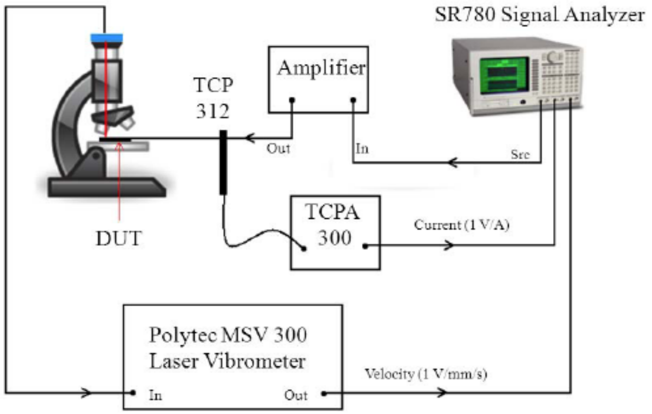
DRIE release the mass

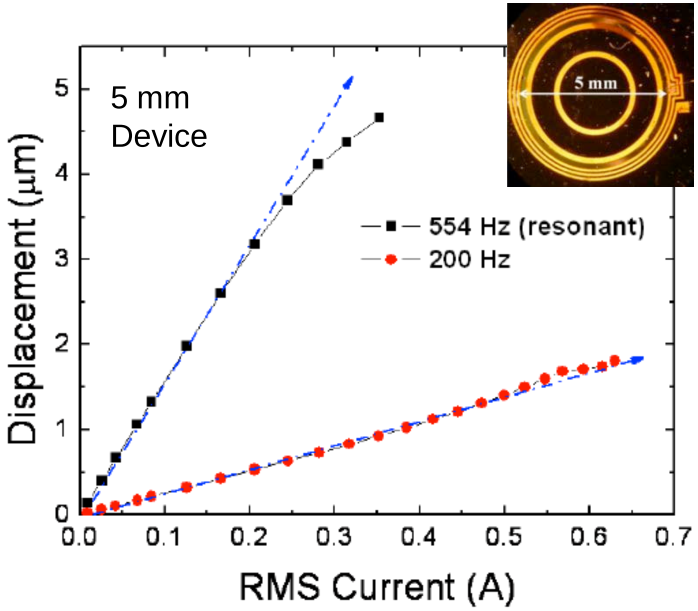


N. Wang, D.P. Arnold, IEEE Trans. Magnetics 2010.

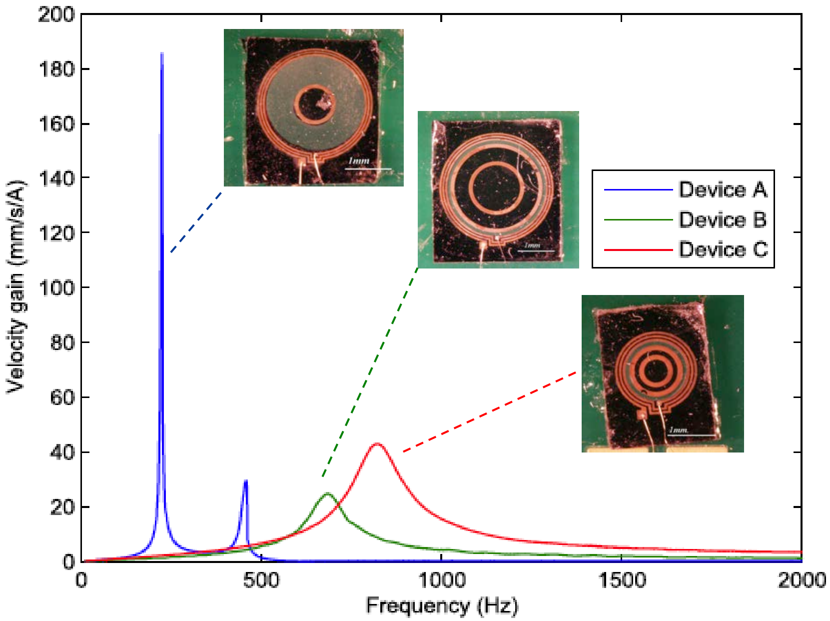
Microactuator Characterization

- Example actuator performance
  - 550 Hz resonance
  - 2 um flat band displacement @ 670 mA_{rms} (450 mW)





N. Wang, PhD Dissertation, UF 2010.

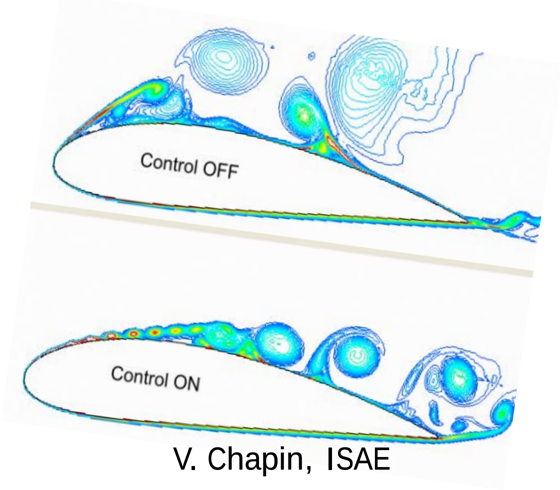


S. Sawant, et al. JMEMS 2013.

Micro Synthetic Jet Actuator

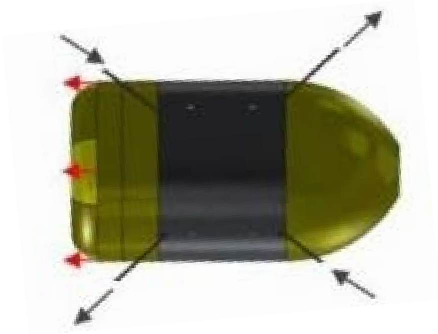
- **Aerodynamic flow-control or cooling applications**

Flow Reattachment

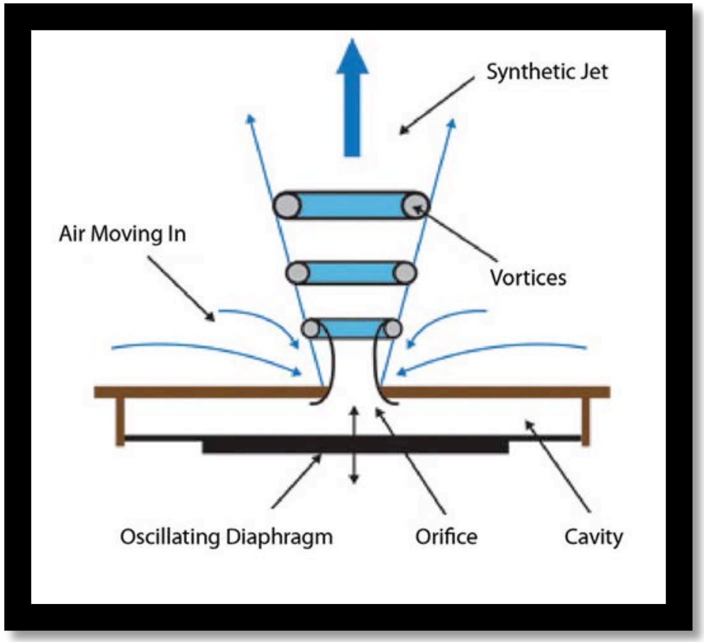


V. Chapin, ISAE

Steerable Bullets

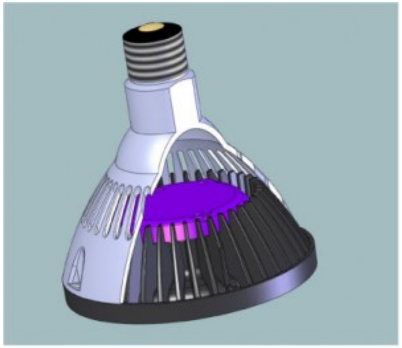


http://www-old.me.gatech.edu/bvukasinovic/flowcontrol.html



http://www.designworldonline.com/lighting-the-way-for-led-development/

Cooling LEDs

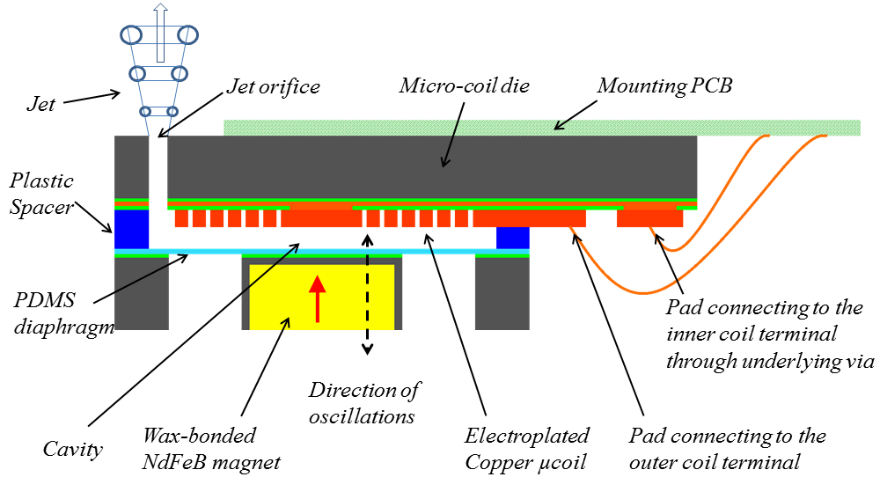


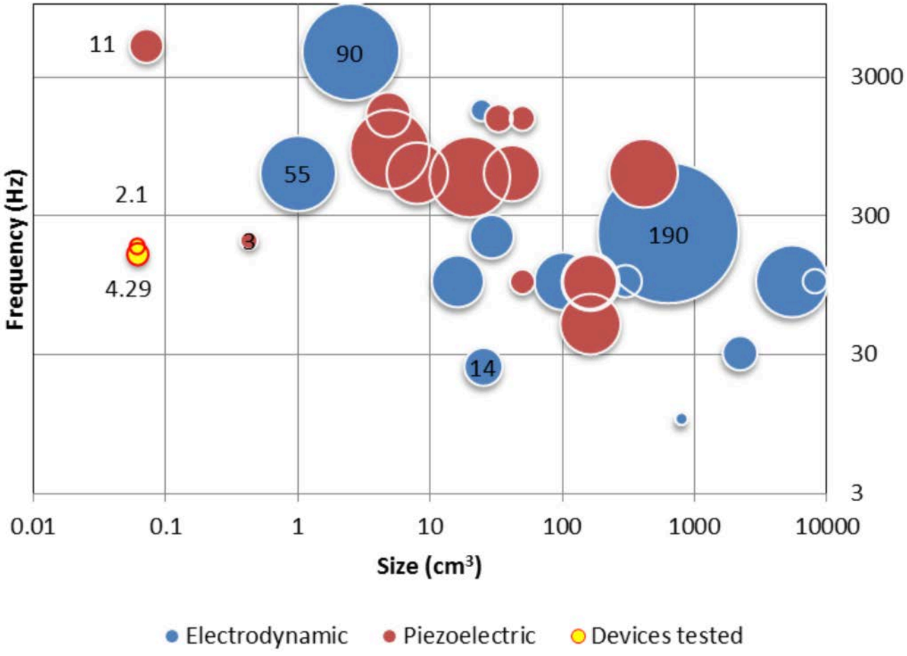
Nuventix, Inc.

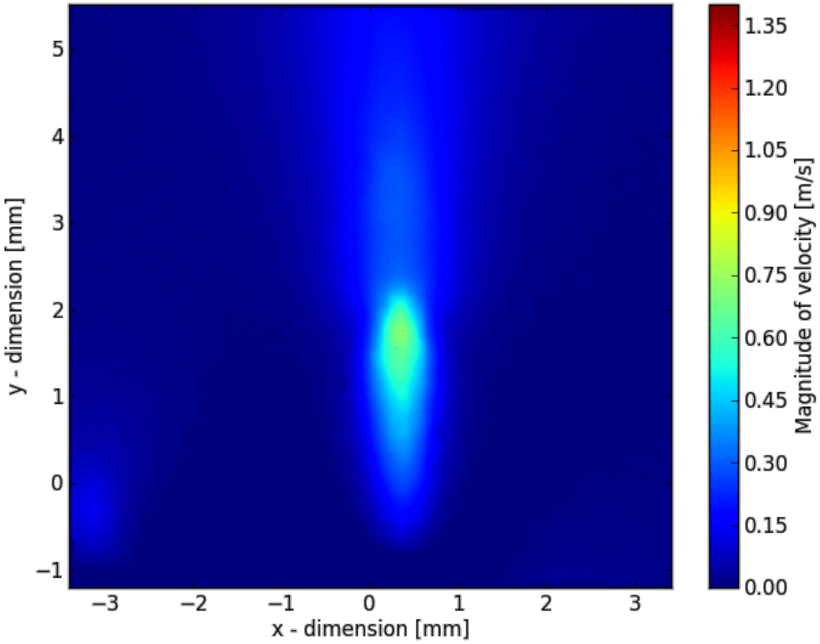
Micro Air Vehicles

http://www.rcuniverse.com/magazine/article_display.cfm?article_id=538

Micro Synthetic Jet Actuator

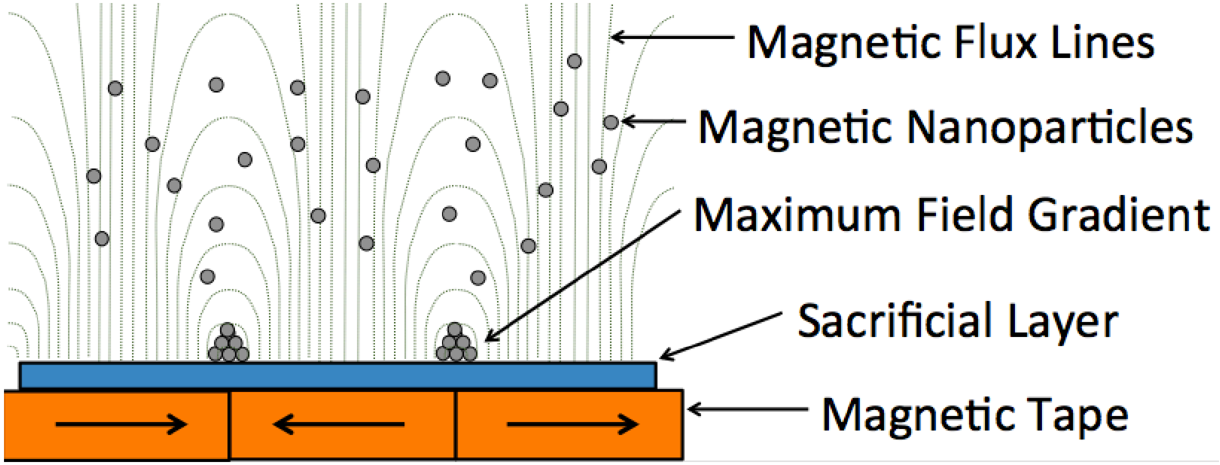


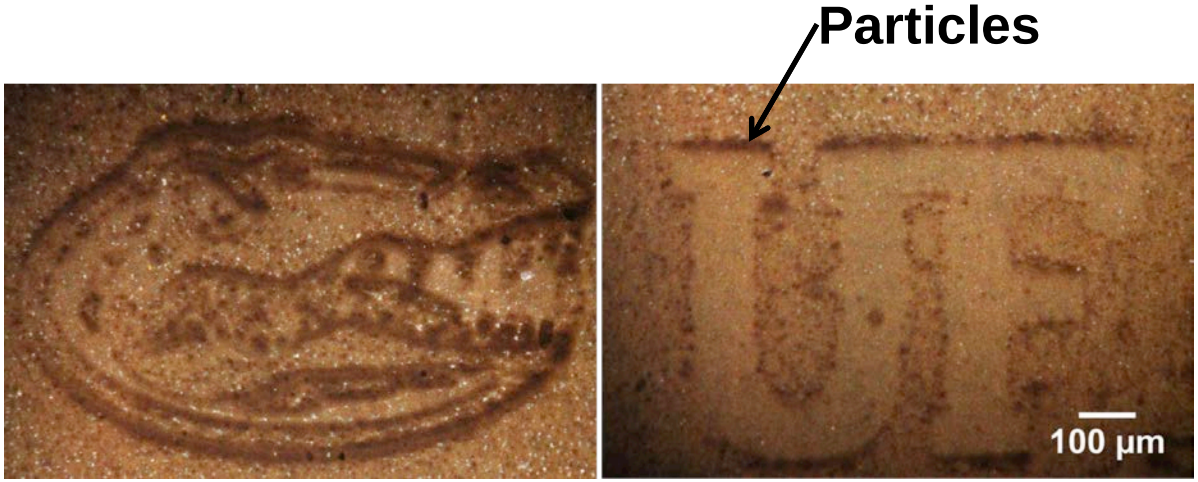


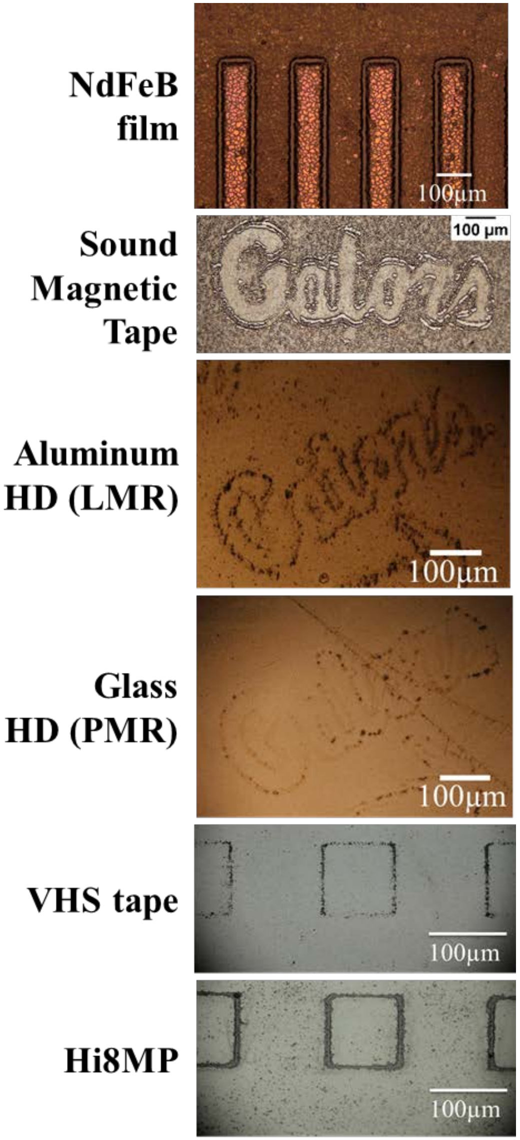


S. Sawant, D.P. Arnold, MEMS 2015.

Magnetic Nanoparticle Self-Assembly





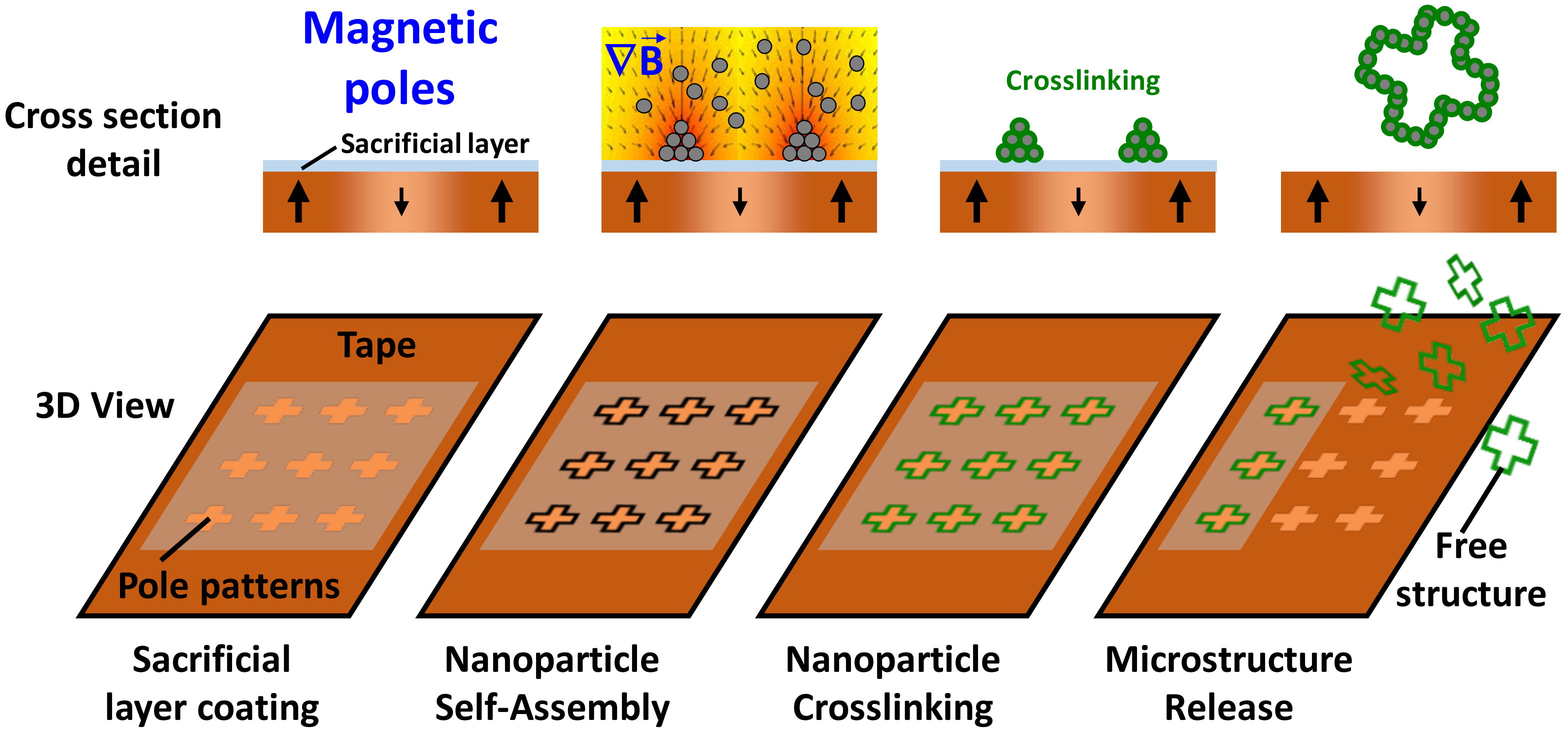


LMR (Longitudinal Magnetic Recording)
PMR (Perpendicular Magnetic Recording)

C. Velez, et al., MEMS 2015.

Nanomanufacturing

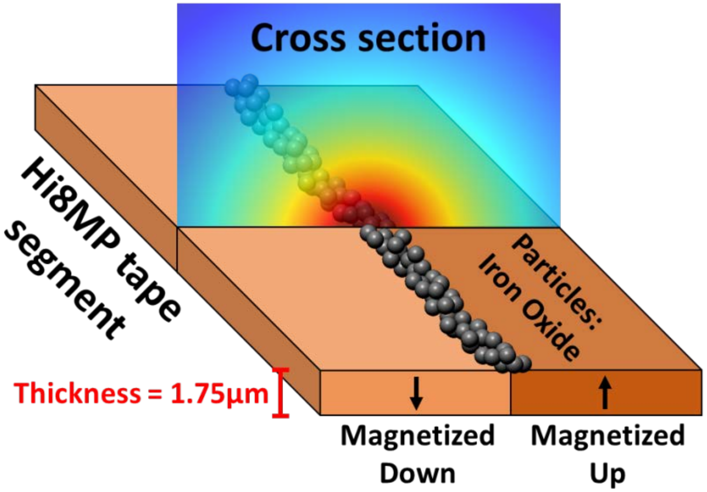
- **Magnetic microstructure manufacturing**

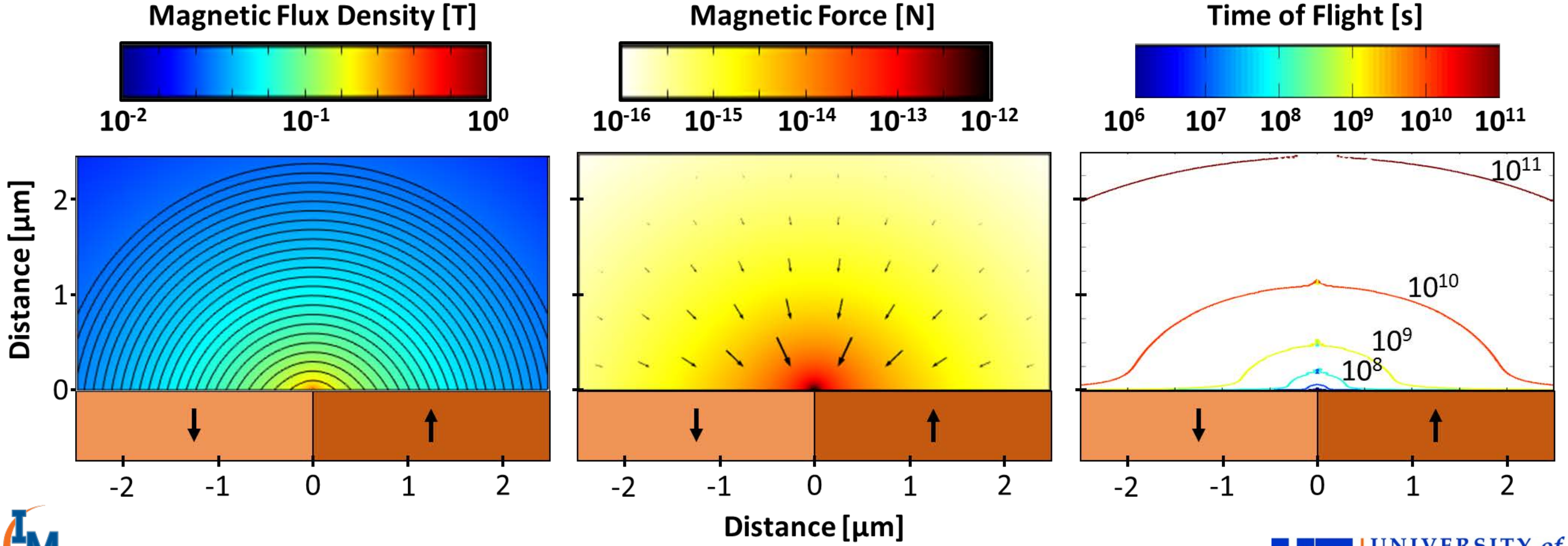


- Photolithography-free; Roll to roll?
- High magnetic particle fraction
- Bonding of particles via polymeric cross-linking
- Release from substrate → Biological swimmers/microtools

C. Velez, et al., ACS Nano 2015.

Modeling of Nanoparticle Assembly

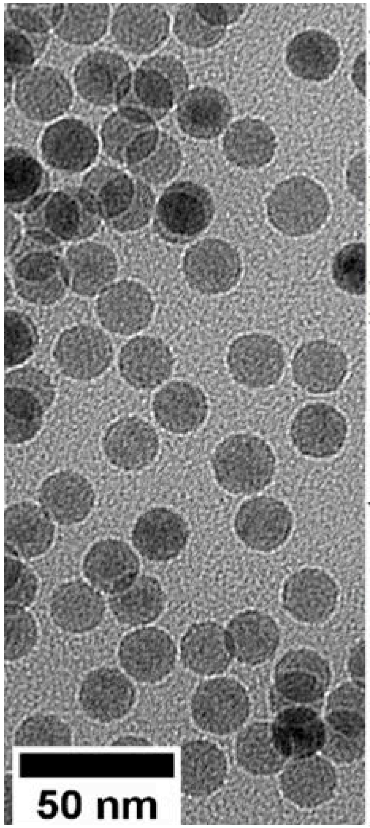


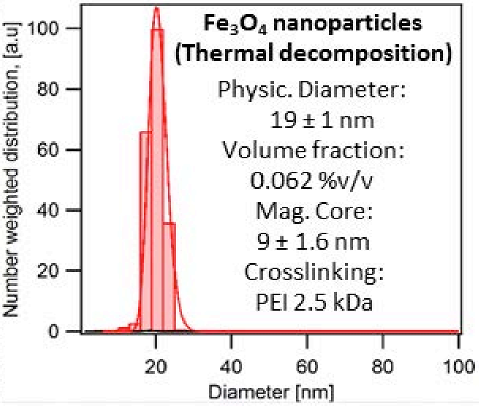


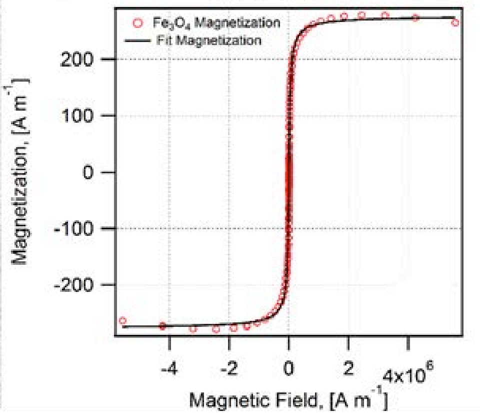
C. Velez, et al., ACS Nano 2015.

Nanoparticle Assembly & Cross-Linking

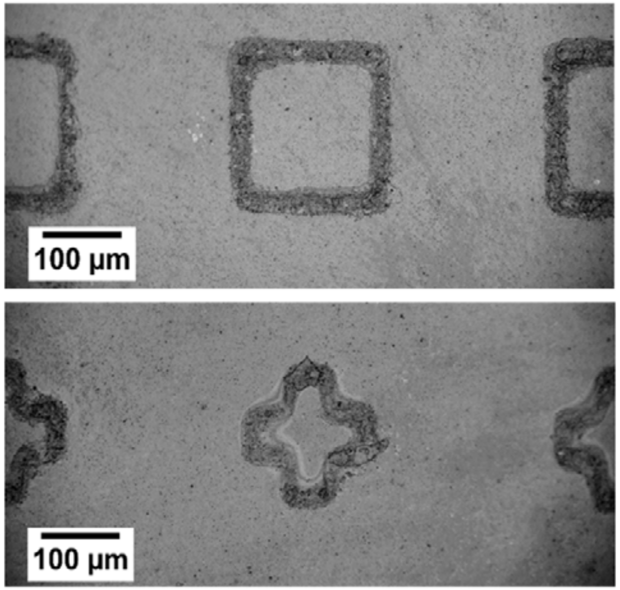
Example Nanoparticles (19 nm Fe_3O_4)



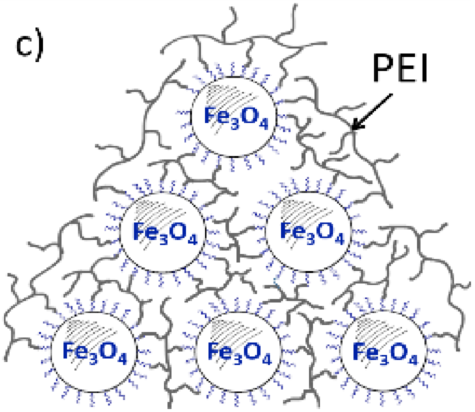




Example Microstructures



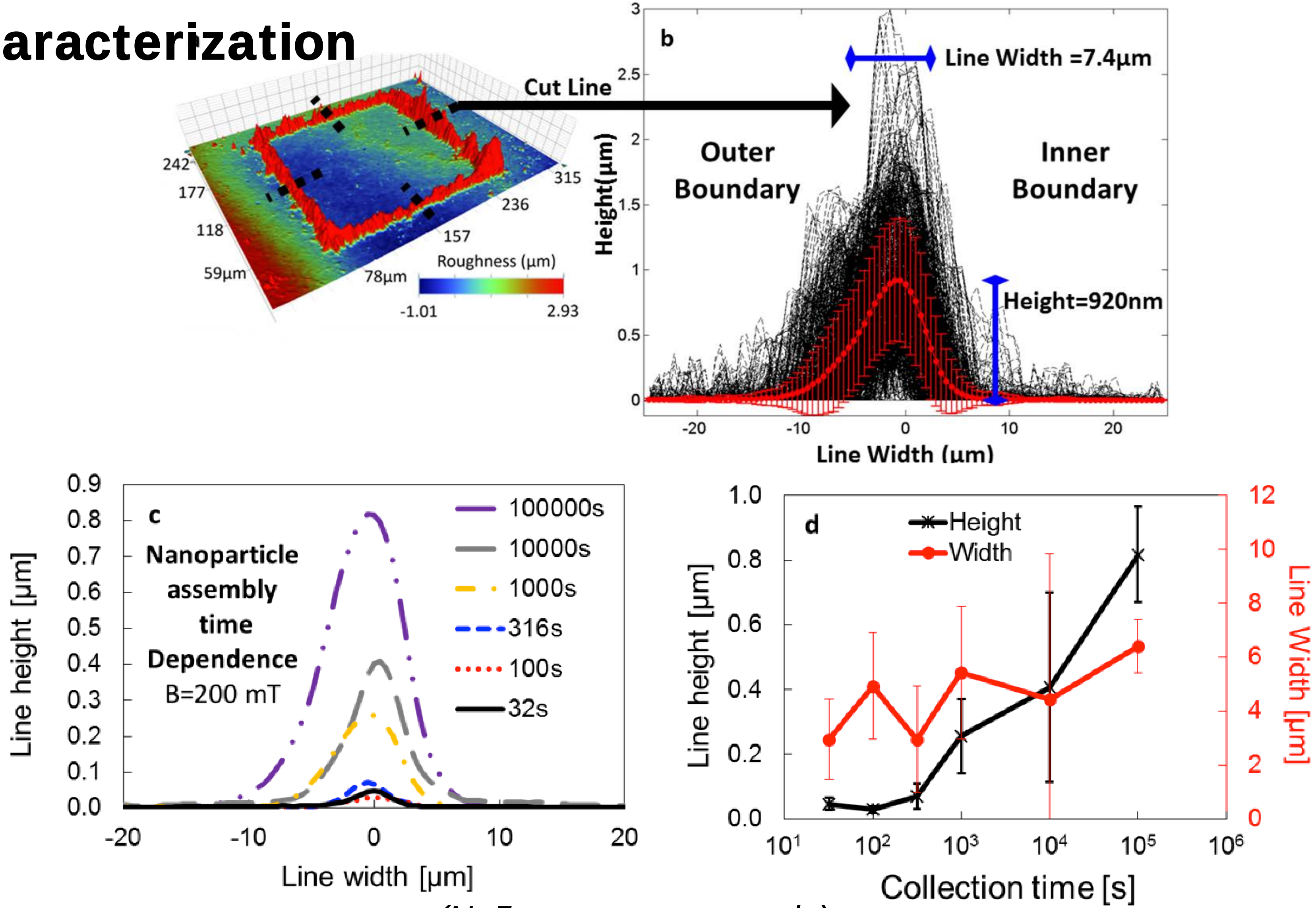
Branched polyethylenimine (PEI) to crosslink the carboxylic acid groups on particle surfaces



C. Velez, et al., ACS Nano 2015.

Self-Assembled Magnetic Microstructures

- **Characterization**



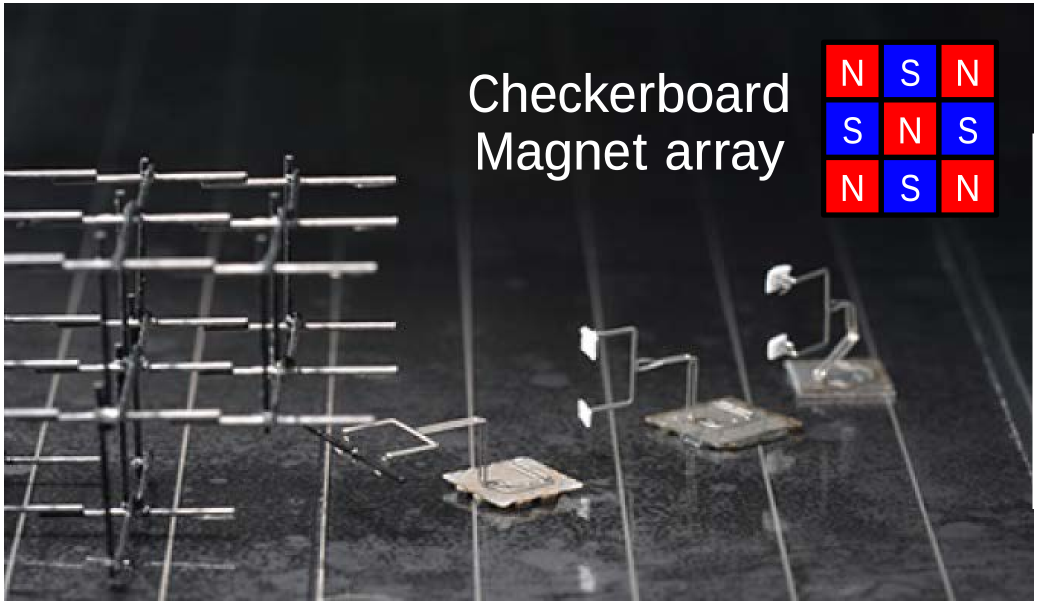
(N=5 squares per sample)

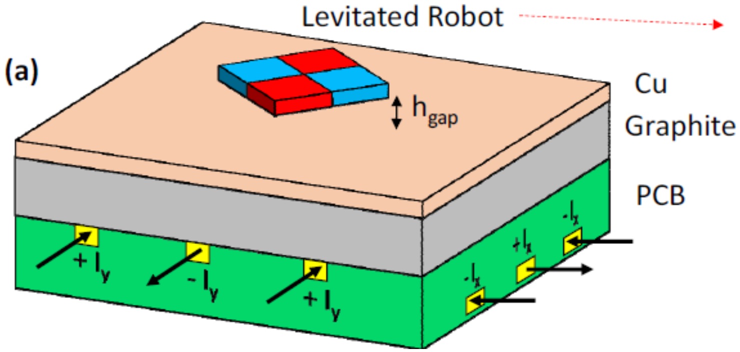
C. Velez, et al., ACS Nano 2015.

Self-Assembled Magnetic Microstructures

Magnetic Microrobots

- **Previous work from SRI International**
  - Robots are 2x2 or 3x3 arrays of NdFeB magnets
  - Levitated above diamagnetic substrate (pyrolytic graphite)
  - Currents through wires provide lateral forces to drive the robots





How to make smaller?
How to make 1000's?? ⇒ Batch Microfabrication

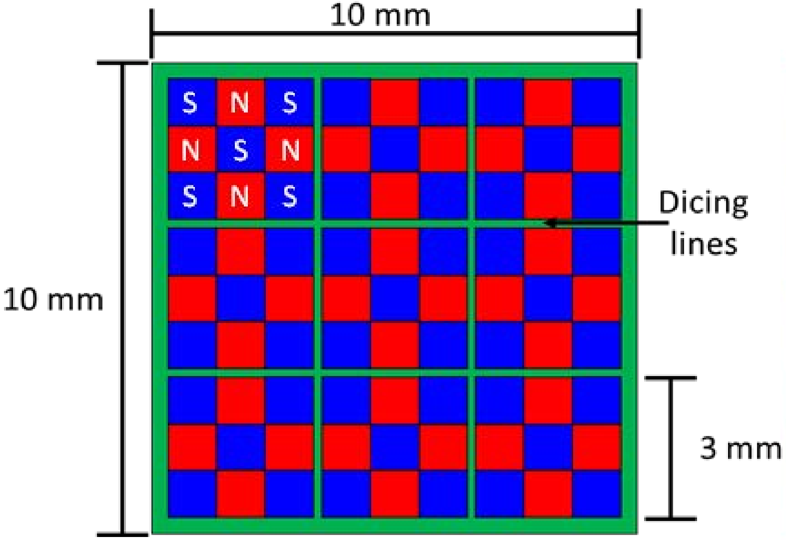
Magnetic Microrobots

- **https://youtu.be/uL6e3co4Qqc**

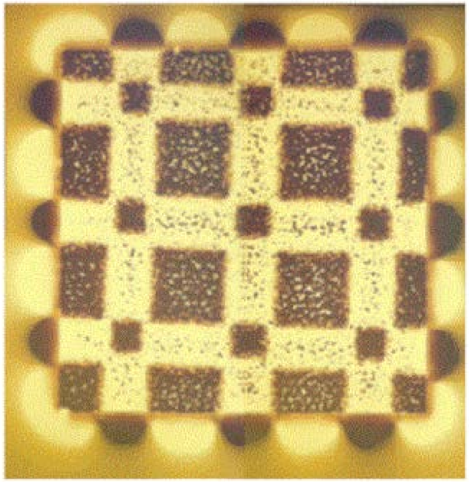
The micro-robots can be very fast.
Maximum speed (so far) is 35 cm/s.

Magnetic Microrobots

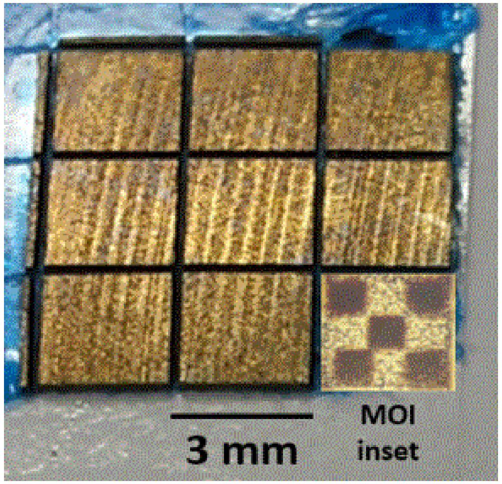
- **Fabrication Strategy**
  - Imprint magnetic patterns on large magnetic substrate (limited sizes)
  - Mechanically dice into multiple robots



Design



Selectively magnetized bases



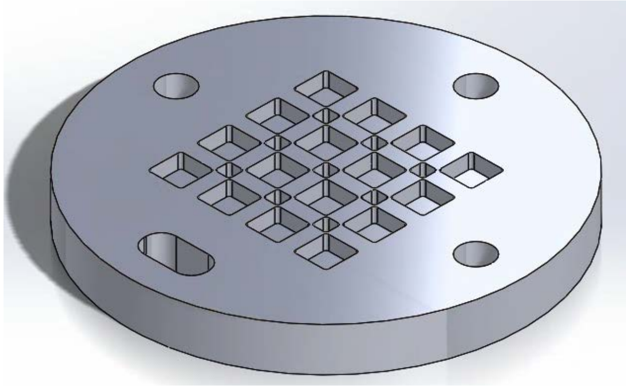
Singulated robots

C. Velez, PhD Dissertation, UF, 2017.

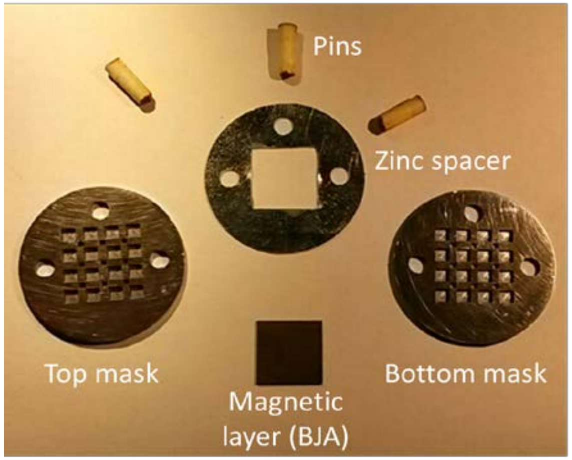
Magnetic Microrobots

- **Selective magnetization mask**

Version 1:

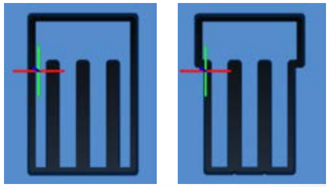


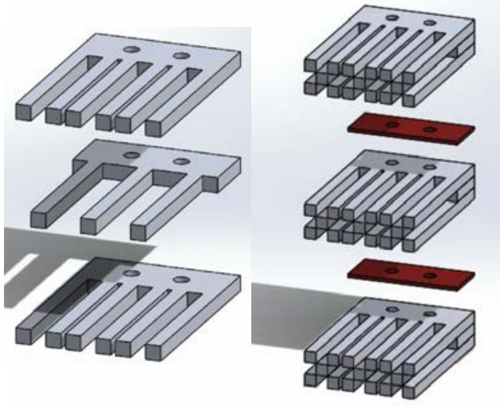
Disassembled magnetization mask



Version 2:

CNC program to machine both parts of mask

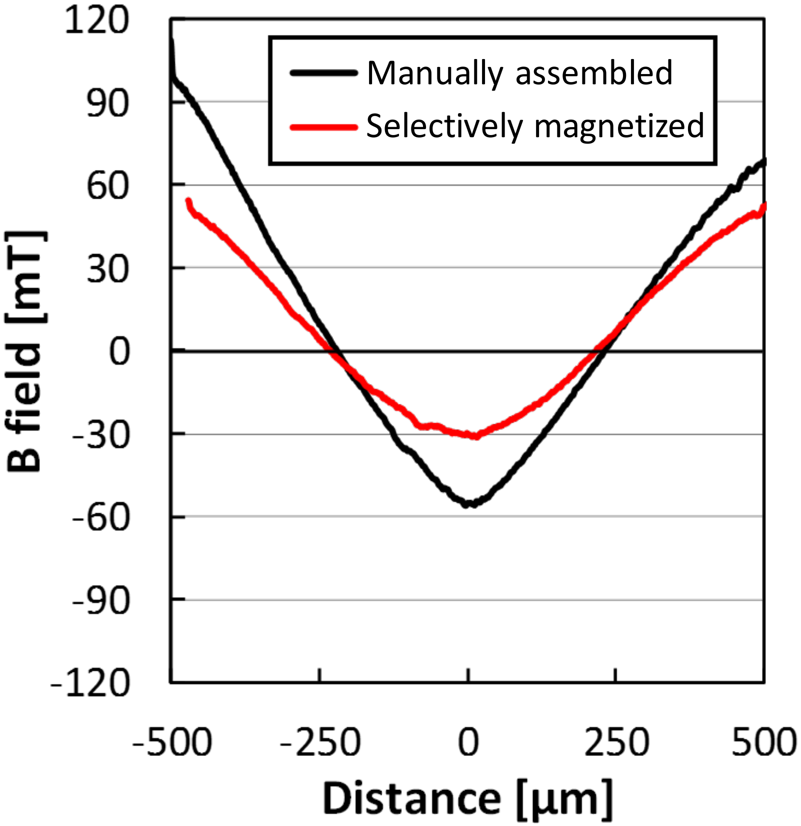




Microfabricated vs. Hand Assembled

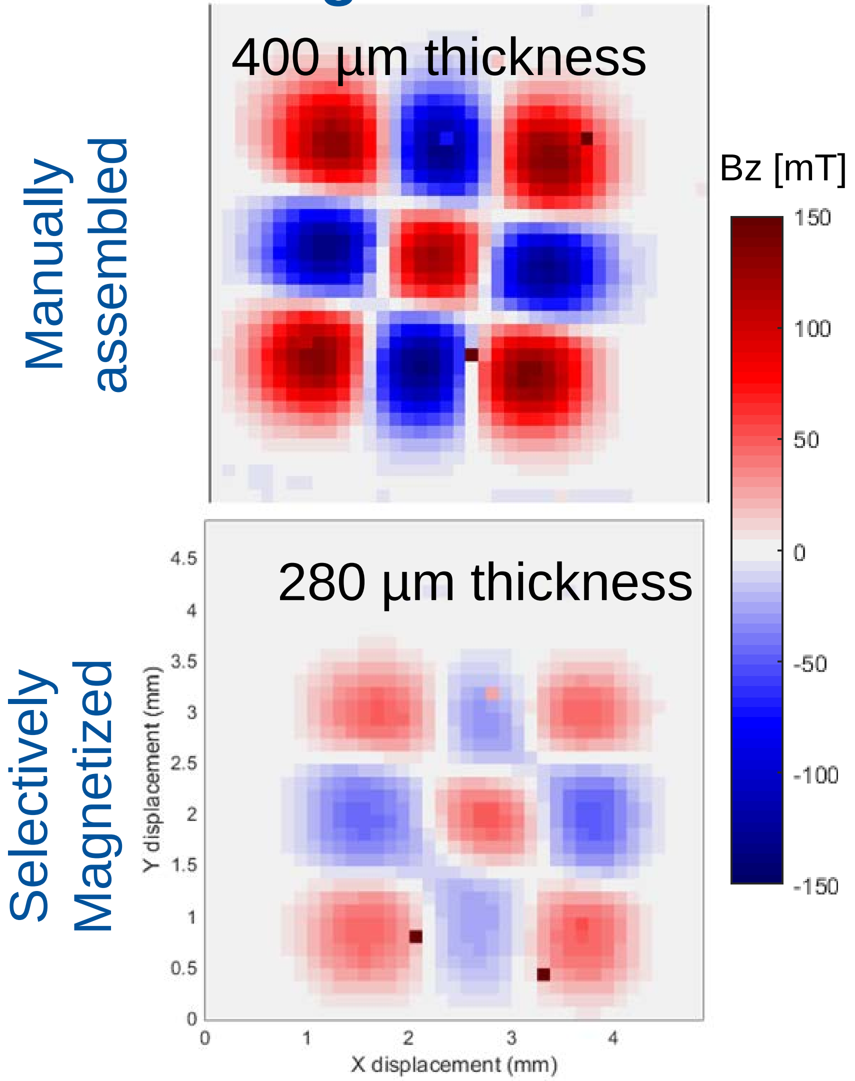
- **Comparison…**

Magneto Optical Imaging



→ Close, but not quite as strong

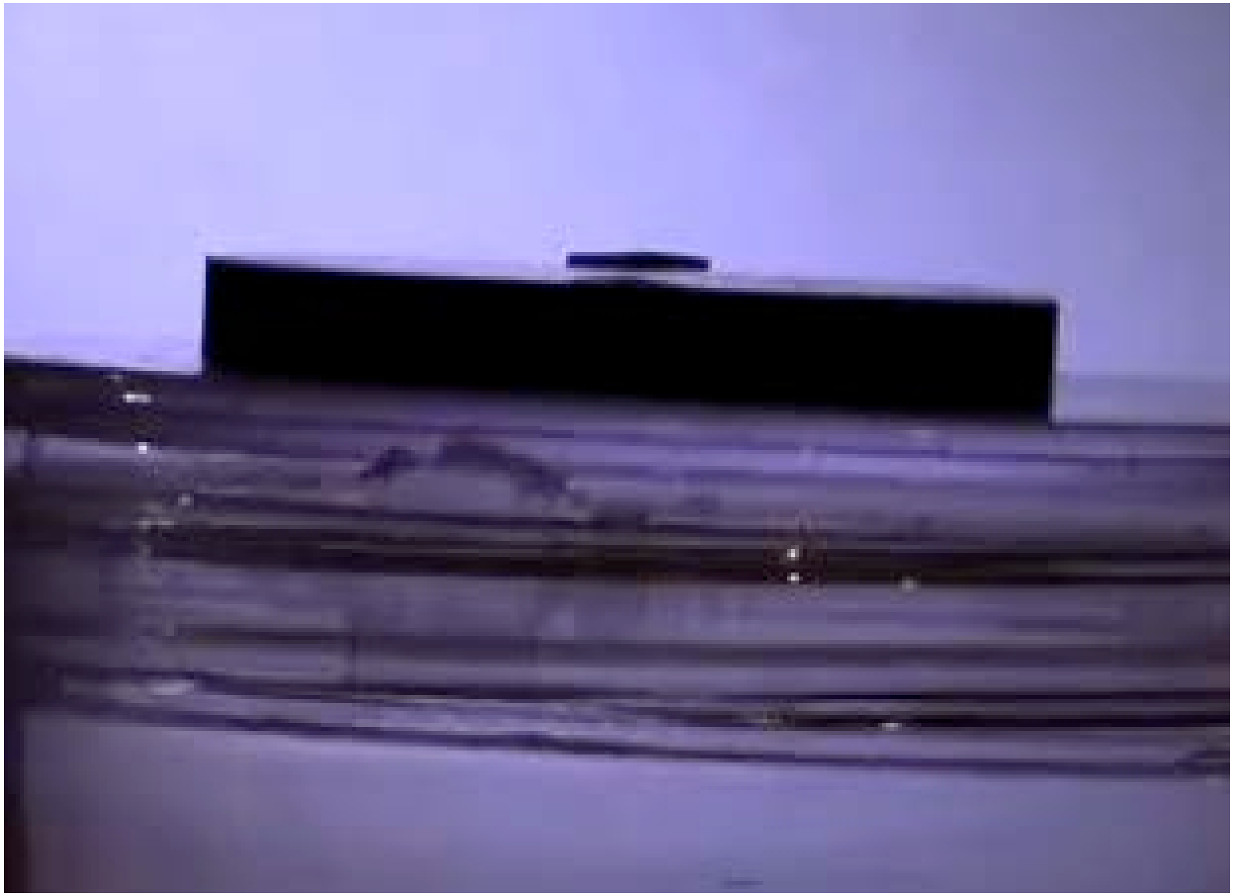
Scanning Hall Probe



C. Velez, PhD Dissertation, UF, 2017.

Magnetic Microrobots

Assisted Levitation (SRI)



Biased levitation of batch-fabricated micro-robot

Sliding test (SRI)

C. Velez, PhD Dissertation, UF, 2017.

Acknowledgements

- **Postdocs**
  - Vinod Challa, Alexandra Garraud
- **PhDs**
  - Janhavi Agashe, Sheetal Shetye, Naigang Wang, Shuo Cheng, Chris Meyer, Shashank Sawant, Ololade Oniku, Chip Patterson, Camilo Velez
- **Masters**
  - Tzu-Shun Yang, Ben Bowers, Raj Natarajan
- **Undergrads**
  - Zak Kaufman, Evan Shorman
- **Collaborators**
  - Carlos Rinaldi and Larry Ukeiley (UF), Lou Cattafesta (FSU), Mark Allen (Penn), Ron Pelrine + Annjoe Wong-Foy (SRI)

- **Project Sponsors:**

NSF ARL ARMY RESEARCH OFFICE NASA DARPA SRI International

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