The Kate Gleason COLLEGE OF ENGINEERING
R·I·T

34 Microelectronic Engineering Conference at RIT

جامعة الملك عبدالله للعلوم والتقنية
King Abdullah University of Science and Technology

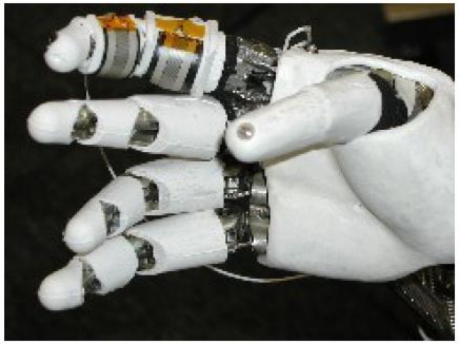
Magnetic Nanocomposite Smart Skin

Ahmed Alfadhel , Jürgen Kosel

Sensing Magnetism and Microsystems Lab (smm.kaust.edu.sa)
Computer, Electrical and Mathematical Sciences and Engineering Division (CEMSE)
King Abdullah University of Science and Technology (KAUST), Saudi Arabia

SMM Sensing, Magnetism & Microsystems

INTRODUCTION

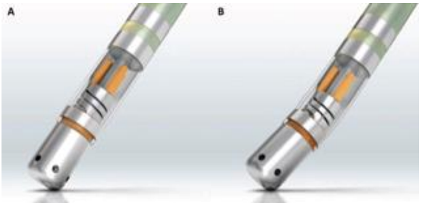


Artificial Skins

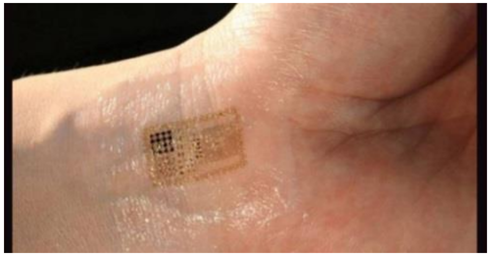
Essential to mimic the human skin capabilities including the sense of touch.

Tactile Sensors

The main component of artificial skins that mimic the sense of touch and allow measuring property of objects through contact.*



Thermocool Smarttouch® ablation catheter with force feedback.

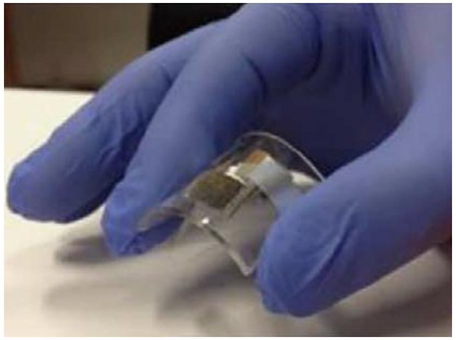

John A. Rogers, University of Illinois

Applications

- Robotics,
- Prosthetics,
- Smart Medical tools,
- ….

Technical challenges in tactile sensor research

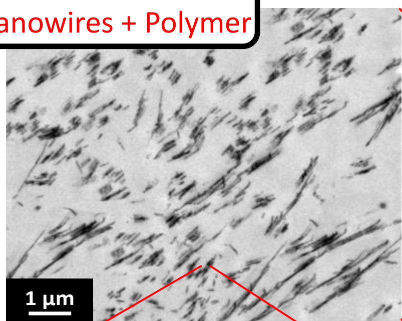
- Sensitivity vs. operating range,
- High power consumption,
- Interference with environmental noise,
- Measurement of shear forces,
- Operation in different environments,…

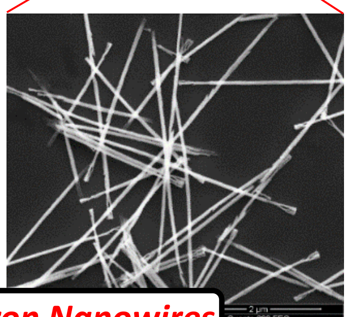

S. Gong et.al, Nature communications, 2014

*M.H. Lee, H.R. Nicholls, Tactile sensing for mechatronics—a state of the art survey. Mechatronics **9**, 1–31 (1999)

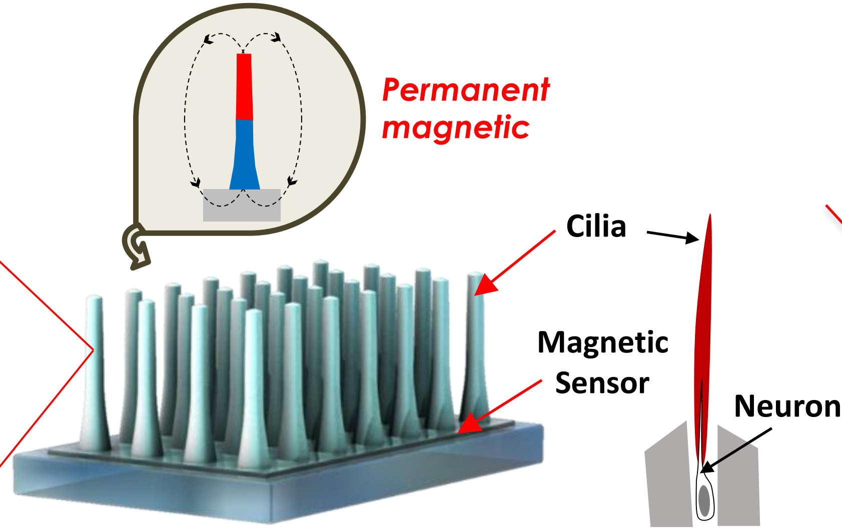
CONCEPT

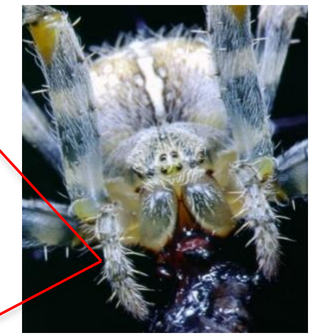
Nanocomposite: Nanowires + Polymer

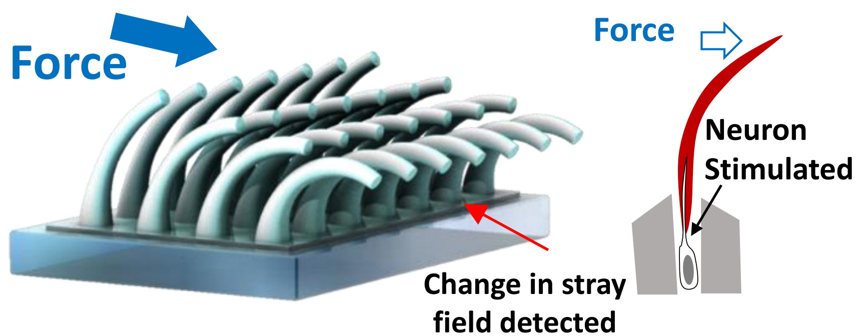




Iron Nanowires







Cilia:

Microscale hair-like structures (e.g. sensory hairs in Spiders)

$$\delta \approx F \frac{l^3}{ED^4}$$

δ: Tip displacement
F: Force
l: Pillar's length
D: Pillar's Diameter

Operating principle:

Detecting the change of the cilia's stray field, using the magnetic sensor, when deflected by an external force (e.g. hand touch, or fluid flow).

Ability to detect Vertical & Shear Forces

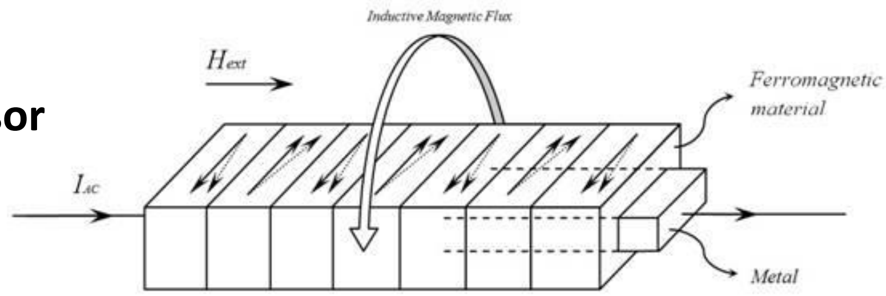
A. Alfadhel, B. Li, J. Kosel: "Magnetic Nanocomposite Sensor". U.S. Patent Application, Appl. No. 62/073,160

CONCEPT

Sensor Design

For Magnetic Field Sensing:

- **Giant Magneto-impedance (GMI) sensor**
  - High sensitivity
  - Simple fabrication
  - Potential for Wireless Operation



- **The GMI effect:** Impedance change of a magnetic material under the change of an external magnetic field >> caused by the variation of the skin depth

$$\delta = \sqrt{\frac{2\rho}{\omega\mu}}$$

δ: Skin depth
ρ: Resistivity
ω: Angular frequency
μ: Magnetic Permeability

Operating principle:

Applying external magnetic field changes:

>> *Magnetic anisotropy*
>> *Magnetic permeability* **>>** *skin depth*
>>> ***Impedance change***

CONCEPT

Sensor Design

Cilia Materials selection:

Single domain Fe Nanowires:

Large magnetization /permanent magnetic /Biocompatible

Polydimethylsiloxane (PDMS):

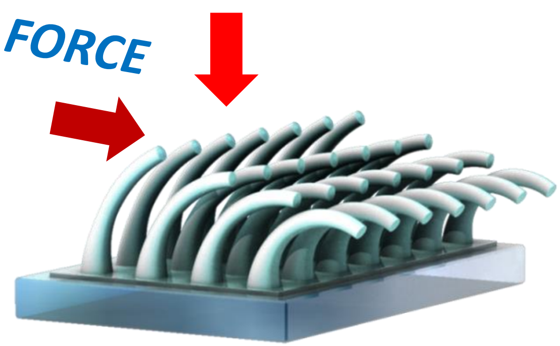
Highly flexible / Chemically resistant / Biocompatible

Composite

- ✓ *Biocompatible*
- ✓ *Permanent magnetic*
- ✓ *Highly elastic*
- ✓ *Corrosion resistant*

Design:

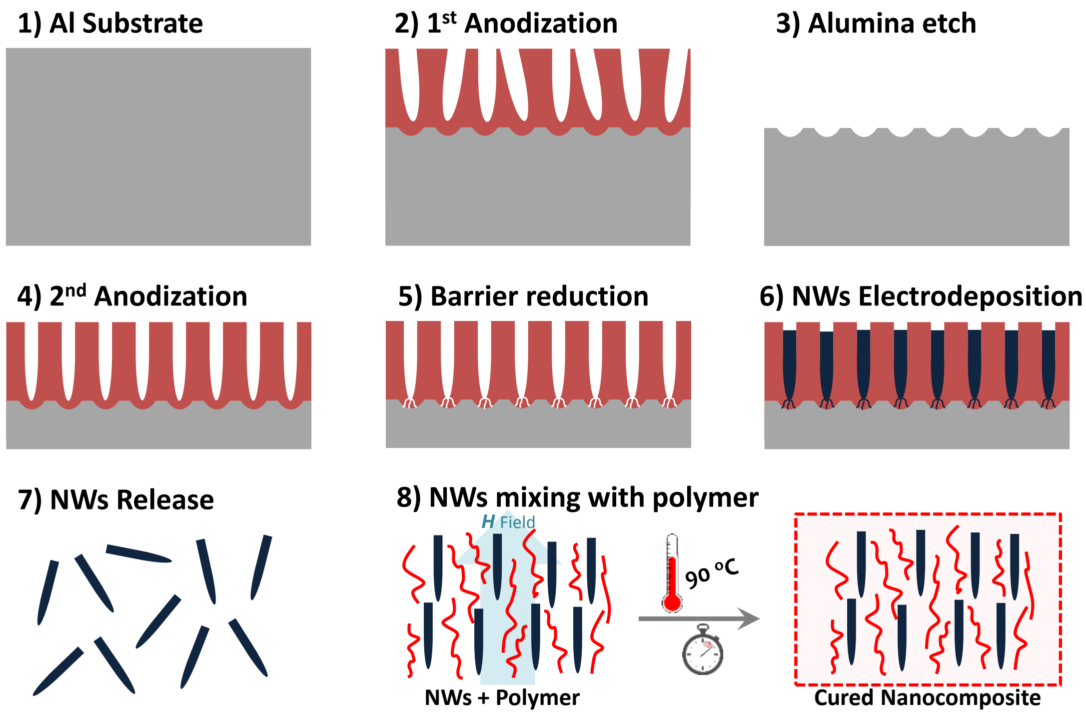
- **2 mm x 2 mm sensing element**
- **Different Cilia Dimensions (***10-200 µm in diameter & 50 µm - 1 mm in length)* to cover:
  - **Ultra-low Pressure** (< 500 Pa) *for microfluidics or biological detection*
  - **Low Pressure** (<10 kPa) *for electronic skins and health monitoring systems*
  - **High Pressure** up to 300 kPa *for industrial applications*

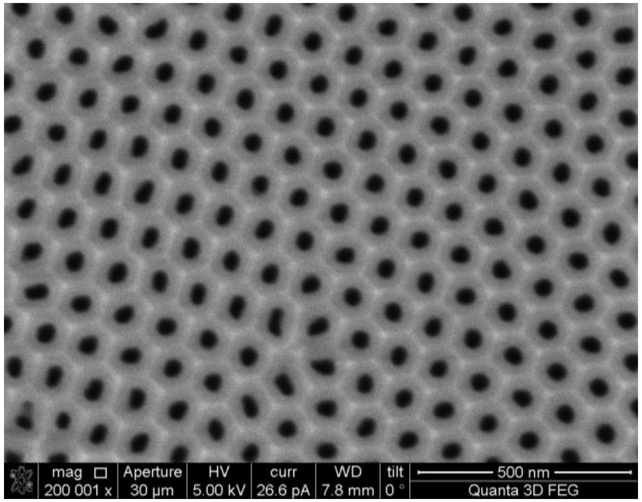


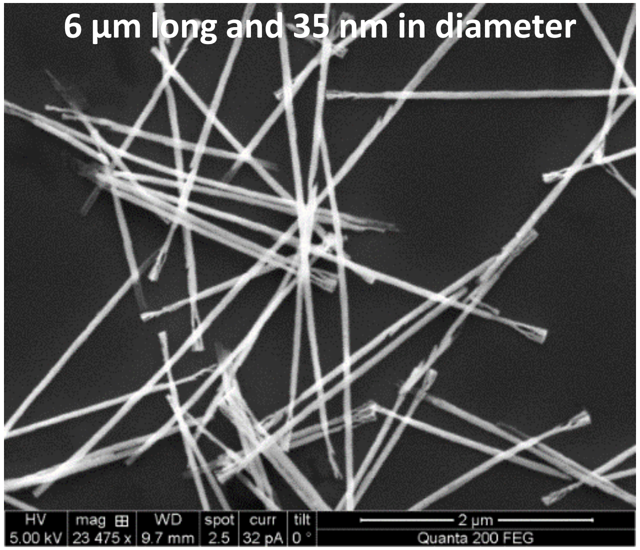
FABRICATION & CHARACTERIZATION

Nanowire & Nanocomposite Fabrication

Fe nanowires are fabricated by electrodeposition into nanoporous aluminum oxide membranes.



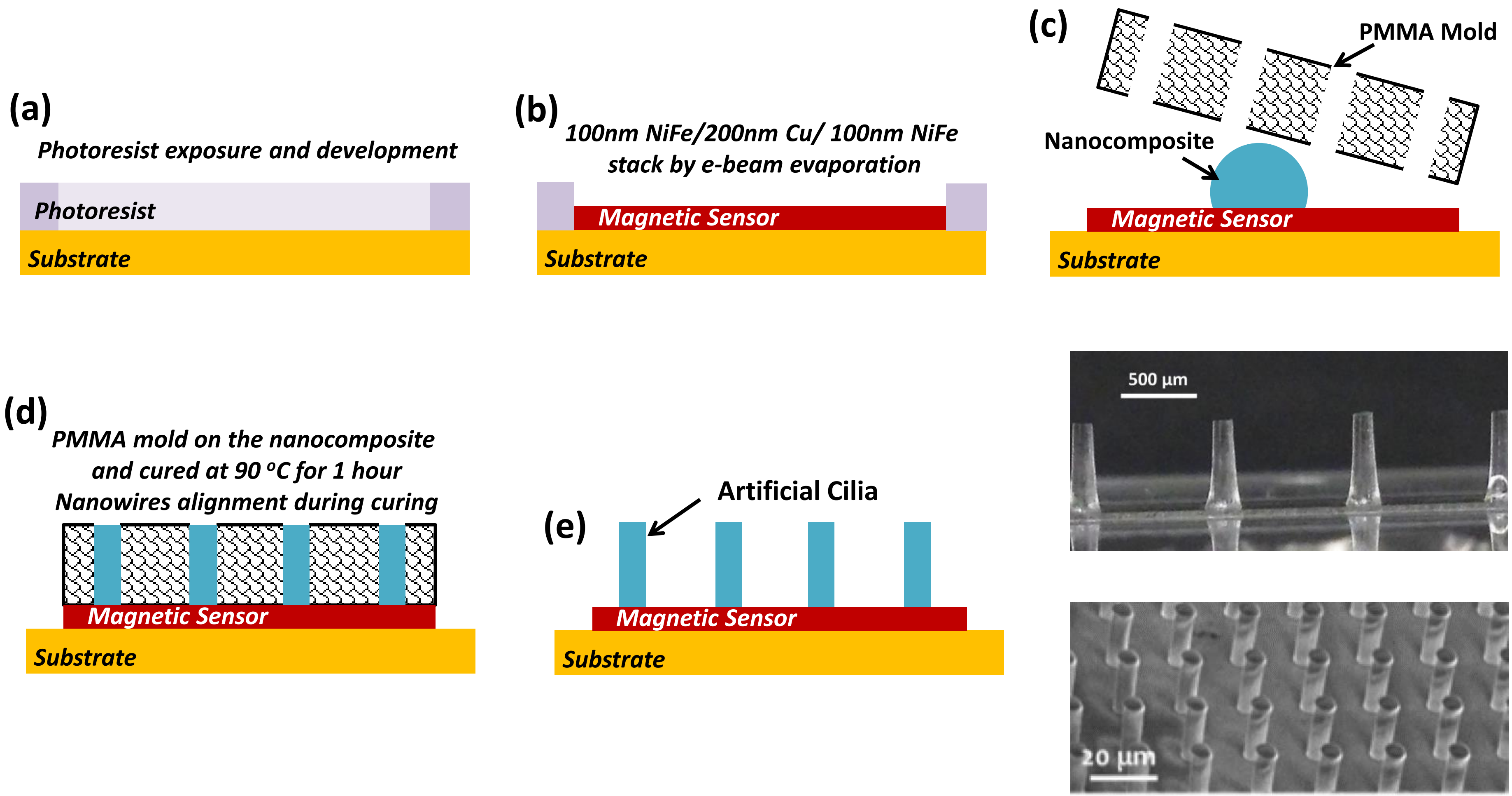




A. Alfadhel, J. Kosel, "Magnetic Nanocomposite Cilia Tactile Sensor," *Advanced Materials*, 27, pp. 7888, 2015.

FABRICATION & CHARACTERIZATION

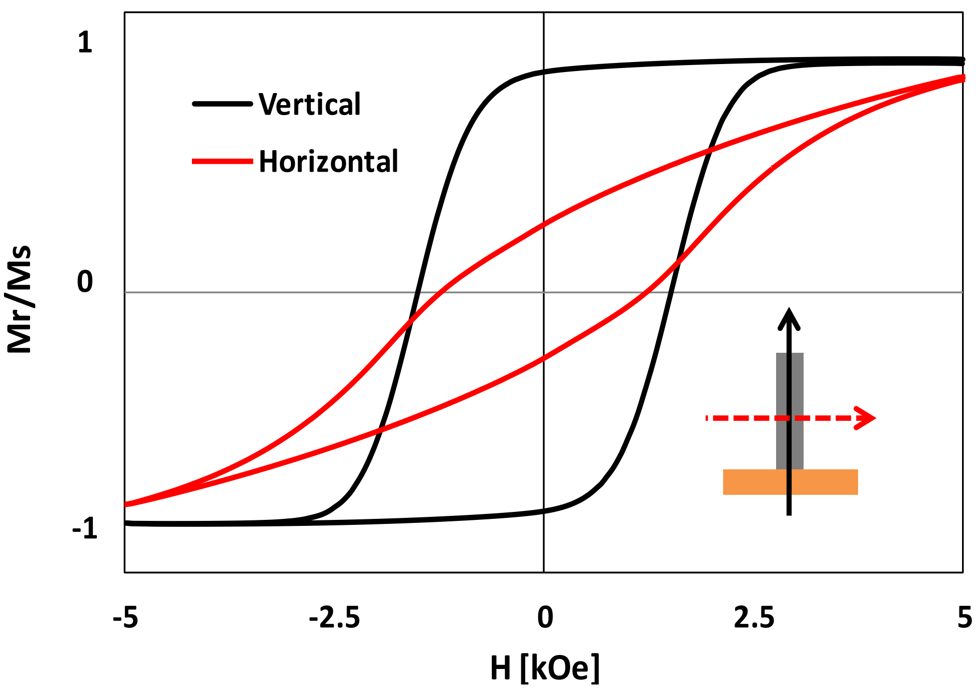
Cilia Sensor Fabrication

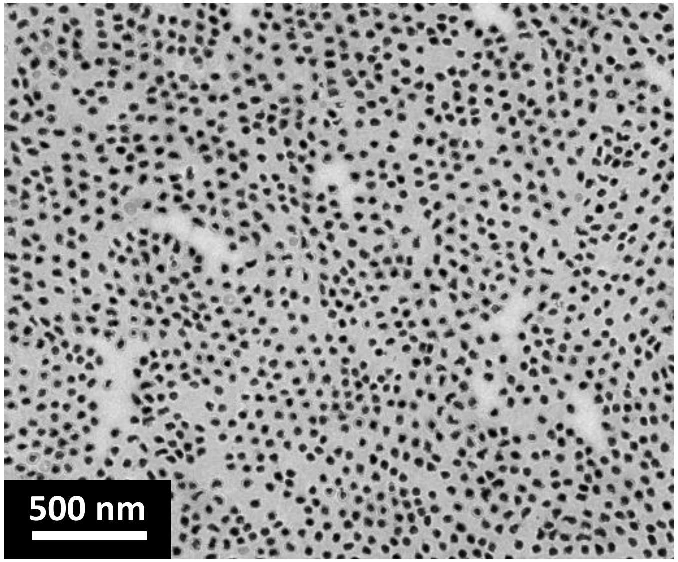


FABRICATION & CHARACTERIZATION

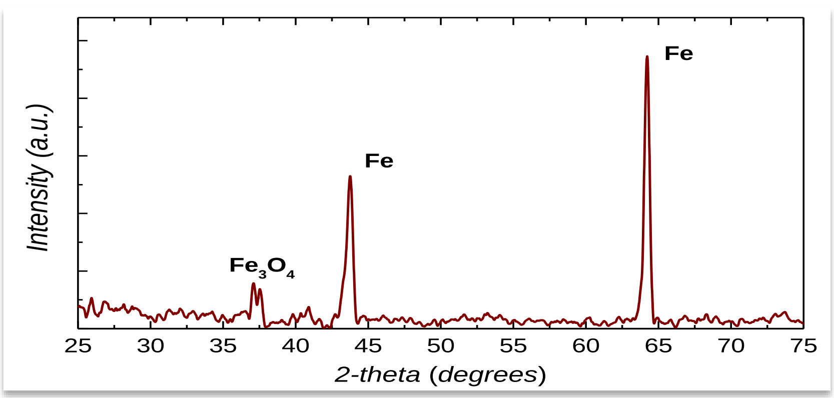
Nanocomposite Characterization

Mr/Ms = 0.95 H_c = 1.5 kOe





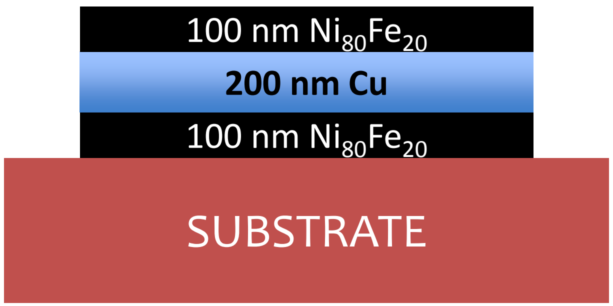
Top cross-section of nanocomposite cilia with 14% nanowires to PDMS volume ratio



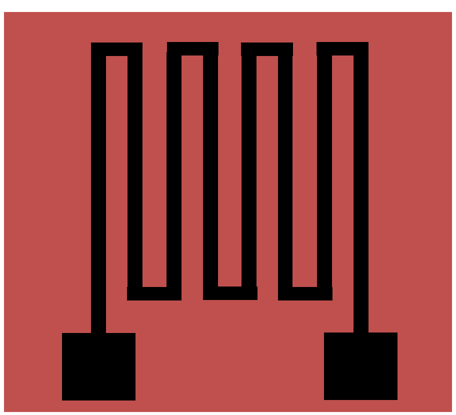
FABRICATION & CHARACTERIZATION

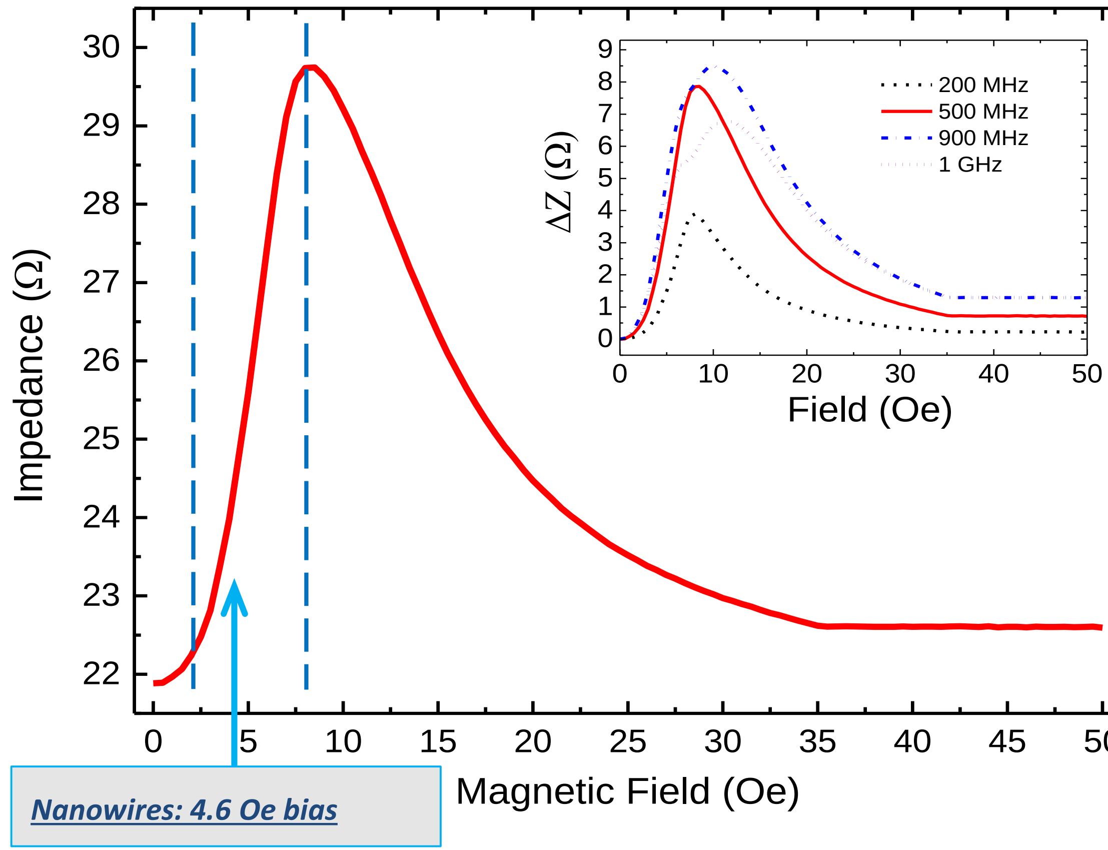
Magnetic Sensor Fabrication & Characterization

Cross section



Top view



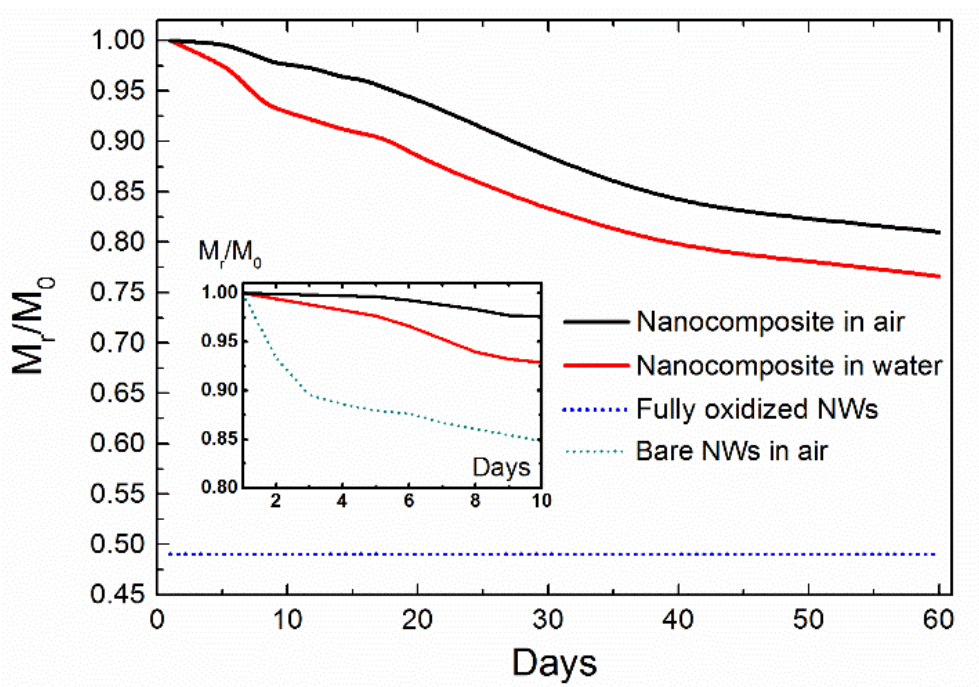


Sensitivity of 1.2 Ω/Oe @ 500 MHz

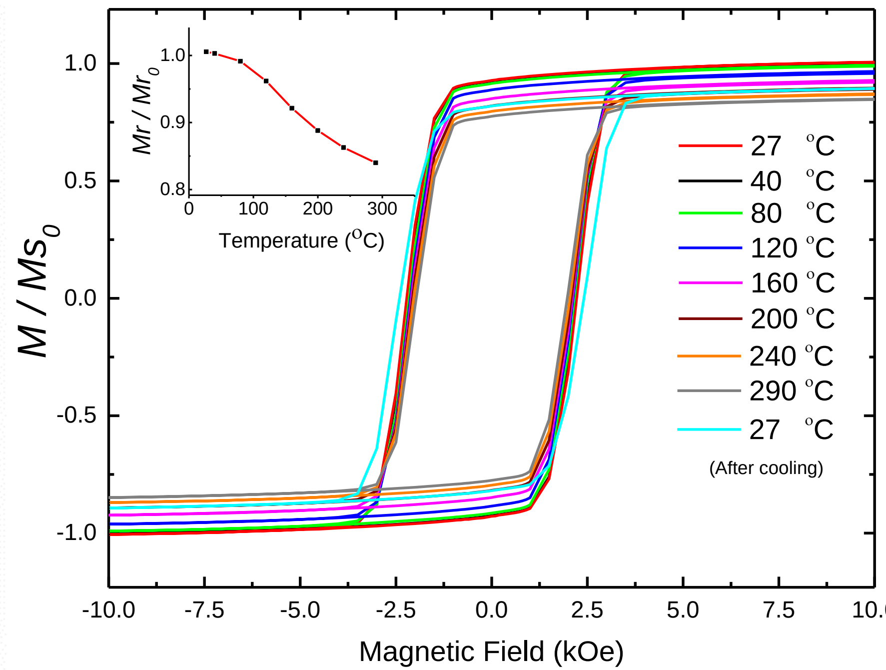
HARSH ENVIRONMENT

Corrosion Study of Nanocomposite

Magnetic Stability in a Humid Environment



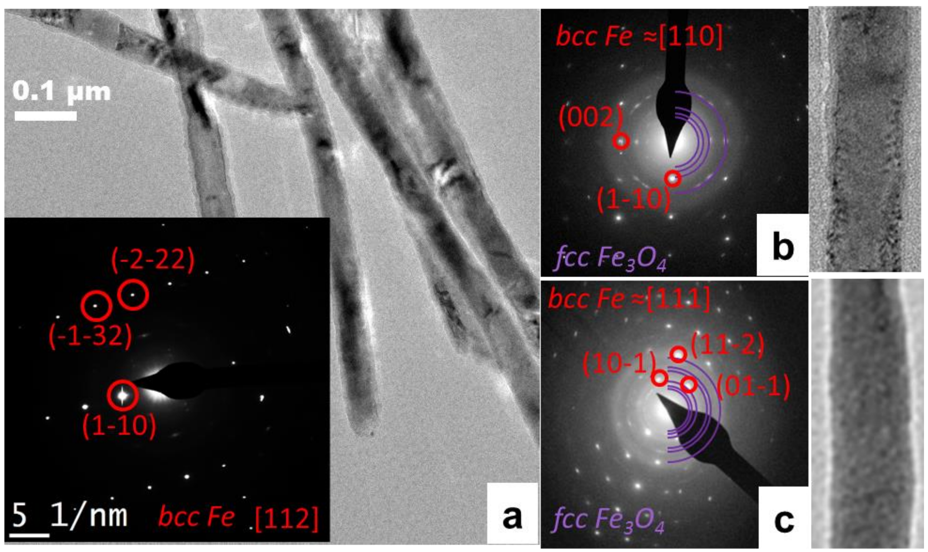
Magnetic Stability at High Temperatures



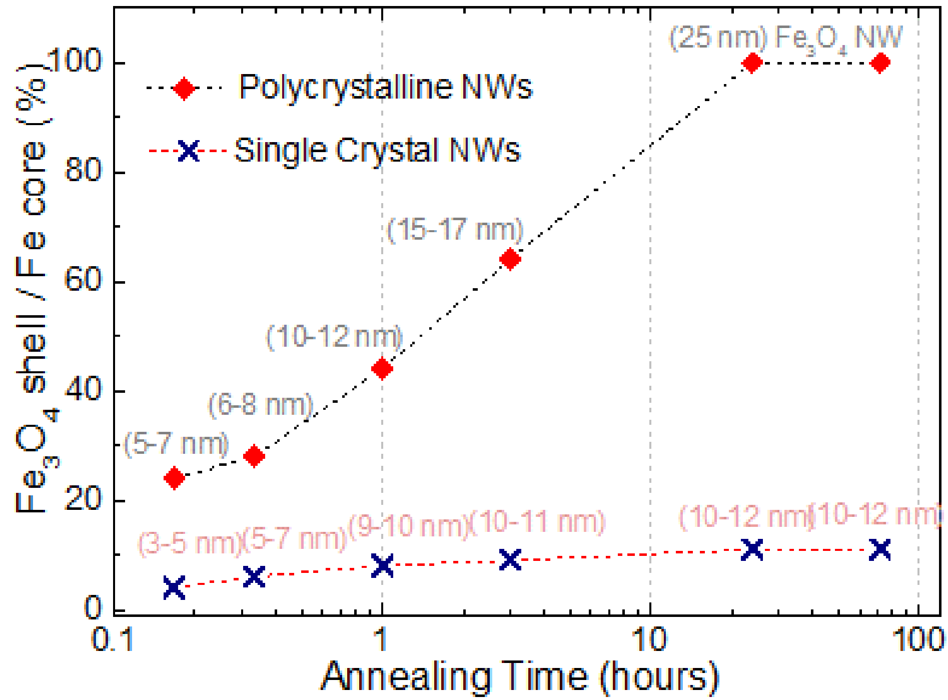
HARSH ENVIRONMENT

New Candidate Material:

Single Crystal Fe Nanowires



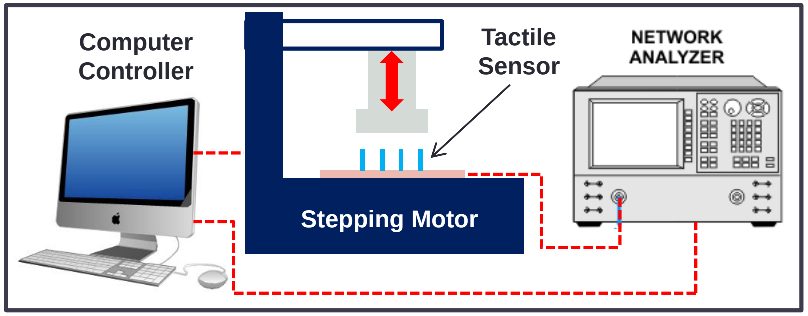
(a) Bright field TEM image and SAED pattern of single-crystalline Fe NWs, Fe-Fe_3O_4 core-shell NWs (b) after 1 hour of annealing and (c) after 72 hours of annealing.

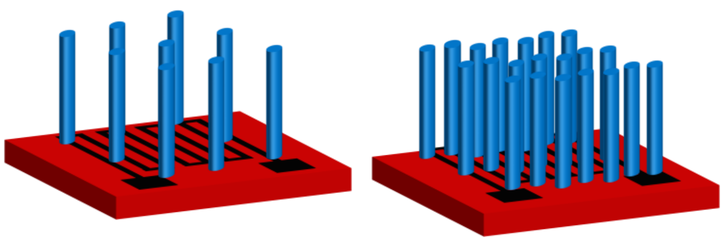


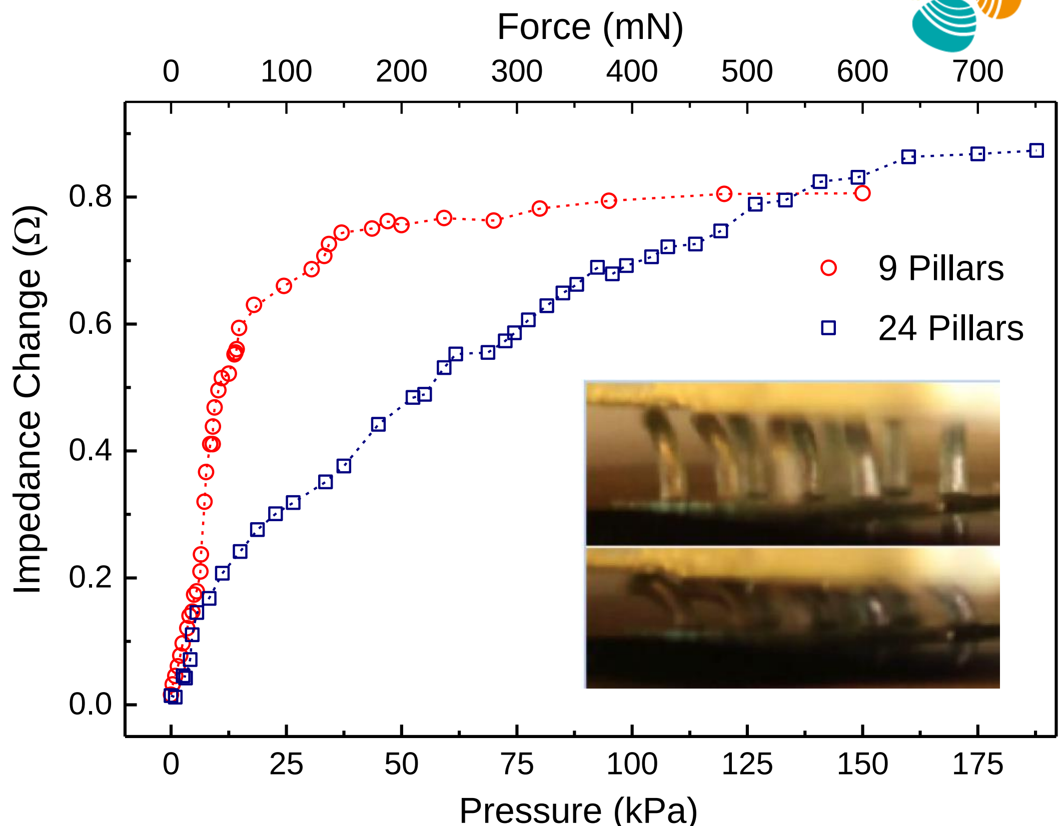
Ivanov, Yurii P., **Alfadhel, Ahmed**, et. al, “Tunable magnetic nanowires for biomedical and harsh environment applications,” Scientific Reports, 6, 2016

RESULTS

Vertical Force Response







9 Cilia Sensor:

Range: 0- 200 mN (50 kPa)
Sensitivity: 15 mΩ/mN (60 mΩ/kPa)
Resolution: 0.9 mN (0.23 kPa)
Maximum ΔZ: 0.8 Ω

24 Cilia Sensor:

Range: 0- 680 mN (170 kPa)
Sensitivity: 4 mΩ/mN (16 mΩ/kPa)
Resolution: 3.5 mN (0.88 kPa)
Maximum ΔZ: 0.86 Ω

Fewer cilia → Higher sensitivity More Cilia → Wider operating range

A. Alfadhel, J. Kosel, "Magnetic Nanocomposite Cilia Tactile Sensor," *Advanced Materials*, 27, pp. 7888, 2015.

RESULTS

Vertical Force Response

A human skin can “feel” irritants (such as the effects of a fly landing).

To mimic the skin sensitivity:

2500 cilia array

50 µm long and 10 µm in diameter

High sensitivity of

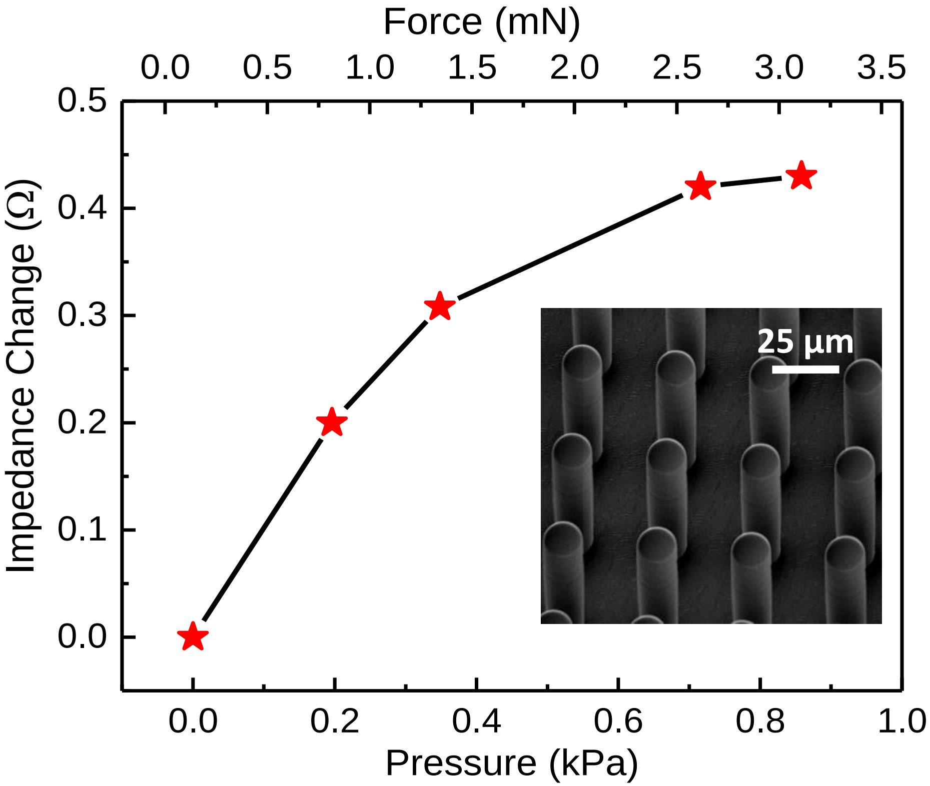
214 mΩ/mN (856 mΩ/kPa)

Ultra-high resolution of

0.065 mN (16 Pa)

Small range up to 3.5 mN (0.85 kPa)

Maximum impedance change of 0.4 Ω.



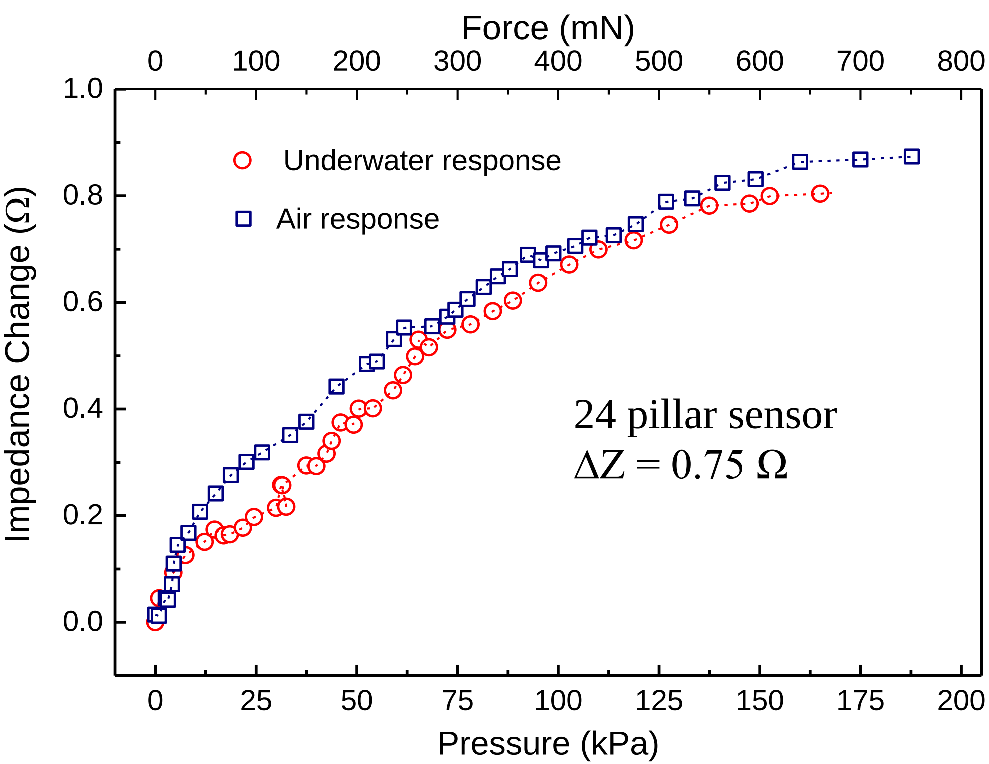
A. Alfadhel, J. Kosel, “Magnetic Nanocomposite Cilia Tactile Sensor,” *Advanced Materials*, 27, pp. 7888, 2015.

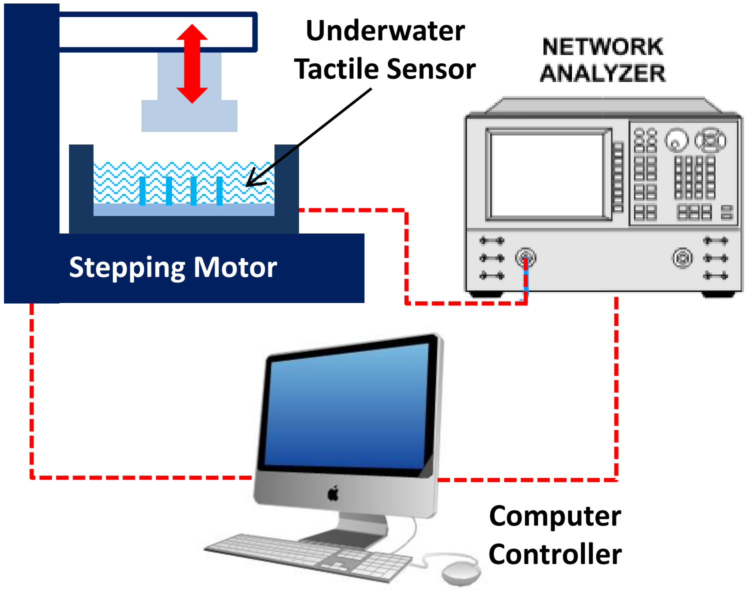
RESULTS

Vertical Force Response

- **Underwater Operation**

The tactile sensor has the ability to operate in different environments (e.g. under water)



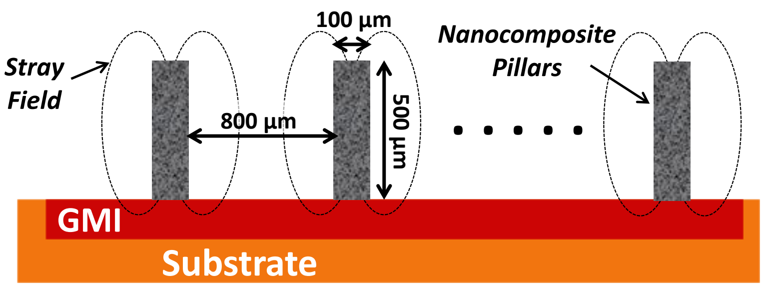


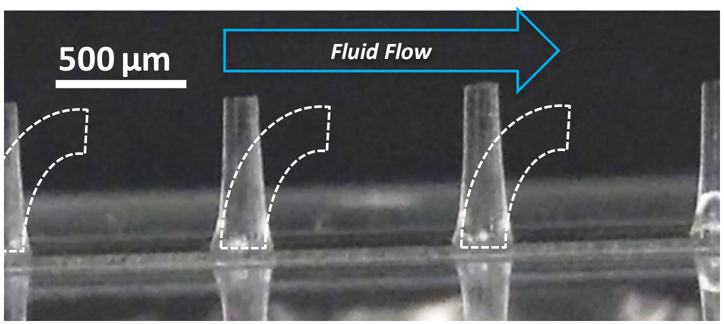
A. Alfadhel, J. Kosel, "Magnetic Nanocomposite Cilia Tactile Sensor," *Advanced Materials*, 27, pp. 7888, 2015.

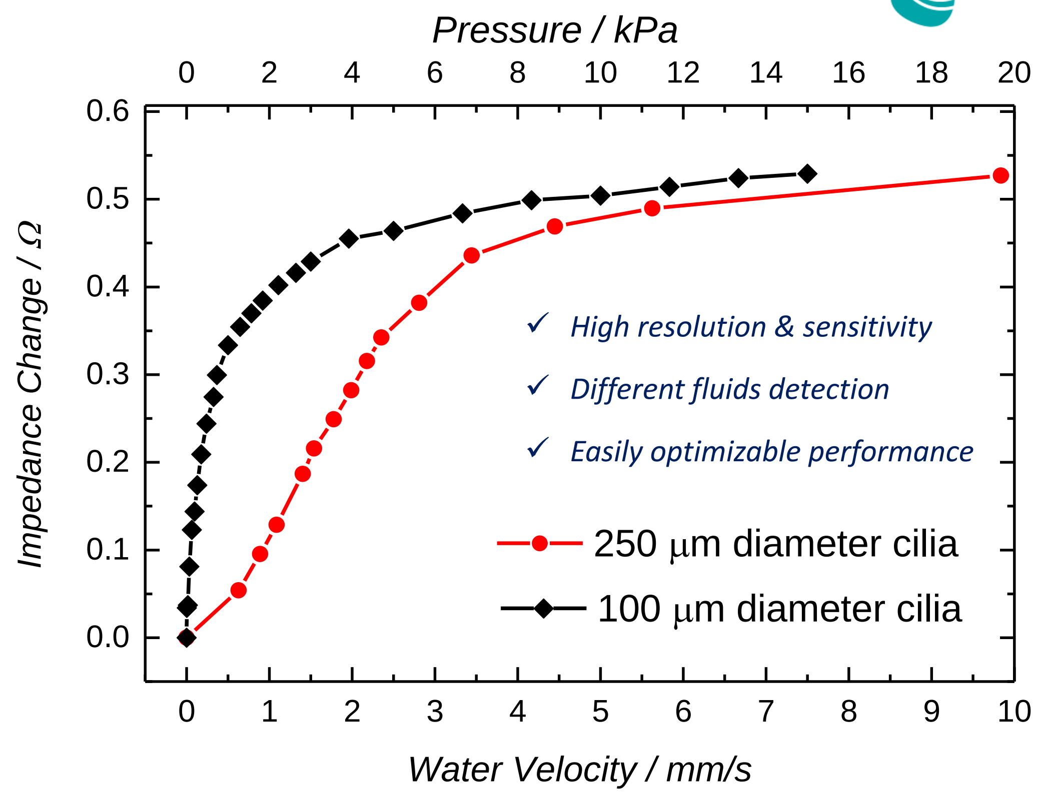
RESULTS

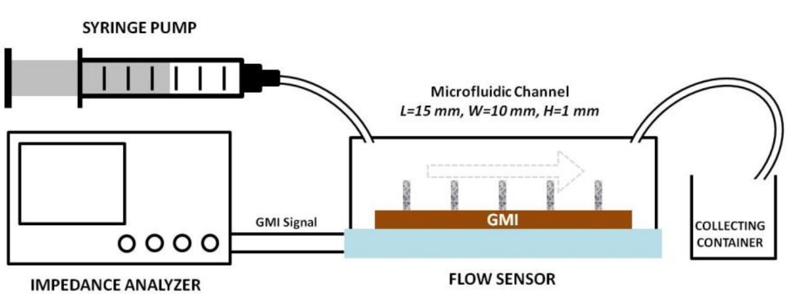
Shear Force Response

➢ Fluid Flow Sensing









	Range [mm/s]	Sensitivity [Ω/(mm/s)]	Resolution [mm/s]
Air Flow	0 – 190	0.024	0.5
Water Flow	0 – 7.8	0.9	0.013

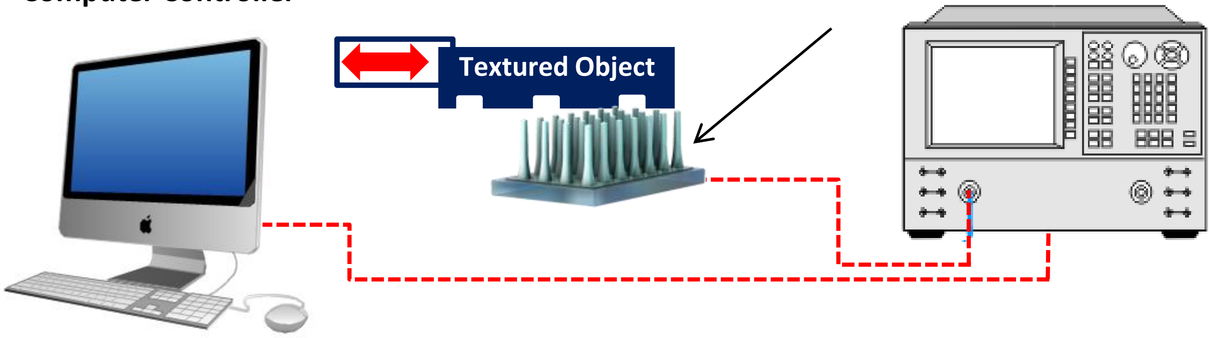
80 nW power consumption!

<u>**A. Alfadhel**</u>, B. Li, A. Zaher, O. Yassine, and J. Kosel, *Lab Chip*, **14**, 4362-4369, 2014.

RESULTS

➢ Feel the Texture

- Texture detection with cilia sensor
- Polymer sheet with 200 µm deep grooves of 2 mm or 4 mm widths is moved horizontally across the cilia sensor
- Real time spectrum analyzer is used to detect the signal.

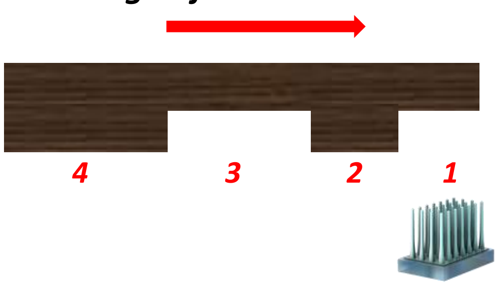


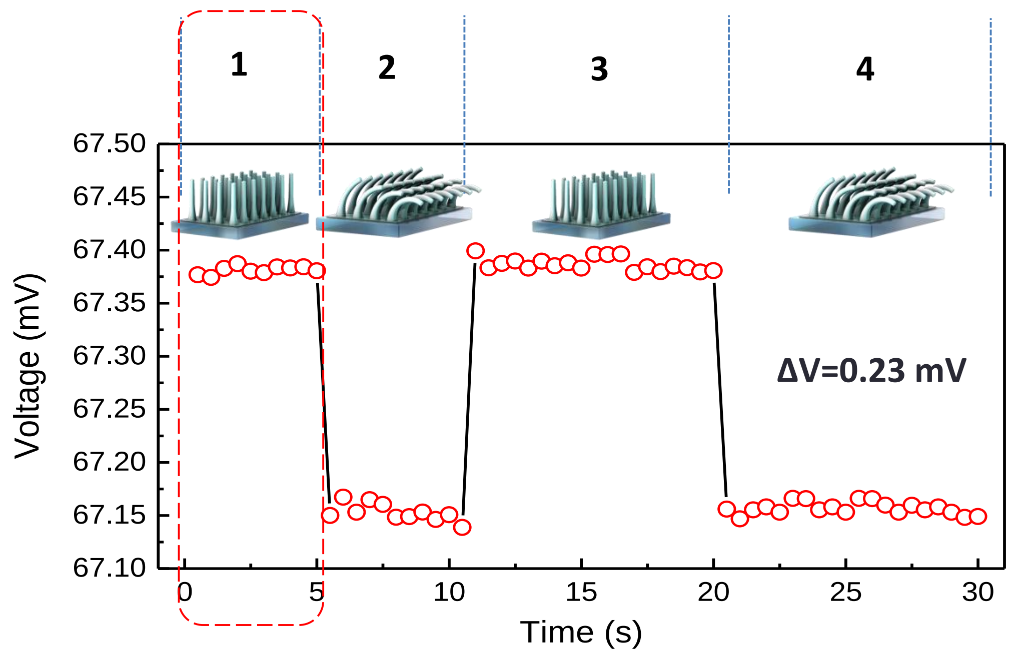
RESULTS

➢ Feel the Texture

- Texture detection with cilia sensor
- Polymer sheet with 200 µm deep grooves of 2 mm or 4 mm widths is moved horizontally across the cilia sensor
- Real time spectrum analyzer is used to detect the signal.

Moving object on the sensor





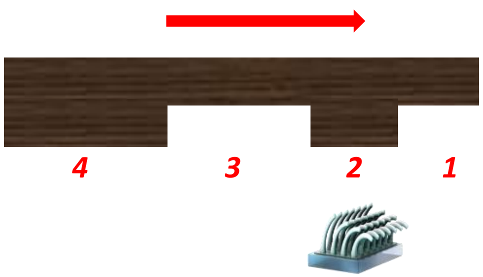
A. Alfadhel, J. Kosel, "Magnetic Nanocomposite Cilia Tactile Sensor," *Advanced Materials*, 27, pp. 7888, 2015.

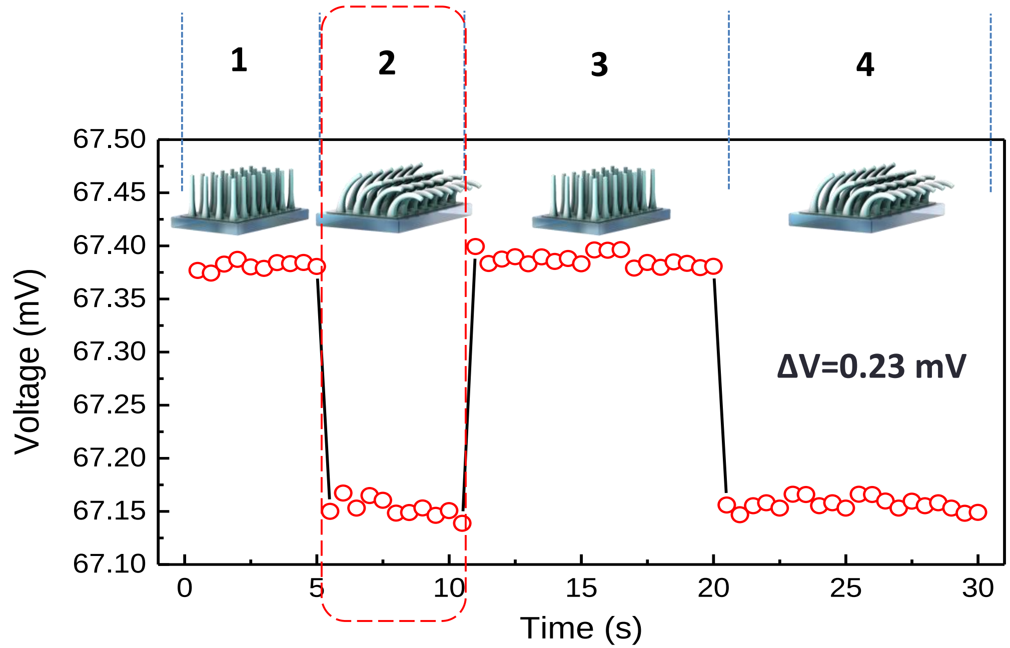
RESULTS

➢ Feel the Texture

- Texture detection with cilia sensor
- Polymer sheet with 200 µm deep grooves of 2 mm or 4 mm widths is moved horizontally across the cilia sensor
- Real time spectrum analyzer is used to detect the signal.

Moving object on the sensor



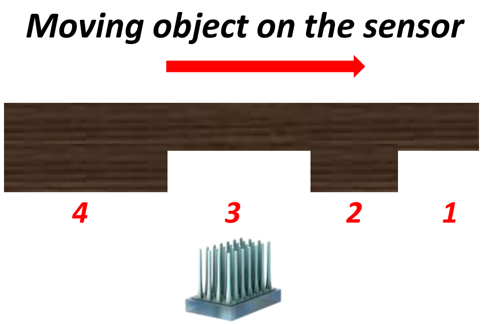


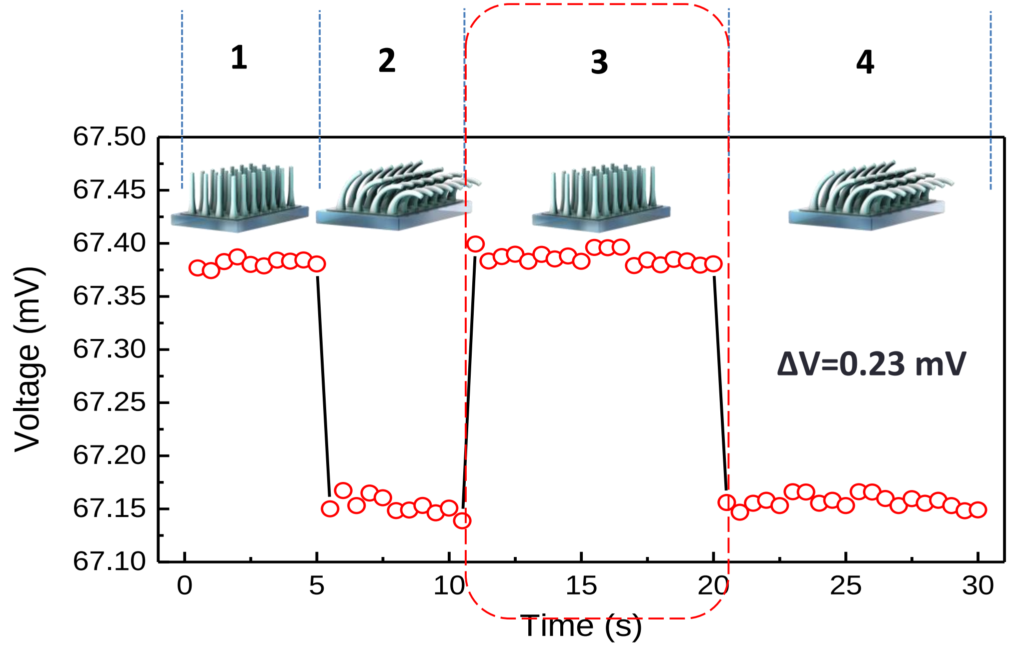
A. Alfadhel, J. Kosel, "Magnetic Nanocomposite Cilia Tactile Sensor," *Advanced Materials*, 27, pp. 7888, 2015.

RESULTS

➤ Feel the Texture

- Texture detection with cilia sensor
- Polymer sheet with 200 µm deep grooves of 2 mm or 4 mm widths is moved horizontally across the cilia sensor
- Real time spectrum analyzer is used to detect the signal.





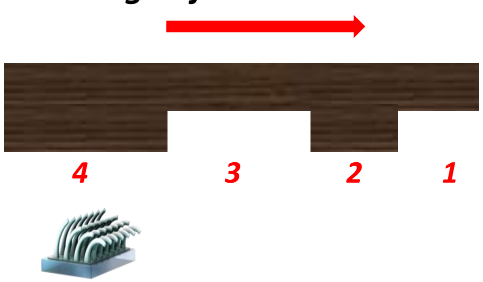
A. Alfadhel, J. Kosel, "Magnetic Nanocomposite Cilia Tactile Sensor," *Advanced Materials*, 27, pp. 7888, 2015.

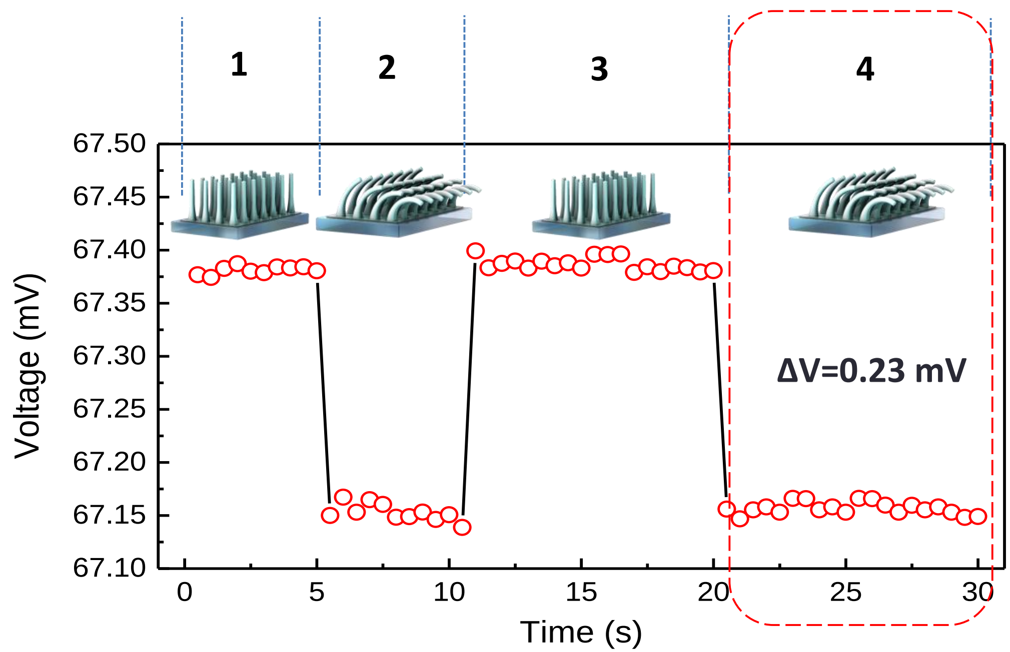
RESULTS

➢ Feel the Texture

- Texture detection with cilia sensor
- Polymer sheet with 200 µm deep grooves of 2 mm or 4 mm widths is moved horizontally across the cilia sensor
- Real time spectrum analyzer is used to detect the signal.

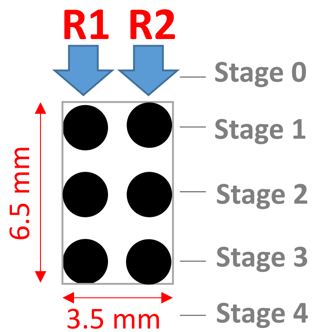
Moving object on the sensor

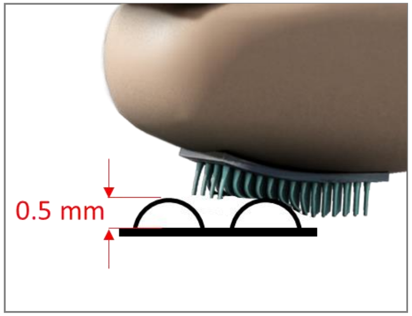


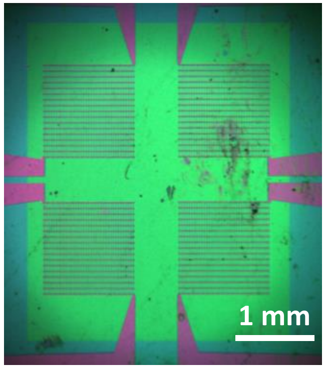


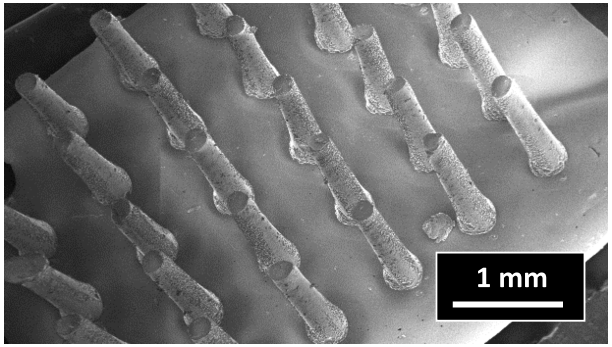
RESULTS

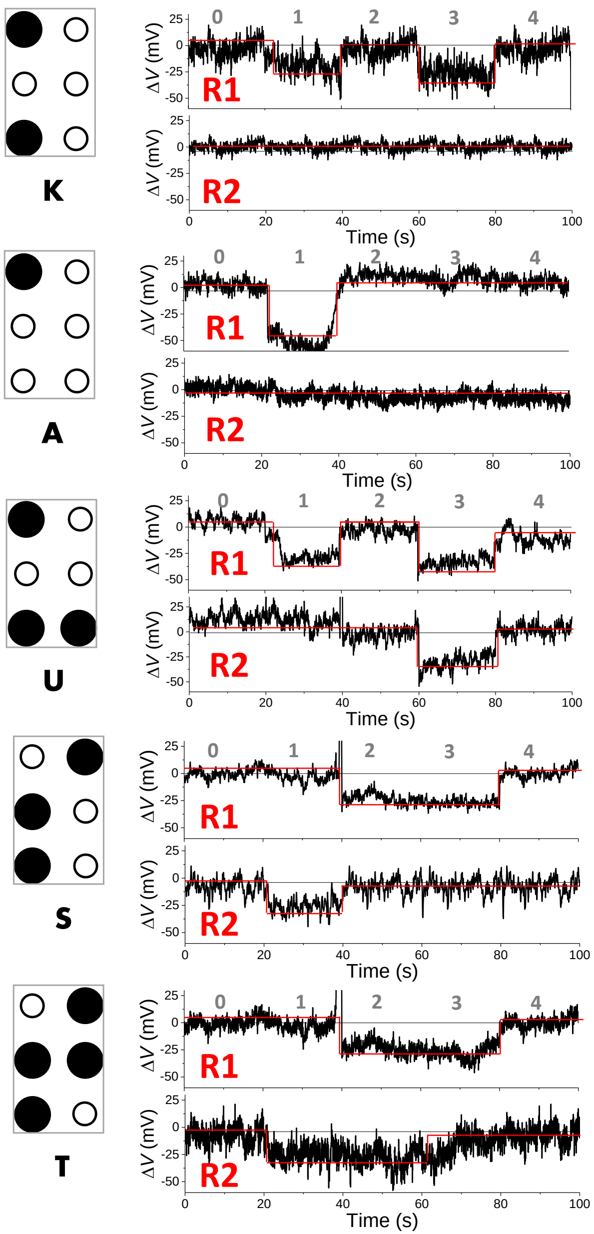
➢ Braille Characters Reading











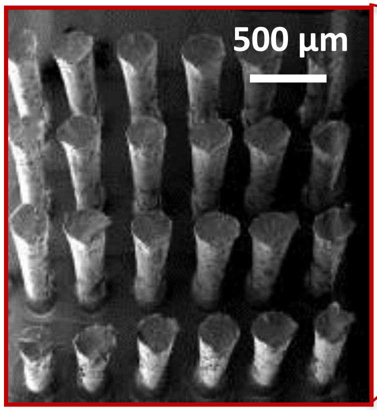
❖Sensor array is used to enable reading a Braille letter in 3 steps.

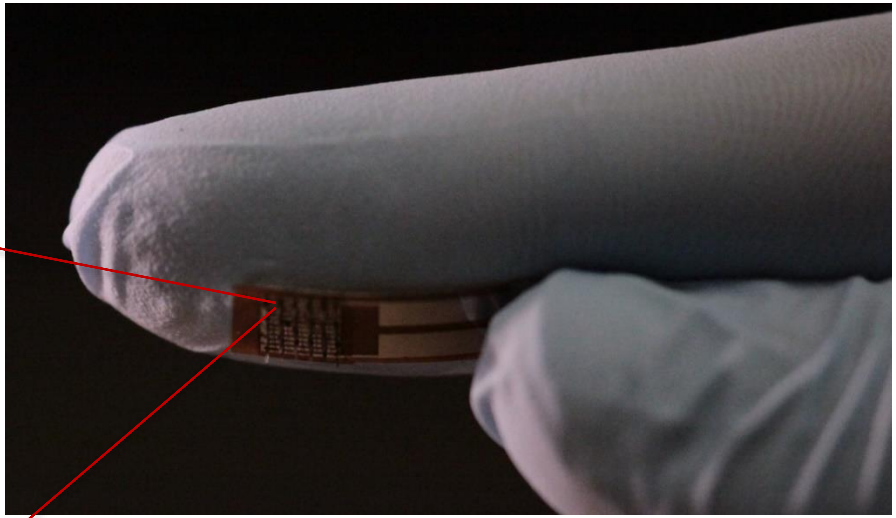
❖4 sensing elements, separated by 0.8 mm. Each sensor is 1.25×1.25 mm^2, and consists of 9 cilia: 200 µm in diameter 1 mm long.

A. Alfadhel, M. Khan, Susana Cardoso, J. Kosel, "Magnetic Tactile Sensor for Braille Reading," *IEEE Sensors*, 2016.

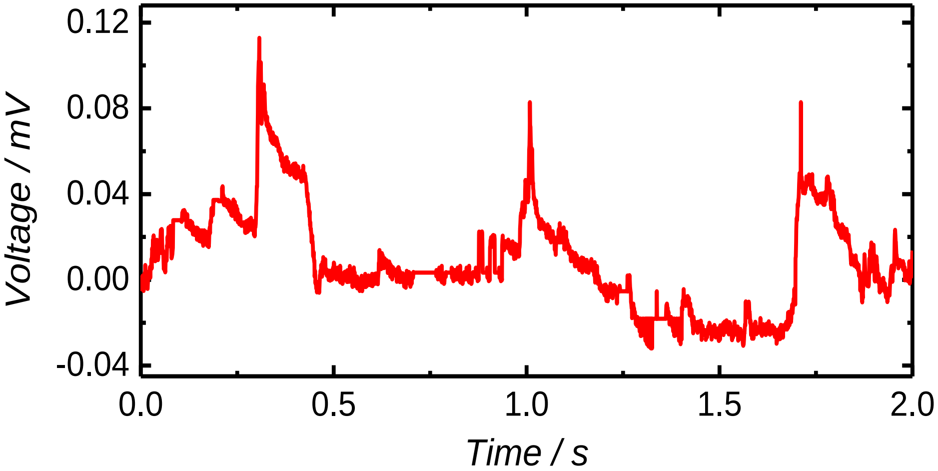
RESULTS

- **Go Flexible**
  Sensors fabricated on flexible Kapton substrate



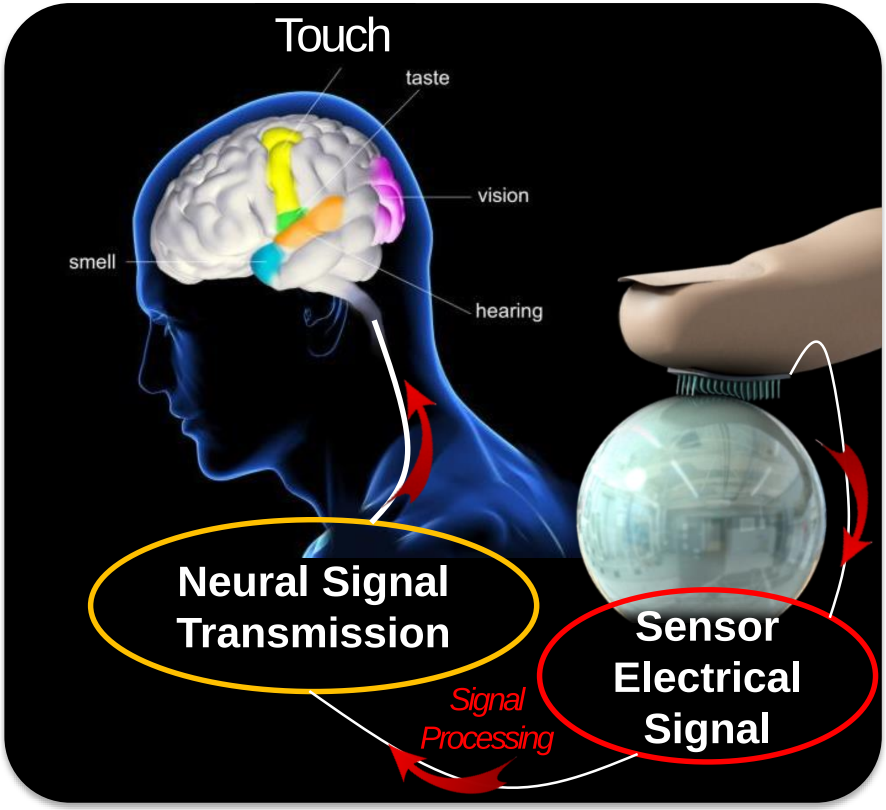


- **Heart Rate Monitoring**



A. Alfadhel, J. Kosel, "Magnetic Nanocomposite Cilia Tactile Sensor," *Advanced Materials*, 27, pp. 7888, 2015.

FUTURE APPLICATIONS



Robotics or Prosthetics

Array of tactile sensors to introduce the "feeling" aspect to robotic hands or prosthetic arms

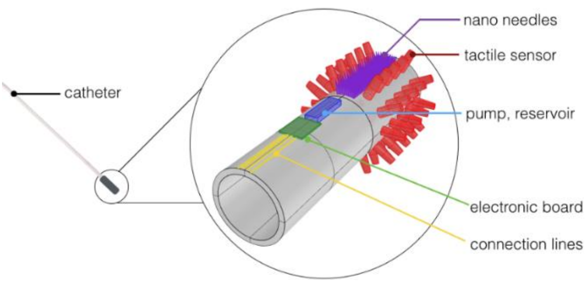
Minimally Invasive Surgical Tools

Smart approach for smart medical tools

SMART TWEEZER

Force sensor at the tip of the tweezer

CATHETER TIP PRESSURE SENSOR



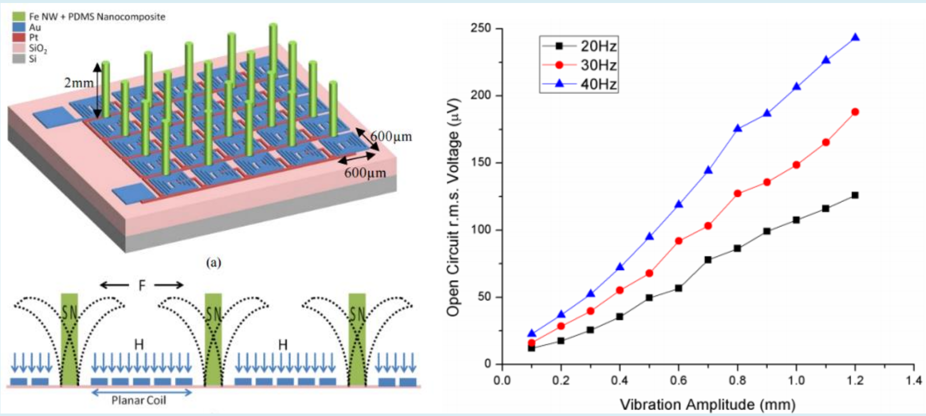
CONCLUSION

- **Developed highly elastic and permanent magnetic artificial cilia**
  - No external magnetic field is required
  - Chemical resistant
  - Simple fabrication process
  - Biocompatible materials
- **The sensing concept offers**
  - High resolution / sensitivity
  - Very low power consumption
  - Easily adjustable performance
- **Multisensory capabilities**
  - Shear and vertical force sensing
  - Operates in air and water
  - Touch / Texture / Flow / Movement of an object

OTHER APPLICATIONS FOR MAGNETIC NANOCOMPOSITES

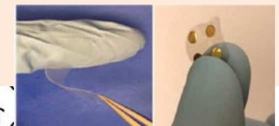
Nanocomposite Energy Harvester

Fe NWs + PDMS Nanocomposite Cilia on Planar Coils

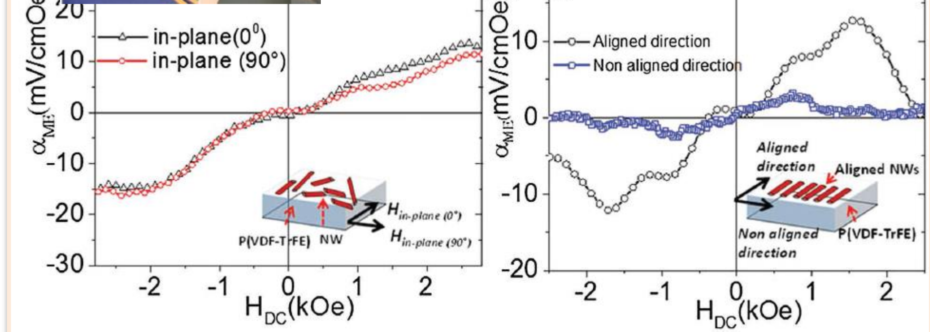


M. A. Khan, **A. Alfadhel** J. Kosel, "Magnetic Nanocomposite Cilia Energy Harvester," in *IEEE Transactions on Magnetics*. **DOI**: 10.1109/TMAG.2016.2527733

Magnetoelectric Nanocomposite



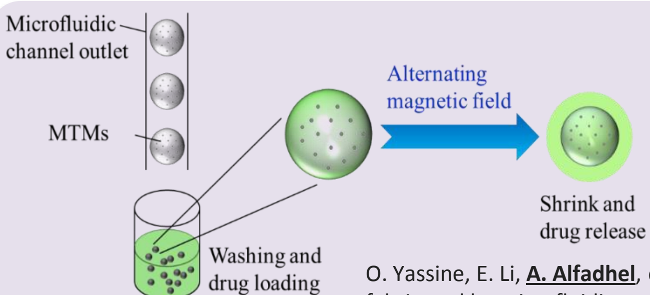
Galfenol NWs + PVDF Nanocomposite

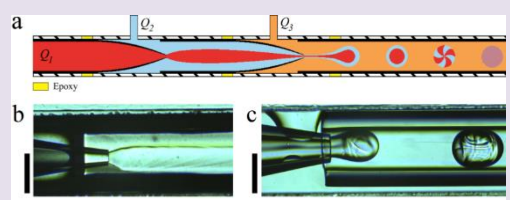


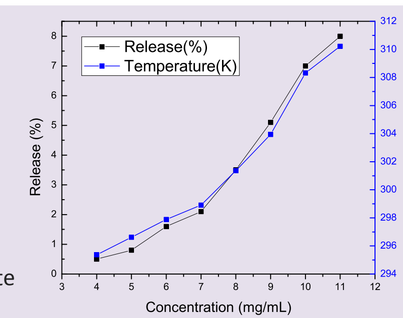
M. Alnassar, Y. Ivanov, and J. Kosel, "Flexible Magnetoelectric Nanocomposites with Tunable Properties," *Adv. Electron. Mater.*, pp. 1600081, 2016.

M. Alnassar, **A. Alfadhel**, Y. Ivanov, and J. Kosel, "Magnetoelectric polymer nanocomposite for flexible electronics," *J. of App. Phys.*, 117, pp. 17D711, 2015.

Thermoresponsive Nanocomposite







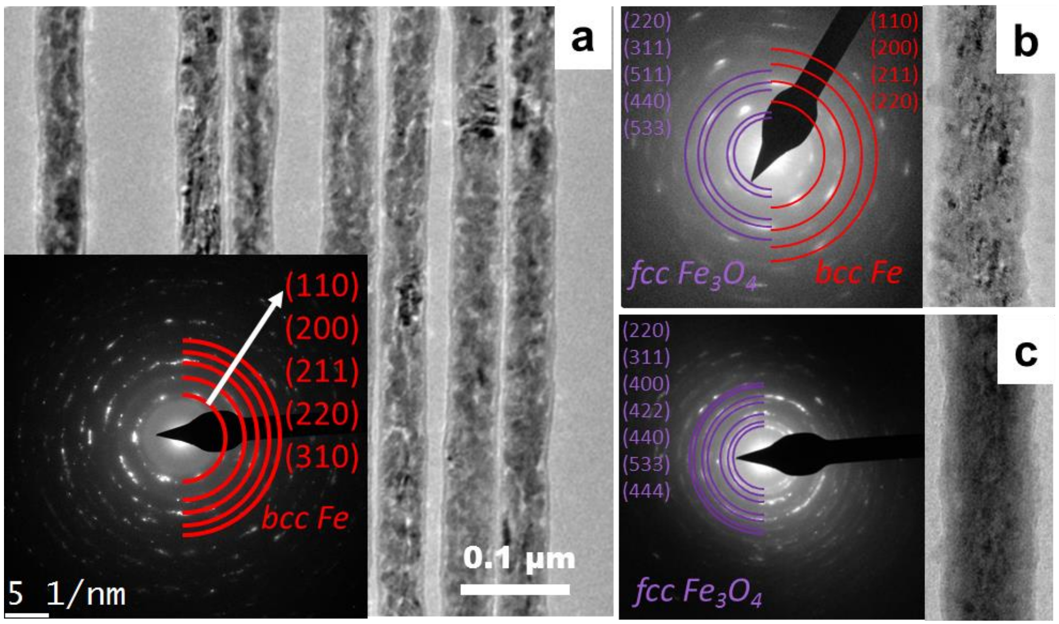
O. Yassine, E. Li, **A. Alfadhel**, et. al, "Magnetically triggered monodispersed nanocomposite fabricated by microfluidic approach for drug delivery," Int. J. of Polymer Science, 2016.

ACKNOWLEDGEMENTS

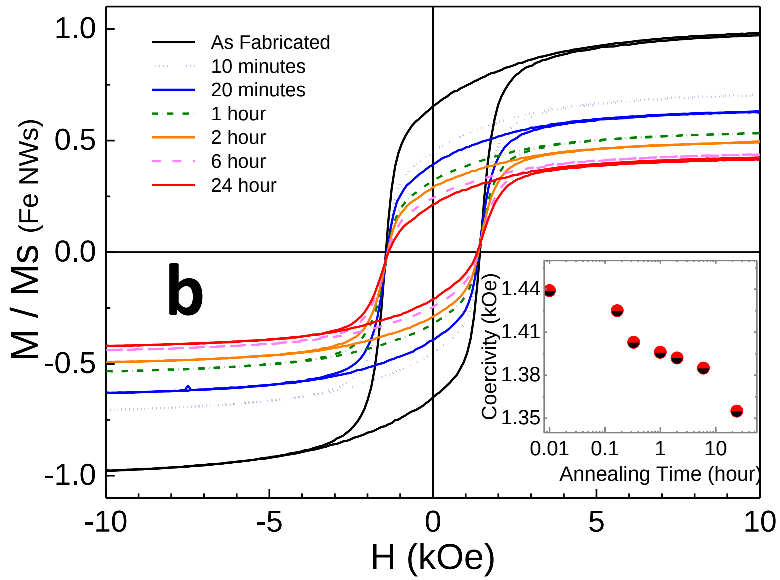
Thank you!

HARSH ENVIRONMENT

Corrosion Study – Bare Nanowires



Magnetization reduction of corroded nanowires



(a) Bright field transmission electron microscopy image and selected area diffraction pattern of polycrystalline Fe NWs.
(b) Fe-Fe_3O_4 core-shell NWs after 20 minutes of annealing at 150 ^{o}C.
(c) Fe_3O_4 NWs after 24 hours of annealing.

Y. Ivanov, **A. Alfadhel**, M. Alnassar, J. Perez, M. Vazquez, A. Chuvilin and J. Kosel, *Scientific Reports* **6**, Article number: 24189, 2016.