Applications to automation: sensors and communication

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Automation or automatic control, is the use of various control systems for operating equipment such as machinery, processes in factories, switching in telephone networks, steering and stabilization of ships, aircraft and other applications with minimal or reduced human intervention.

Automation has been achieved by various means including **mechanical, hydraulic, pneumatic, electrical, electronic and computers**. Complicated systems, such as modern factories, airplanes and ships typically use all these combined techniques.

Industrial automation in manufacturing is **the use of “intelligent” machines in factories so that manufacturing processes can be carried out with minimal human intervention**. It involves the application of various control systems to enable operating equipment to carry out on their own, with little human intervention, tasks that require speed, endurance and precision.

↓

More efficient use of energy, raw material and human resources.

Today’s sensor market offers thousands of sensor types (over 100,000 different types of sensors), for almost every measurable quantity, for a broad area of applications, and with a wide diversity in quality.

Challenges:

- explore new technologies,
- investigate new principles and structures,

aiming at reducing the size and price, at the same or even better performance.

VERY IMPORTANT!

The sensor electronics can limit the performance, cost, and range of aplicability.

The careful design of sensor electronics can allow the optimal extraction of information from a noisy signal.

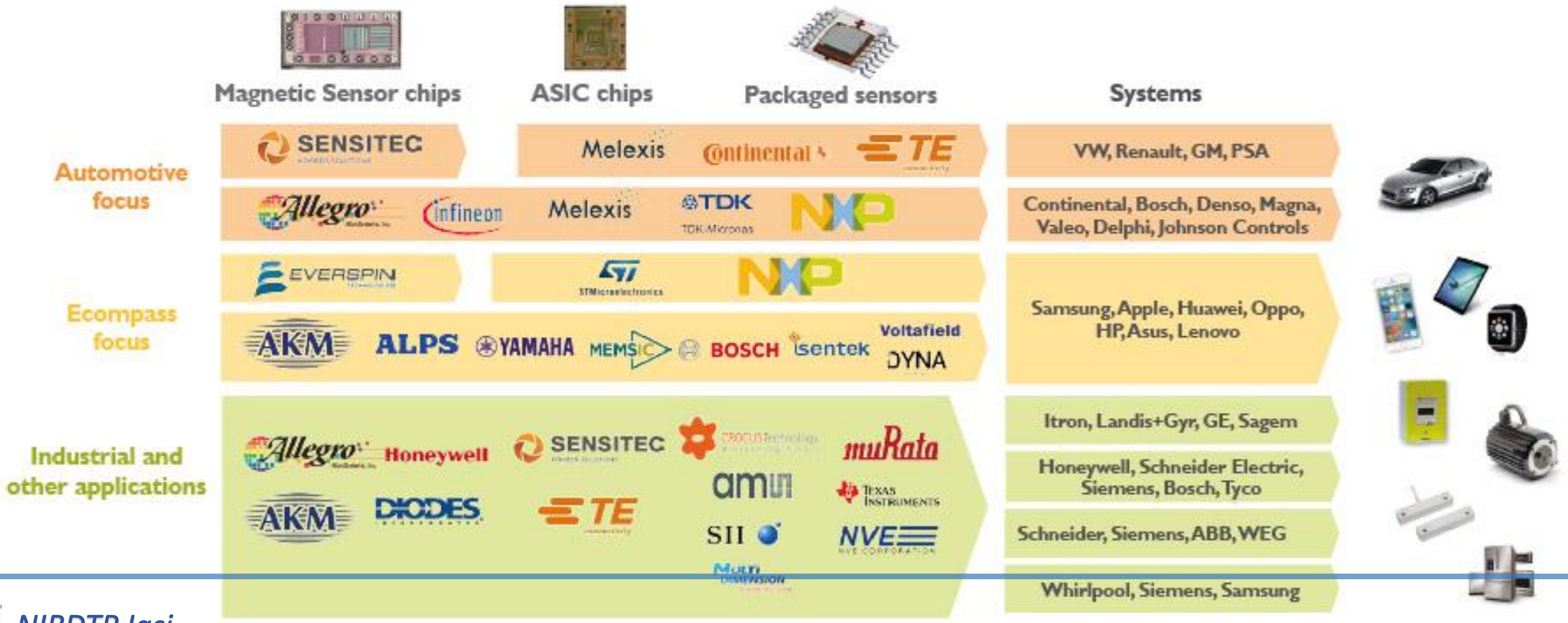
Most sensors do not directly produce voltages, but rather act like passive devices (e.g., resistors), whose values change in response to external stimuli. In order to produce voltages suitable for input to microprocessors and their analog-to-digital converters, **the sensor must be „biased” and the output signal needs to be „amplified”.**

The magnetic sensor market is driven by Automotive and the Internet-of-Things (IoT) !!!

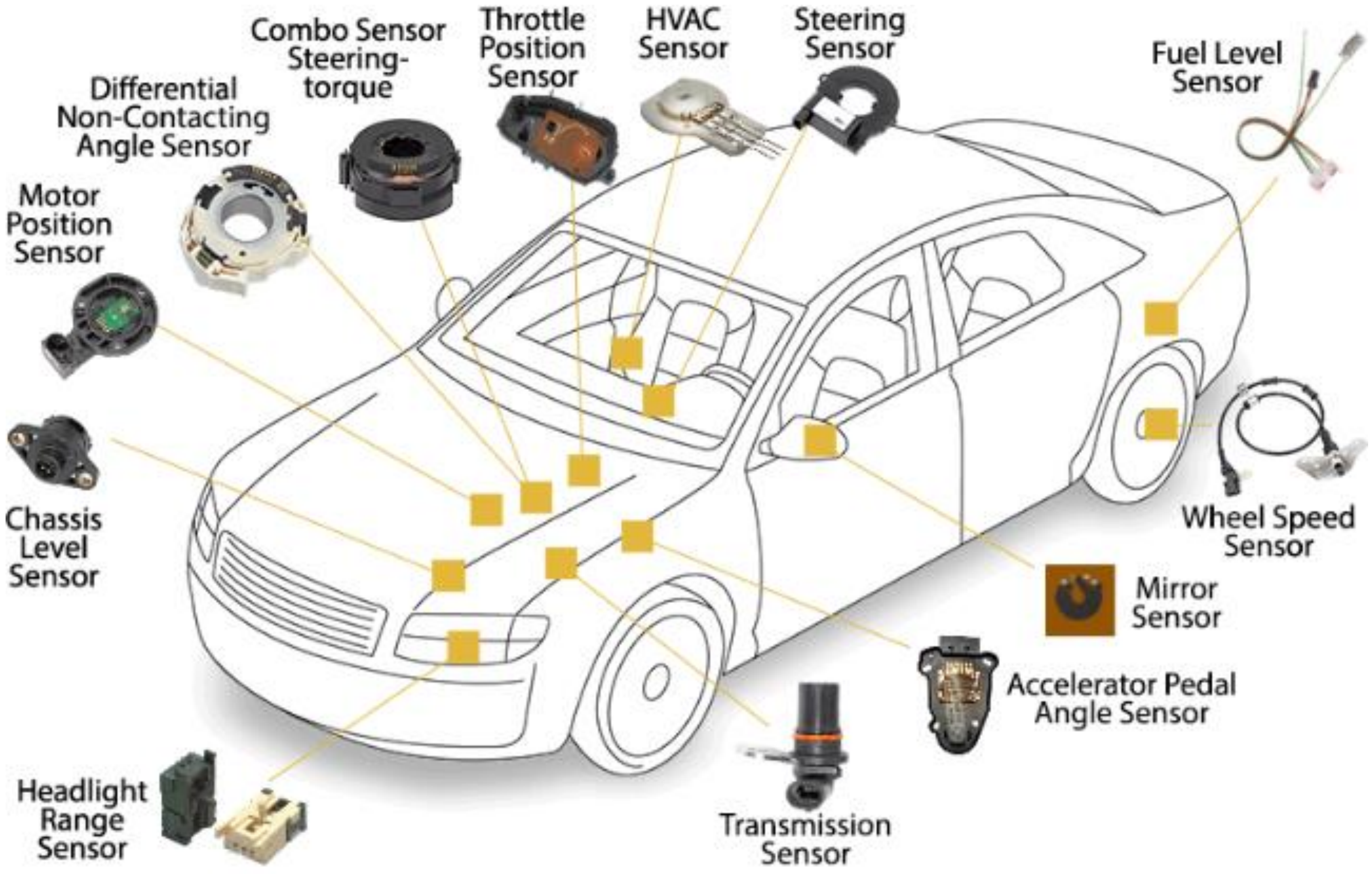
Magnetic sensor supply chain and key players*

(Source: *Magnetic Sensor Market and Technologies 2017 report, Yole Développement, November 2017*)

By far the biggest magnetic sensor business is automotive;
it accounts for more than 50% of the magnetic sensor market's $1.646B value.



*Non-exhaustive list of the magnetic sensor supply chain and its key players



Today, the average internal combustion engine (ICE) car uses 20 – 30 magnetic sensors, a number that rises to as many as 35 in hybrid cars, which require additional current sensors.

Magnetic sensors are used for position and speed sensing, switching, and current sensing, and have the advantage of being contactless and thus very robust. Magnetic sensors' already-significant contribution to car electrification will continue in the coming years in both powertrain and auxiliary brushless motors, and as reliability requirements increase for autonomous cars.

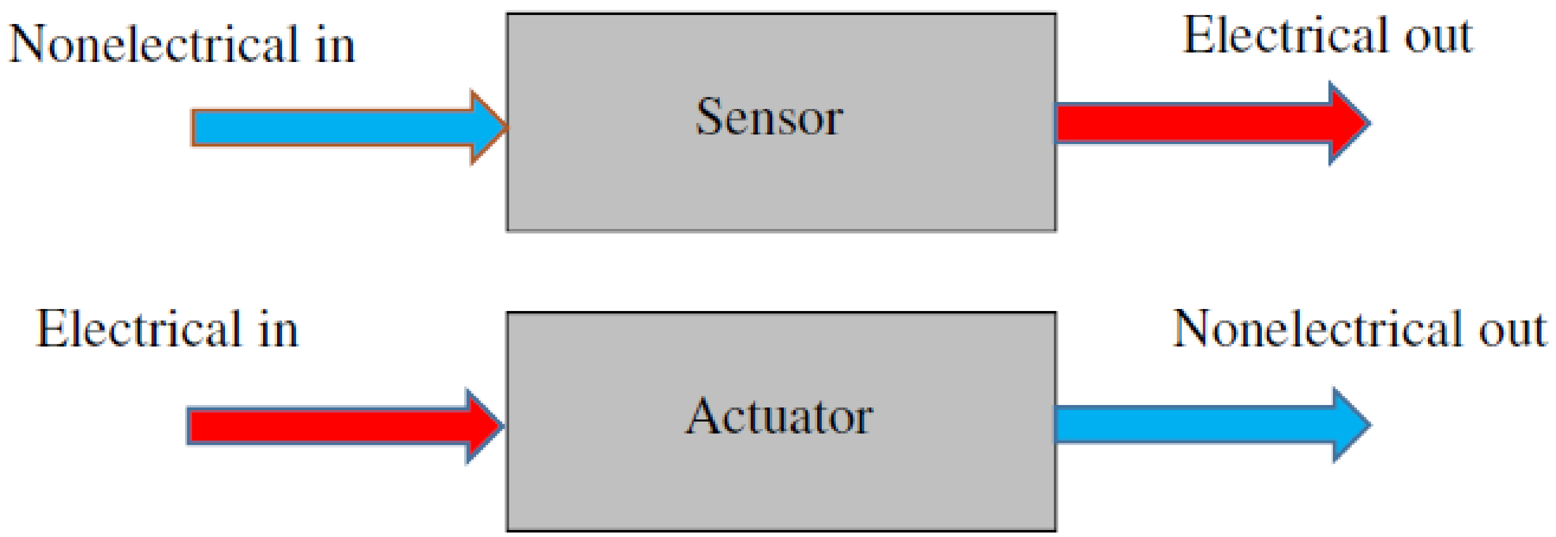
Attractive Opportunities in the Magnetic Sensor Market

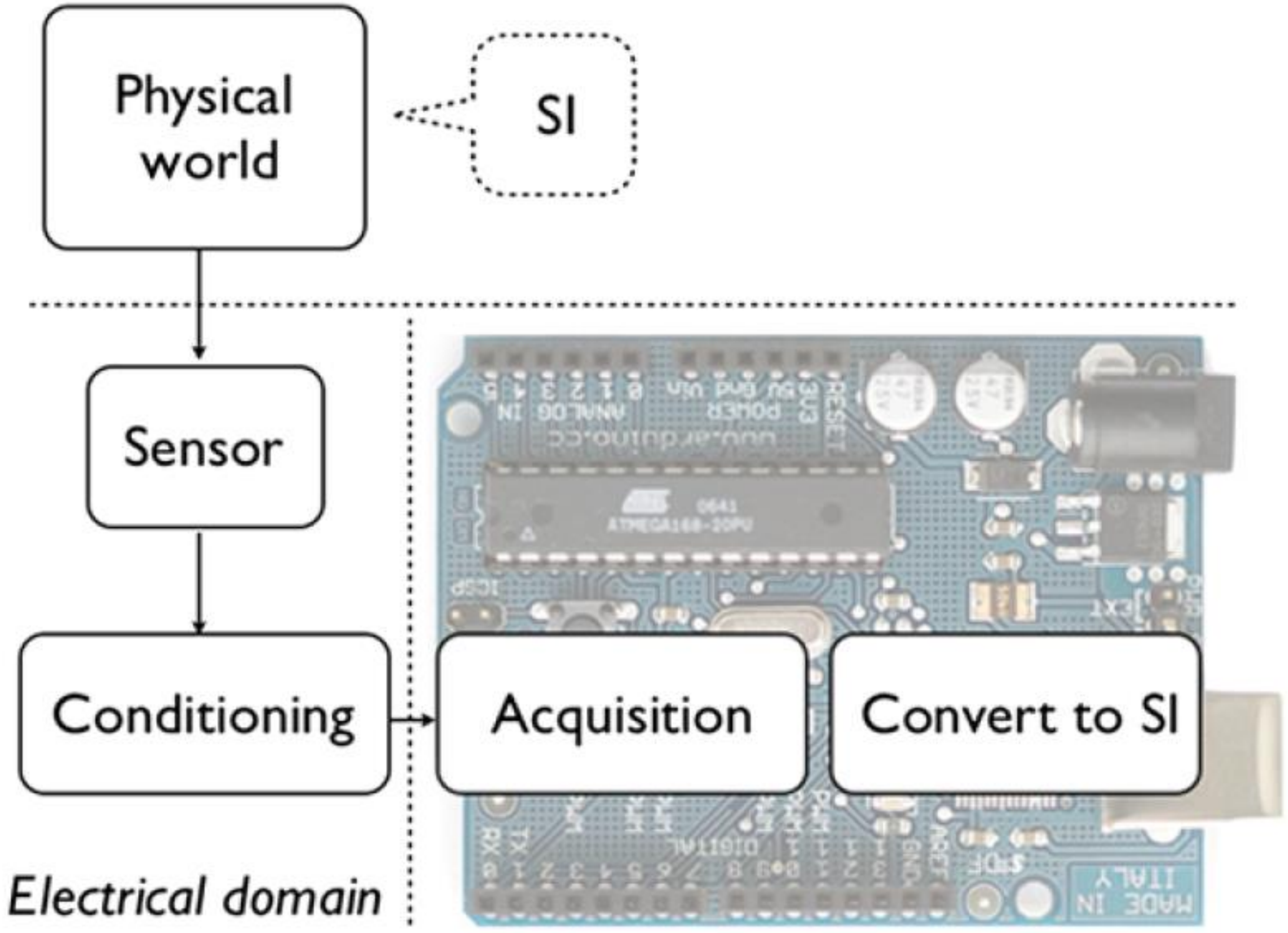
In 2019, Hall effect sensors held the largest share of the magnetic sensor market and is expected to continue to account for the largest share over the forecast period.

Sensor = a device that converts a physical phenomenon into an electrical signal, representing part of the interface between the physical world and the world of electrical devices, such as computers.

The other part of this interface is represented by **actuators**, which convert electrical signal into physical phenomena.

Transducer = convert one type of energy into another (includes both sensors and actuators).




Physical world
SI
Sensor
Conditioning
Acquisition
Convert to SI
Electrical domain

Reasons for the increasing interest in sensors are as follows:

1) **Reduced prices:** the price of sensors not only depends on the technology but also on production volume.
   Today, the price of a sensor runs from several ten thousands of euros for single pieces down to a few eurocents for a 100 million volume.
2) **Miniaturization:** the IC-compatible technology and progress in micromachining technology are responsible for this trend.
   Pressure sensors belong to the first candidates for realization in silicon (early 1960s). Micro-ElectroMechanical Systems (MEMS) are gradually taking over many traditionally designed mechanical sensors. Nowadays, solid-state sensors (in silicon or compatible technology) for almost every quantity are available, and there is still room for innovation in this area.
3) **Smart sensing:** the same technology allows the integration of signal processing and sensing functions on a single chip.
   Special technology permits the processing of both analogue and digital signals ("mixed signals"), resulting in sensor modules with (microprocessor compatible) digital output.

Sensor Performance Characteristics:

- **transfer function:** the relationship between physical input signal and electrical output signal;
- **sensitivity:** the derivative of the transfer function with respect to the physical signal;
- **span or dynamic range:** the range of input signals that may be converted to electrical signals by the sensor (or the range over which other performance characteristics described in the data sheets are expected to apply);
- **accuracy or uncertainty**: the largest expected error between actual and ideal output signal (**accuracy** is a qualitative term, while **uncertainty** is quantitative);
- **hysteresis:** the difference between the output value when the input stimulus is cycled up or down;
- **nonlinearity** (often called linearity): the maximum deviation from a linear transfer function over the specified dynamic range;
- **noise:** is generally distributed accross the frequency spectrum (white noise);
- **resolution:** the minimum detectable signal fluctuation;
- **bandwidth:** the frequency range between the lower and the upper cutoff frequencies.

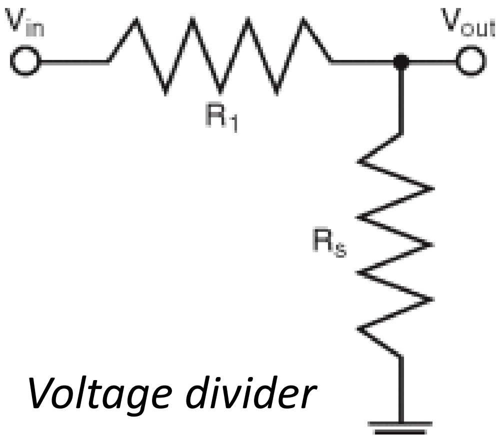
Types of Sensors:

- **Resistive sensor circuits**

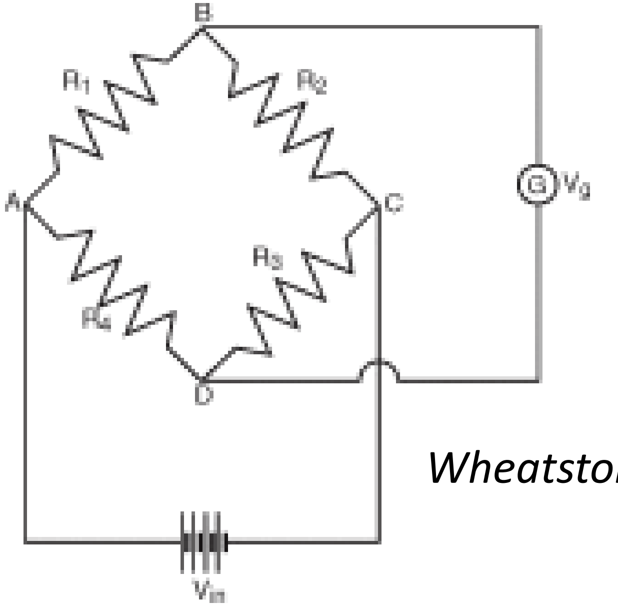
Limitations:

1) *Lead resistance* (the resistance of the wires leading from the resistive sensor element)

2) *Output impedance* (the characteristic resistance of the measuring network)



Voltage divider



Wheatstone bridge circuit.

- **Capacitance measuring circuits**

Limitations:

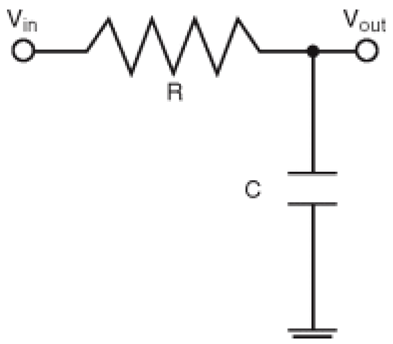
1) *Stray capacitance* (the finite capacitance of the wires that run from the sensor to the rest of the circuit)

- **Inductance measurement circuits** ($X_L = 2\pi fL$)

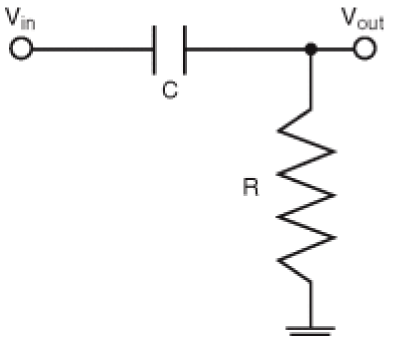
Filters:

- Low-pass

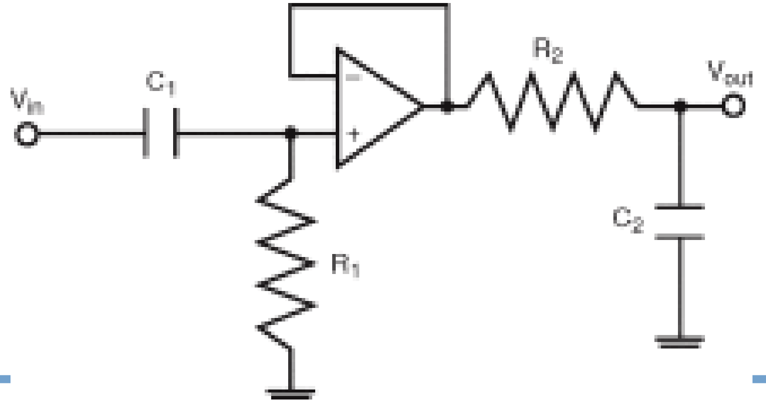
(the „resistance” of C decreases at high f,
so V_{out} decreases as the input frequency increases)



- High-pass



- Bandpass



Property	Sensor	Active/Passive	Output
Temperature	Thermocouple	Passive	Voltage
	Silicon	Active	Voltage/Current
	Resistance Temperature Detector (RTD)	Active	Resistance
	Thermister	Active	Resistance
Force/Pressure	Strain Gauge	Active	Reistance
	Piezoelectric	Passive	Voltage
Acceleration	Accelerometer	Active	Capacitance
Position	Linear variable differential transformer (LVDT)	Active	AC Voltage
Light intensity	Photodiode	Passive	Current

1) **Active sensors** require an external source of excitation (current or voltage).
2) **Passive** (or **self-generating**) **sensors** generate their own electrical output signal without requiring external voltages or currents.

Sensor’s Output Signals Classification:

1) **Analog Output** - The output of these sensors is an analog voltage that can be measured, then determine the desired physical parameter using the sensor’s transfer function. It may also be capacitive or resistive or anything analog.
2) **Digital Output** - The output of these sensors is digital data that can be read via serial or parallel communication buses (as UART, SPI, I2C, etc). The typical format for the data is demonstrated exactly in the sensor’s datasheet.

Sensor’s Physical Parameter Classification:

There are sensors to measure everything you can possibly think of. The most common ones are listed below:

Temperature Sensors	Chemical Sensors	Proximity Sensors	Touch Sensors
Light Sensors	Tilt Sensors	Metal Detectors	Cameras
Humidity Sensors	Vibration Sensors	Magnetic Sensors	Color Sensors
Current Sensors	Pressure Sensors	Fingerprint Sensors	GPS
Motor Speed Sensors	Bending Sensors	Passive Infrared Sensors (PIR)	Position Sensors
Lidar Sensors	Ultrasonic Sensors	Gyroscope Sensors	Accelerometer Sensors
Digital Compass Sensors (Magnetometers)	Sound Sensors (Mic.)	IR Sensors	Odometer Sensors

Classification based on electrical conversion principles (and sensor examples):

Type	Material property	Geometry (sensor examples)	Relative movement
Resistive	Resistivity (piezoresistor, LDR)	Relative length (potentiometer; metal strain gauge)	
Capacitive	Permittivity (fluid level sensor)	Relative electrode distance capacitive displacement (LVDC)	
Magnetic	Permeability (magnetoresistor)	Distance source-detector (magnetic displacement sensor)	Induction (magnetic velocity sensors)
Inductive		Inductance self-inductance mutual inductance reluctance (inductive displacement sensors, LVDT and resolver)	Induction (inductive velocity sensors)
Optical	Index of refraction absorptivity (fibre optic sensors)	Distance transmitter–receiver (intensity modulation sensors, interferometer and TOF sensor) transmissivity and reflectivity (optical encoder and tachometer)	Doppler frequency (Doppler velocimeter)
Acoustic	Acoustic impedance	Distance transmitter–receiver (TOF displacement sensors)	Doppler frequency (Doppler velocimeter)
Piezoelectric	Polarization (piezoelectric sensors)	Deformation (piezoelectric sensors)	

Resistive sensors

Resistive sensors

- Behave as an electric resistor whose resistance is affected by a particular physical quantity.
- The resistance may change according to a change in material properties, a modification of the geometry or a combination of these.
- Quantities that can easily be measured using resistive effects are:
  - ✓ temperature (thermistors and metal thermometers),
  - ✓ light (LDR or light-dependent resistor),
  - ✓ deformation (piezoresistors), and
  - ✓ magnetic field strength (magnetoresistors).
- By a special construction or material choice, resistors can be made useful for sensing various quantities:
  - ✓ force,
  - ✓ torque,
  - ✓ pressure,
  - ✓ distance,
  - ✓ angle,
  - ✓ velocity, and
  - ✓ acceleration.

Electrical conductivity
(pure material property, that does not depend on shape or size of the device)

$$\sigma = \frac{1}{\rho} = \frac{J}{E}$$

J : current density J (A/m²)
E : electric field strength (V/m)

$$R = \frac{V}{I}$$

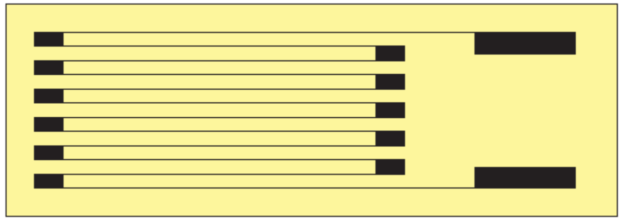
$$R = \rho \frac{l}{A}$$

distance sensors and angular displacement sensors → **potentiometric sensors**

- can also be used for the measurement of acceleration, force, pressure, and level

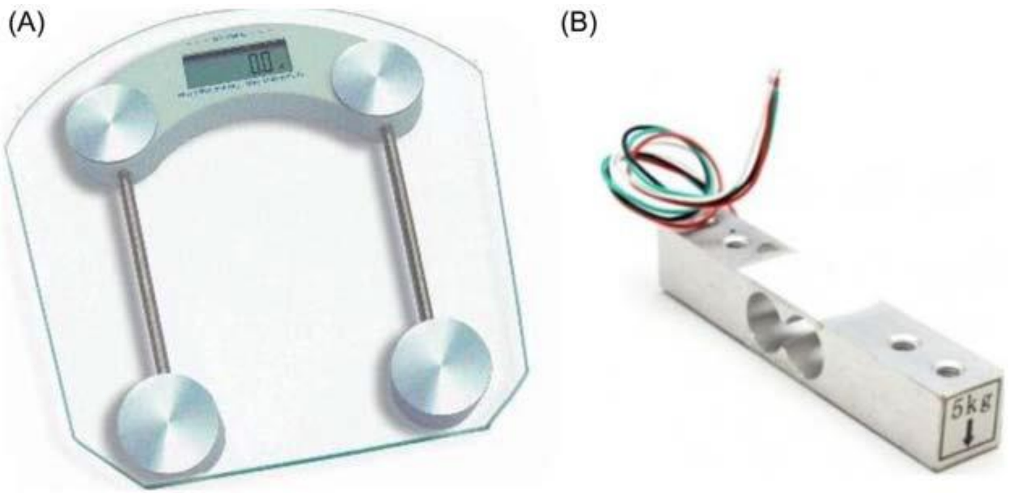
ρ is the property of interest in **piezoresistive, magnetoresistive, thermoresistive, and optoresistive sensors**

applied in force and pressure sensors → **strain gauges**

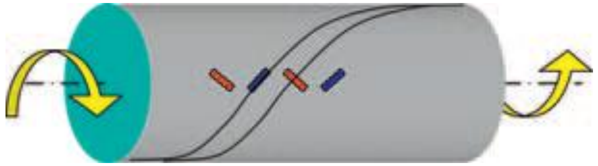


wire or film resistors deposited on a thin, flexible carrier material

<u>**Strain gauges**</u> - excellent devices for the measurement of force and torque

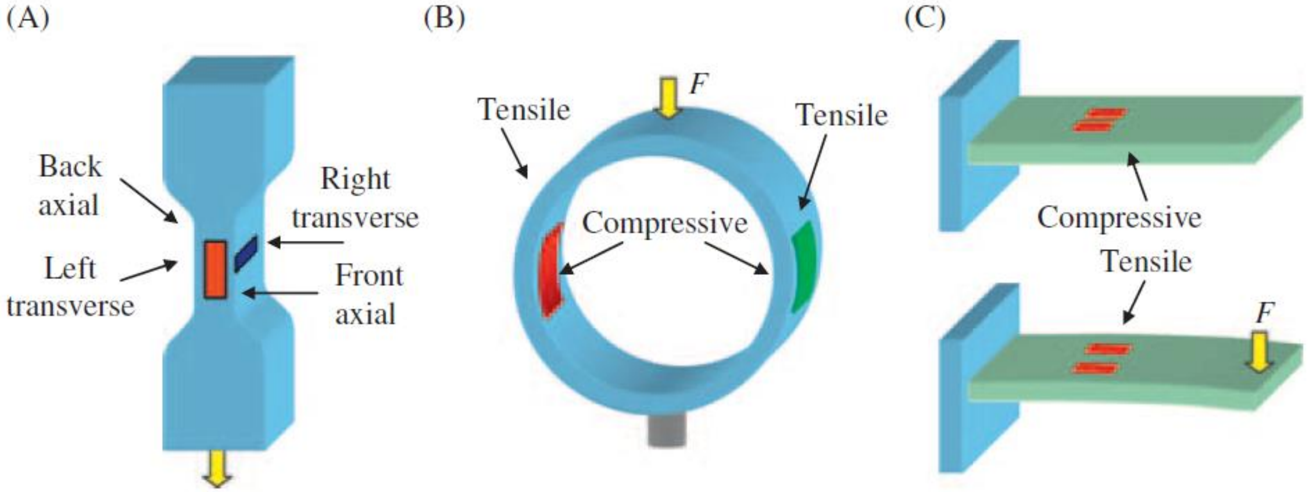


(A) *Bathroom scale using four-point load cells.*
(B) *Full-bridge yoke used in kitchen scales.*



Measurement of torque with strain gauges.

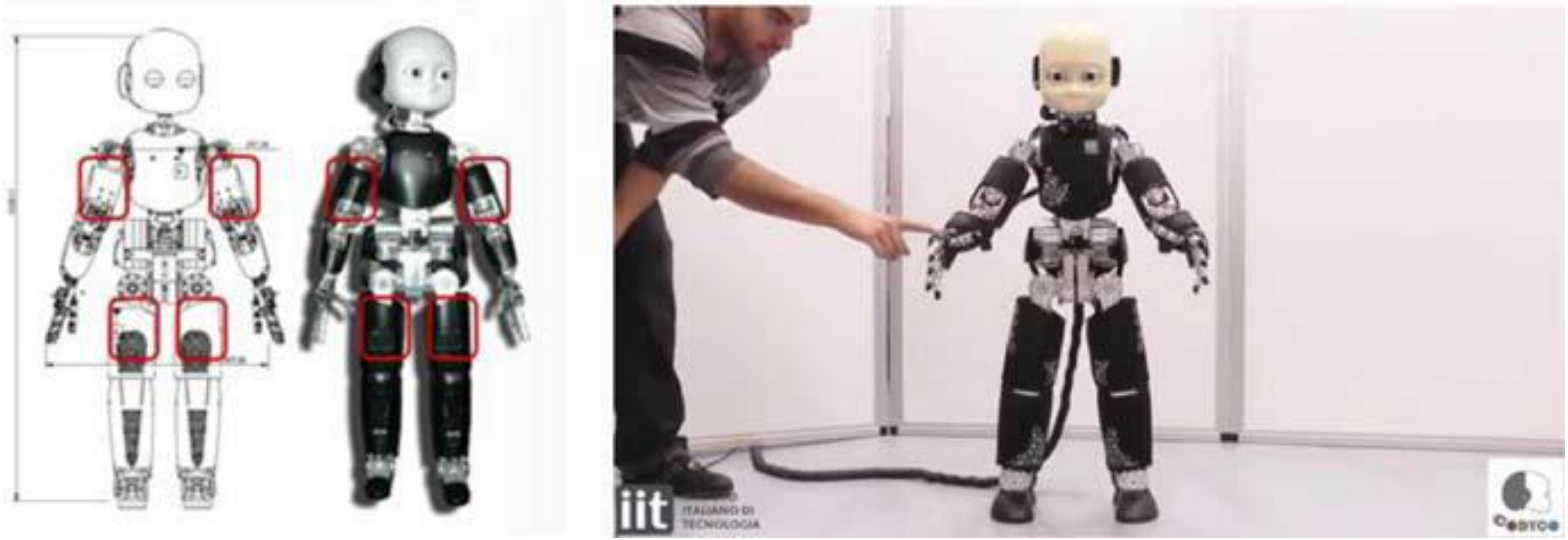
- can be mounted on almost any part of the construction that experiences a mechanical force or moment;
- robotic manipulators;
- humanoid robotics;



Different spring element designs: (A) column type, (B) yoke type, and (C) bending beam.

After P. Regtien & E. Dertien, ***Sensors for Mechatronics*** (2nd Edition), 2018, Elsevier.

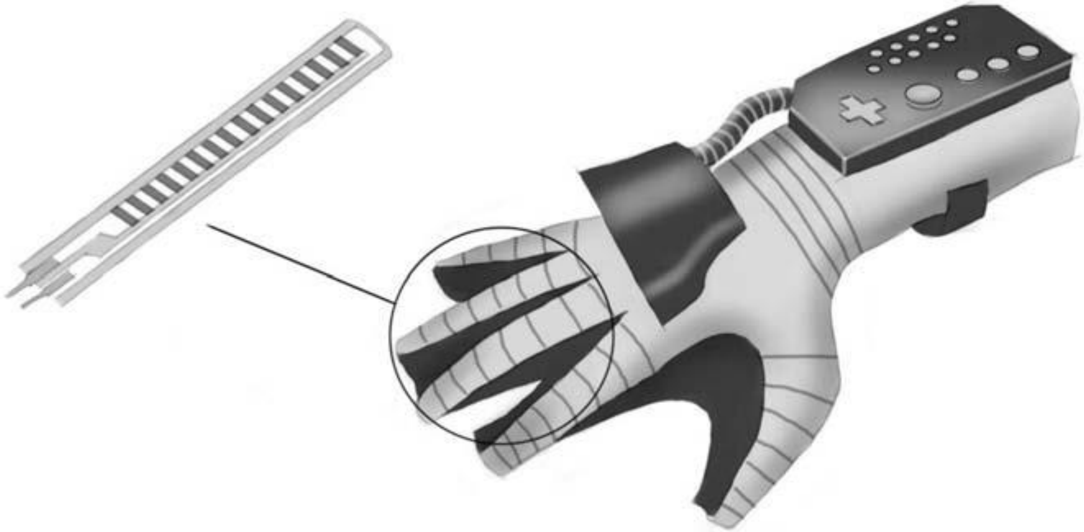
Strain gauges - excellent devices for the measurement of force and torque



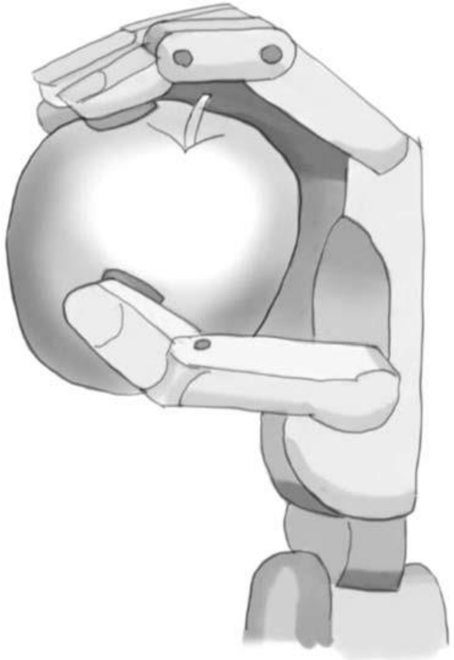
Picture of the iCub robot (http://www.icub.org/) showing locations of six-d.o.f. force/torque sensors necessary for balancing.

Piezoresistive sensors

- based on the change in electrical resistivity of a material when this is deformed;
- many materials show piezoresistivity, but only those with a high sensitivity are suitable to be applied in sensors, e.g. semiconducting materials (the most popular is silicon, especially because it can be integrated with the electronics), some elastomers (conductive particles – C, Ag, in a nonconducting elastic material);



Resistive bend sensor and application example in a glove (Nintendo glove).



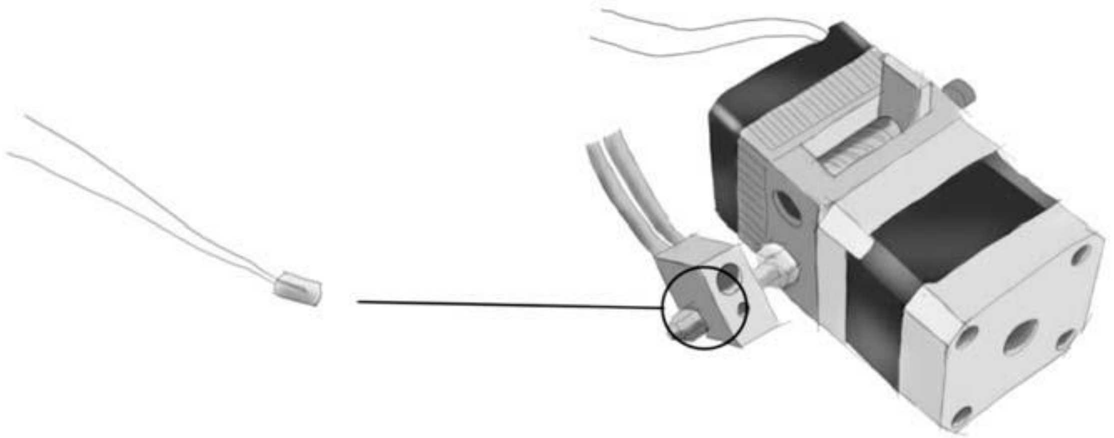
Robot hand using piezoresistive elastomers in the fingertip (tactile sensors).

Resistive touch screens are still used in industrial interface applications, but they are largely replaced by capacitive screens because the latter have a higher repeatability and support multitouch (no-calibration needed).

After P. Regtien & E. Dertien, ***Sensors for Mechatronics*** (2nd Edition), 2018, Elsevier.

Thermoresistive sensors

- The temperature coefficient of the resistivity is used to construct temperature sensors.
- Both metals and semiconductors are applied. They are called (metal) resistance thermometers (Pt the most used) ($-200^0C < T < 1000^0C$) and thermistors ($-270^0C < T < 350^0C$), respectively.
- Thermistors are based on ceramics (sintered oxides from the iron group, e.g., Cr, Mn, Ni, Co, Fe, doped with elements of different valence to obtain a lower resistivity, giving them semiconductor properties).
- Their sensitivity is much larger than that of metal resistance thermometers.
- Furthermore, the size of thermistors can be very small, so that they are applicable for temperature measurements in or on small objects.
- Compared to metal resistance thermometers, a thermistor is less stable in time and shows a much larger nonlinearity.



Generic 3D printer extruder and a 100 kΩ thermistor.

After P. Regtien & E. Dertien, ***Sensors for Mechatronics*** (2nd Edition), 2018, Elsevier.

Optoresistive sensors

- The resistivity of some materials, for instance CdS and CdSe, depends on the intensity of incident light. This is called the photoresistive effect.
- A photoresistor is also known as a light-dependent resistor (LDR) or photo-conductive cell.
- Apparently below 400 nm and above 850 nm the LDR is not sensitive. The spectral sensitivity of this material matches rather well that of the human eye.
- For other wavelengths, other materials are used: in the near-IR region (1-3 µm) PbS and PbSe, and in the medium and far IR (up to1000 µm), InSb, InAs, and many other alloys.
- LDRs are used in situations where accuracy is not an important issue (dark-light detection only), for example in alarm systems, in the exposure-meter circuit of automatic cameras, and in detectors for switching streetlights on and off.
- The simplicity of use and convenient interfacing (using a voltage divider) make the LDR the standard device for getting started with (resistive) sensors in embedded systems.

Capacitive sensors

Capacitive sensors

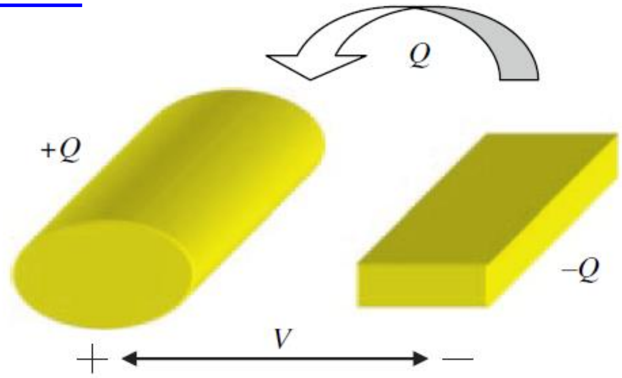
+ Capacitive sensors for displacement and force measurements have a number of advantages.
+ A capacitor consists of a pair of conductors; since no other materials are involved, capacitive sensors are very robust and stable, and applicable at high temperatures and in harsh environments.
+ Suitable for applications with high demands (for instance extreme temperatures).
+ The dimensions of capacitive sensors may vary from extremely small (in MEMS) up to very large (several m).
+ Highly linear response.
+ The measurement range of capacitive sensors can be extended almost without limit, while maintaining the intrinsic accuracy.
+ Excellent resolution because of the analog nature of the capacitive principle.
+ Furthermore, extremely small capacitance changes (down to 1 fF) can be measured with simple interface circuits.
+ Finally, stray capacitances and other capacitances due to wiring and amplifiers can easily be eliminated using guarding, virtual grounding, and proper interfacing.

- The capacitance value changes with variation in the geometry.

Capacitive sensors

$$V = \frac{Q}{C}$$

$$C = \varepsilon \cdot \frac{A}{d}$$

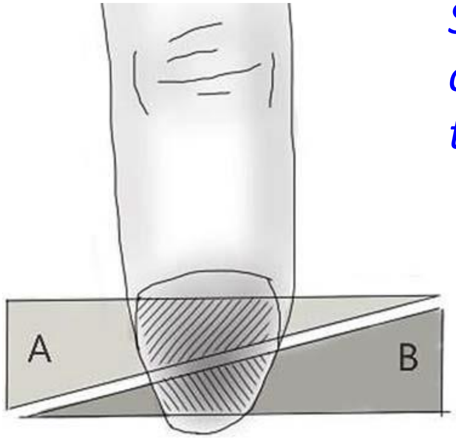


C : capacitance (or capacity)
Q : the charge on the conductor
V : the potential
ε : permittivity
A : surface area of the conductors
d : distance between the conductors

Audio player with capacitive input device.

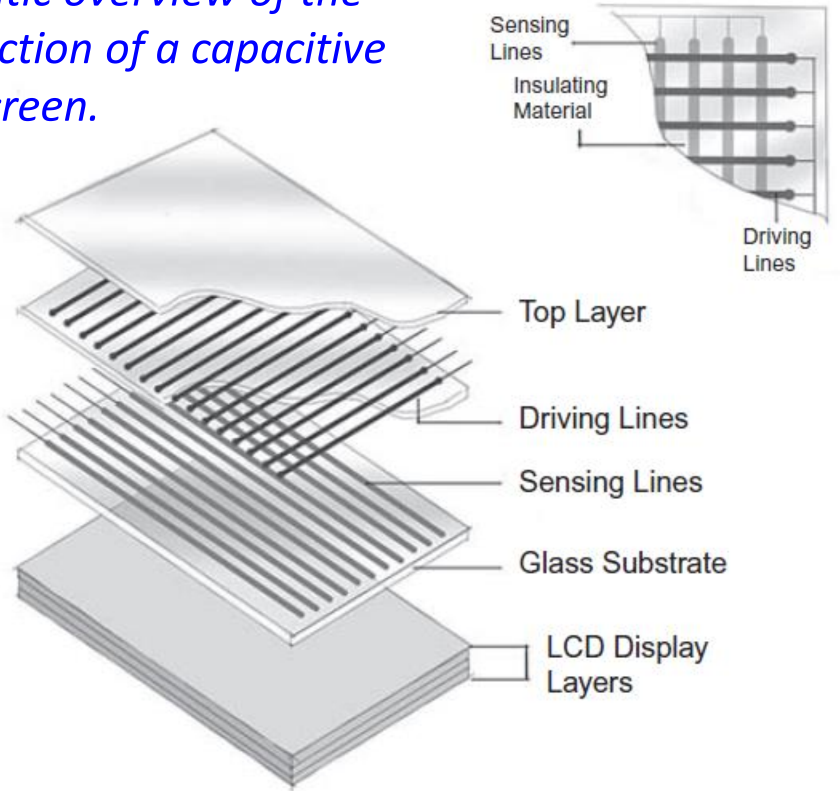
Applications:

- measurement of tire strains;
- on-line weighing of cars;
- measure liquid level in a tank;
- detect water drops on a windscreen (a rain sensor);
- detect the presence or passage of persons;
- detect the presence of a person on a car seat;
- measure flow velocity of a substance moving through a pipe;
- condenser or electret microphone.



Measuring the finger position by a capacitance difference.

Schematic overview of the construction of a capacitive touchscreen.



After P. Regtien & E. Dertien, ***Sensors for Mechatronics*** (2nd Edition), 2018, Elsevier.

Inductive and magnetic sensors

Inductive and magnetic sensors

- Inductive sensors employ variables and parameters like magnetic induction (B), magnetic flux (Φ), self-inductance (L), mutual inductance (M), or magnetic resistance (R_m).
- By a particular construction of the device, these quantities are made dependent on an applied displacement or force.
- The permeability of FM materials is strongly nonlinear: the nonlinearity of μ_r is employed, for instance, in fluxgate sensors; mumetal is often used for shielding system parts that are sensitive to magnetic fields.

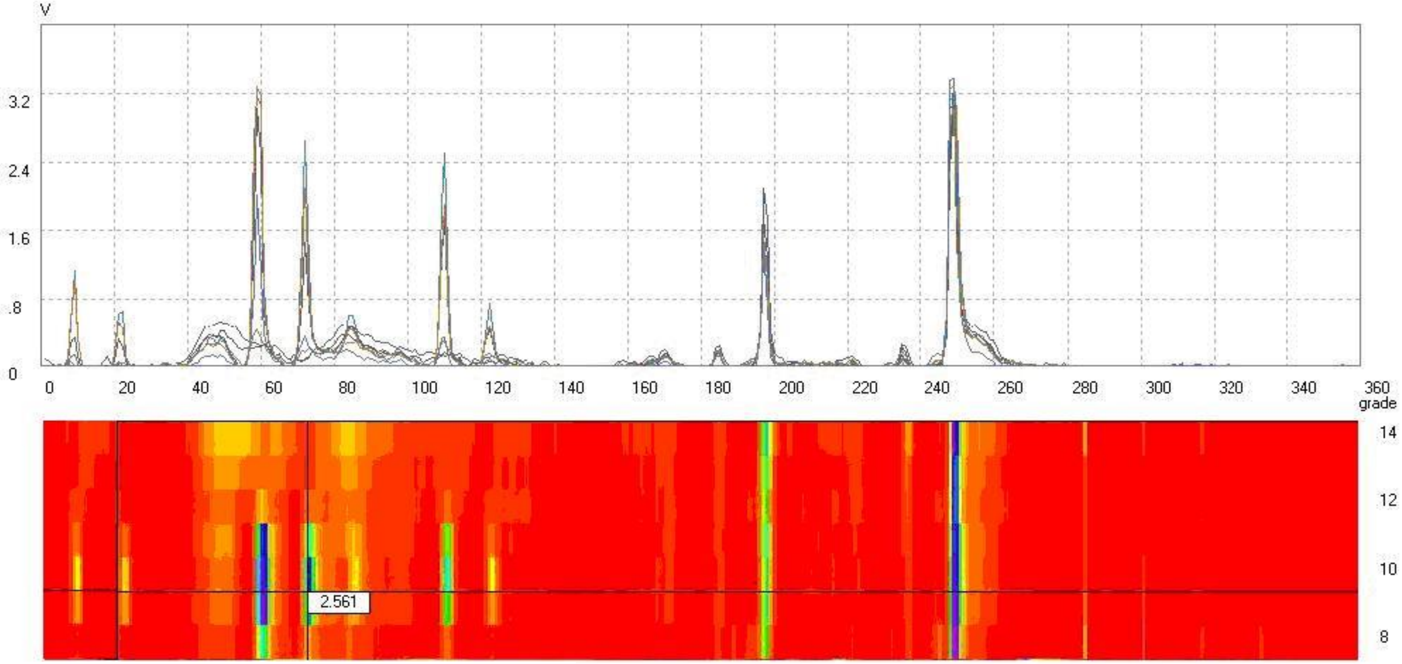
Permeability of various sensor materials

Material	μ_r (max)	B_s (T)
Vacuum	1	
Pure iron	5,000	2.2
Transformer steel	15,000	2.0
Mumetal ($Fe_{17}Ni_{56}Cu_5Cr_2$)	100,000	0.9
Supermalloy ($Fe_{16}Ni_{79}Mo_5$)	1,000,000	0.8

NDT Sensor

- a magneto-inductive sensor;
- the sensor consists of a very thin coil having a high permeability core made of nearly zero magnetostrictive CoFeSiB amorphous wire, which exhibits very high sensitivity and is able to detect both uniform magnetic and localized gradient fields;
- the inductance of the sensing coil feed with an AC signal having a frequency of 150 kHz is changing dramatically with the applied magnetic field.
- The device is simple, very sensitive (1 V/Oe and resolution better than 6×10^{-4} Oe), has a small size, it is versatile, inexpensive and sufficiently robust to meet the demands of the industry.

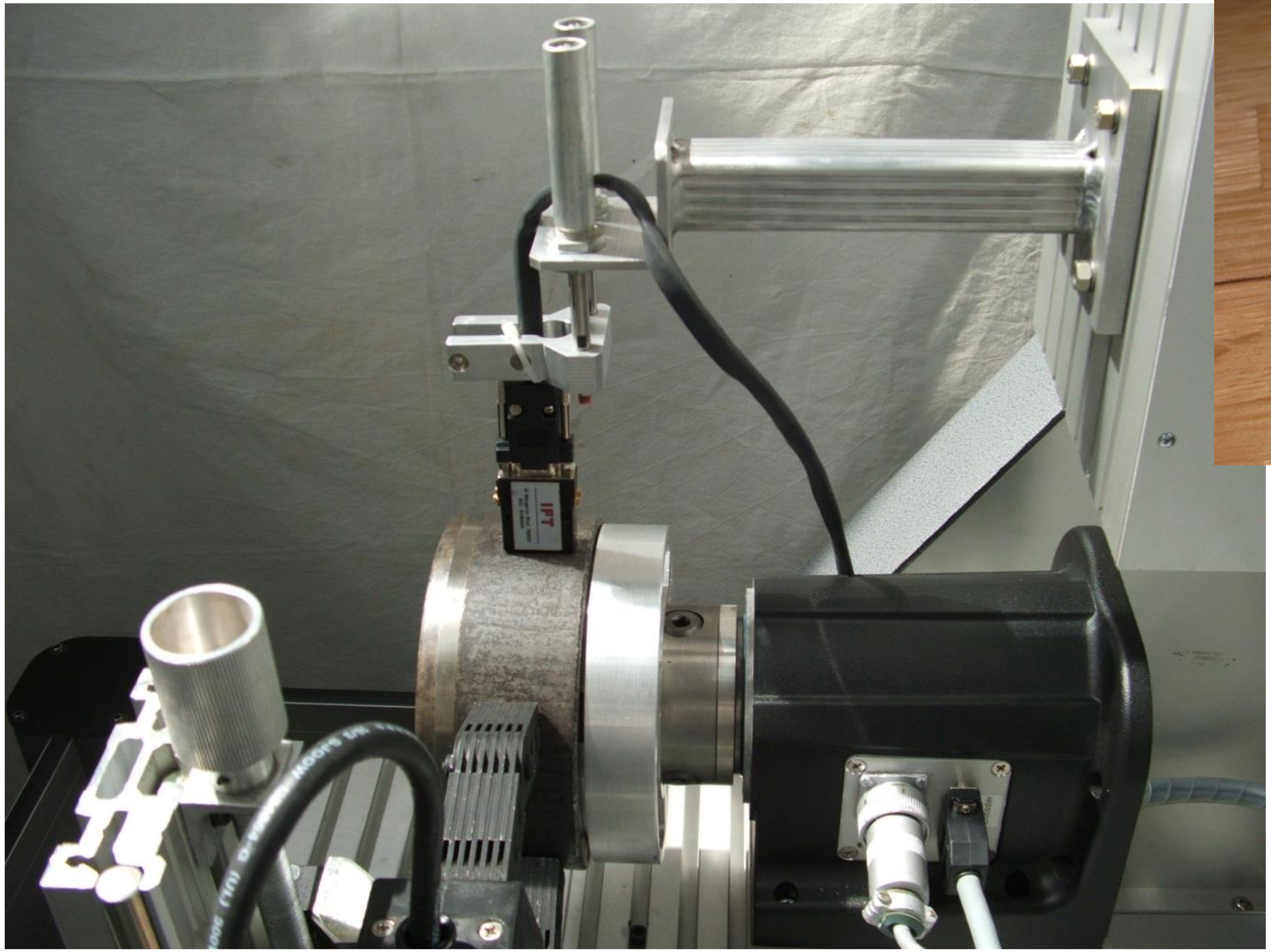
Artificial defects made by electric spark erosion machining for calibration of the sensor

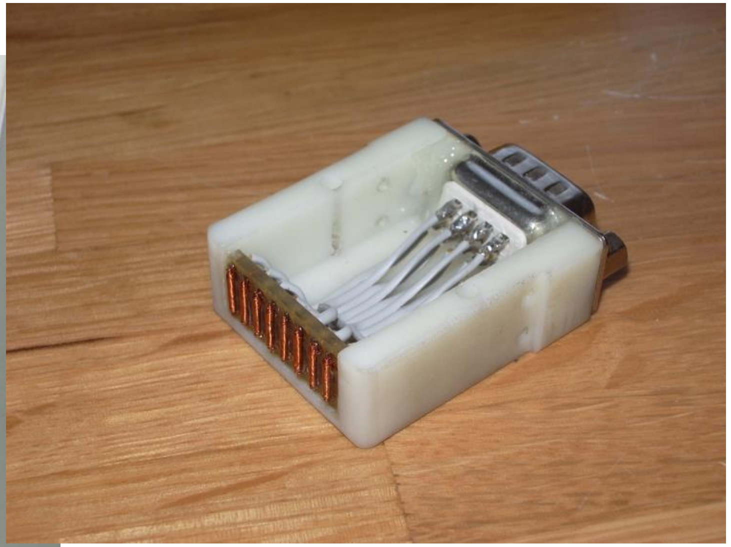


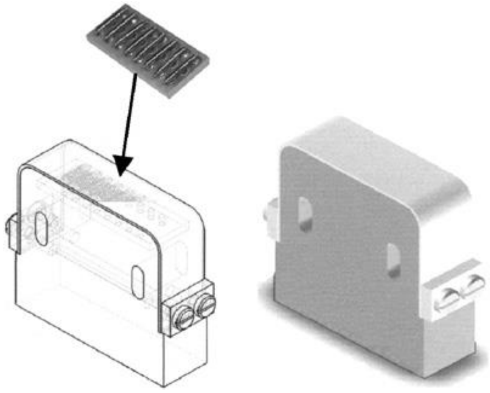
Output signal of the sensor for a complete rotation of the calibration specimen

M. Țibu, H. Chiriac, JMMM 320 (2008) e939

NDT Sensor

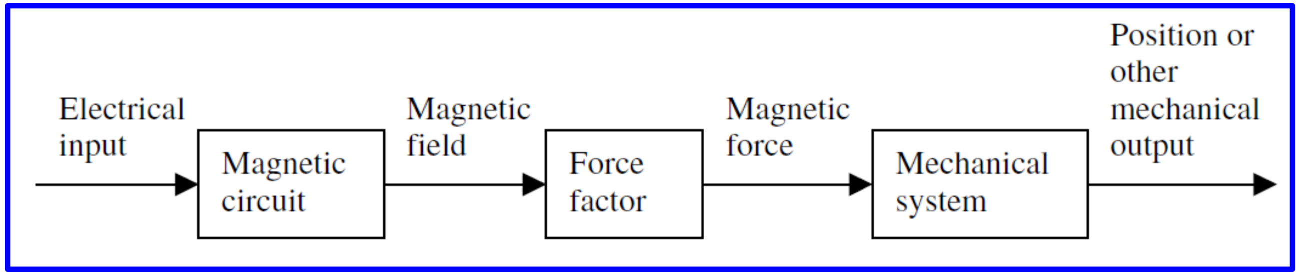






Sensor prototype.

- Magnetic sensors and actuators use magnetic field to produce and sense motion.
- Both magnetic actuators and magnetic sensors are energy conversion devices.

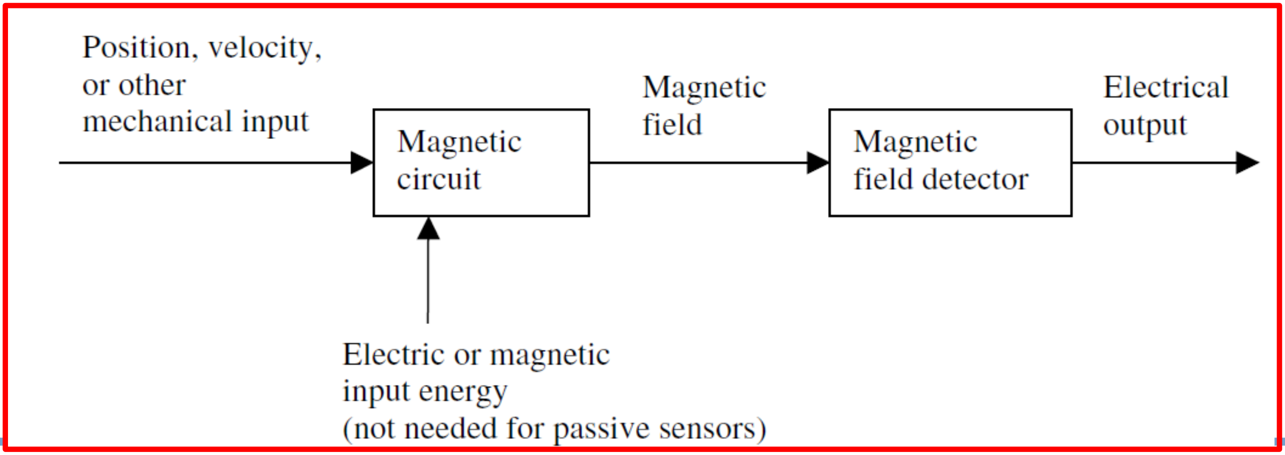


Magnetic actuators:

- Electrohydraulic valves in airplanes, tractors, robots, automobiles, and other mobile or stationary equipment
- Fuel injectors in engines of automobiles, trucks, and locomotives
- Biomedical prosthesis devices for artificial hearts, limbs, ears, and other organs
- Head positioners for computer disk drives
- Loudspeakers
- Contactors, circuit breakers, and relays to control electric motors and other equipment
- Switchgear and relays for electric power transmission and distribution

Magnetic sensors:

- Proximity sensors to determine presence and location of conducting objects for factory automation, bomb or weapon detection, and petroleum exploration
- Microphones that sense air motion (sound waves)
- Linear variable-differential transformers to determine object position
- Velocity sensors for antilock brakes and stability control in automobiles
- Hall effect position or velocity sensors



Magnetic field sensors (measure the magnetic field strength or magnetic induction)

- coil sensors,
- Hall sensors,
- fluxgate sensors,
- magnetoresistive sensors,
- magnetostrictive sensors,
- SQUID sensors (based on superconducting loops containing Josephson junctions; very sensitive - are sensitive enough to measure fields as low as 5×10^{-14} T; operates at cryogenic temperature and are used mainly in medical applications and for material research),
- Giant Magnetoimpedance (GMI) sensors,
- … and so on.

Magnetic field sensors (measure the magnetic field strength or magnetic induction)

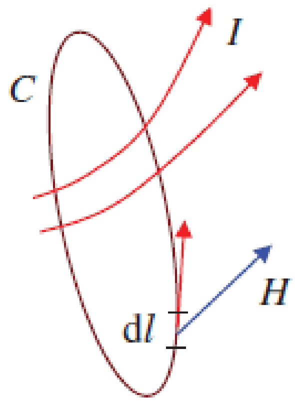
There is a wide range of magnitudes of magnetic fields in the universe:

- Biomagnetic fields (brain, heart): B ≈ 10 fT … 1 pT;
- Galactic magnetic field: B ≈ 0.25 nT;
- Interplanetary magnetic field at Earth orbit: B ≈ 4 … 10 nT;
- In the 1-m distance from the electrical household appliance: B ≈ 600 nT;
- Earth's magnetic field (magnetic south is near geographic north): B ≈ 60 μT;
- Electrical power machines and cables (in 10-m distance): B ≈ 0.1 … 10 mT;
- Permanent magnets at their surface: B ≈ 100 mT … 1T;
- Electromagnets: B ≈ 2T;
- NMR tomography (superconducting magnets): B ≈ 1.5T … 4T;
- Superconducting magnets for nuclear fusion: B ≈ 10T … 20T;
- Pulse fields by coils: B ≈ 60T … 100T;
- Surface of neutron stars: B ≈ 100 MT.

The magnetic field strength, H, generated by a flow of charged particles, is defined according to:

$$I = \oint_C H \cdot \mathrm{d}l$$

I : the current passing through a closed contour

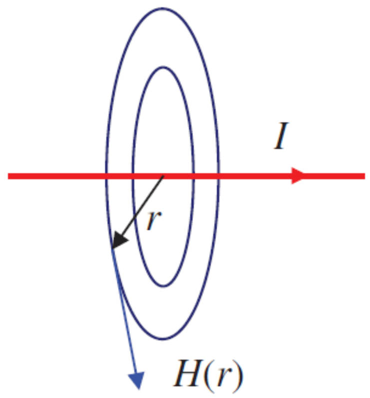


Magnetic field generated by current I.

A current I through a long, straight wire produces a magnetic field:

$$H = \frac{I}{2\pi r}$$

at a distance r from the wire.



Calculation of field strength due to a straight wire carrying a current I.

By increasing I, a stronger field is created.

A more efficient method is to make multiple turns of the wire. Each turn carries the current I, thus contributing to the field strength.

The self-inductance of a magnetic circuit with coupled flux, L, is found as follows:

$$L = \frac{n^2}{R_\mathrm{m}} = n^2 \cdot \frac{\mu A}{l}$$

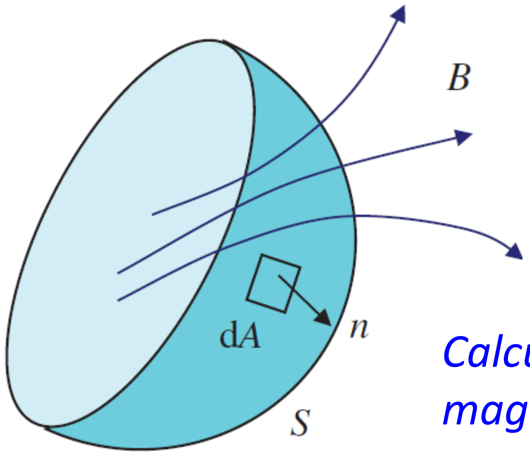
and is proportional to the square of the number of turns, n, and inversely proportional to the reluctance, R_m.

Coil sensors

The most straightforward method for the transduction from magnetic field to an electric voltage is a coil.

$$V_{\text{ind}} = -\frac{d\Phi}{dt}$$

$$\Phi = \iint_S B \cdot dA$$

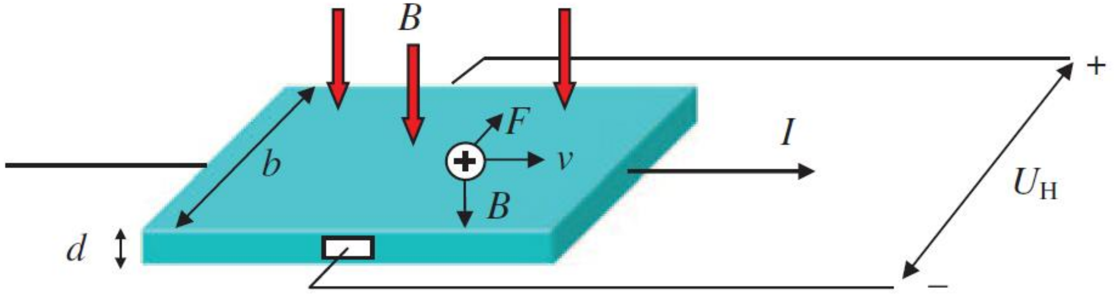


Calculation of magnetic flux.

AC fields can be measured in this way since the induced voltage is proportional to the rate of change in flux.

Static fields can nevertheless be measured, just by rotating the coil → **disadvantages of the method are movable parts**.

Hall plate sensors



The Hall plate is based on the magnetoresistive effect.

The Hall effect is caused by the Lorentz forces on moving charge carriers in a solid conductor or semiconductor, when placed in a magnetic field.

The force, *F*, on a particle with charge *q* and velocity *v* equals: $F_1 = q(v \times B)$

The direction of this force is perpendicular to both *B* and *v*. As a result, the flow of charges in the material is deflected and an electric field *E* is built up, perpendicular to both *I* and *B*.
The charge carriers experience an electric force, $F_e = qE$, that, in the steady state, counterbalances the Lorentz force: $F_e = F_1$.

Hence: $E = v \times \mathrm{B}$

The voltage across the Hall sensor becomes: $V = \frac{1}{nq} \cdot \frac{IB}{d} = R_H \cdot \frac{IB}{d}$, with *n* the particle density.

Hall coefficient (R_H)

Hall plate sensors

Traditional Hall sensors are sensitive in one direction only, perpendicular to the plate or chip.

A triaxial sensor can simply be created by mounting three of these sensors orthogonally on a common base.
Example: a magnetodosimeter for monitoring exposure to strong magnetic fields.

To achieve a low offset, spinning current Hall devices (manufactured in CMOS technology) are used.

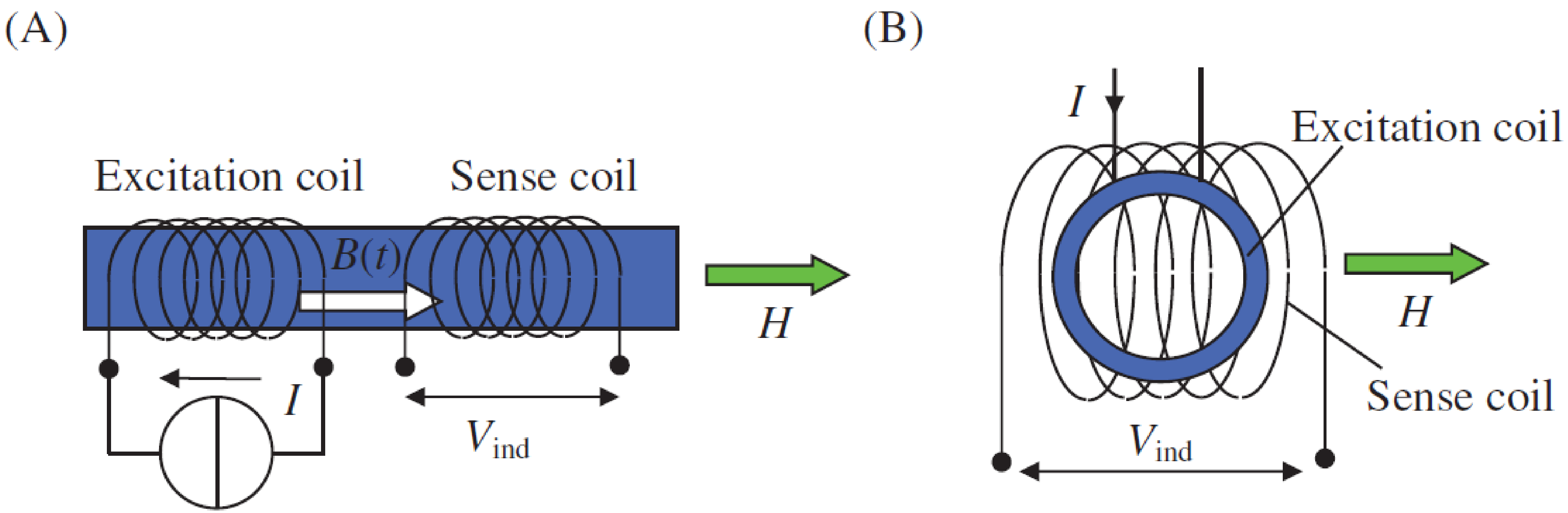
Hall sensors are still a subject of research, aiming at higher sensitivity, lower offset, and reduced manufacturing costs.

Fluxgate sensors

Like the Hall plate, the fluxgate sensors measure magnetic field strength.

Basically, the fluxgate sensor (or saturable-core magnetometer) consists of a core from soft magnetic material and two coils: an excitation coil and a sense coil.
The excitation coil supplies an AC current that periodically brings the core into saturation. Hence the permeability of the core material changes with twice the excitation frequency, between values corresponding to the unsaturated and the (positive and negative) saturated states. An external magnetic field H produces an additional induction field B in the core of the sensor. Since the permeability varies periodically, so does this added field: it is modulated by the varying permeability. In the sense coil a voltage is induced.

Structure of a fluxgate sensor: (A) basic structure and (B) ring shaped.



Fluxgate sensors

Coils are relatively bulky components and are not easy to miniaturize.

Many attempts have been made to decrease the size of fluxgate sensors without deteriorating their performances.

Various configurations and technological solutions have been proposed and tested to further reduce size, increase sensitivity, improve directivity, extending the frequency range and create multi-axis sensors.

Specifications of commercial fluxgate sensors

Parameter	Value (typ.)	Unit
Range	10^{-4}	T
Resolution	10^{-10}	T
Sensitivity	10	μV/nT
Noise	10	$pT/\sqrt{Hz}$
Excitation frequency	0.4–100	kHz
Bandwidth	1	kHz
Offset drift	1	pT/K
Maximum temperature	70	°C

Comparison of various magnetic field sensors

Property	Fluxgate	AMR	Hall (Si)	Unit
Range	10^{-4}	10^{-3}–10^{-2}	100	T
Sensitivity	4×10^{4}	5	0.1	V/T
t.c. sensitivity	30	600		ppm/K
Linearity	10^{-5}	10^{-2}		–
Offset	0.001–0.01	10–100	1–100	μT
t.c. offset	0.03–0.2	10–100		nT/K
Bandwidth	10–10^{4}	10^{6}–5×10^{6}		Hz

Core Materials

The selection of the core material generally depends on the type and geometry of the sensor, on the type of processing of the output signal, and also on the excitation frequency and required temperature range.

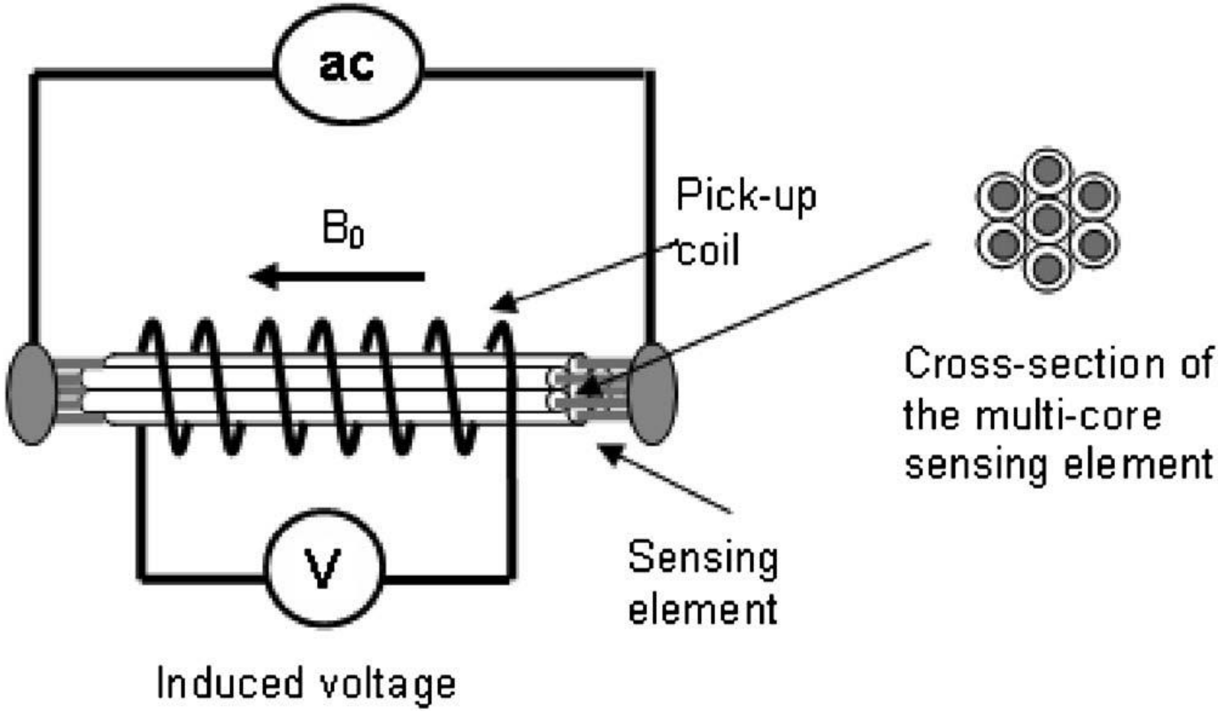
General requirements for the material properties:

1. High permeability (permeability may be further intentionally reduced by thermomagnetic treatment to reduce the noise);
2. Low coercivity;
3. Nonrectangular shape of the magnetization curve (points 2 and 3 are equivalent to the smallest possible area of the B-H loop);
4. Low magnetostriction;
5. Low Barkhausen noise;
6. Low number of structural imperfections, low internal stresses;
7. Smooth surface;
8. Uniform cross-section and large homogeneity of the parameters;
9. Low saturation magnetization;
10. High electrical resistivity.

Orthogonal fluxgate sensor using magnetic amorphous microwires as sensing element

- one orthogonal fluxgate sensor with the sensing element formed by a CoFeSiB glass-coated amorphous wire with Φ_m = 16 μm and t_g = 2 μm – **single-core sensing element**
- one orthogonal fluxgate sensor with the sensing element formed by 16 closely packed glass-coated amorphous wires with Φ_m = 16 μm and t_g = 2 μm – **multicore sensing element**

L = 18 mm
I = 6 mA
1000 turn pickup coil

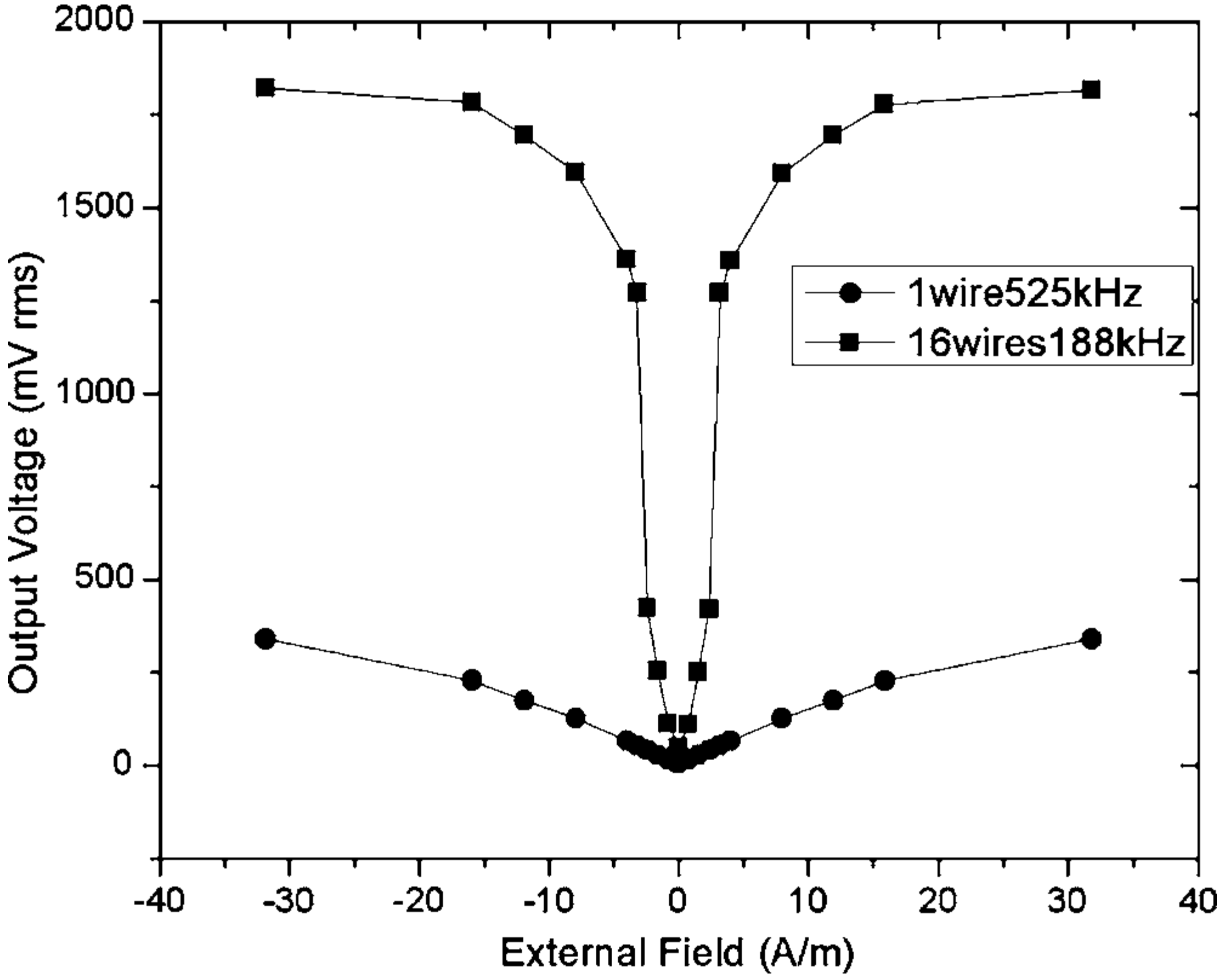


Orthogonal fluxgate sensor using magnetic amorphous microwires as sensing element

In the tests, the excitation currents passing through the sensing elements for both sensors were set in such a way that each of the amorphous wires in the sensing elements was driven by a current of equal magnitude.
The current excitation frequency for each sensing element was determined such that the sensor gave the maximum sensing output.

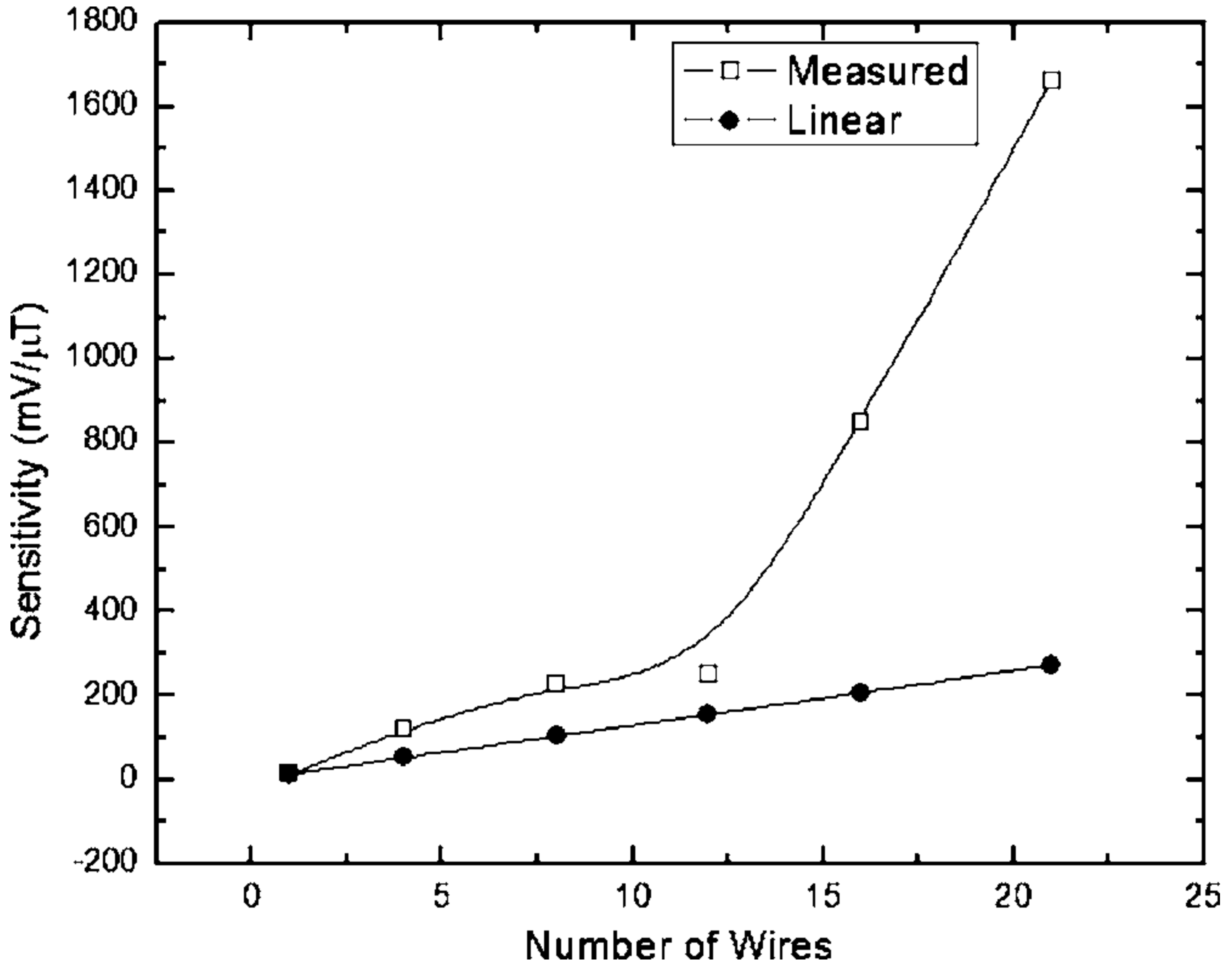
The results showed that under the excitation current of optimum frequencies the sensitivity of the 16-core sensor was 65 times higher than that of the single-core sensor, in a trend of increasing exponentially against the increase of the number of cores in the sensing element.

X.P. Li et al., JAP 99 (2006) 08B313



Comparison of the sensing outputs of the single-core sensor and 16-core sensor. The sensitivities of the single core sensor and 16-core sensor at the external field of 4 μT were 13 and 850 mV/μT, respectively. Also, note that the optimum frequency for the 16-core sensor was lower than that for the single-core sensor.

Orthogonal fluxgate sensor using magnetic amorphous microwires as sensing element



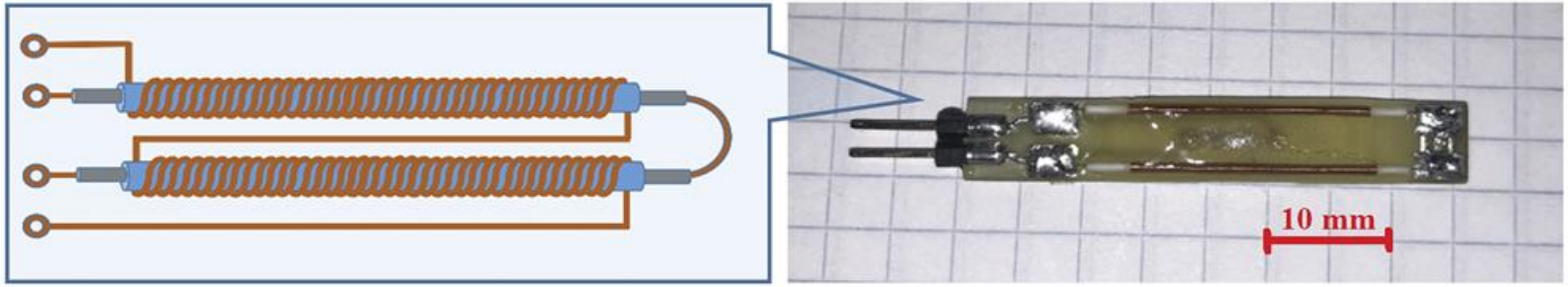
The measured sensitivity of the multicore sensor increased exponentially as the number of core wires increased from 1 to 21.

A "linear" curve calculated by multiplying the number of single-core sensors and the sensitivity of a single-core sensor is shown for comparison.

The increase of the sensitivity of the multicore orthogonal fluxgate sensor could be due to the magnetic coupling of the multiple ferromagnetic wire cores in the sensing element under AC excitation.

Orthogonal fluxgate magnetometer based on amorphous wire cores

Requirements: magnetic field resolution in the fT to pT range, small physical dimensions to assure high spatial resolution, ambient temperature operation and reduced energy consumption.
Aim: to obtain a maximum signal to noise ratio.



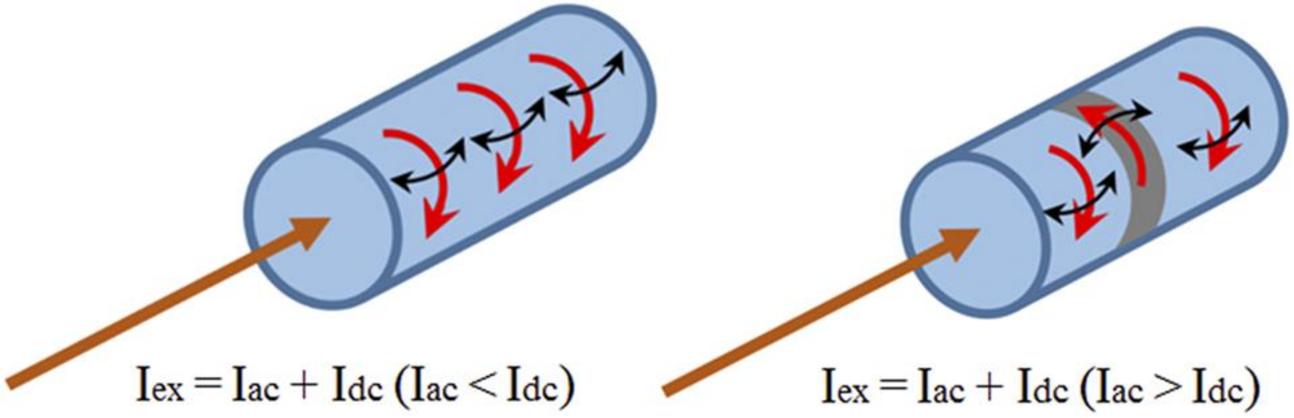
Sensor head.

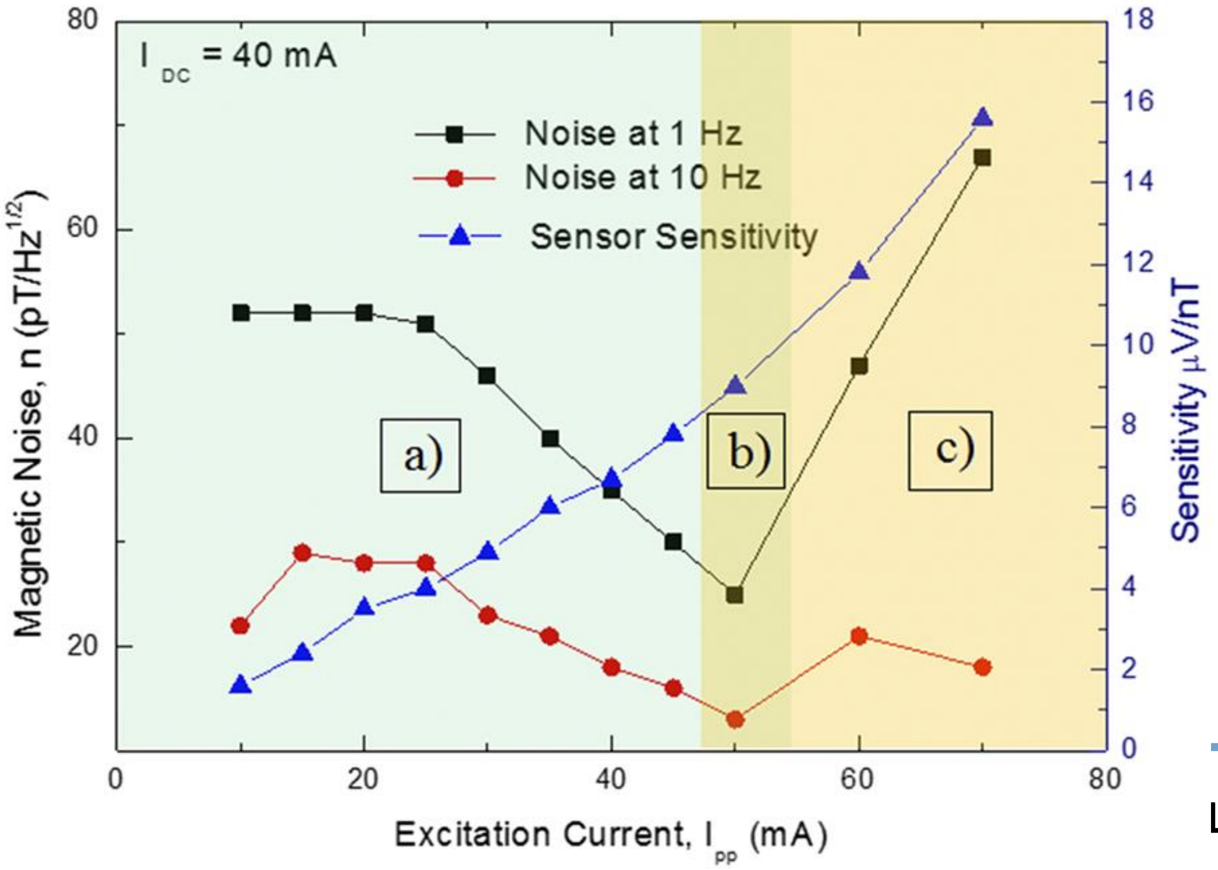
The two sensing coils consist of two layers having 500 turns each.
Sensing element: Co-Fe-Si-B amorphous wires with Φ = 120±3 μm
The distance between the centers of the two sensing coils is 5 mm, each coil having 20 mm in length.

The anisotropy direction changes from circumferential in the absence of the applied field, to a strong helical anisotropy in the presence of a magnetic field applied along the core axis.

The AC excitation is set below 50 mA, to guarantee that magnetization takes place only by rotation and no Barkhausen noise is present.

Orthogonal fluxgate magnetometer based on amorphous wire cores





Equivalent magnetic noise and sensitivity dependences on the excitation current for a DC bias current of 40 mA.

The three regions correspond to different magnetization mechanisms, namely:

- *regions (a) & (b) - reversible magnetization processes (magnetization by coherent rotation)*
- *region (c) - irreversible magnetization processes (nucleation of domains and domain wall movement).*

The sensitivity of the sensor for which is achieved the maximum signal to noise ratio is 9.5 µV/nT.

The performance of the sensor can be further improved by using annealed core and well adapted excitation parameters.

L

M. Țibu et al., AIP Advances 11 (2021) 015113

Magnetostrictive or elastomagnetic sensors

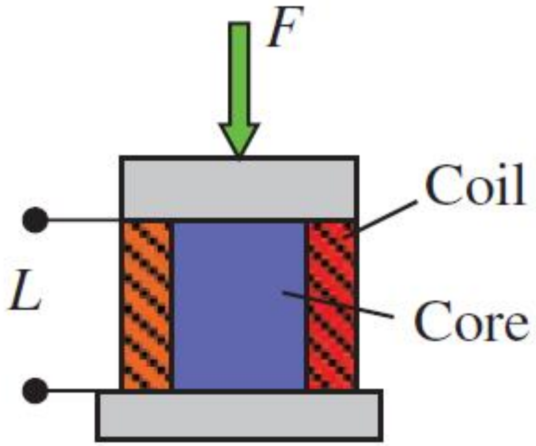
A magnetostrictive (or magnetoelastic or elastomagnetic) sensor is based on the change of the magnetic flux in a magnetic material due to deformation. Therefore, the effect is mainly used for force sensing.

Basically, two different magnetoelastic sensor systems can be recognized: uni- and multidirectional.

Unidirectional sensors consist of a coil with (cylindrical) core from a suitable magnetostrictive material. Upon compression of the core the permeability changes, and so do the reluctance and the self-inductance, according to the expression:

$$\frac{\Delta L}{L} = -\frac{\Delta R_{\mathrm{m}}}{R_{\mathrm{m}}} = \frac{\Delta \mu_{\mathrm{r}}}{\mu_r} = k \cdot T$$

k is the sensitivity
T is the mechanical stress in the material



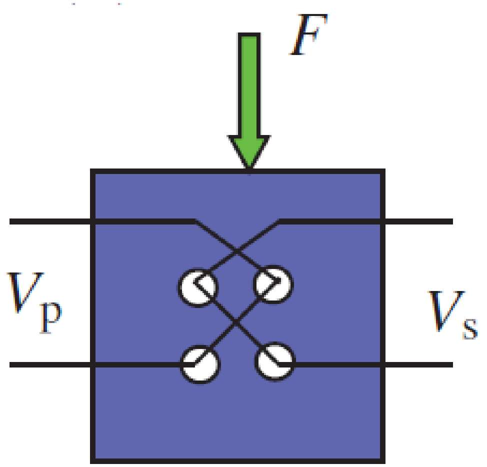
The output signal depends on the temperature and on the frequency and amplitude of the supply voltage.

The overall accuracy is several percent.

Magnetostrictive or elastomagnetic sensors

Multidirectional sensors use the effect that magnetic flux lines change direction when a force is applied.

Such sensors can be used for the measurement of force or torque and using special designs for both force and torque simultaneously.

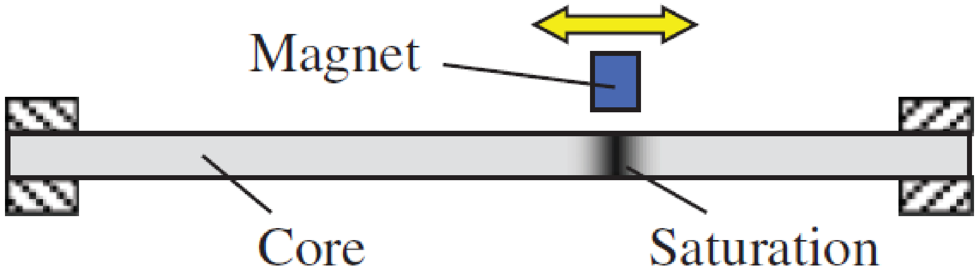


The core consists of a pile of ferromagnetic lamellae.
Both primary and secondary coils have only a few turns, positioned perpendicularly to each other.
When no load is applied, the magnetic field lines of the primary coil, do not cross the secondary coil, hence the transfer is low. Upon an applied force the permeability of the magnetic material looses its isotropy, resulting in an asymmetric pattern of field lines. In this situation, field lines can intersect the secondary coil, generating an output signal proportional to the force.

Magnetostrictive or elastomagnetic sensors

An alternative for the magnetostrictive metal is stress-sensitive amorphous ribbon.

When taped on the curved surface of an axis, the ribbon is stressed, becomes anisotropic, and exhibits magnetoelastic properties that can be used to measure torque, similar to strain gauges.



Linear displacement sensor based on local saturation.

M. Hardcastle, T. Meydan, Sens. Actuators A 81 (2000) 121125

Magnetoresistive (MR) sensors

Magnetoresistive sensors

- Measure essentially the magnetic field strength (down to pT region).

1856	The anisotropic magnetoresistance (AMR) effect was discovered by W. Thomson *(a fundamental phenomenon in which the electrical resistivity depends on the relative angle between the magnetization direction and the electric current direction)*
1970	The first AMR head for magnetic recording appeared.
1985	A commercial tape drive with the MR head was introduced (*IEEE Trans. Magn. 28(5) (1992) 2283*).
1980's	Magnetoresistive devices with much larger sensitivity were realized (GMR and GMI).
1995	Commercial GMR sensors appeared.

Magnetoresistive sensors are well suited for use in medium field strengths (e.g., Earth field navigation or position measuring systems). They can be manufactured (also with on-chip electronics) by the technology of integrated circuits at small sizes and low costs, which are the main prerequisites for mass-market acceptance.

Compared to Hall sensors, ferromagnetic magnetoresistors have higher sensitivity, lower noise, and higher operational temperature. They have better offset stability, as they do not have a piezo effect.

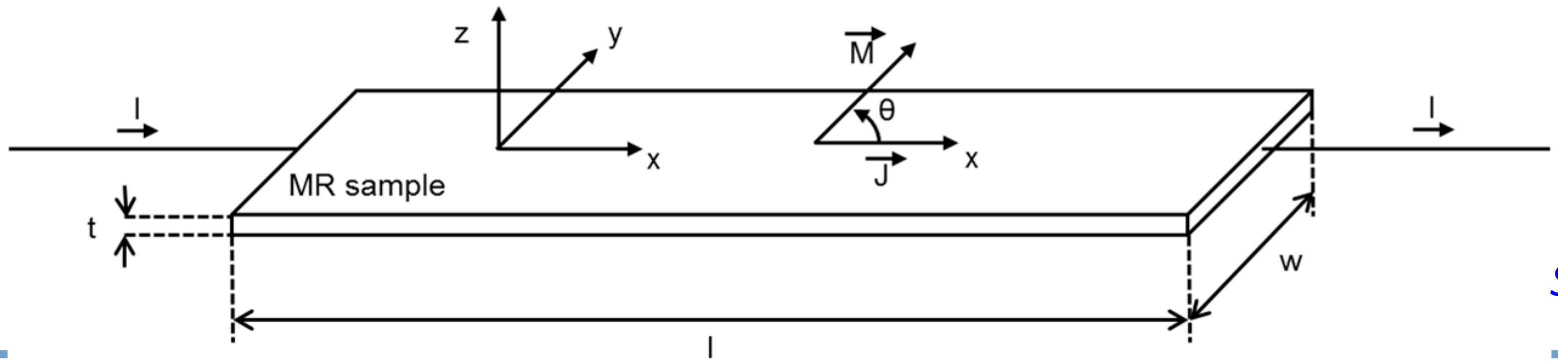
AMR sensors

The AMR effect occurs in 3d transition metals and can be observed macroscopically by a change of resistivity when a magnetic field is applied on a current-carrying sample of such material.

This directional dependence of the magnetic properties of such material is denominated magnetic anisotropy.

On the microscopic level, different sources that cause magnetic anisotropy can be distinguished:

- **magnetocrystalline anisotropy** : directional dependence of magnetic properties due to the crystalline structure of the sample;
- **shape anisotropy** : directional dependence of magnetic properties due to the outer shape of the sample.
- **magnetoelastic anisotropy** : tensions cause a change of the magnetic behavior of the sample.
- **exchange anisotropy** : a result of interactions between antiferromagnetic and ferromagnetic materials. Does not occur in AMR sensors, since no antiferromagnetic materials are used.



Schematic of an AMR thin film element.

AMR sensors

- Thin film elements of ferromagnetic materials can be used as contactless angle or rotation sensors. Sensors for angle and rotation measurements are designed for rather strong magnetic fields, in order to lower the impact of interfering magnetic fields.

- Nonetheless, AMR sensors can also be used for the measurement of rather low magnetic fields like the Earth's magnetic field, permitting the use of AMR sensors as compasses.

- The thin film elements are usually operated in a Wheatstone bridge in order to compensate temperature drift and to double the signal output.

- The single thin film elements typically feature meander shaped geometry for two main reasons: (1) this shape induces a strong magnetic anisotropy, providing the sensor with a well-defined orientation of sensitivity; (2) the length of the sensing element is increased, thus the absolute value of the change of resistance rises as well. This improves the sensitivity of the sensor.

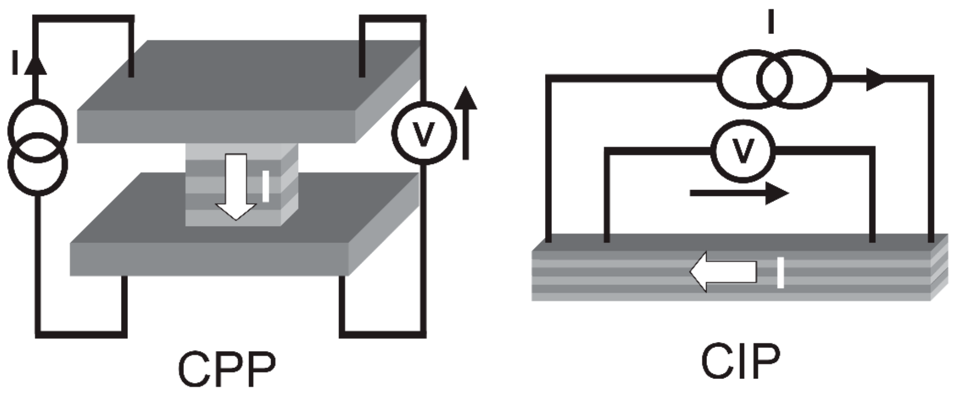
Comparison of magnetoresistive sensors

Type*	AMR	GMR	GMI	Units
Sensitivity	5	75	240	mV/G
Linear range	6	2	>2	G
Frequency range	5000	1000	1	kHz
Number of axes	2	1	3	-

**AMR: HMC1052 (Honeywell); GMR: AAH00202 (NVE Corp.); GMI: AGMI302 (Aichi Corp.)*

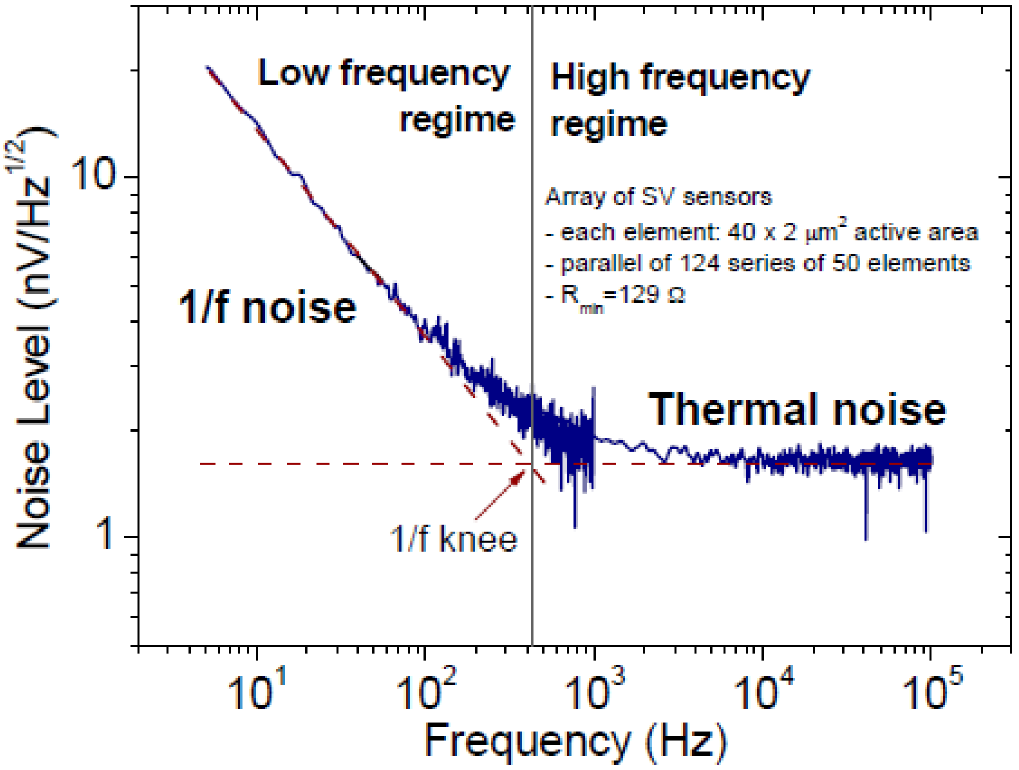
GMR sensors

- The GMR effect can be measured with the electrical current flowing in the plane of the thin films or perpendicular to it, i.e. current-in-plane (CIP) and current-perpendicular-to-plane (CPP).
- **In most industrial applications, the CIP setup is used**, as the film resistance in the CPP configuration is very small due to the very thin layers and therefore not easily to detect. While the noise decreases in the lower-resistance CPP layers, so does the signal itself, resulting in low signal-to-noise ratios. Additionally, the fabrication process for CPP is more complex than for the CIP configuration, which means that fabrication time and costs increase.



- GMR sensors are employed for angle, speed and position sensing, e.g., in automotive applications as well as magnetic field and electrical current sensing in many industrial applications.
- In biological methods, GMR sensors implemented in Lab-on-a-Chip devices detect magnetic nanoparticles that are used as tags for different biomolecules.
- However, the strongest impact of GMR technology was achieved in magnetic storage technology.

GMR sensors



Typical noise spectrum of a MR device (SV array), reaching the thermal level for frequencies around 400 Hz.

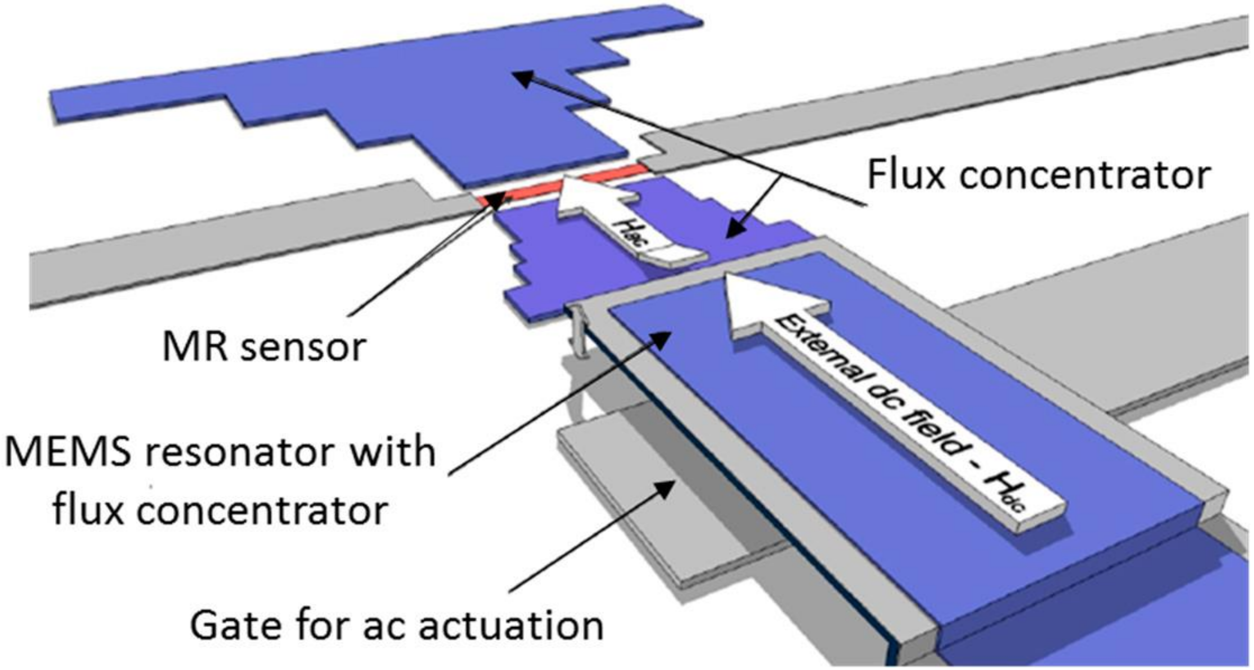
In the low frequency regime the 1/f noise is dominant, while in the high frequency regime the spectrum is reduced to its thermal level.

Both electronic and magnetic noise components are present since the spectrum was recorded with the sensor operating on its linear range.

The integration of MFCs is the used strategy to enhance significantly the sensor sensitivity. These elements increase the magnetic flux through the sensor and consequently decrease the linear operating range without introducing additional noise.

Depending on the geometry and profile, MFCs can yield a sensitivity gain up to 100 times, reflecting in a detection level decrease.

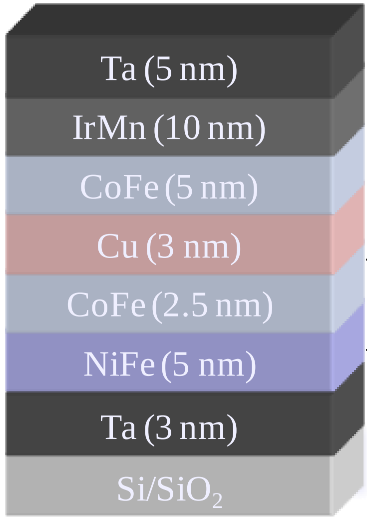
GMR sensors

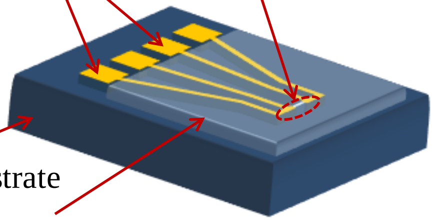


The combination of robustness and high sensitivity of MR sensors with the low power consumption and high frequency operation of MEMS resonators results in high frequency magnetic field modulation, deflection detection of micro-bridges, and 1/f noise suppression in SVs and MTJs.

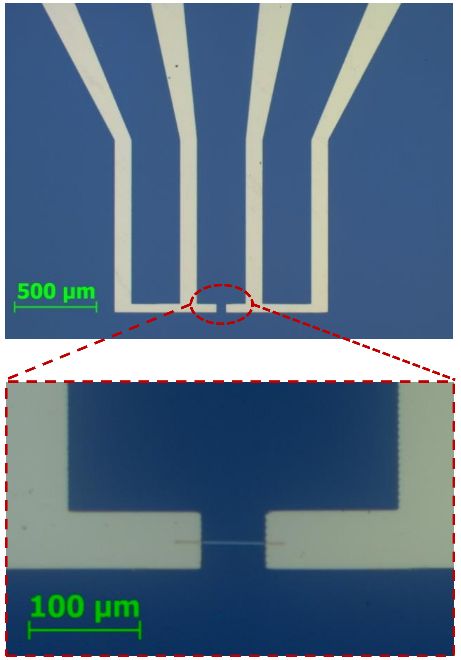
Microfluidic device for nanoparticles detection

Spin valve multilayer stack

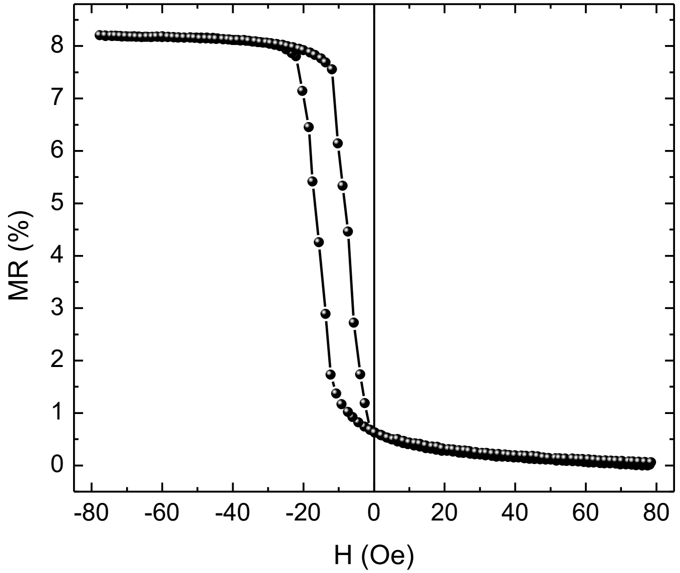


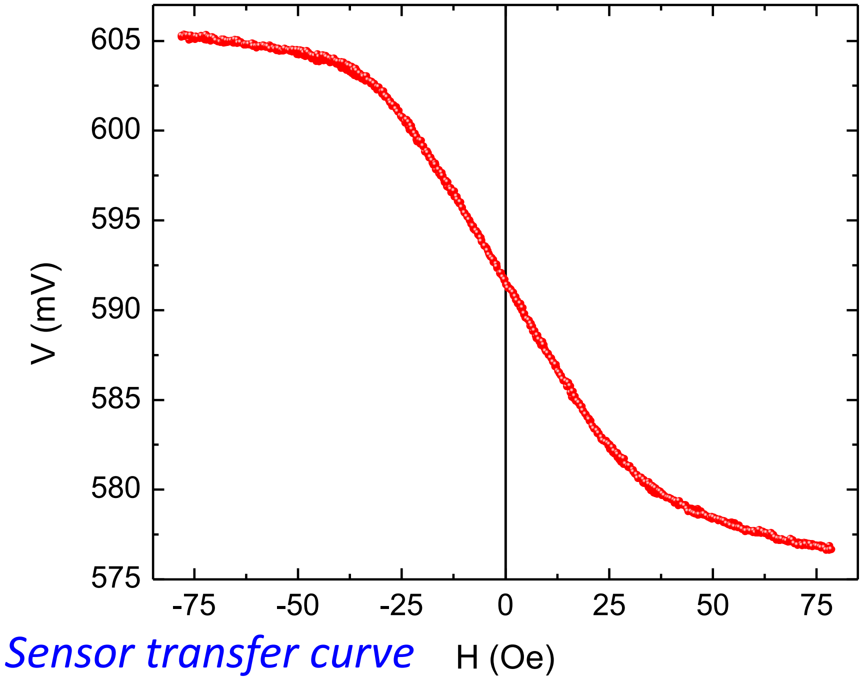


Schematic representation of the spin valve sensor



Optical microscope image of a 100 µm x 2.5 µm spin valve sensor.





Sensor transfer curve

SV sensor properties:

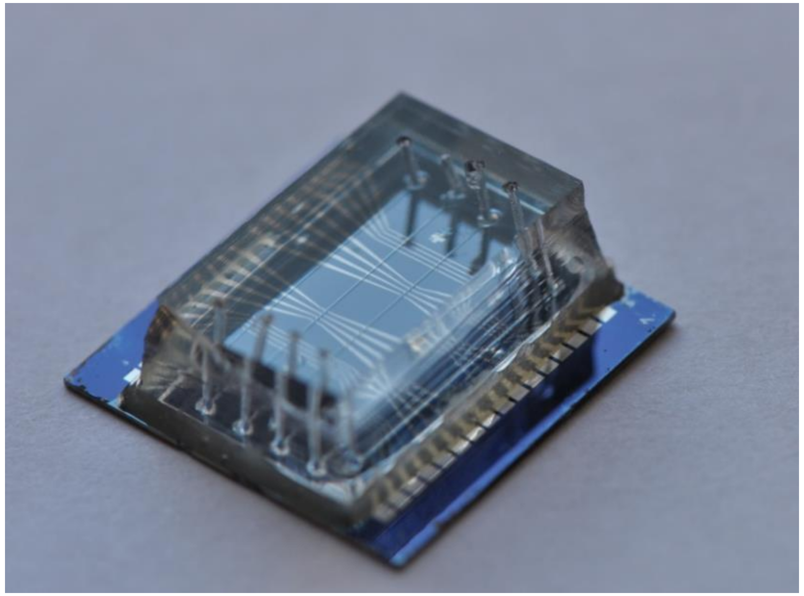
MR = 5.2%

H_c = 0.36 Oe

S = 0.38mV/Oe

H_{linear} = ±30 Oe

Microfluidic device for nanoparticles detection



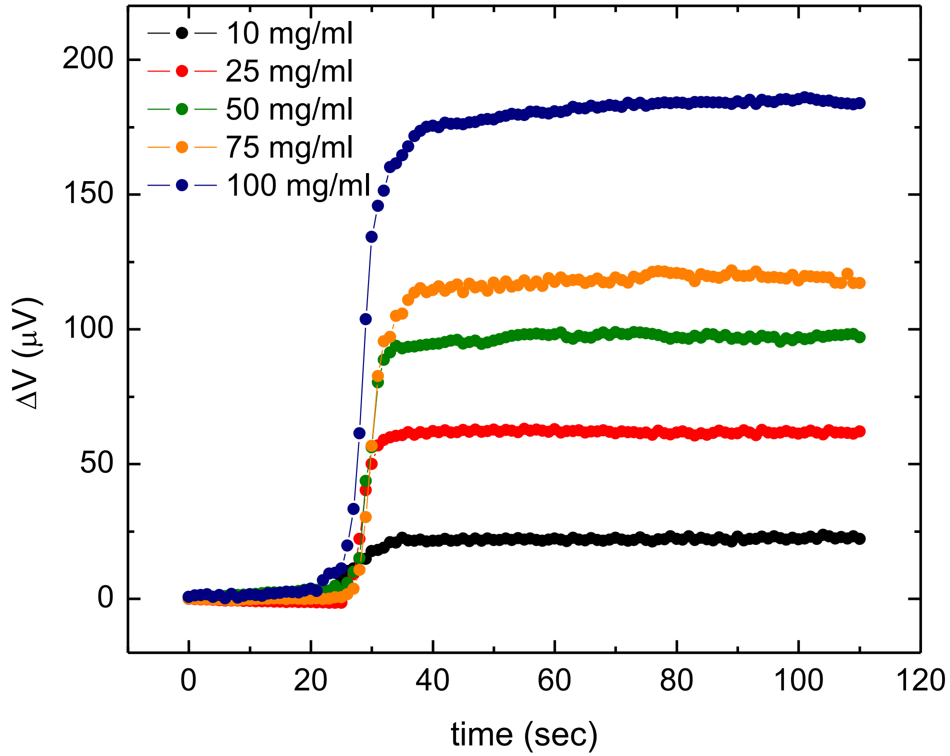
Microfluidic device used for nanoparticles detection

- 16 spin valve sensors (100 µm x 2.5 µm)
- 4 microchannels (100 µm x 100 µm)
- 4 sensors in each channel

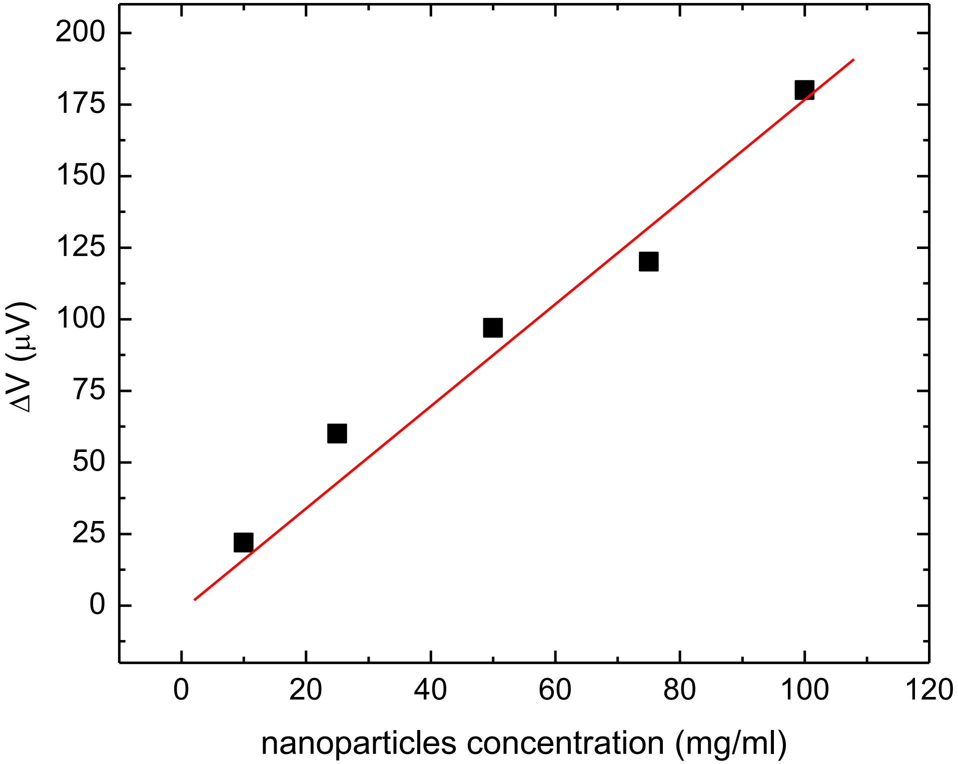
- The nanoparticles are injected through the microchannels and the output voltage of the sensor is recorded.
- The spin valves sensors detects the fringe field created by the magnetized nanoparticles.

Microfluidic device for nanoparticles detection

1. Estimation of nanoparticles concentration in a magnetic fluid



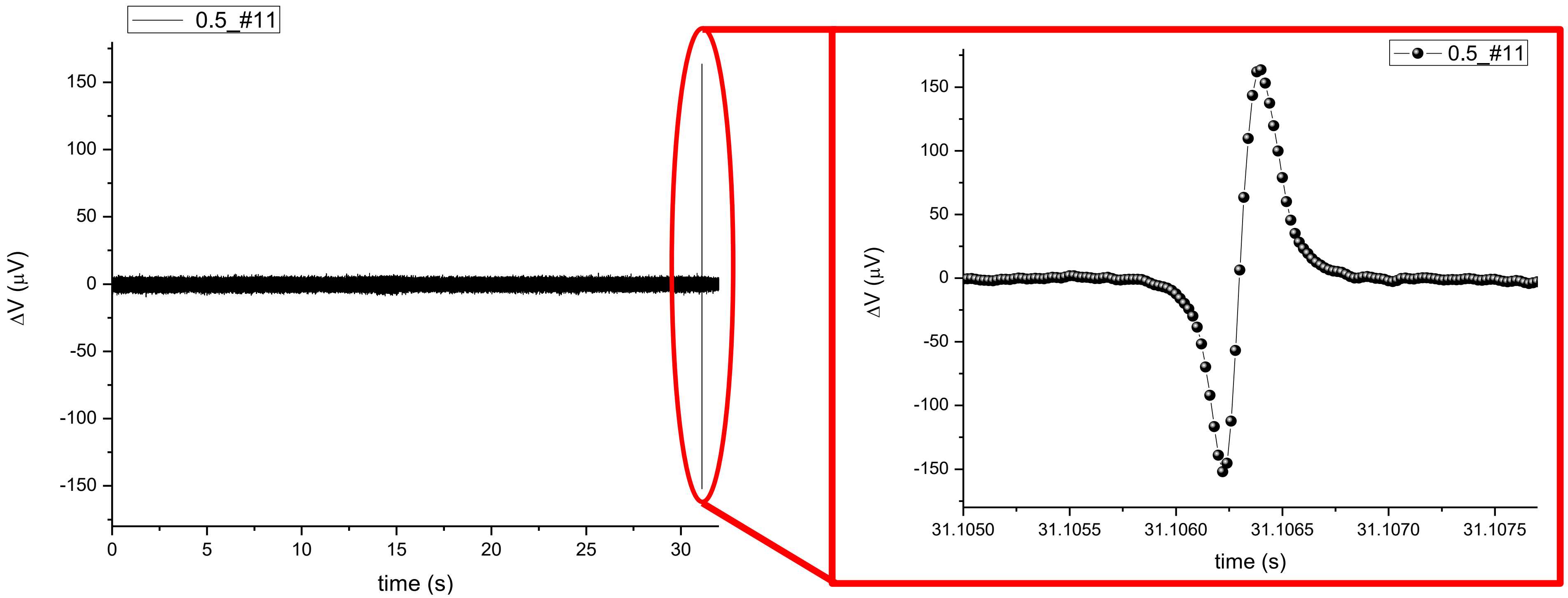
Sensor output voltage versus time trace for different nanoparticles concentrations.



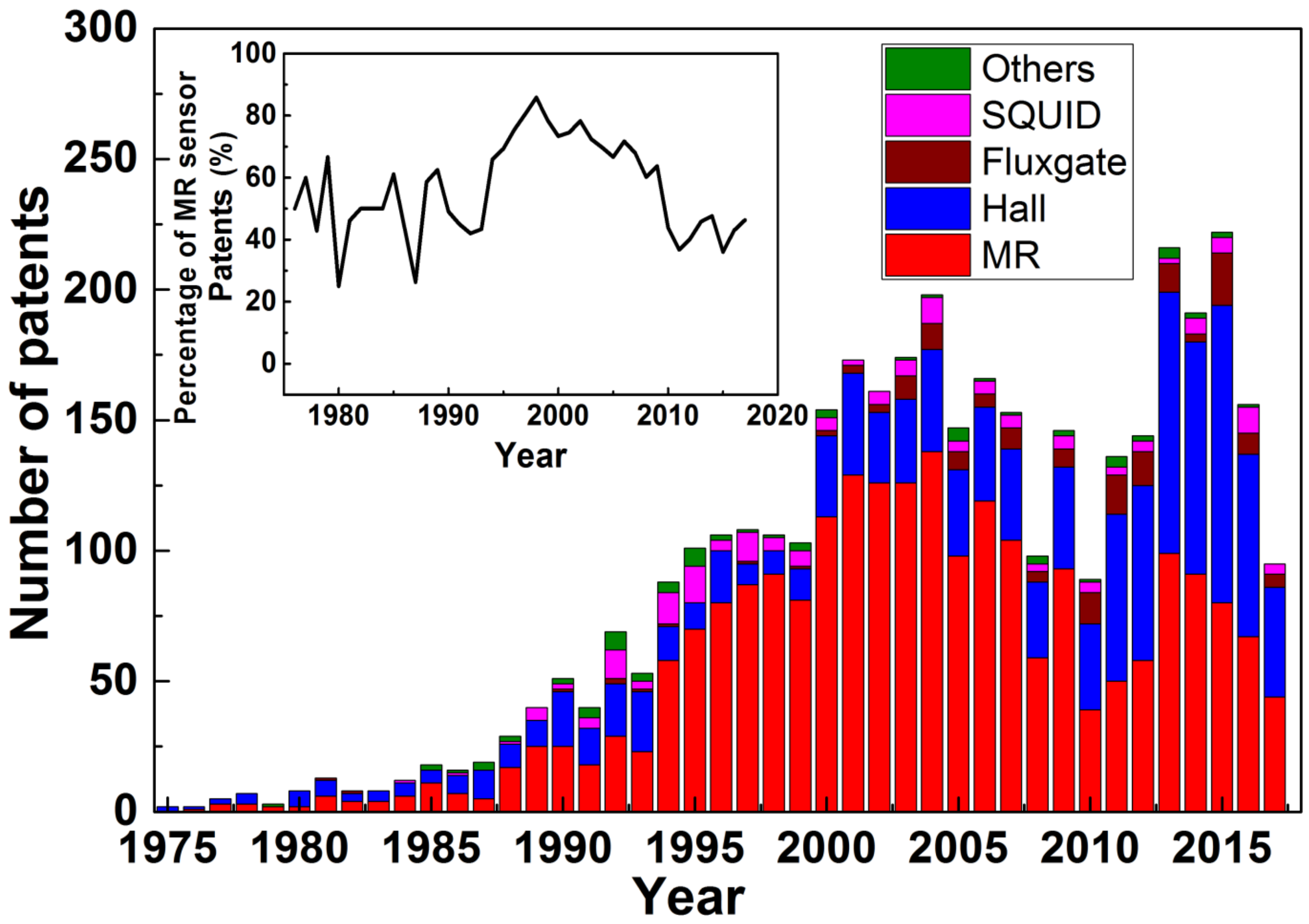
Sensor output voltage versus nanoparticles concentration.

Microfluidic device for nanoparticles detection

2. Magnetic counter (detection of magnetically labeled biomolecules or cells)

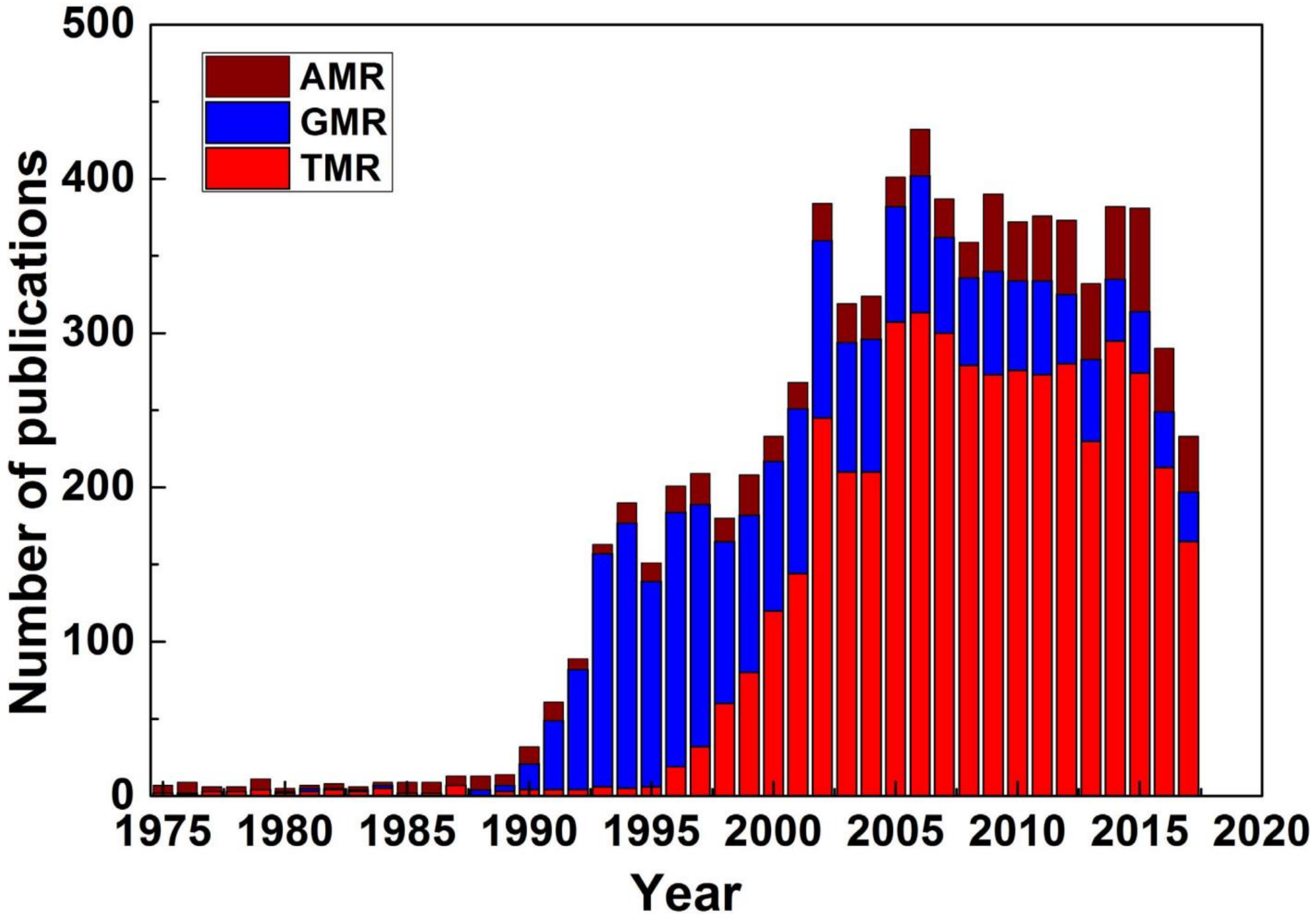


Sensor output voltage versus time



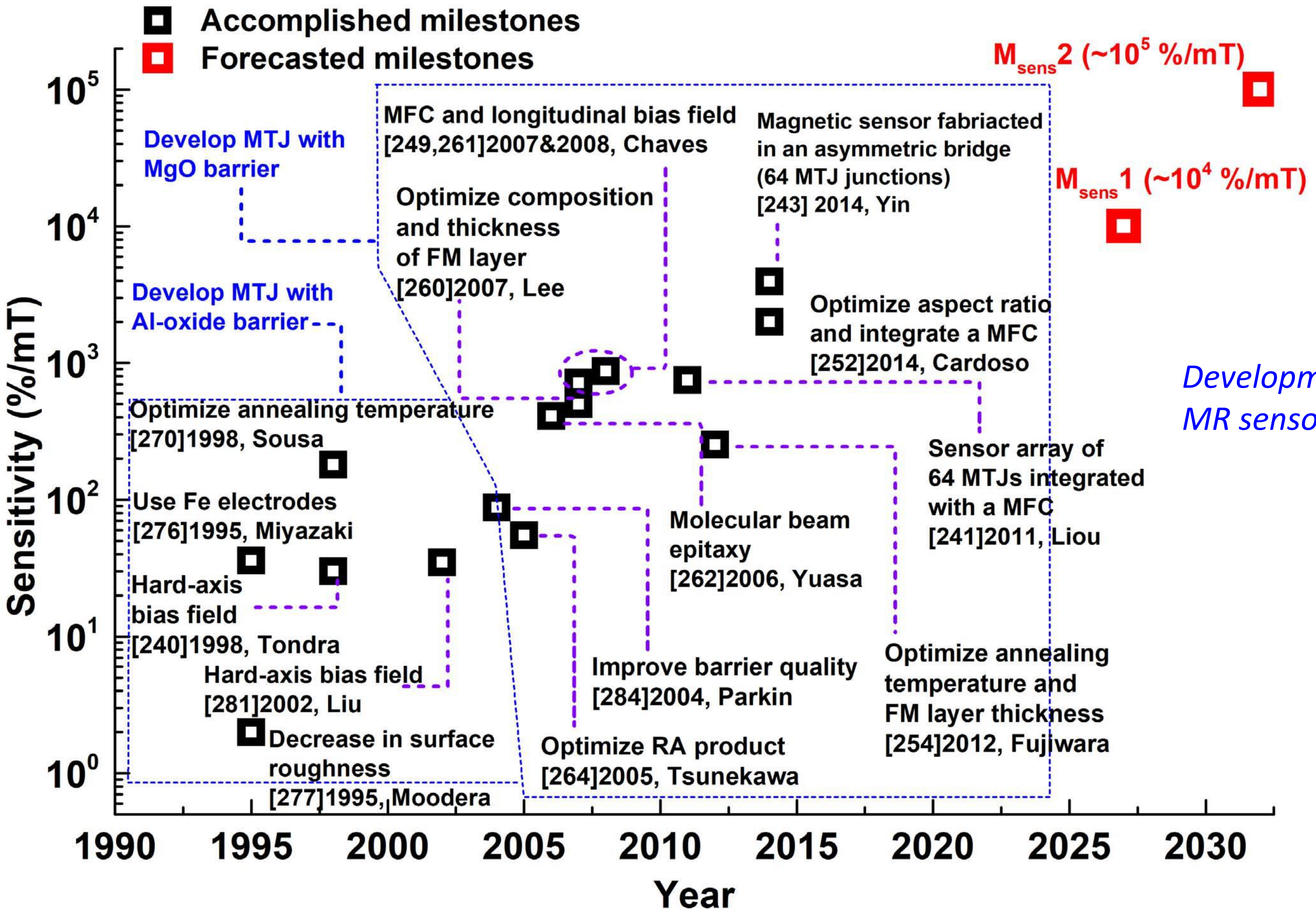
Statistics of common magnetic sensors from 1975 to 2017 in the selected patent databases compiled by EPO, USPTO, STPO, and TIPO.
(Inset): Percentage of MR sensor patents among all types of magnetic field sensors.

C. Zheng et al., „Magnetoresistive Sensor Development Roadmap (Non-Recording Applications)", IEEE T Magn 55(4) (2019) 0800130



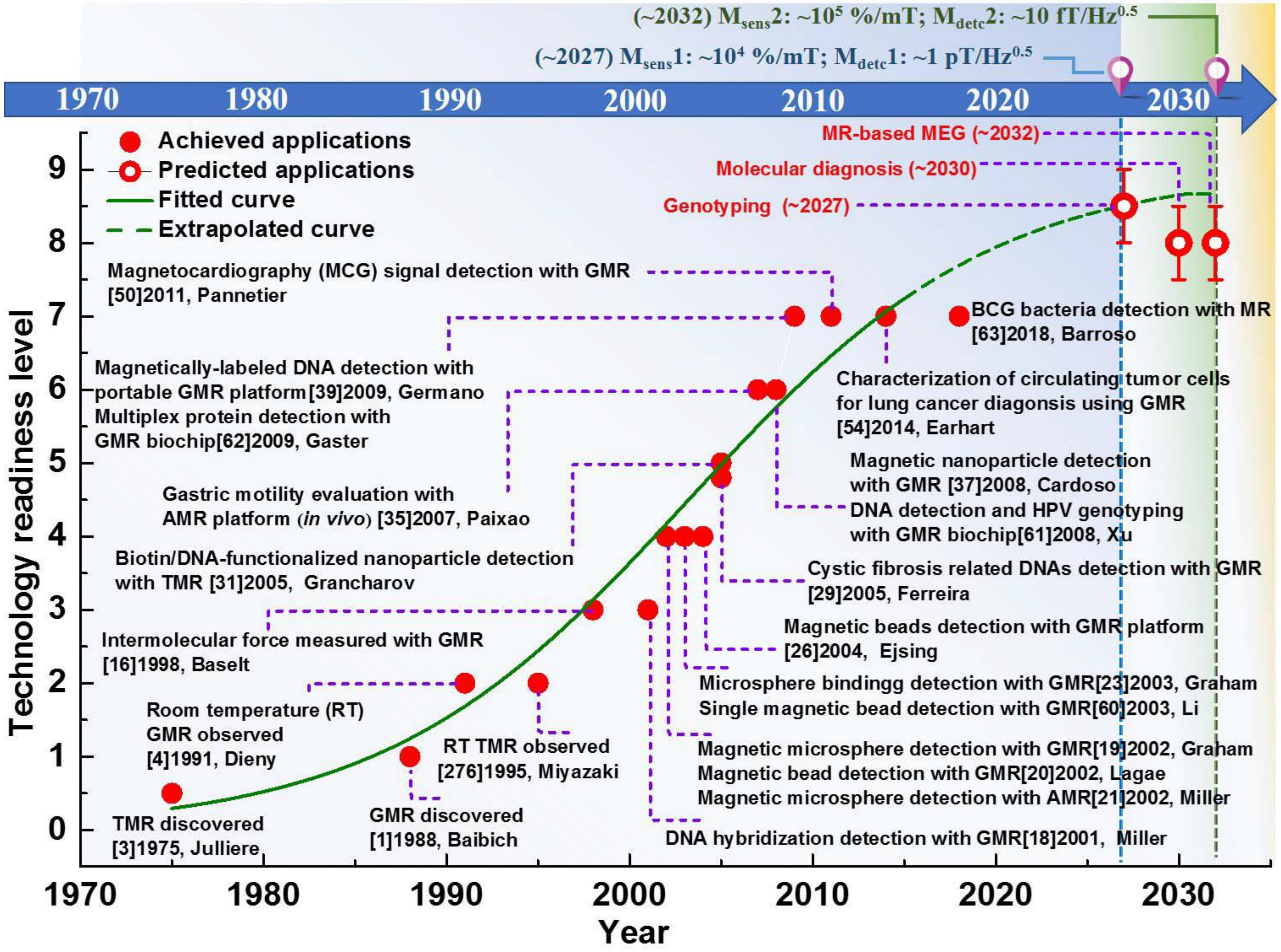
Publication statistics of AMR, GMR, and TMR sensors from 1975 to 2017 in the Web of Science.

C. Zheng et al., „Magnetoresistive Sensor Development Roadmap (Non-Recording Applications)", IEEE T Magn 55(4) (2019) 0800130



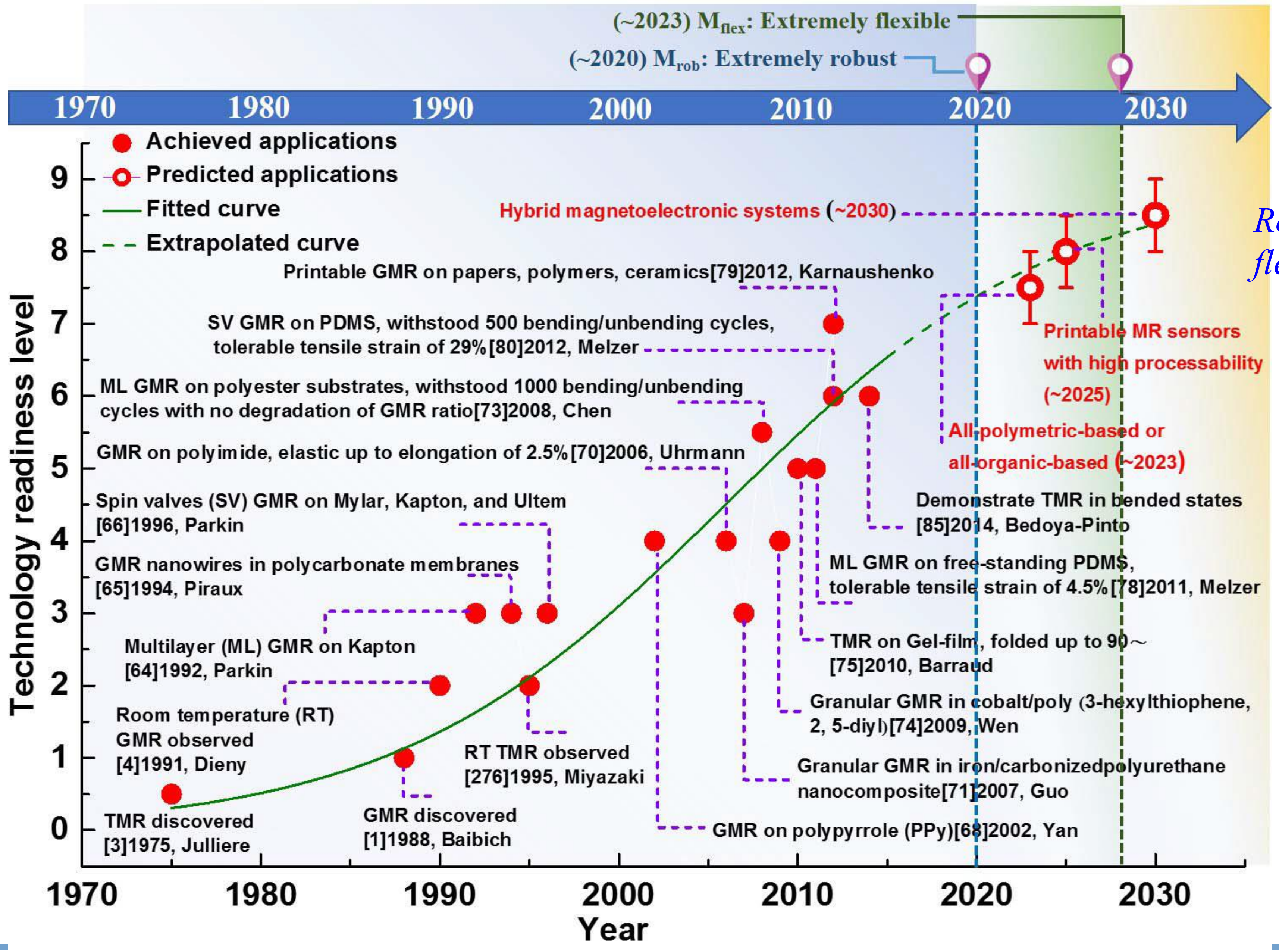
Development trend for the sensitivity of MR sensors at RT from 1995 to 2032.

C. Zheng et al., „Magnetoresistive Sensor Development Roadmap (Non-Recording Applications)", IEEE T Magn 55(4) (2019) 0800130



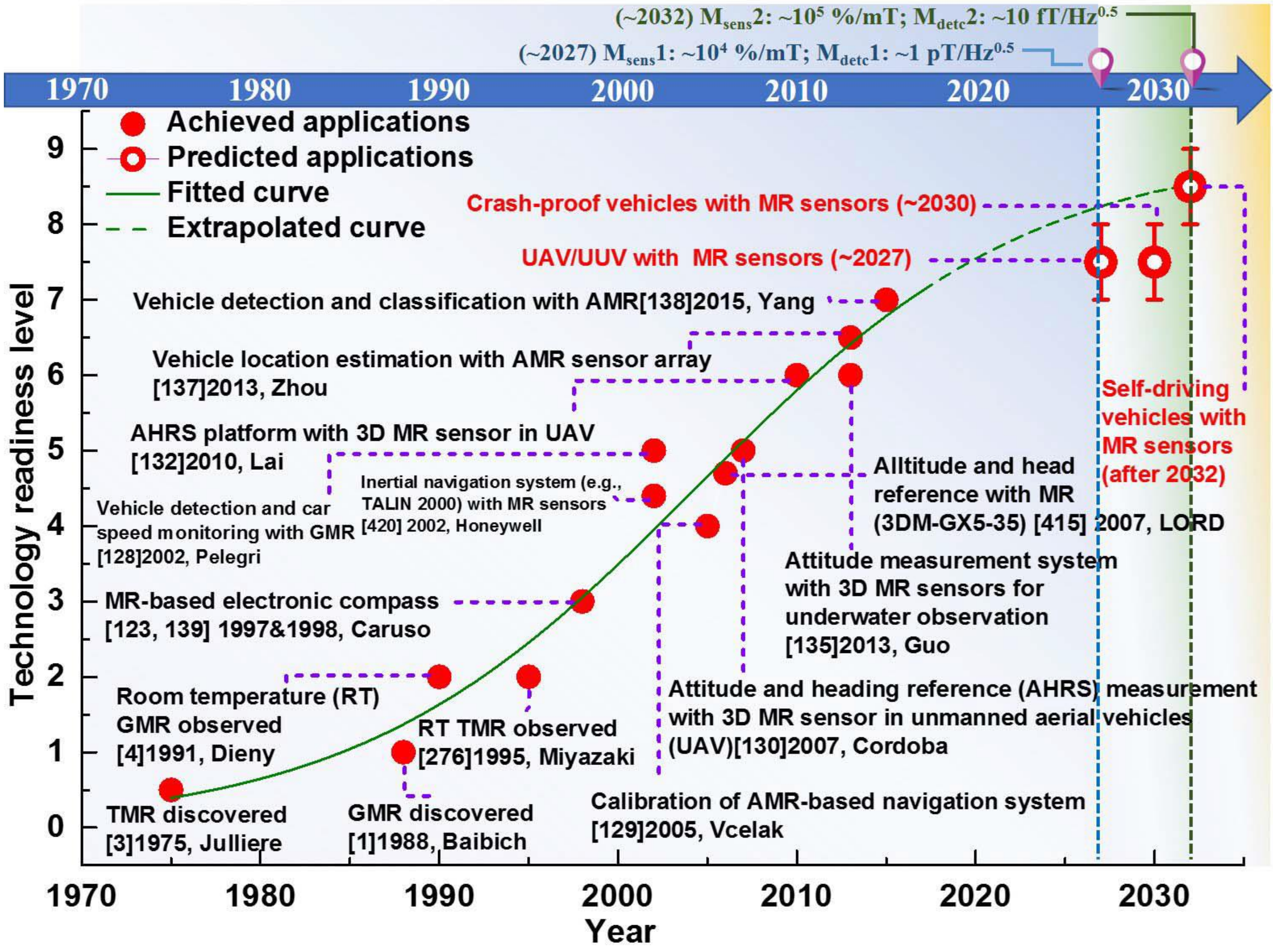
Roadmap for MR sensors in biomedical applications from 1970 to 2032.

C. Zheng et al., „Magnetoresistive Sensor Development Roadmap (Non-Recording Applications)", IEEE T Magn 55(4) (2019) 0800130



Roadmap for MR sensor applications in flexible electronics from 1970 to 2032.

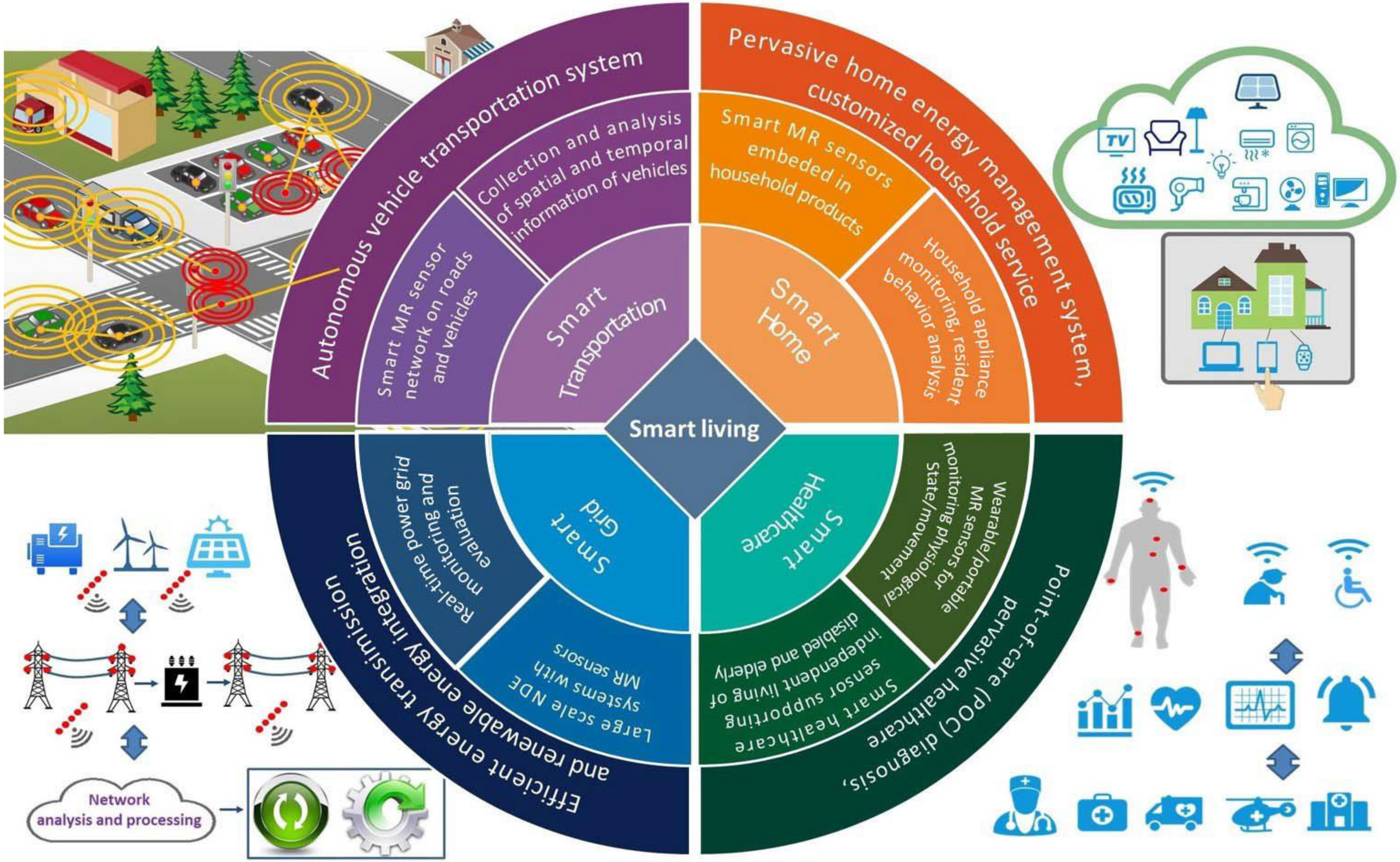
C. Zheng et al., „Magnetoresistive Sensor Development Roadmap (Non-Recording Applications)”, IEEE T Magn 55(4) (2019) 0800130



Roadmap for MR sensor applications in navigation and transportation from 1970 to 2032.

C. Zheng et al., „Magnetoresistive Sensor Development Roadmap (Non-Recording Applications)", IEEE T Magn 55(4) (2019) 0800130

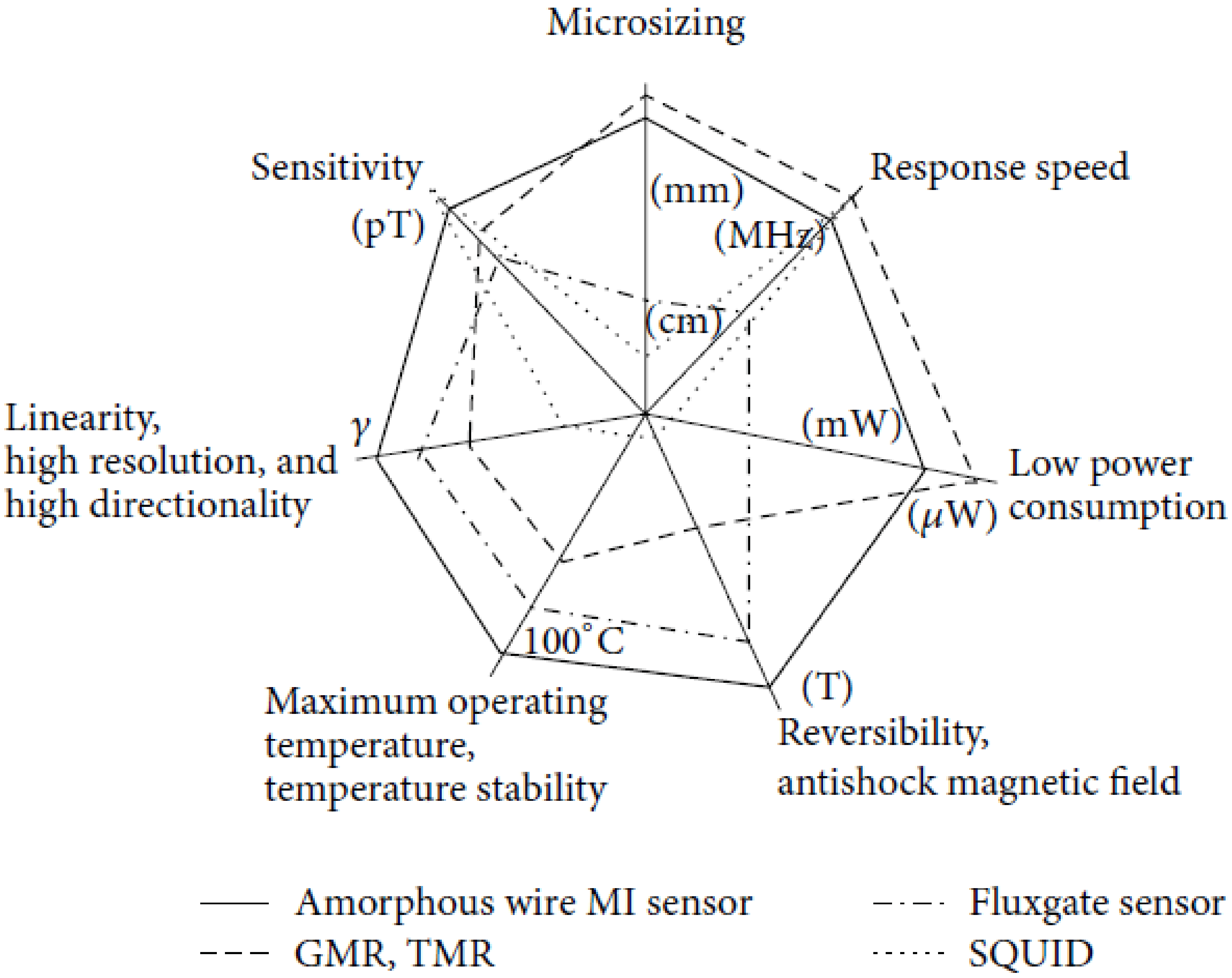
Contribution and impact of MR sensor technology in the concept of smart living, including smart home, smart healthcare, smart grid, and smart transportation.



C. Zheng et al., „Magnetoresistive Sensor Development Roadmap (Non-Recording Applications)", IEEE T Magn 55(4) (2019) 0800130

Giant Magnetoimpedance (GMI) sensors

A comparison of seven sensor features among magnetic sensors.



After K. Mohri et al., Journal of Sensors (2015) Article ID 718069

Giant Magnetoimpedance Effect

High frequency processes – GMI, FMR – are significantly influenced by:

- surface magnetic anisotropy;
- surface magnetization processes.

The GMI is related to the skin effect in ferromagnetic metals.
An AC current propagating through a conductor is not uniformly distributed in the cross-section, but is concentrated in the surface layer of thickness (the so-called **skin depth**):

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

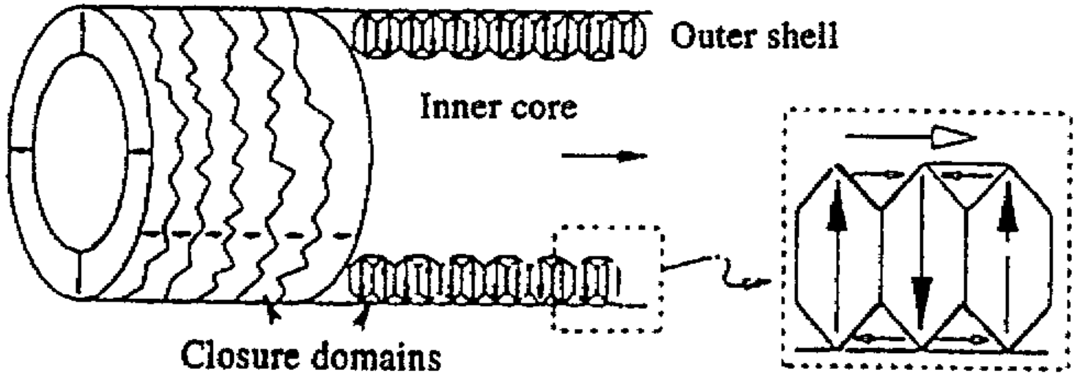
In ferromagnetic metals, the skin depth can be changed by applied magnetic field because of field dependence of permeability μ. **The maximum impedance is obtained when δ is minimum.**

At MHz frequencies and higher, the eddy currents effectively damp the domain wall movements and only magnetization rotations are responsible for magnetization process. Then the theory of GMI becomes similar to the theory of ferromagnetic resonance in metals.

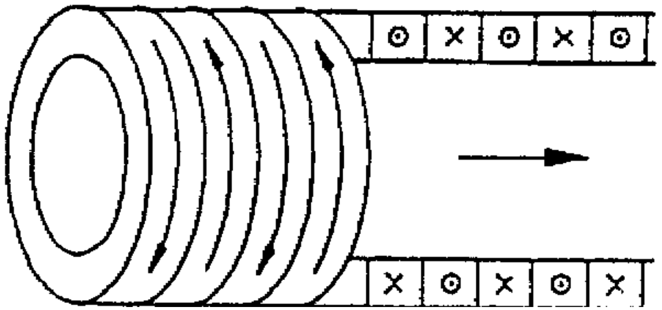
Giant Magnetoimpedance Effect

1) GMI effect in low magnetostrictive amorphous wires is mainly influenced by two factors:
   i. the specific circumferential magnetic domain structure and
   ii. the dynamic magnetization processes.

(a)



(b)



Simplified diagram of the core-shell domain model for:
(a) positive magnetostrictive conventional amorphous wire, and
(b) negative magnetostrictive conventional amorphous wire.

After H. Chiriac and T.A. Óvári, Prog. Mater. Sci. 40 (1996) 333.

Giant Magnetoimpedance Effect

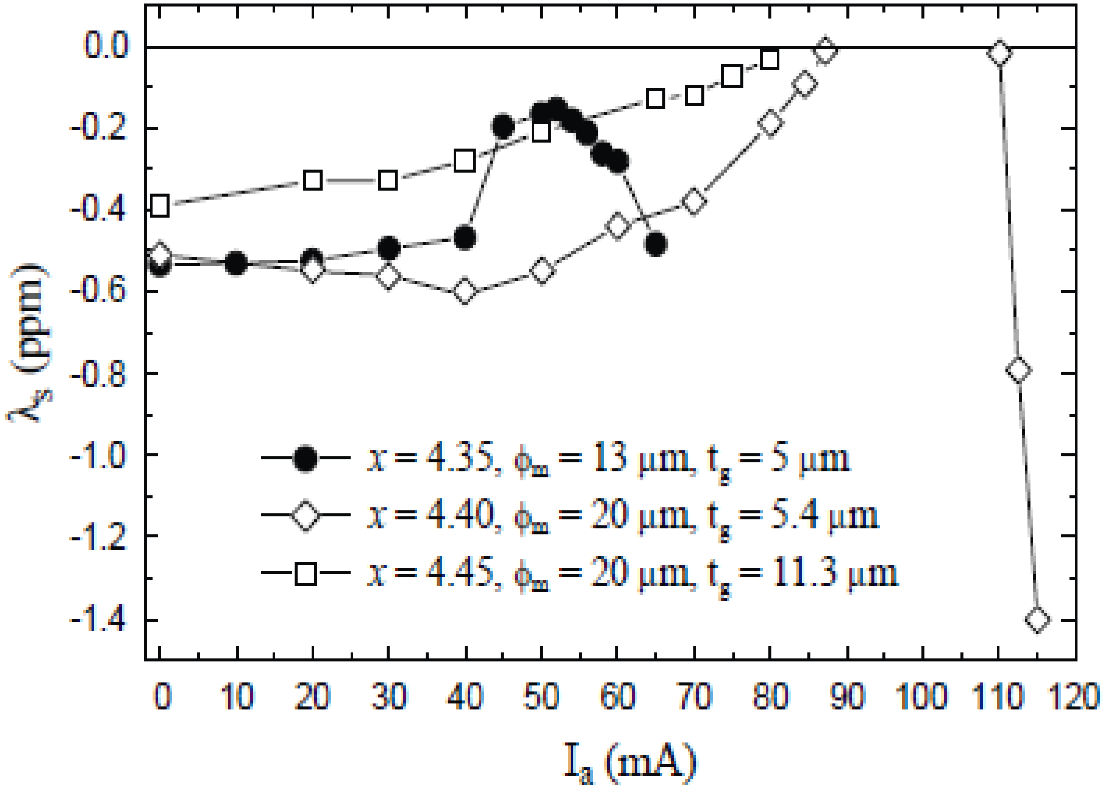
2. The glass cover induces an additional anisotropy, which strongly influences the magnitude of the GMI effect in low magnetostrictive amorphous glass-covered wires.

3. From the point of view of sensing applications, the amorphous glass-covered wires are often preferred against the conventional amorphous wires due to their more reduced dimensions, i.e. the diameter of the metallic core varies from a few micrometers to a few tens of micrometers.

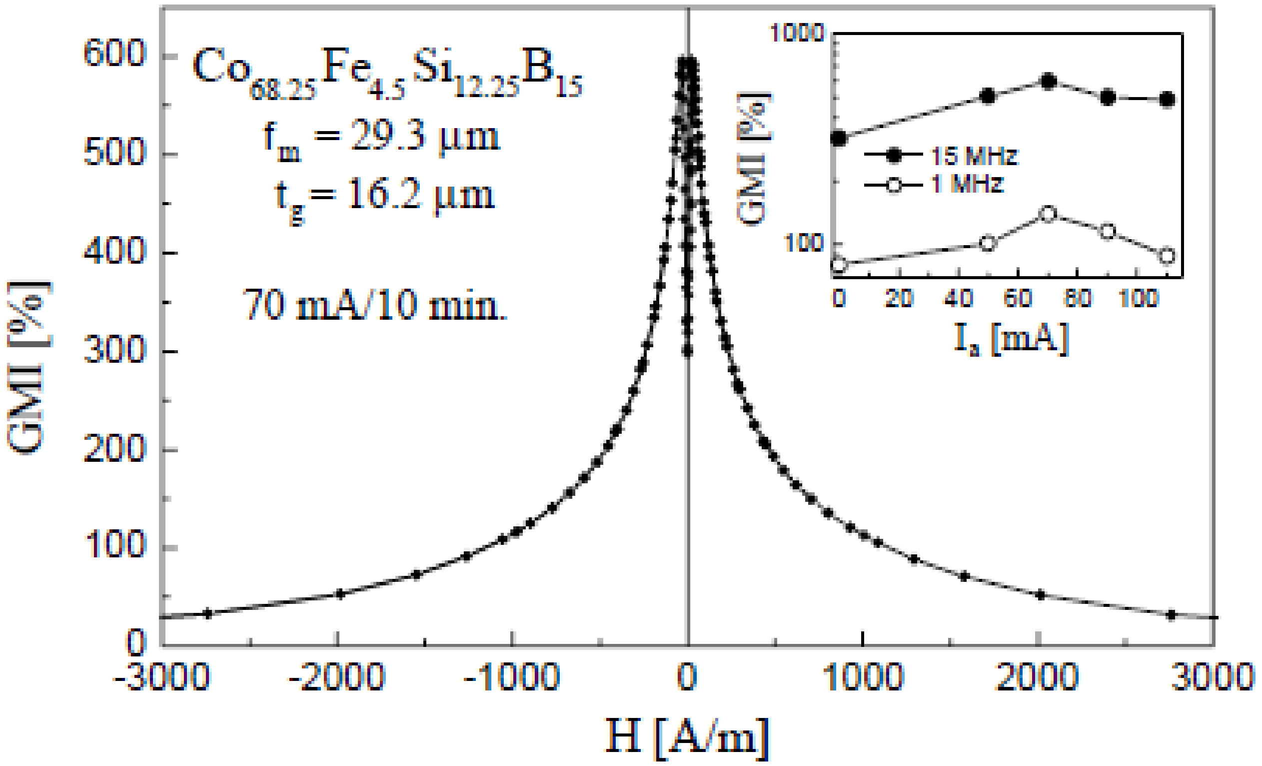
The GMI effect, *which is very important for GCAW sensing applications*, is very sensitive to:
- sample's magnetostriction.
- sample's composition, and
- sample's geometry.

Giant Magnetoimpedance Effect

Annealing with applied tensile stress was used to induce magnetic anisotropy perpendicular to the wire axis.



Magnetostriction constant as a function of annealing current.



GMI of Joule-heated glass-covered microwire measured at 15 MHz with current of 1 mA.

L. Kraus et al., JMMM 254–255 (2003) 399

Amorphous Wire – CMOS IC MI Sensor Projects

Micro size MI HIC chip project

2010 –
Electronic compass chips for Smart Phones
(Aichi Steel Co.)

2002 –
Electronic compass chips for mobile phones
(Aichi Steel Co.)

1998 JST High Tech Consortium

Pico-Tesla MI sensor project

Bio magnetic field detection
- Bio-cell function
- Magneto-encephalogram
- Magneto-cardiogram
- Magneto-spinogram
- Magneto-myogram

Security systems
Magnetic telecommunication

GHz MI sensor project

Plasma current detection,
Leak pulse current sensor

Magneto-Protonics project

Water magnetization measurement
Evaluation of bio effect

1999 MI sensor with Analog Switch, 3 axis MI sensors
1997 Amorphous wire and CMOS IC MI sensor with Pulse Magneto-Impedance
1993 Magneto-Impedance effect in $\lambda \fallingdotseq 0$ amorphous wires
1992 Magneto-Inductive effect in $\lambda \fallingdotseq 0$ amorphous wires

1981-1991: Amorphous wire Research & Developemnt	T. Masumoto, I. Ohnaka, R.E O'Handley, J.E.L Bishop for wires F.B. Humphrey, K. Mohri, J. Yamasaki, R. Malmhall, L.V. Panina for Large Barkhausen effect and domain model

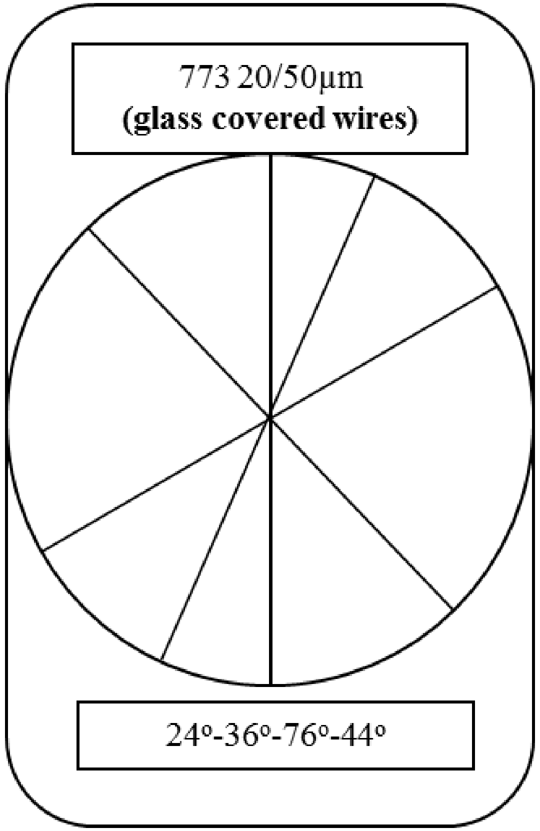
After T. Uchiyama et al., IEEE Trans. Magn. 48(11) (2012) 3833

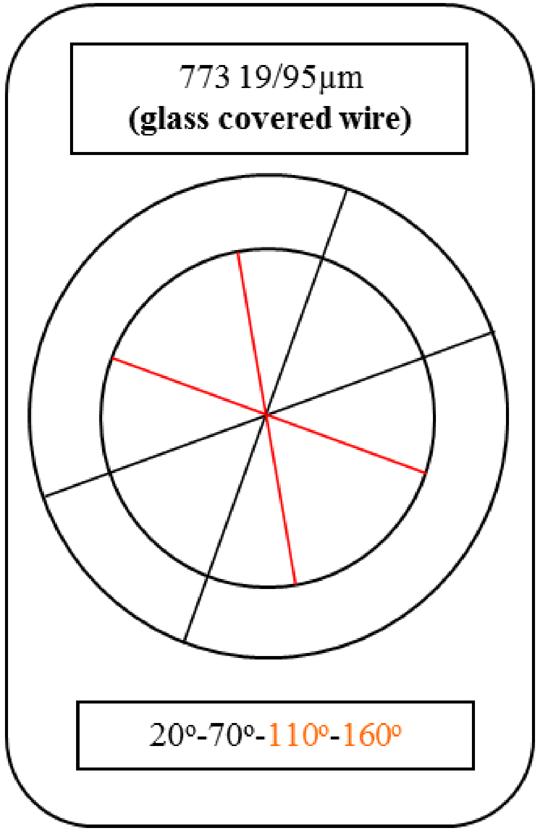
Sensor for Remote Detection of Objects (Electronic Article Surveillance)

- The active element is an amorphous wire or microwire with specific magnetic and electric properties, which gives a specific electromagnetic response when subjected to an electromagnetic field.
- The sensor modulates the amplitude of the RF signal.
- The working principle is based on the GMI effect of magnetic wires and microwires.

Low magnetic field sensors

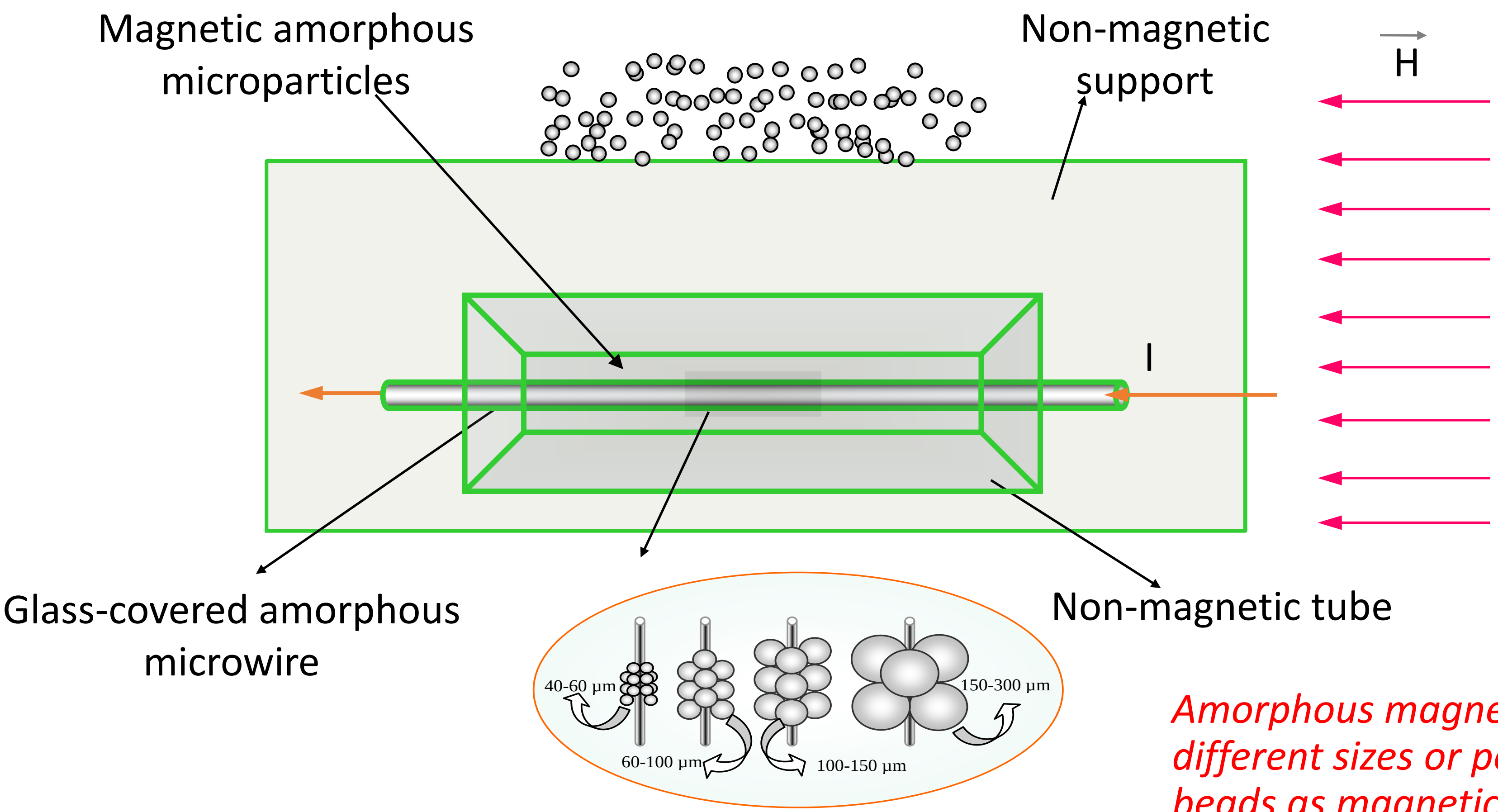
- monitor the bio-magnetic fields generated by human heart or brain;
- detect magnetic anomalies (e.g. the passing of large ferrous objects, such as ships, submarines or even aircrafts)





Giant magneto-impedance (GMI) spin rate sensor - for determining the spin rate of a rotating body within an external magnetic field, such as the magnetic field of the earth.

GMI biosensor

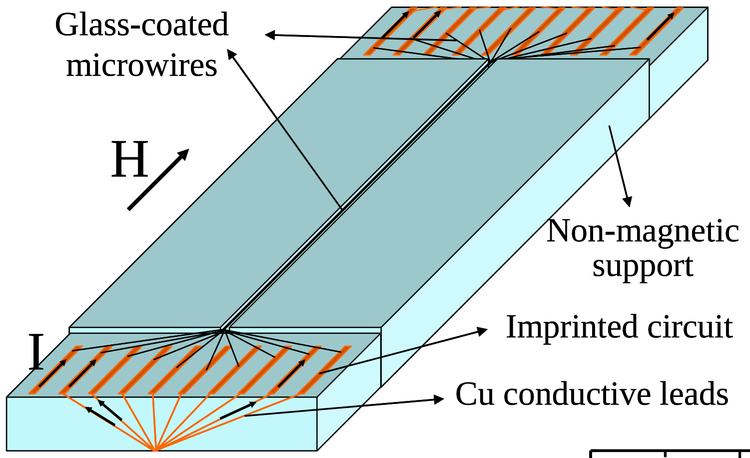


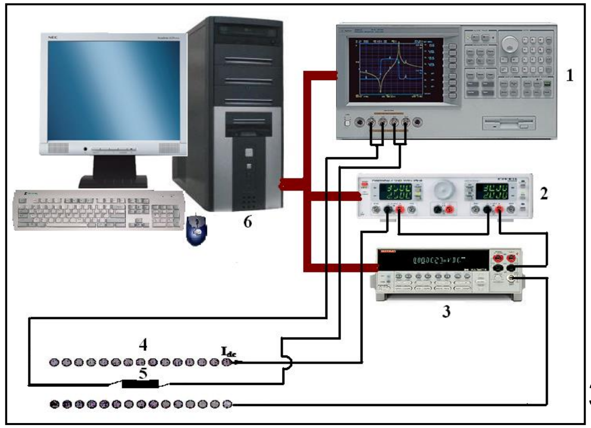
Amorphous magnetic microparticles with different sizes or polymer-based magnetic beads as magnetic markers.

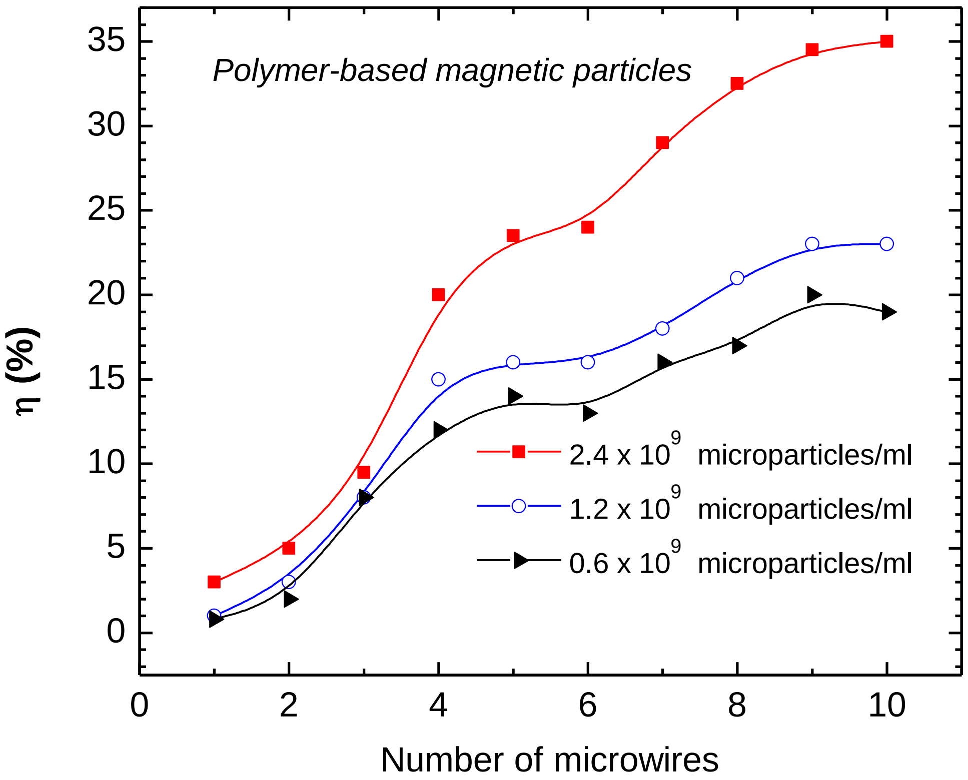
Glass-covered amorphous microwires or polymer-functionalized glass-covered amorphous microwires as sensing elements of the GMI magnetic bio-sensor prototype.

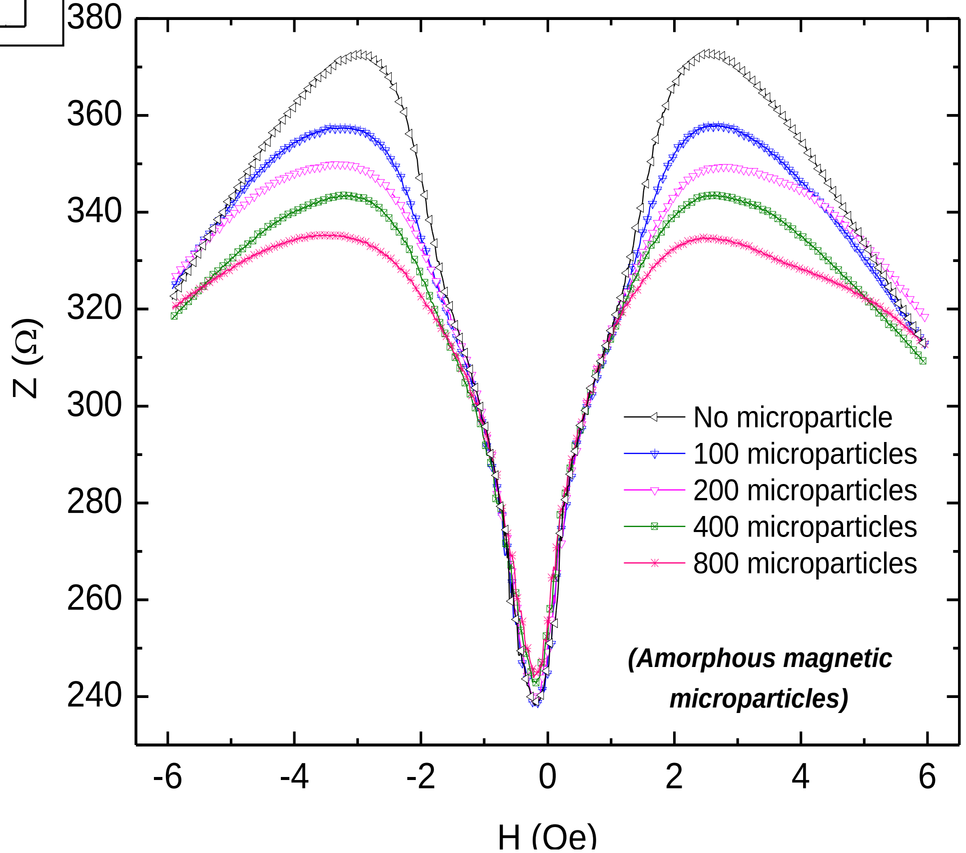
H. Chiriac et al., J. Magn. Magn. Mater. 311 (2007) 425

GMI biosensor









NIRDTP Iași

H. Chiriac et al., J. Magn. Magn. Mater. 311 (2007) 425

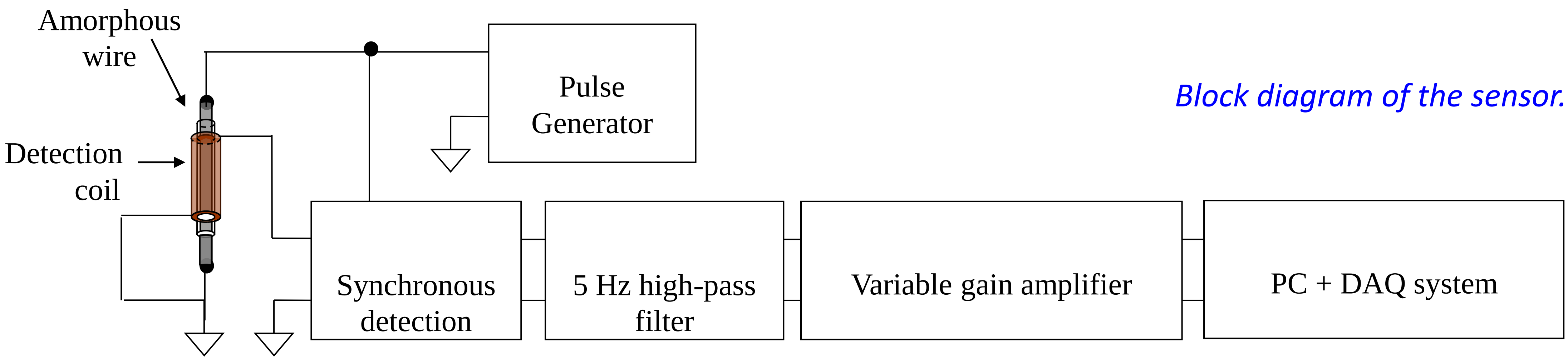
GMI biosensors have some advantages over other sensors, such as:
- lower power consumption (10 mW);
- sensitivity (< 10^{-10} Tesla);
- high response speed (10 MHz);
- and small size (< 2 mm).


Other medical applications of GMI sensors:

1) in catheter navigation systems
2) sensors to detect position and 3D images of a tumor in brain using a micro magnetoimpedance sensor and fine magnetic particles
3) eye and eyelid movement detection during blinking
4) detection of extremely low biomagnetic signals with applications in magneto-cardiography
5) detection and remote monitorization of mechanical stress and temperature from implants and organs
6) detection of the level of atherosclerosis (attached to implanted stents)
7) detection of the heart-attack damage – based on magnetic sensors and nanoparticles to detect specific biomarkers

Non-intrusive flowmeter using GMI sensors

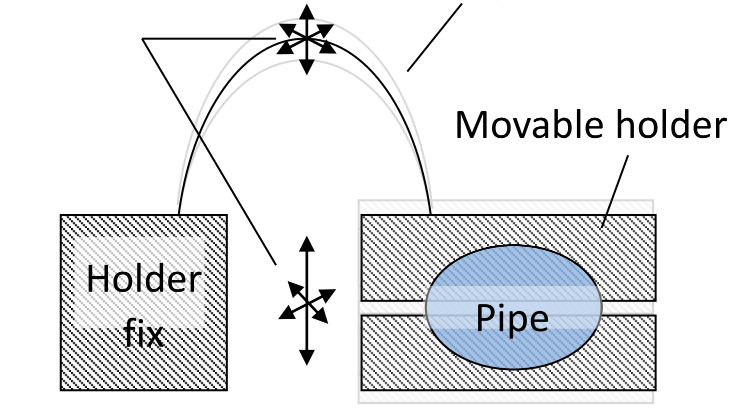
- Low cost non-invasive flowmeters are required in various applications, from civilian water supply and wastewater management systems to the geothermal, chemical, and even nuclear industries.
- Current solutions, e.g. those based on laser and ultrasonic technologies, are either expensive, not applicable to clean liquids, or not accurate enough in comparison with the classical inline, professionally installed invasive flowmeters.
- A novel solution for non-invasive flow measurements, specifically a flow sensor based on the magneto-impedance effect and its sensitivity to vibrations in the pipe wall at different values of the volumetric flow rate.



Block diagram of the sensor.

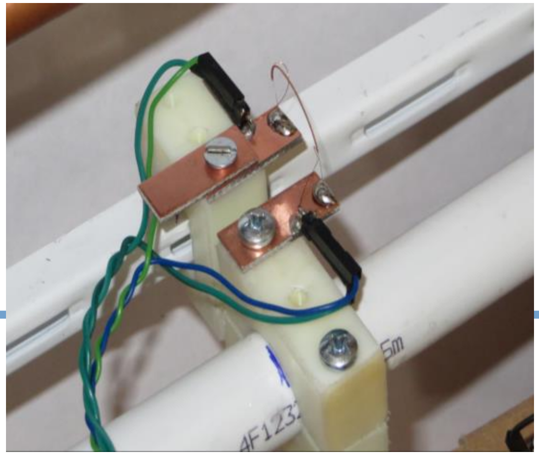
Non-intrusive flowmeter using GMI sensors

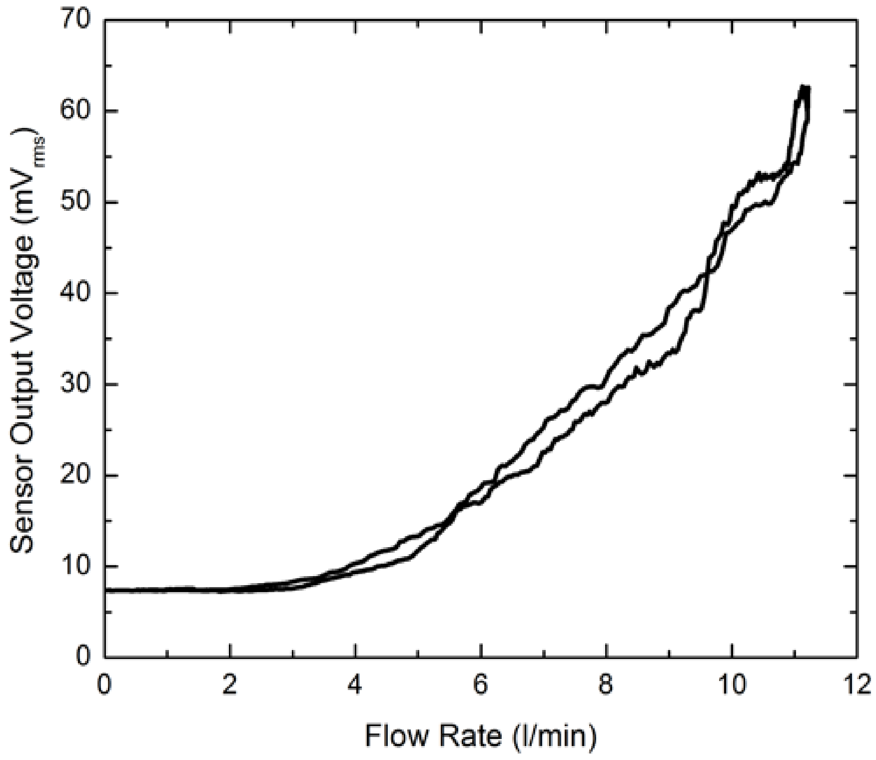
- The sensitive element is made of a 100 µm in diameter $Co_{68.18}Fe_{4.32}Si_{12.5}B_{15}$ amorphous wire with ultra-soft magnetic properties, prepared by in-rotating-water spinning at NIRDTP Iași.
- The actual sensor is a 4 cm long piece of amorphous wire with a 400 turns coil wound around it (0.07 mm enameled Cu wire).
- Frequency of excitation pulses: 500 kHz.



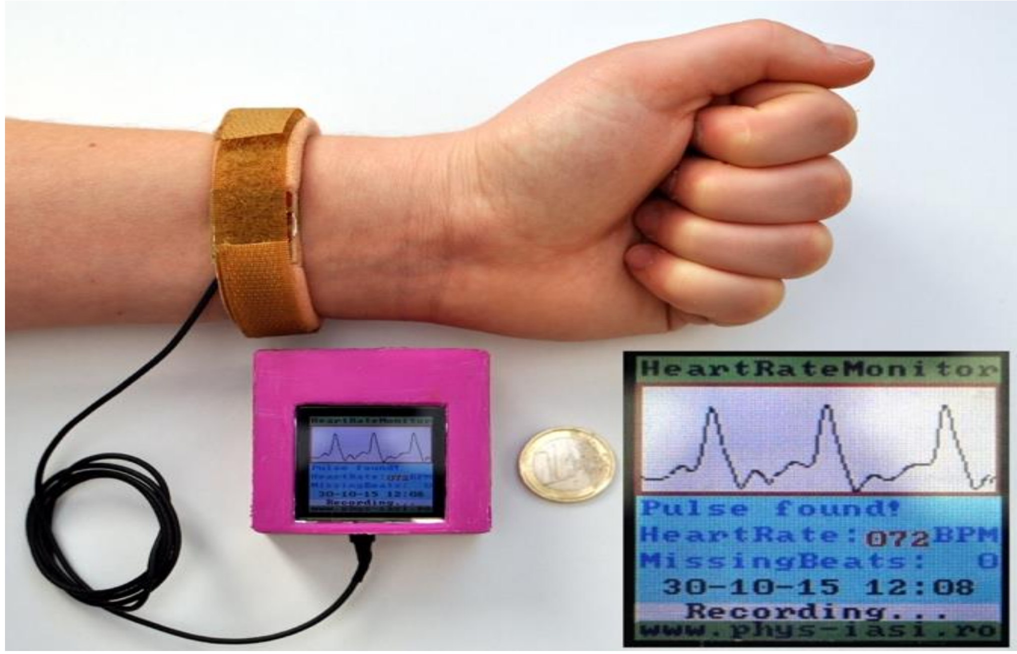
Schematic of the sensor configuration for the detection of vibrations generated by the water flow.

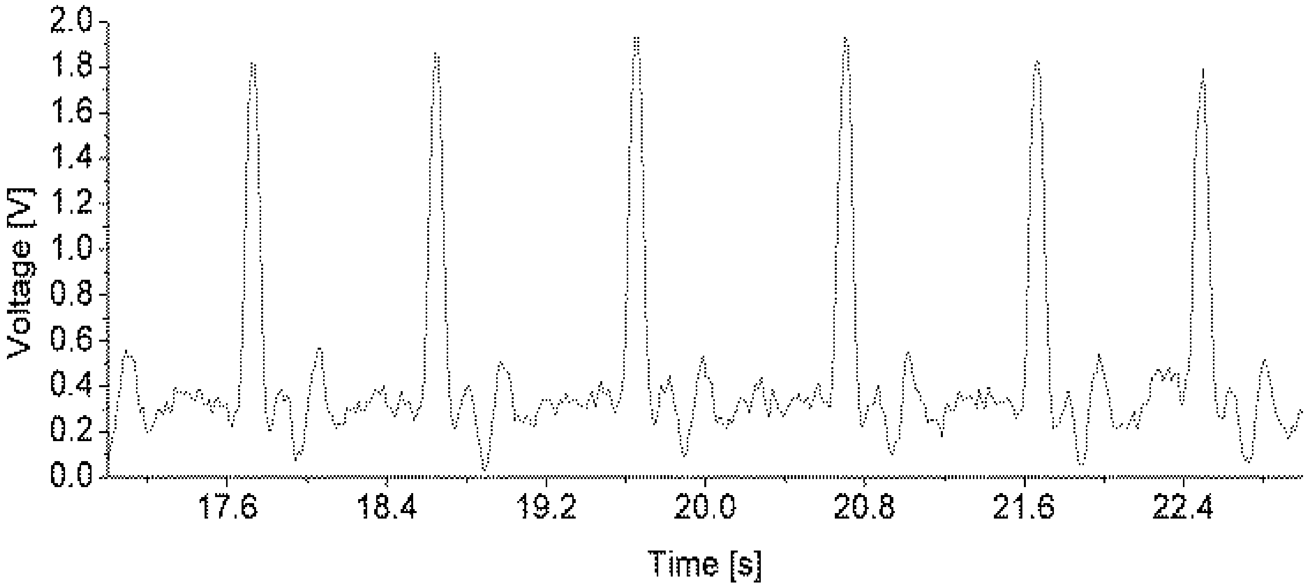
Sensor output voltage vs. volumetric flow rate of water for the proposed magneto-impedance sensor using an amorphous wire as the sensing element.





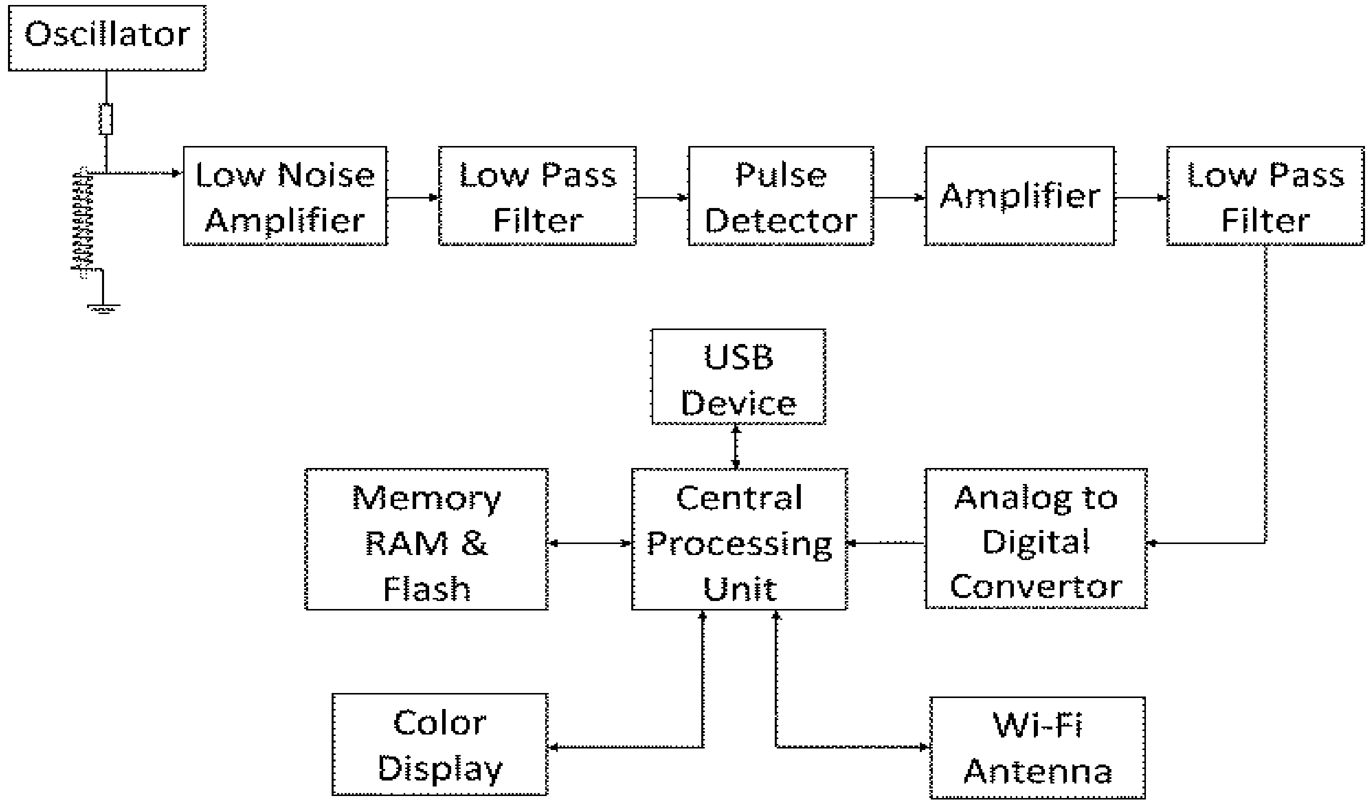
Pulse wave detection magnetoelastic sensing device based on nanocrystalline microwires for the indirect diagnosis of paroxysmal rhythm disorders





- The sensor consists of a magnetic microwire – the sensing material – and a small coil wound around it.
- **The magnetic microwire should exhibit a very high magnetic permeability and a strong dependence of permeability on mechanical strain**.
- A nearly zero magnetostrictive amorphous wire ($Co_{68.18}Fe_{4.32}Si_{12.5}B_{15}$), with a large permeability which varies with mechanical strain, has been previously used to demonstrate the operating principle for such an application.

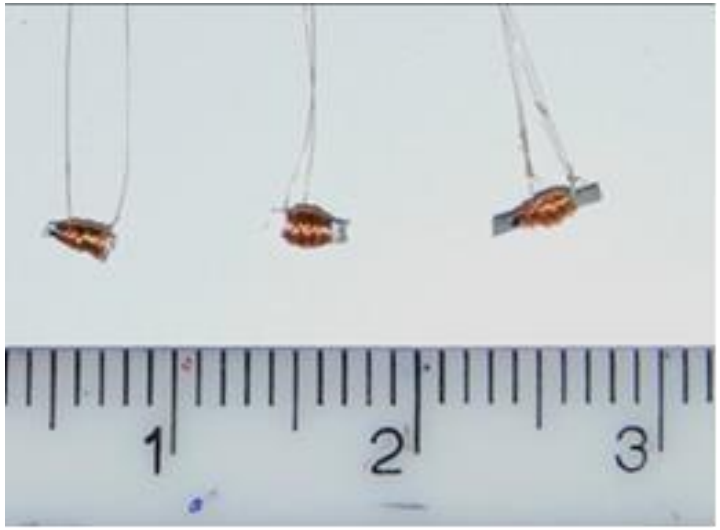
Pulse wave detection magnetoelastic sensing device based on nanocrystalline microwires for the indirect diagnosis of paroxysmal rhythm disorders



The device consists of two main parts, the first one being for analog signal processing, whereas the second one is for digital signal processing.

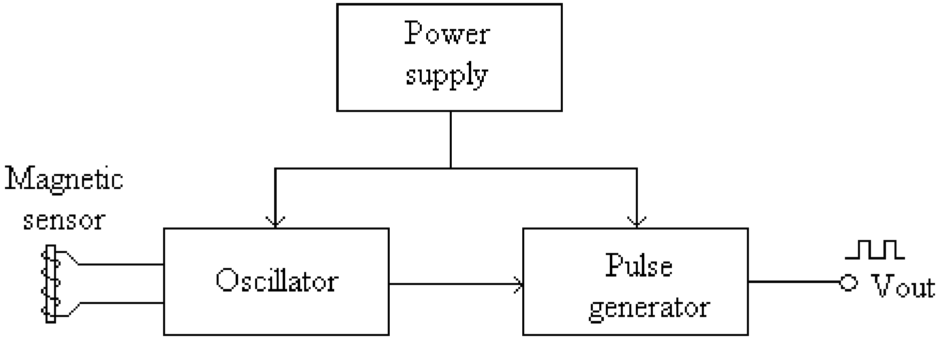
- The magnetoelastic sensor device could approximate intra-arterial pressure operating as a non-invasive blood pressure measurement device.
- By processing the detected signal amplitude during tachyarrhythmia compared with detected signal amplitude during sinus rhythm could allow the indirect diagnosis of arrhythmias origin.
- A decreased signal during arrhythmia compared with the signal during normal sinus rhythm is suggestive for ventricular arrhythmia origin.
- The decreased amplitude of the signal could be appreciated by direct observation of monitor by the patients themselves.

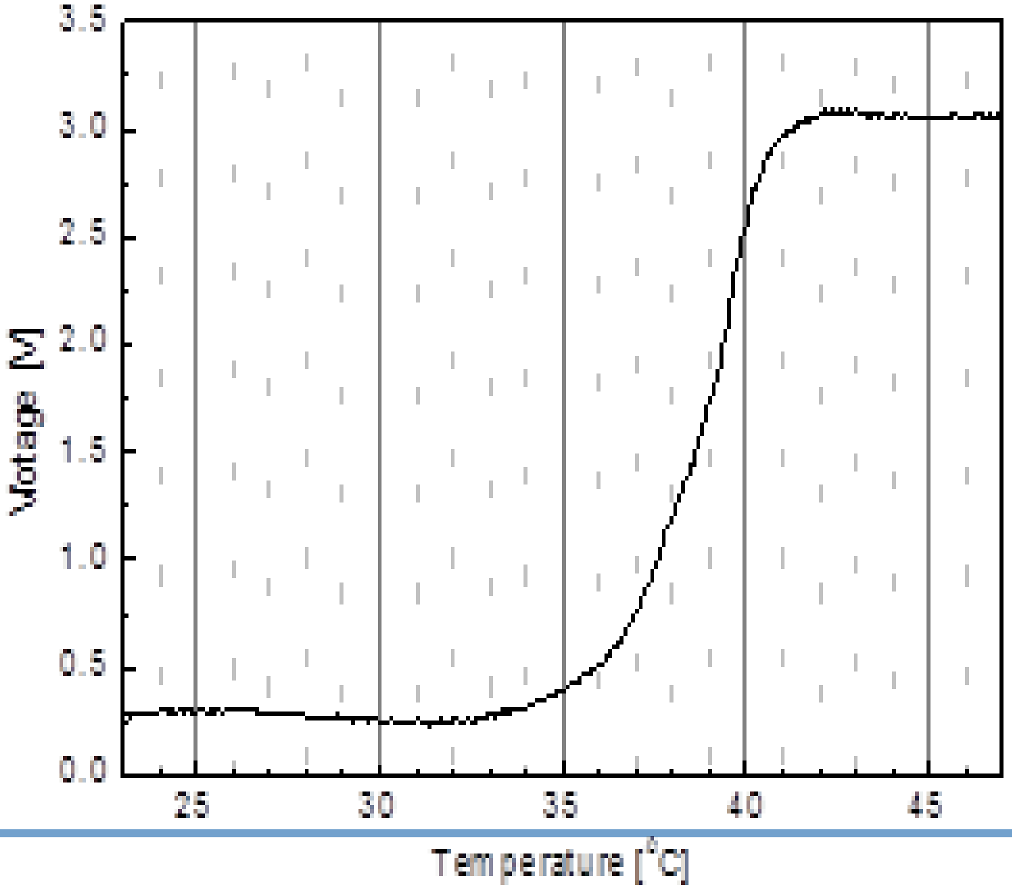
Low T_C temperature sensor



The sensor operation is based on the change of magnetization with temperature of a magnetic core having the Curie temperature ranging between 20ºC and 70ºC.

The skin temperature microsensor is built by winding 150 turns on a temperature-sensitive magnetic material (e.g., magnetic Fe-Cr-Nb-B MSRs)





The measurable parameter of the sensor is the frequency, which depends on temperature, but using a frequency to voltage converter the sensor can give a voltage output proportional to temperature.

Sensors based on magnetic wires and microwires

The large Barkhaussen effect (LBE), Matteucci effect, inverse Wiedemann effect, GMI effect, LGE effect, Magnetostrictive Delay Line (MDL) effect are in fact the operating principles for magnetic sensors based on wires and microwires.

Magnetic sensors based on wires and microwires:

(1) Magnetic field sensors
(2) Vibrating sensors
(3) Position sensors
(4) Displacement sensors
(5) Torque sensors
(6) Stress sensors
(7) NDT sensors
(8) Electronic Surveillance Labels / Tags
(9) Safety Systems
(10) Fluxgate sensors
(11) Microsensors for blood pressure and heartbeat monitoring, magneto-encephalography, etc.
(12) Biosensors for the detection of biomolecules

Energy Harvesting Devices (EHD)

What is energy harvesting?

Energy harvesting is commonly defined as the conversion of ambient energy into electrical energy.

Ambient energy - Energy is all around us, in many different forms – thermal, chemical, electrical, mechanical and more.

Requirement: a suitable transducer to convert the energy.

Off-grid energy - Energy harvesting is used where another supply of energy is not available. Harvesters cost money, so it only makes sense to use them when it is too expensive or physically impossible to use other energy sources such as grid electricity or batteries.

On-demand energy - An energy harvester has to supply power when it is needed, not simply when it is available, and some form of energy storage is generally required to match the demand with the supply.

Sources of energy

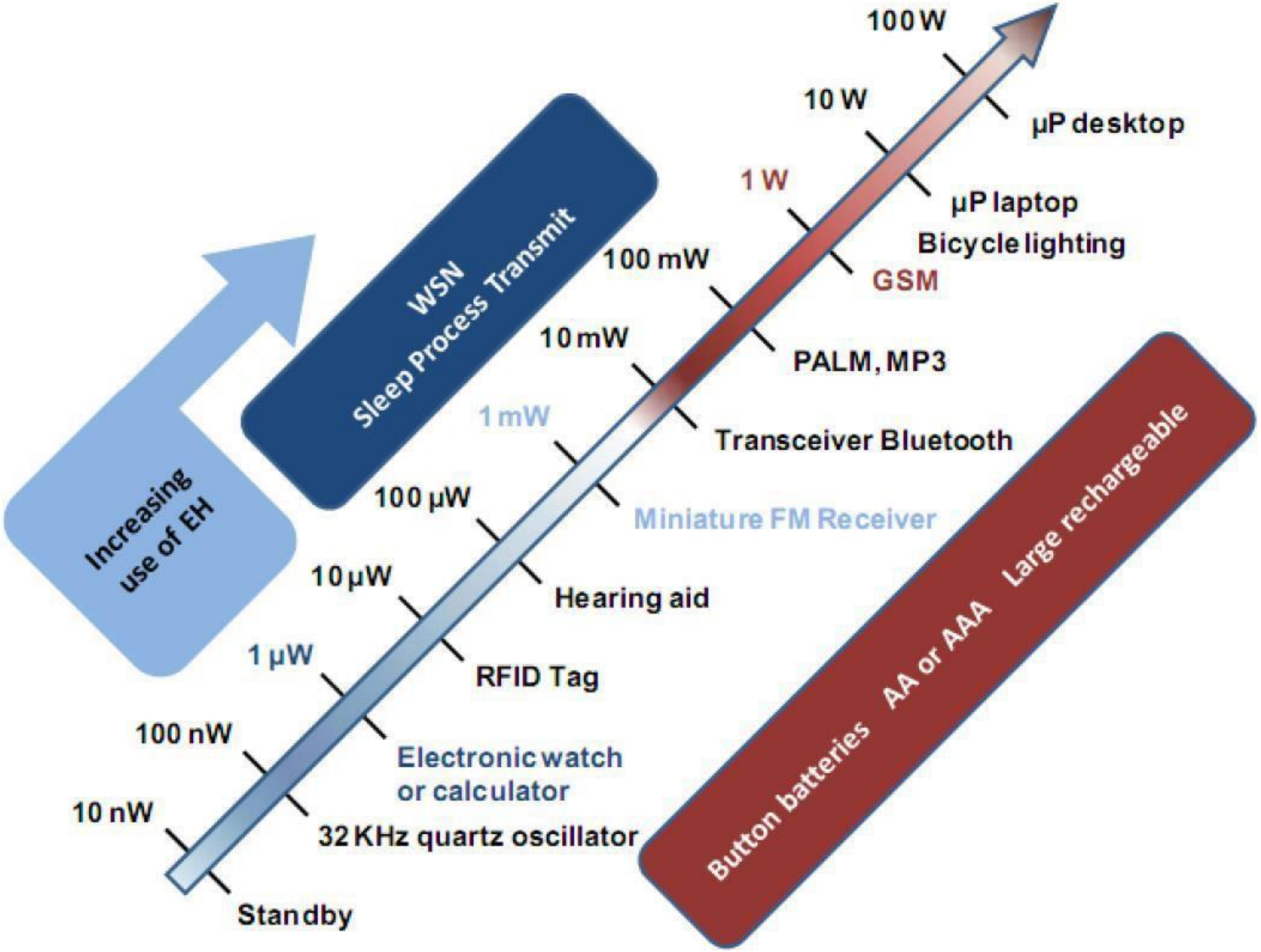
- Radiation (light, solar, cosmic rays, electromagnetic radiation)
- Thermal
- Mechanical (potential, kinetic, elastic, fluid)
- Gravitational
- Chemical (battery, fuel cell, fossil fuels, phase change)
- Nuclear
- Magnetic (magnetisation, currents etc)
- Electric

However, in practice many have no value for energy harvesting.

Types of energy by location

Energy Source / Location	Radiation	Wind	Sunlight	Artificial lighting	Human	Machine vibration	Tidal	Gravitational hydroelectric	Thermal gradients
Home / Office	X			X	X				
Roadside	X	X	X						
Bridge	X	X	X			X		X (river)	
Vehicle	X	X	X			X			X
Pumping Station	X	X	X			X			X
Oil Rig	X	X	X			X	X		X
Battlefield	X	X	X		X	X			

Energy usage requirements for a range of devices



Source IDTechEx report "Energy Harvesting and Storage for Electronic Devices 2009-2019".

Energy usage requirements for a range of devices

Device	Power usage	Energy usage over 24 h	Assumptions
Cardiac pacemaker	50 μW	5 J	70 beats per minute
Wired sensor	100 μW	10 J	1 Hz strain sensor
Wireless sensor	1 mW	10 J	Humidity sensor 10% duty cycle
Hearing aid	0.4 mW	70 J	Continuous
Mobile phone	15 mW standby 1.5 W transmit	5 kJ	23¼ hours standby 45 minutes talk time
GPS receiver	100 mW	8 kJ	Continuous
Low power computer	2W	60 kJ	8 hours on, 16 hours off
Laptop computer	15 – 25 W	500 kJ	8 hours on, 16 hours off
Desktop computer	50 – 150 W	5 MJ	8 hours on, 16 ours standby

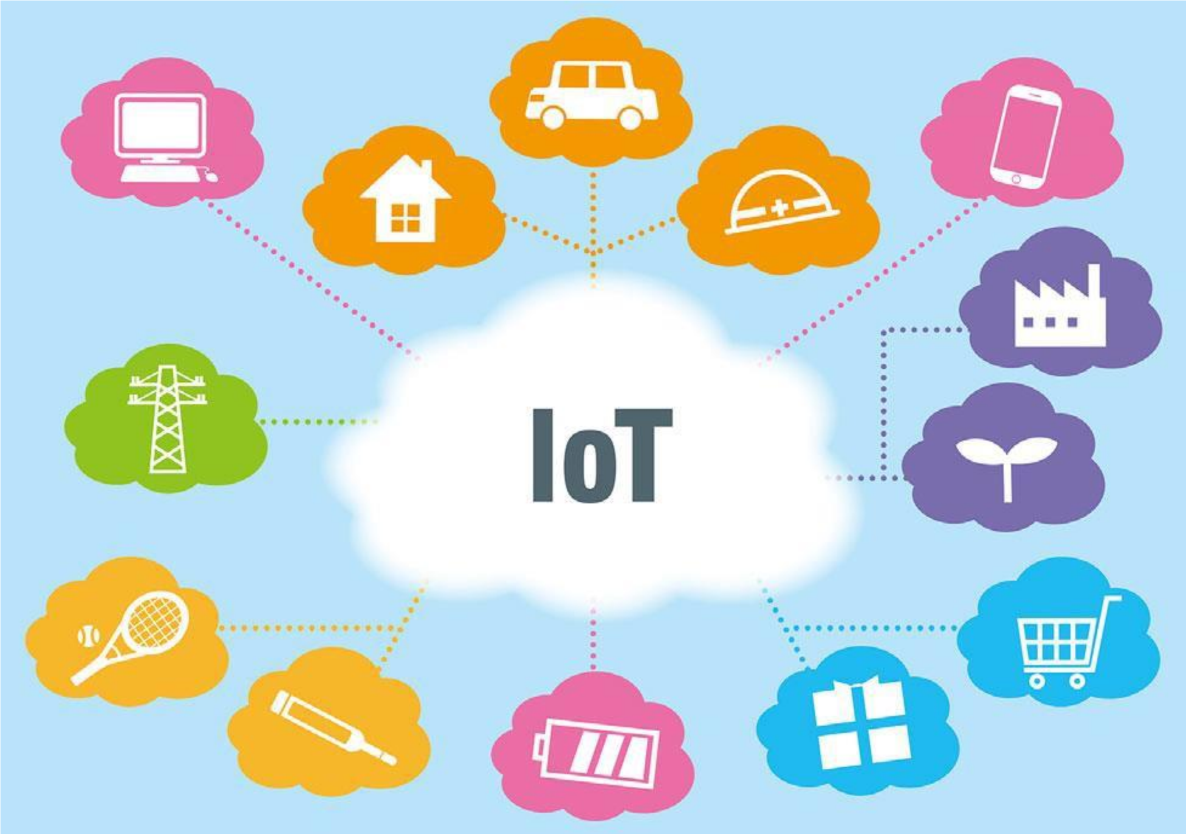
When is the energy harvesting useful?

1) **There is a match between the available energy and the energy needed.**
2) **Energy harvesting provides a benefit that is not achievable using batteries or grid electricity.**

Energy field	Transducer	Shortcomings
Light	Photovoltaic cells	Efficiency is typically 15 to 20%. It’s not always best to have the highest efficiency, as a larger lower efficiency device may provide the power at lower cost.
Vibration	Linear electromagnetic generator	Harvesters can only harvest at a single frequency, and vibrations must be high amplitude. Power harvested is proportional to the vibrating mass in the harvester, so bigger is better.
Heat / Temperature	Peltier thermoelectric module	Power produced is proportional to the square of the temperature difference across the Peltier module, so big temperature differences (50^{0}C) are much more useful than small ones (5^{0}C).

Smart cities

Piezoelectric ceramics/polymers

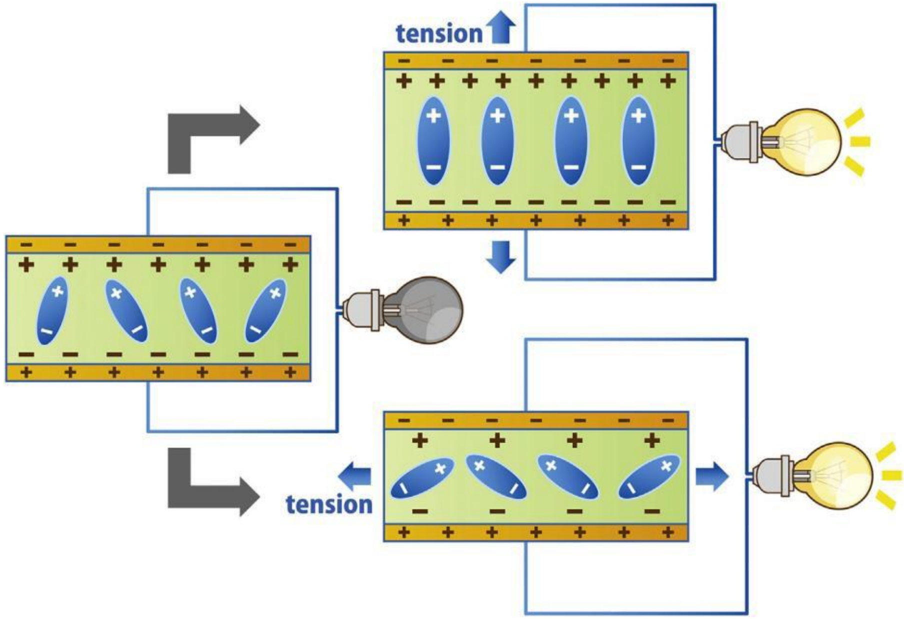


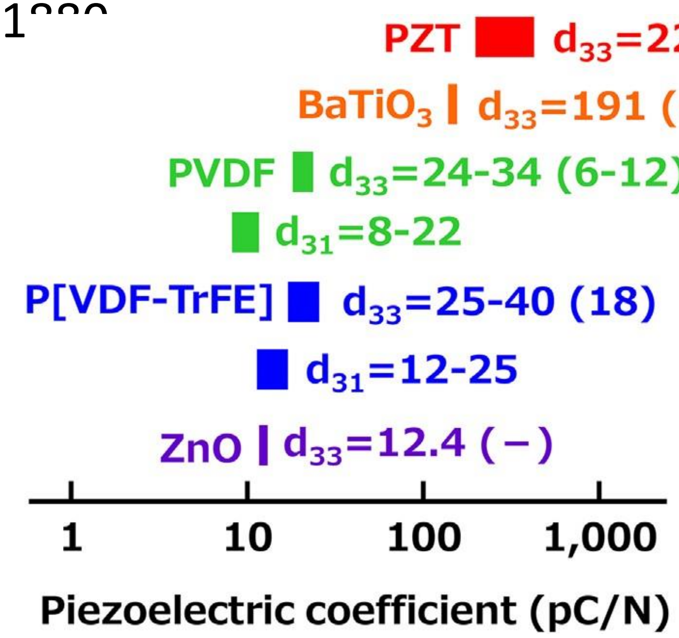
Magnetostrictive alloys

Magnetoelectric (ME) multiferroic composites

Piezoelectric ceramics/polymers

Piezoelectricity - the change in polarization that some materials, such as ferroelectrics, undergo when subjected to mechanical deformation (vibrations or strain).
Jacques and Pierre Curie discovered piezoelectricity in 1880.



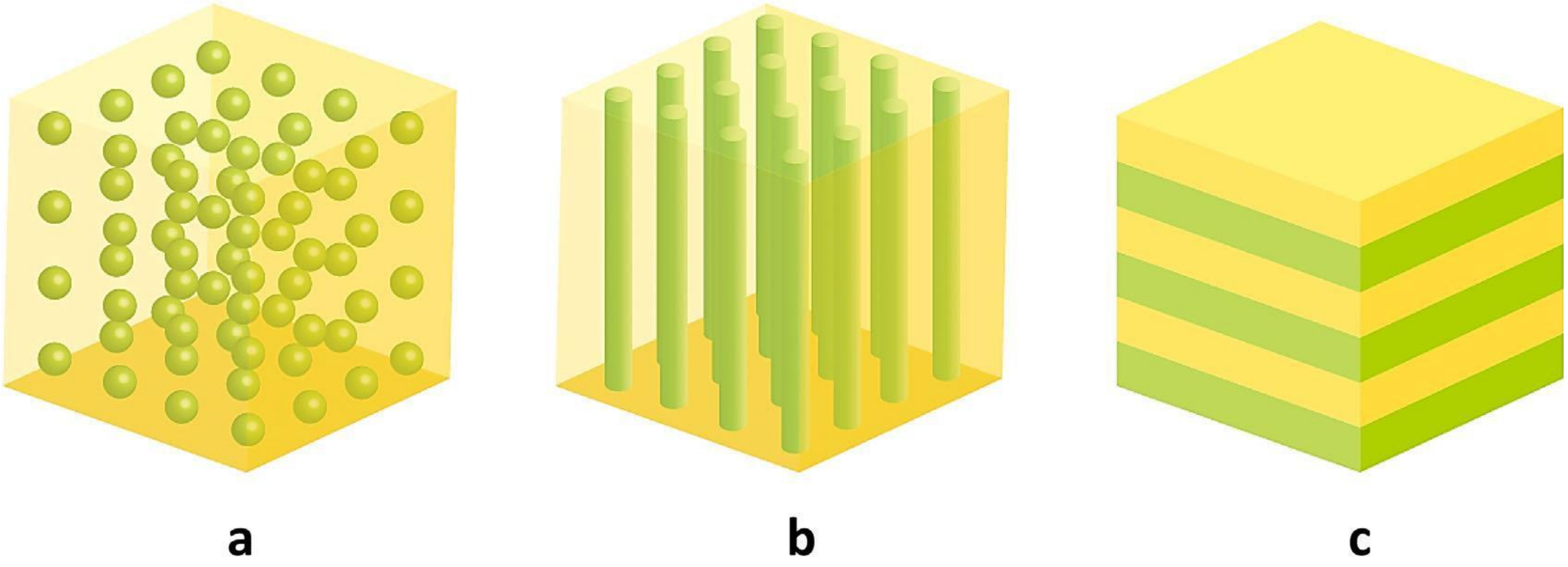


Piezoelectric polymers:
- polyvinylidene fluoride (PVDF),
vinylidene fluoride trifluoroethylene (P(VDF-TrFE))

Advantages over piezo-ceramics of the piezoelectric polymers: flexible and with large elastic compliance; can easily be formed on the surfaces of curved structures.

Piezoelectric ceramics/polymers

The piezoelectric effect is a reversible process: materials exhibiting the piezoelectric effect (the internal generation of electrical charge resulting from an applied mechanical force) also exhibit the reverse piezoelectric effect, the internal generation of a mechanical strain resulting from an applied electrical field.



Schematic of composite types: a) 0–3, b) 1–3, and c) 2–2.

Magnetostriction and magnetoelastic coupling

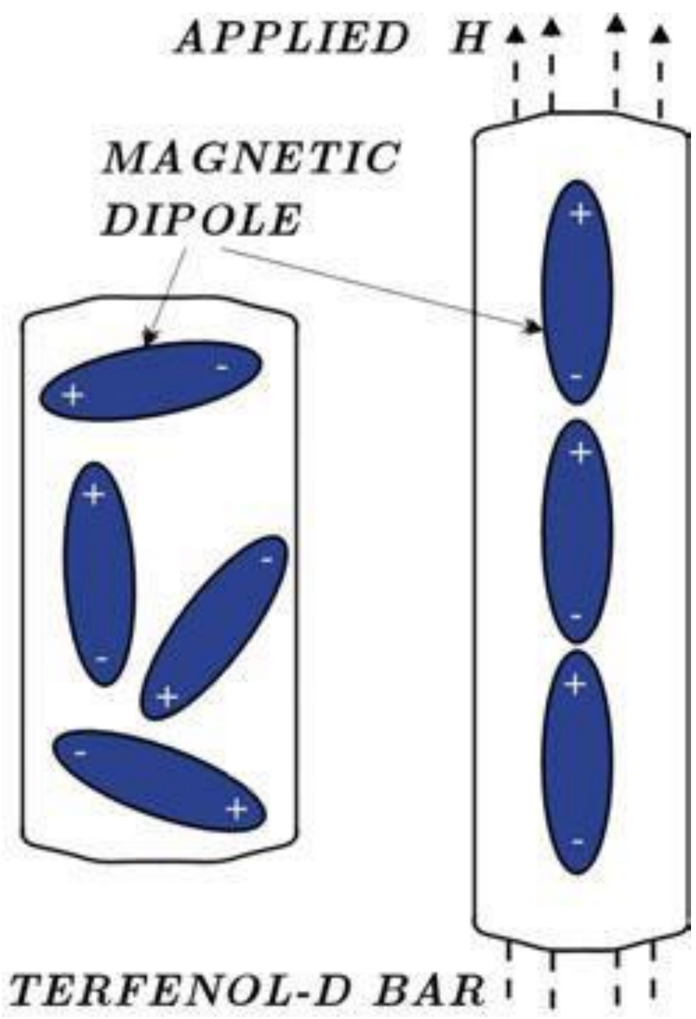
Magnetostriction is a property of ferromagnetic materials that causes them to change their shape when subjected to a magnetic field. The effect was first identified in 1842 by James Joule when observing a sample of nickel.

Magnetoelastic coupling : The interaction between the magnetization of a magnetic material and the strain.

Magnetostriction

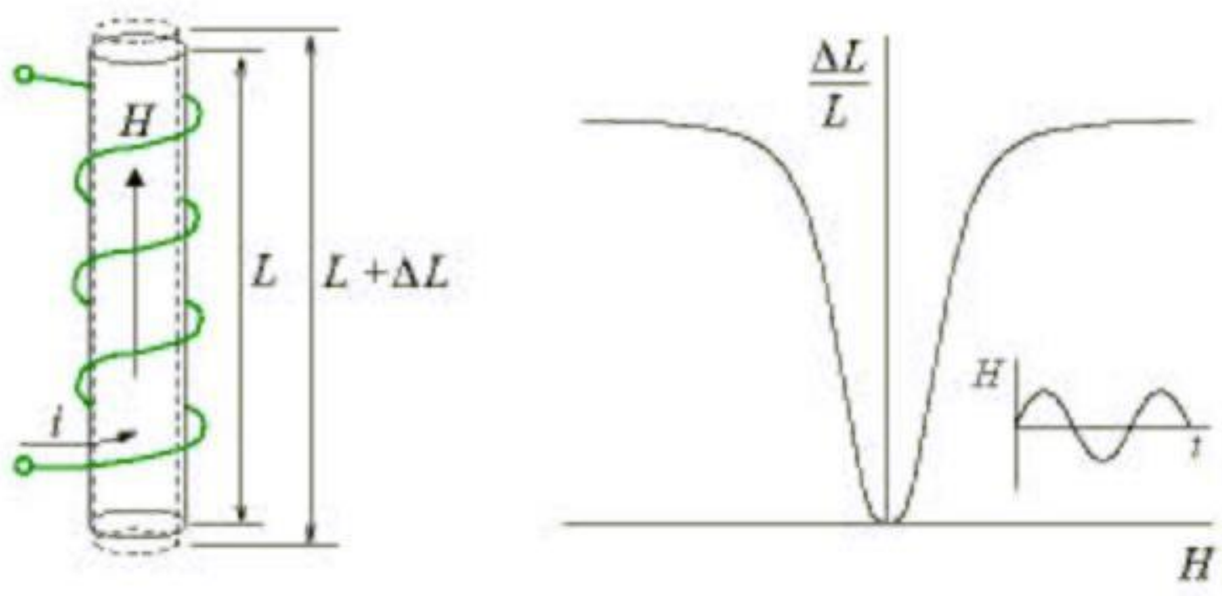
Magnetostriction is a phenomenon observed in all ferromagnetic materials. It couples elastic, electric, magnetic and in some situations also thermal fields and is of great industrial interest for use in sensors, actuators, adaptive or functional structures, robotics, transducers and MEMS.

A magnetostrictive material develops large mechanical deformations when subjected to an external magnetic field. This phenomenon is attributed to the rotations of small magnetic domains in the material, which are randomly oriented when the material is not exposed to a magnetic field. The orientation of these small domains by the imposition of the magnetic field creates a strain field. As the intensity of the magnetic field is increased, more and more magnetic domains orientate themselves so that their principal axes of anisotropy are collinear with the magnetic field in each region and finally saturation is achieved.



Magnetostriction

Magnetostriction or **Joule magnetostriction** is a consequence of the **magnetoelastic coupling**. It pertains to the strain produced along the field direction and is the most commonly used magnetostrictive effect.
Joule magnetostriction is the coupling between the magnetic and elastic regimes in a magnetostrictive material.
Magnetostriction is **an intrinsic property of magnetic materials.**



Magnetoelastic effects

Direct Effects	Inverse Effects
Joule magnetostriction Change in sample dimensions in the direction of the applied field	**Villari effect** Change in magnetization due to applied stress
ΔE effect Magnetoelastic contribution to magnetocrystalline anisotropy	Magnetically induced changes in the elasticity
Wiedemann effect Torque induced by helical anisotropy	**Matteuci effect** Helical anisotropy and e.m.f. induced by a torque
Magnetovolume effect Volume change due to magnetization (most evident near the T_C)	**Nagaoka-Honda effect** Change in the magnetic state due to a change in the volume

Magnetostrictive Materials

TERFENOL-D

1. Cubic C15 structure
2. Large magnetostrictive strains of the order of 0.1 % at and above RT
3. Brittle, large field for saturation, expensive Tb and Dy

METGLAS

1. Amorphous
2. Low saturation magnetostriction (30÷40 ppm for Fe-B-Si alloys)
3. Low field for saturation, large magnetomechanical coupling coefficient

Alternatives:

- Fe-(Ga,Al) alloys (Galfenol/Alfenol), as single crystals and polycrystalline melt- spun ribbons
- Ni-Mn-Al and Co-based magnetic shape memory alloys (MSMs)

Properties of Different Smart Materials

Material	Material Type	Maximum Strain (%)	Actuation Voltage (V)	Relative Response Speed	Curie Temperature (K)
$Tb_{0.3}Dy_{0.7}Fe_{1.9}$ (Terfenol-D)	Magnetostrictor	0.16-0.24	< 15	Fast	653
KelvinAll® (EMERGEN)	Magnetostrictor	0.14-0.2	< 15	Fast	660
Fe-Ga (Galfenol)	Magnetostrictor	0.013-0.025	< 15	Fast	~923
Ni-Mn-Ga	FSMA	5	> 50	Fast	~380
Ni-Ti (Nitinol)	SMA	> 5	10-20	Slow	N/A
PZT	Piezoelectric	0.12	> 1000	Fast	N/A
P(VDF-TrFE)	Electroactive polymer	4	10-100	Medium	N/A

Comparison between vibration energy harvesters

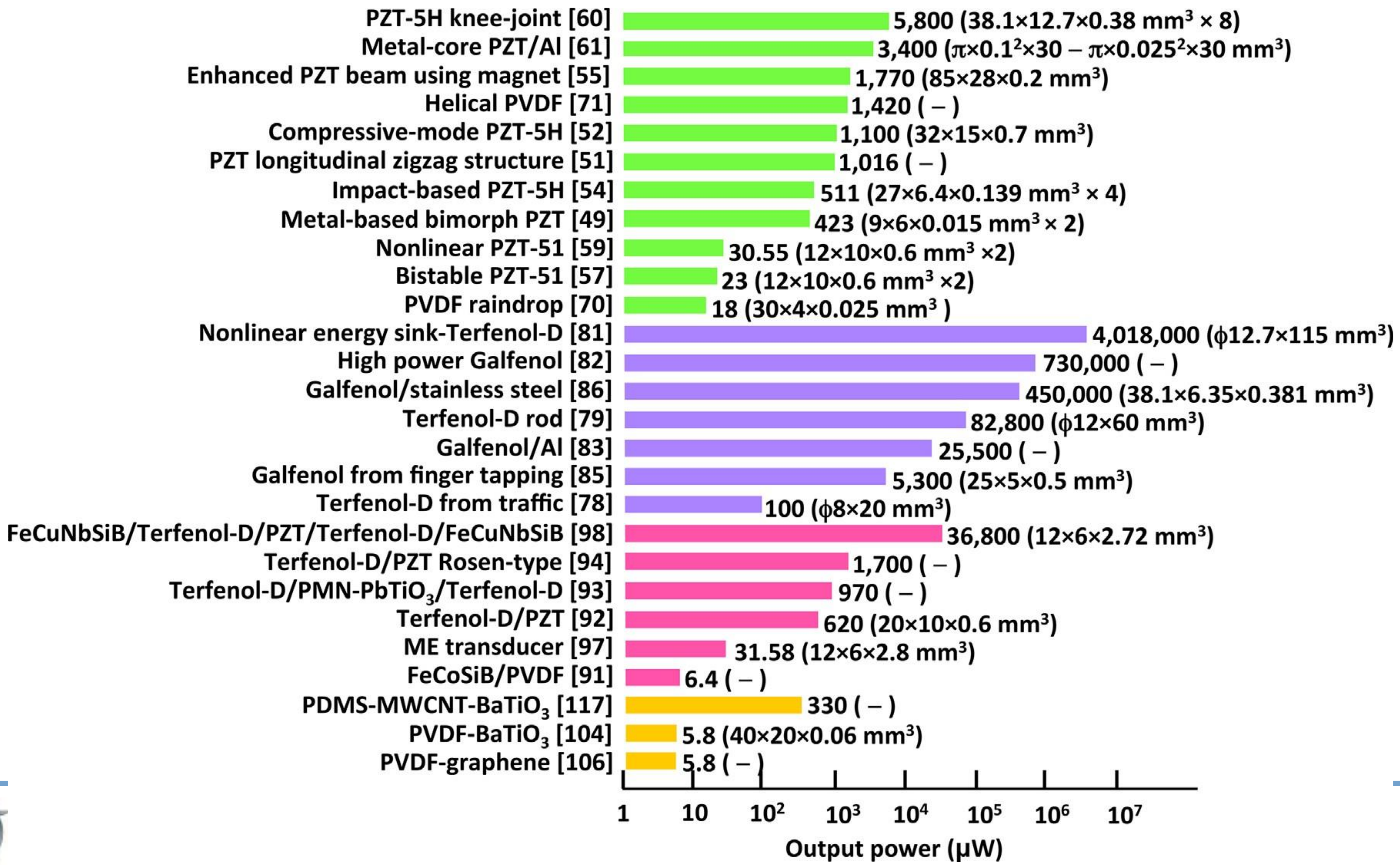
Type	Advantages	Disadvantages
Electromagnetic	1) passive materials 2) low output impedance	1) bulky pickup coils 2) bulky magnets
Electrostatic	1) passive materials 2) compatible with MEMS	1) need external voltage/charge sources 2) high output impedance 3) charge leakage
Piezoelectric	1) compatible with MEMS 2) high coupling coefficient	1) depolarization/aging 2) brittle bulk piezolayer 3) flexible PVDF with low coupling 4) high output impedance 5) charge leakage
Magnetostrictive	1) high coupling coefficient 2) no depolarization/aging 3) high mechanical strength (Galfenol/Metglas/Alfenol) 4) low output impedance 5) high frequency application 6) can possibly be compact (through microscale deposition)	1) highly nonlinear 2) bulky bias magnets and pickup coils

Magnetoelectric (ME) multiferroic composites

- The ME effect has been observed in a very few single-phase materials such as Cr_2O_3 and $BiFeO_3$. However, in general the ME effect is weak at RT.
- Piezoelectric-piezomagnetic composites can exhibit a large ME effect around RT.
- Combinations of FE and FM materials:
  - Vitrovac/PVDT trilayered and bilayered flexible ME composites (75V/cmOe in trilayers and 66V/cmOe in bilayers),
  - FeNi/PZT laminate and multipole magnetic rings,
  - Ni foils/high capacitance PZT plate,
  - ME particulate composite films composed of Terfenol-D particles embedded in P(VDF-TrFE) (70/30),
  - planar structure containing mechanically coupled layers of amorphous FeBSiC ferromagnet and PVDF,
  - Fe73.5Cu1Nb3Si13.5B9/Terfenol-D/Be-bronze/PZT (FTBP) laminates,
  - textured PZT thin films deposited on nickel substrates using a pulsed laser deposition (PLD) technique, and so on…

Progress of energy harvesters

F. Narita and M. Fox, *Adv. Eng. Mater.* 2018, **20**, 1700743



Energy Harvesting Device (EHD) based on nanocrystalline ribbons

The most important aspects of our work focused on two main directions:

(i) preparation and characterization of the magnetic material to be used as a core for the electromagnetic energy harvesting devices,

(ii) design and testing of the energy harvesting devices in order to achieve maximum electrical power.

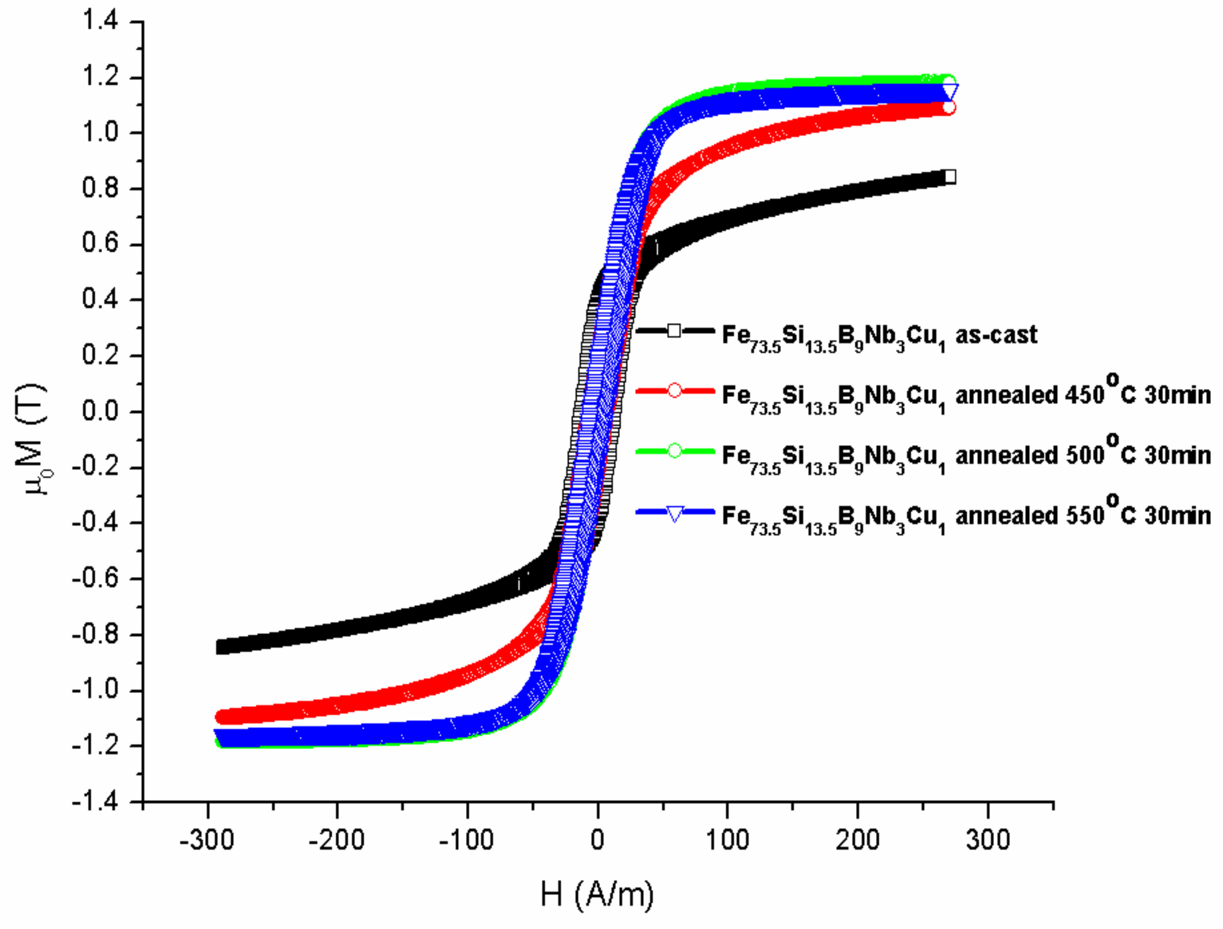
Requirements:

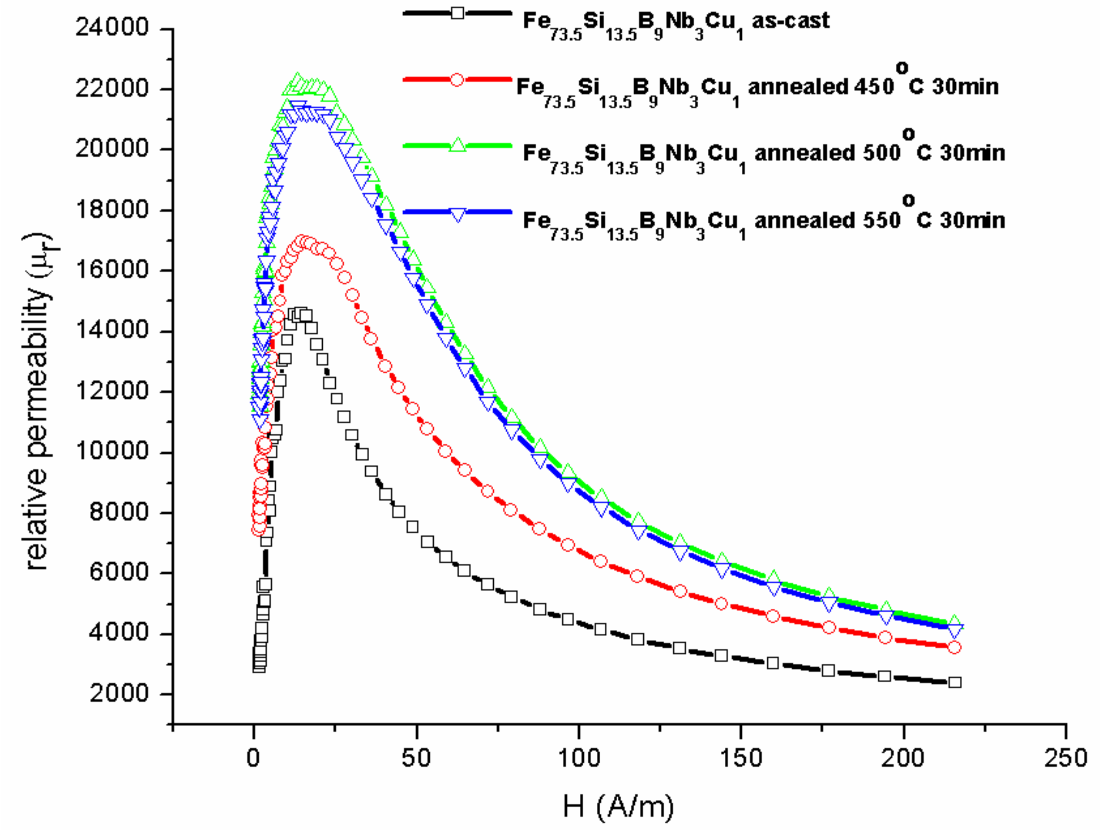
1) high magnetic permeability
2) large saturation magnetization

The best candidates are the high permeability soft magnetic materials, such as amorphous and/or nanocrystalline ribbons, for the following reasons:

- enhanced magnetic and magnetoelastic properties;
- possibility to tailor the properties by adjusting the composition of the alloy and/or annealing conditions.

Energy Harvesting Device (EHD) based on nanocrystalline ribbons





Different annealing parameters were tested to optimize the core material.

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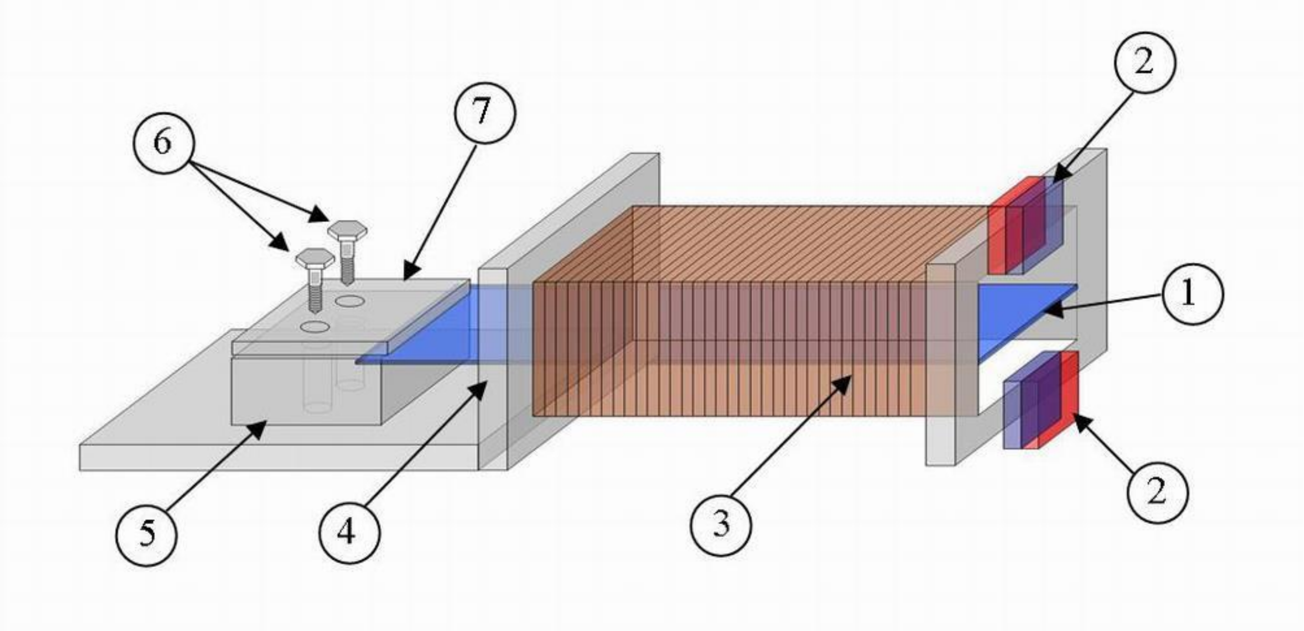
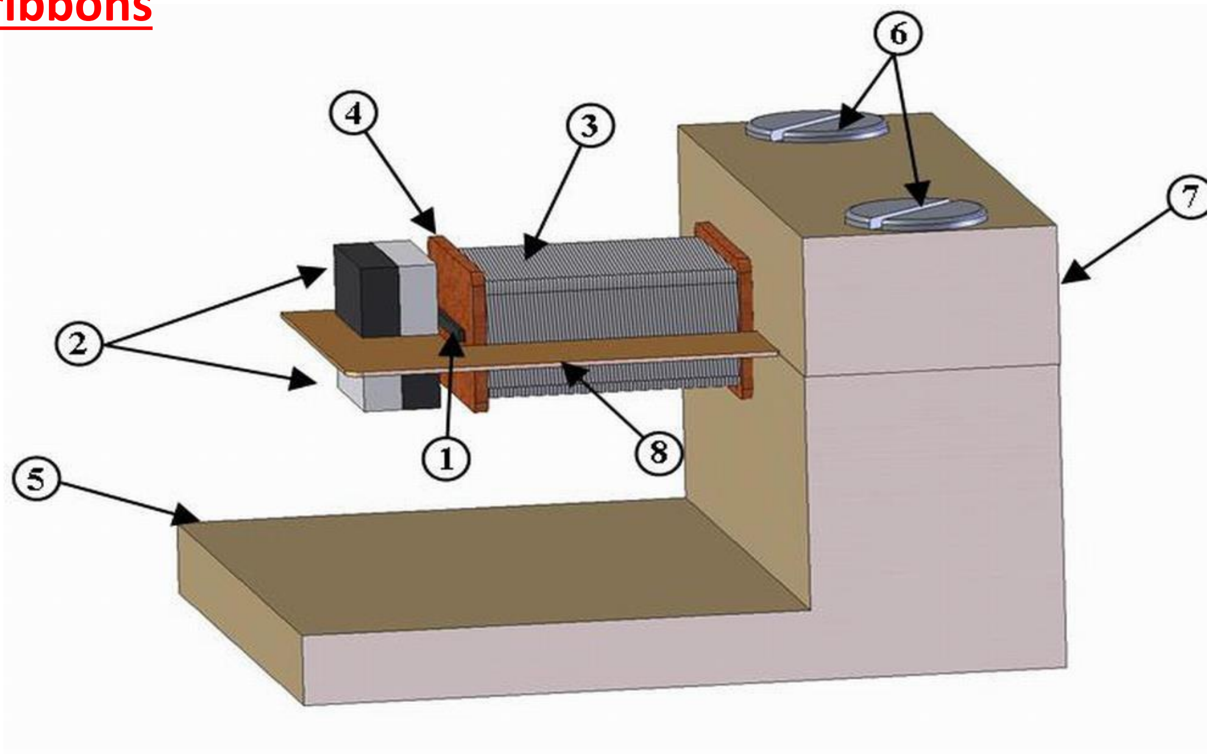
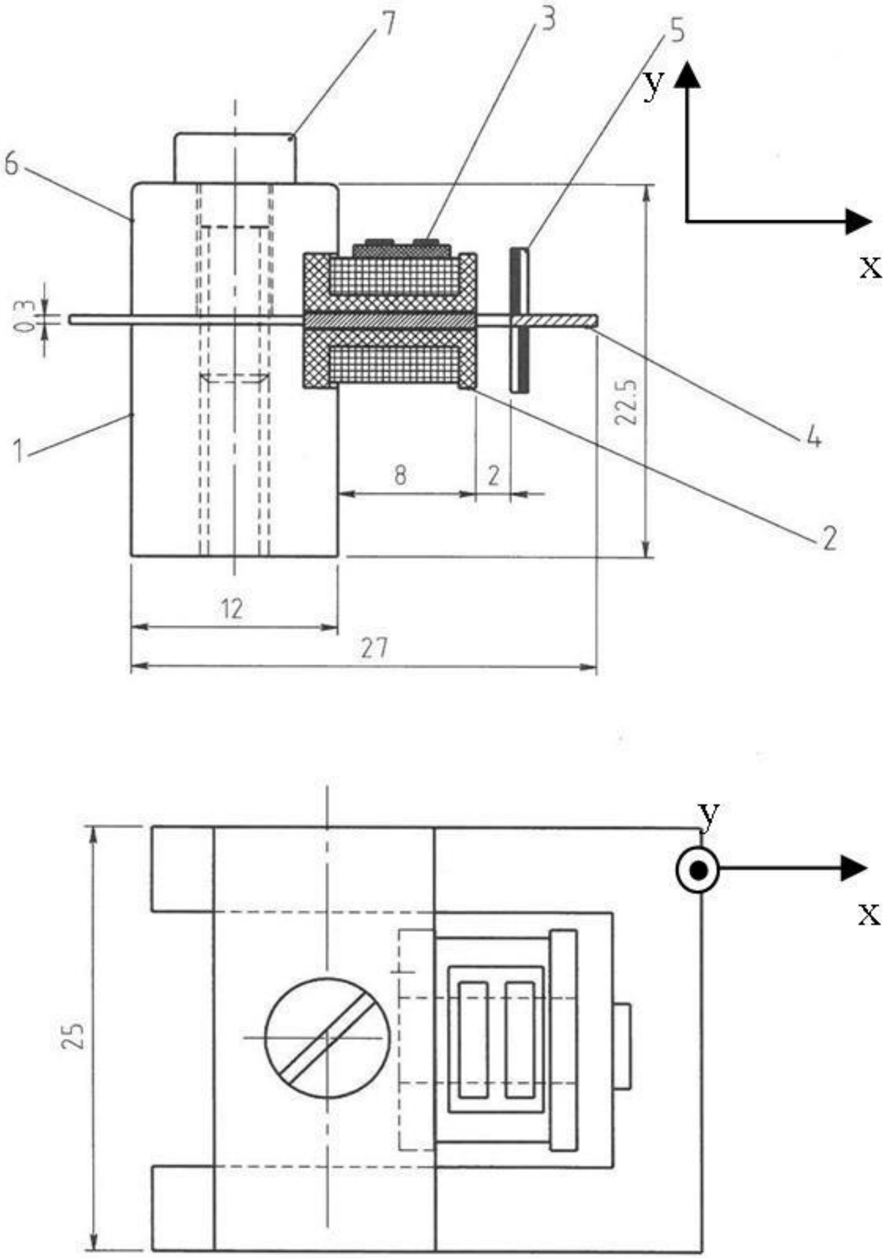


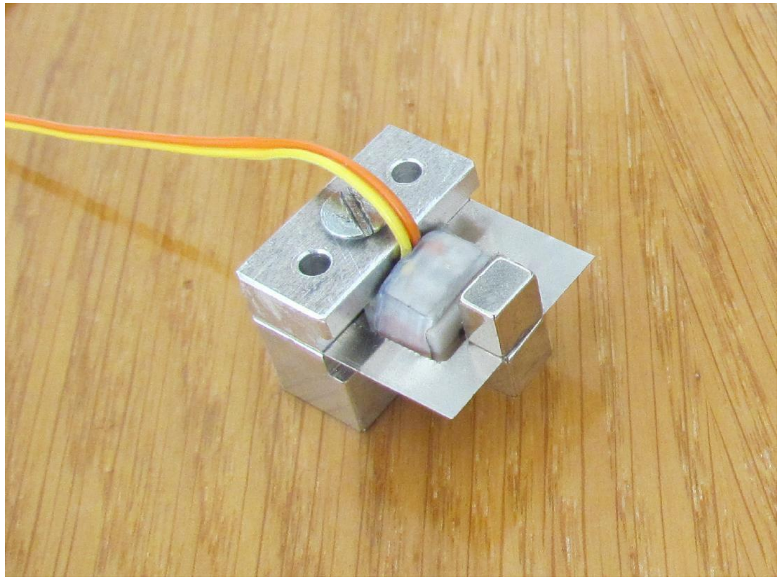
First configuration of the harvester prototype:
(1) multilayer nanocrystalline ribbons beam anchored in a support to work as a cantilever; (2) permanent magnets; (3) coil; (4) coil housing; (5) fixing support; (6) fixing screws; (7) fixing plate.



Second configuration of the harvester prototype:
(1) Multilayer nanocrystalline ribbons core; (2) permanent magnets; (3) coil; (4) coil housing; (5) fixing support; (6) fixing screws; (7) fixing plate; (8) cantilever.

Energy Harvesting Device (EHD) based on nanocrystalline ribbons

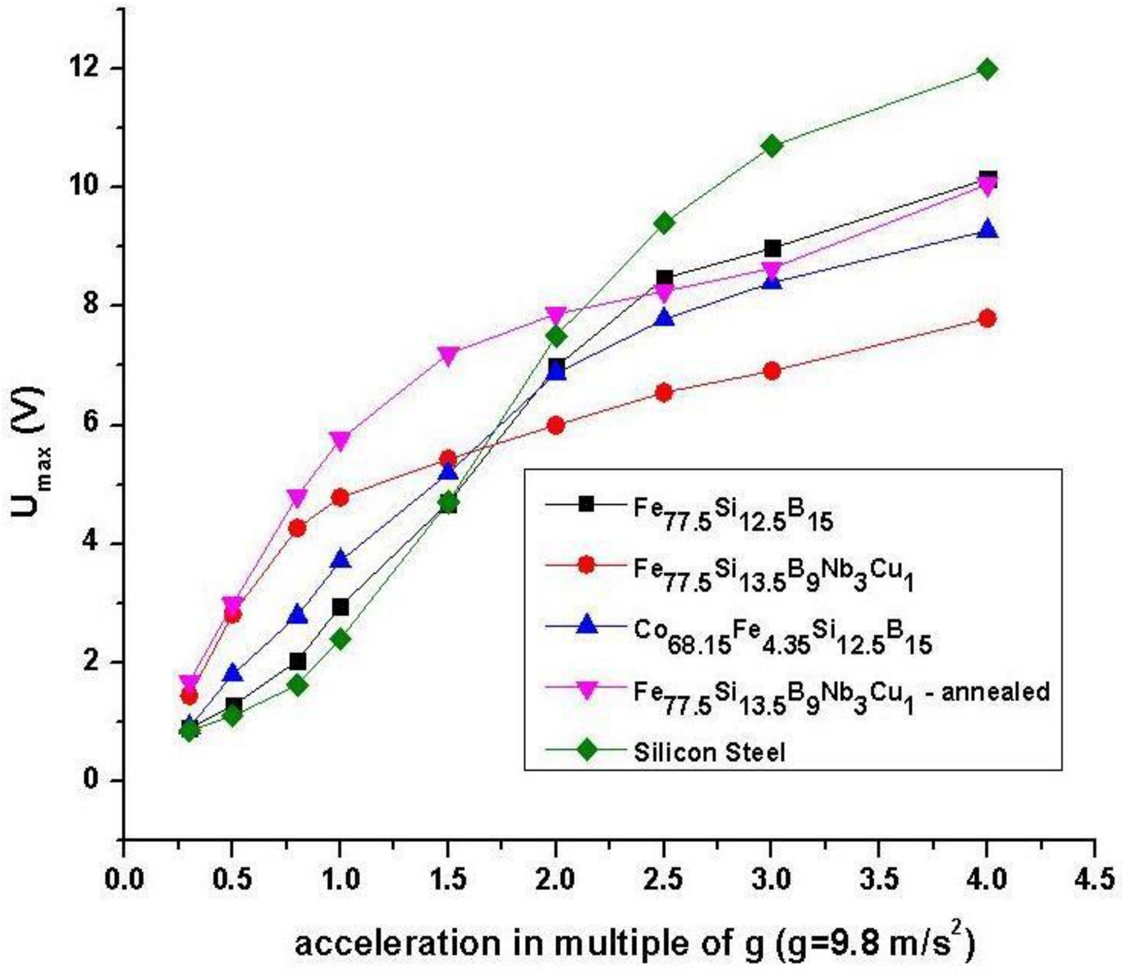




Small electrical generator:
1 — support; 2— coil; 3 — soldering pads; 4 — elastic lamella;
5 — permanent magnets pair; 6 — fixing plate; 7 — screw.

M. Tibu et al., IEEE Trans. Magn. 50(11) (2014) 8002204

Energy Harvesting Device (EHD) based on nanocrystalline ribbons



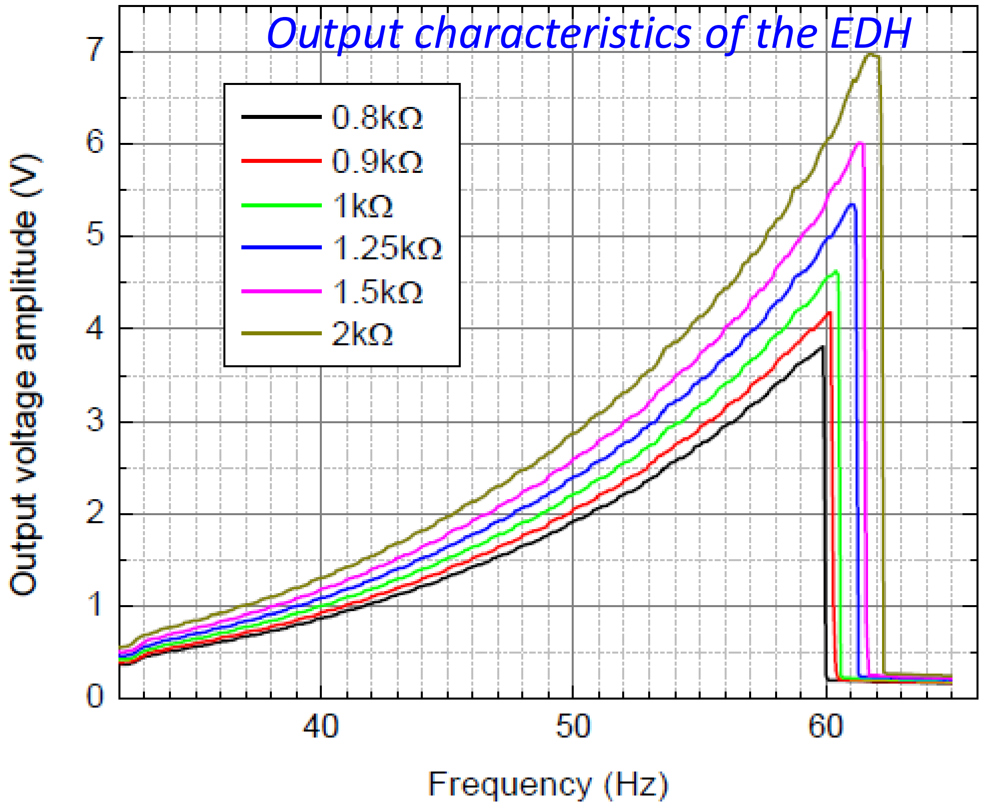
By using a multilayer nanocrystalline core with high magnetic permeability, one has the advantage of obtaining higher voltage and power at low acceleration levels of the vibration source.

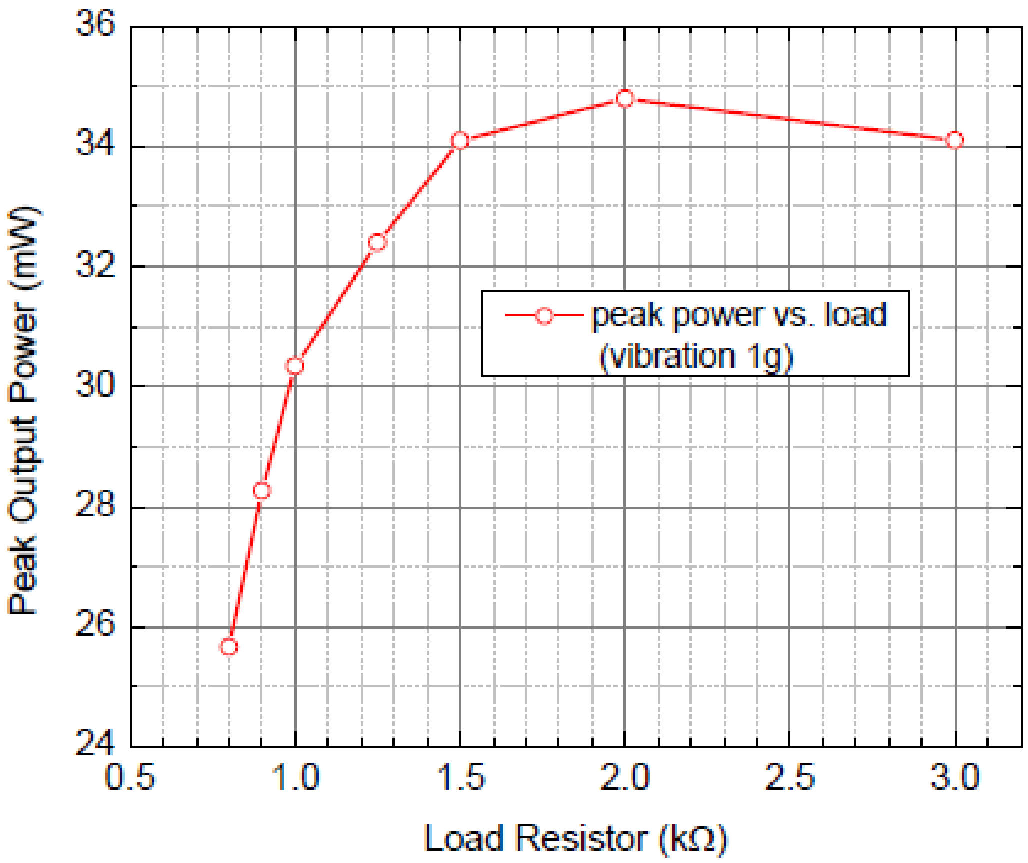
This is an important achievement for an energy harvester, since the most common acceleration levels of the vibration met in practice are not always very high.

M. Tibu et al., IEEE Trans. Magn. 50(11) (2014) 8002204

Energy Harvesting Device (EHD) based on nanocrystalline ribbons

The maximum output power (peak power) delivered on the load resistor (R_{load}= 1.5÷2 kΩ) was 35 mW for an acceleration of 1g.





Maximum power density: 46.5 mW/cm³
Conversion efficiency of the generator: more than 50%

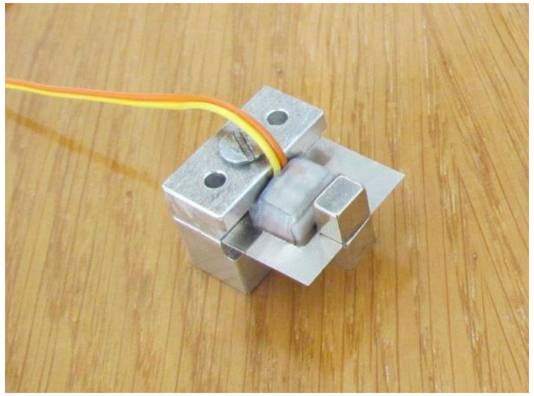
Resonant frequency: 47 Hz
Bandwidth: 5 Hz

Energy Harvesting Device (EHD) based on nanocrystalline ribbons

Alternatives for improving the performances of the EHD:

1) use materials with high B_s and high μ for the core;
2) use small and powerful PMs (NdFeB);
3) increase the surface of the circuit by increasing the number of turns - **limited by the requirements regarding miniaturization and internal resistance**;
4) increase the rate of flux change by the frequency of oscillations – **limited by the application (vibration spectrum)**;
5) optimize the harvester design.

Energy Harvesting Device (EHD) based on nanocrystalline ribbons



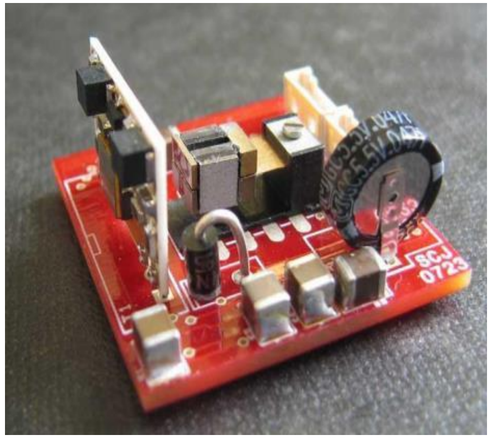
Vibrations - promising renewable and reliable source of energy for mobile electronic and WSN powering.

A strong magnetic coupling between the coil's core and the permanent magnets determines the enhanced output power and power density compared with the conventional air cored electromagnetic harvesters.

Our electromagnetic generator : 35 mW @ 1g (47 Hz)

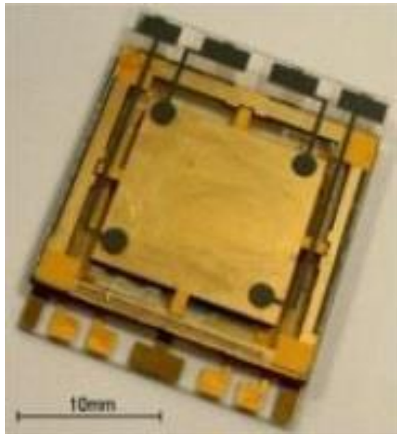
Perpetuum PMG17 (England)

Up to 45mW @ 1g rms (15Hz)



Micro-electromagnetic generator (Univ. Southampton, UK) 46µW at 0.59 g (52Hz)

Mide' Volture (USA) 5mW @ 1grms (50Hz)



Imperial College, Mitcheson 2005 (UK) Electrostatic generator 20Hz 2.5uW @ 1g

Energy Harvesting Device (EHD) based on nanocrystalline ribbons

►Wireless sensor monitoring system based on ultra low power MSP430F2274 microcontroller and CC2500 2.4-GHz wireless transceiver from TI.

►SimpliciTI™ wireless communication protocol between the sensor nodes and the network access point.

<u>Testing conditions:</u>

►Vibration source: harmonic excitation by shaker (LDS V201)

►Frequency : 35÷60 Hz

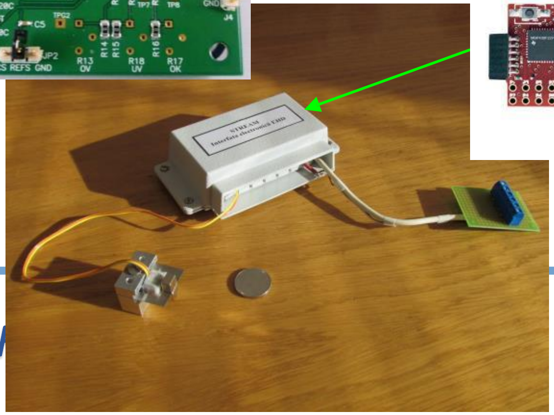
►Acceleration: 1g

►Data sent from embedded sensors: temperature, acceleration, voltage

Powering a Wireless System

TI BQ255004EVM-674 ultra low power boost converter with battery

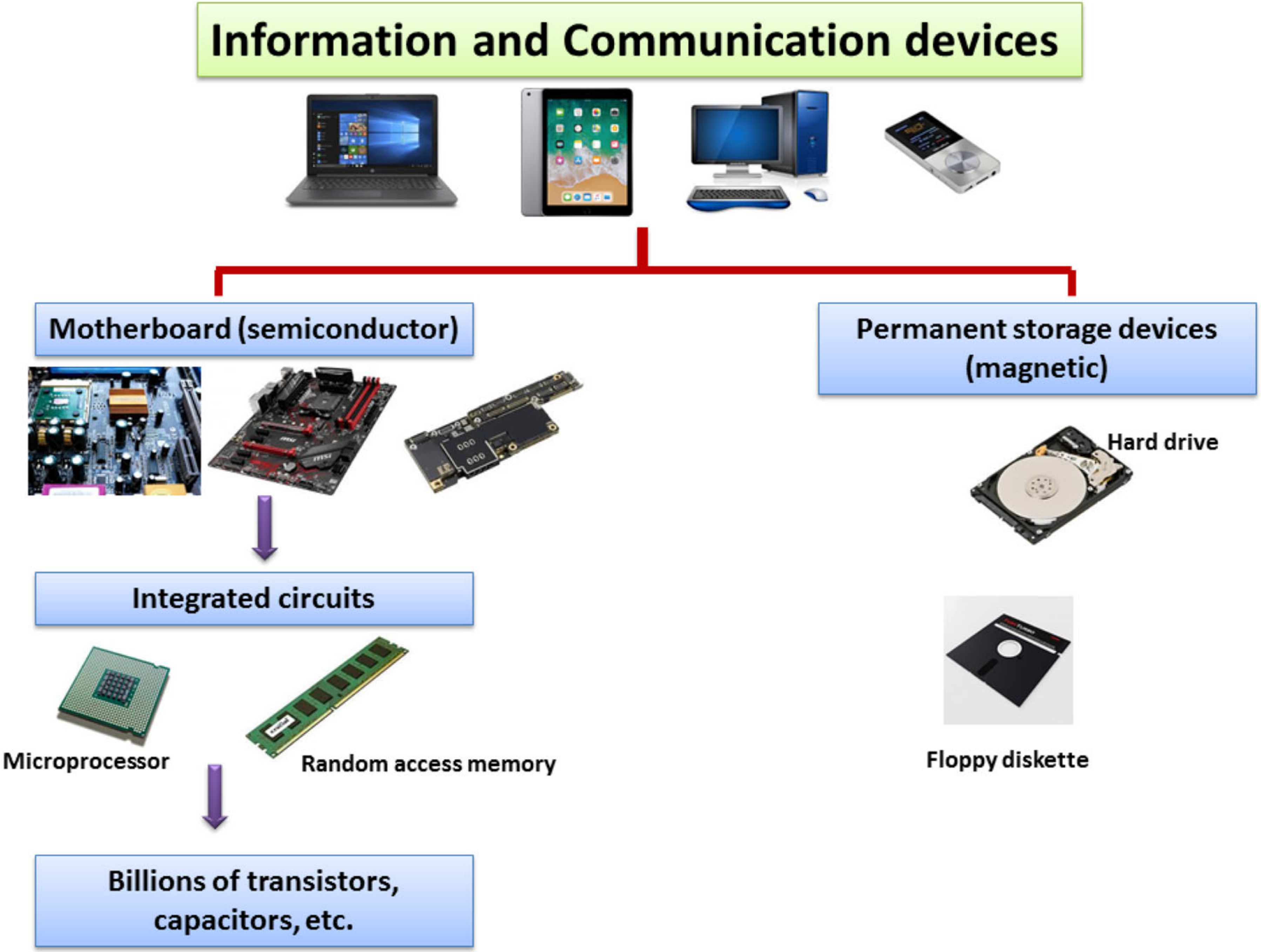
TI CC2500 2.4GHz wireless transceiver

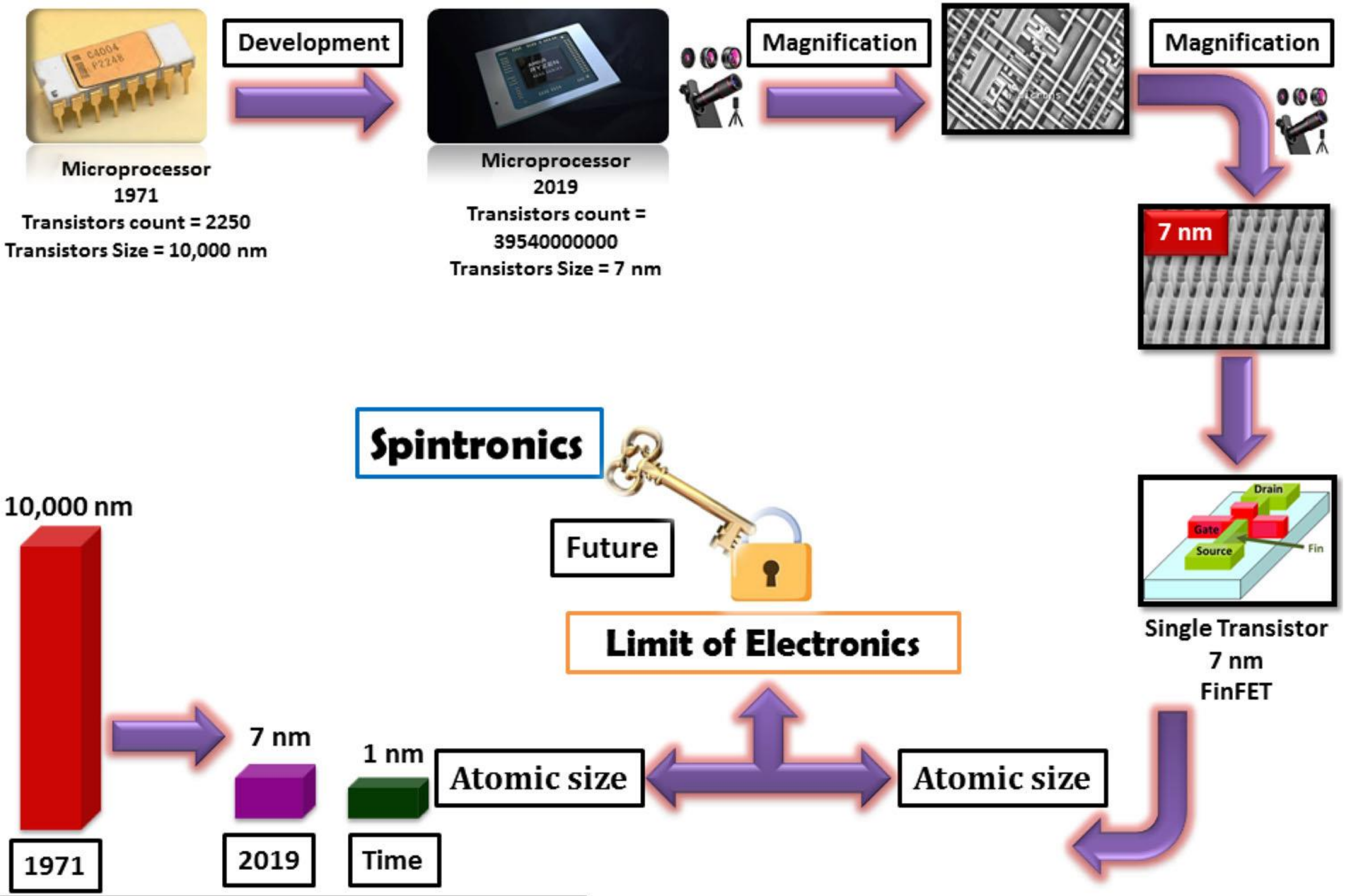


Network access point

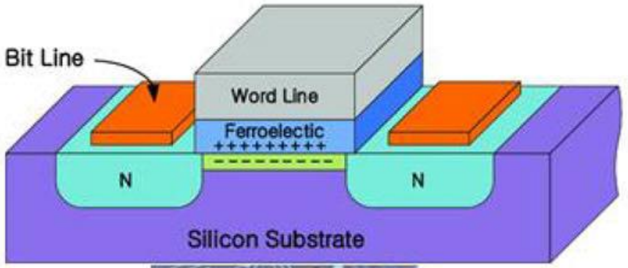
The electromagnetic generator and an accelerometer (Vibrasens) installed on a shaker

Spintronics for communication

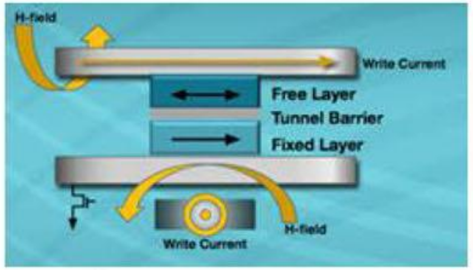

Information and Communication devices
Motherboard (semiconductor)
Permanent storage devices (magnetic)
Hard drive
Integrated circuits
Microprocessor
Random access memory
Floppy diskette
Billions of transistors, capacitors, etc.



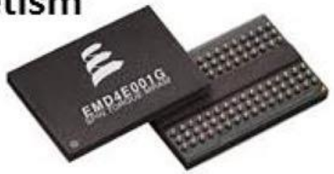
Size of Transistor in Microprocessor (1971-2019)



Ferroelectricity
(Charge)



Ferromagnetism
(spin)



- **Faster**
- **Energy efficient**
- **Nonvolatile capability**

Low storage density, high cost with overall capacity limitation

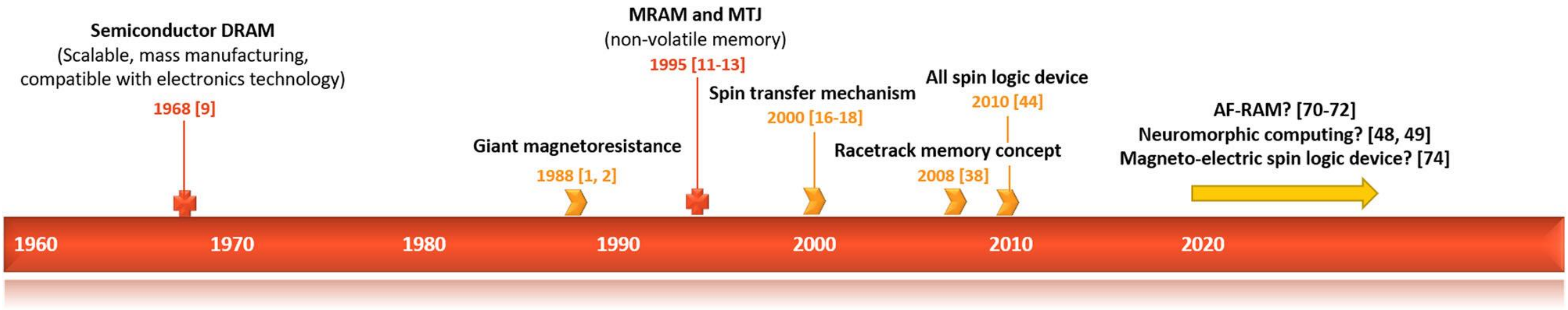
- **High storage density**
- **retain data without power**
- **No boot up**

Large magnetic field
for switching magnetic states
(consume large amount of energy)

Integrate

Multiferroic (magneto-electric coupling)

Ultimate memory device
Nonvolatile, dense, robust, fast, no boot up and less energy expensive



Timeline of major research and technology milestones in data storage devices.

For more information:

1) ***Sensors Technology Handbook***, Ed. Jon S. Wilson, 2005, Elsevier.
2) Paul Regtien & Edwin Dertien, ***Sensors for Mechatronics*** (2nd Edition), 2018, Elsevier.
3) ***Magnetic Sensors and Magnetometers*** (2nd Edition), Ed. Pavel Ripka, 2021, Artech House, 685 Canton St. Norwood, MA.
4) J. Puebla, J. Kim, K. Kondou, Y. Otani, ***Spintronic devices for energy-efficient data storage and energy harvesting***, Communications Materials 1 (2020) 24.
5) S. Mabrouk Yakout, ***Spintronics: Future Technology for New Data Storage and Communication Devices***, Journal of Superconductivity and Novel Magnetism 33 (2020) 2557.
6) X.F. Liang et al., ***Roadmap on Magnetoelectric Materials and Devices***, IEEE Transactions on Magnetics 57(8) (2021) 400157.
7) Q.M. Shao et al., ***Roadmap of Spin–Orbit Torques***, IEEE Transactions on Magnetics 57(7) (2021) 800439.
8) C. Zheng et al., ***Magnetoresistive Sensor Development Roadmap (Non-Recording Applications)***, IEEE Transactions on Magnetics 55(4) (2019) 0800130.