Magnetic Sensors: An Overview

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Outline

- Part A: Engineering Theory of Magnetism
  - A short introduction to magnetics
  - The magnetization process
  - Magnetic effects for engineering applications

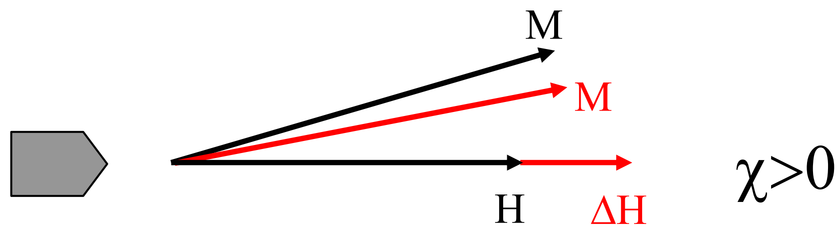
- Part B: Sensors Based on Magnetic Materials
  - Sensing principles based on magnetic effects
  - Applications of sensors based on magnetic materials
  - Developing a sensor

Part A:

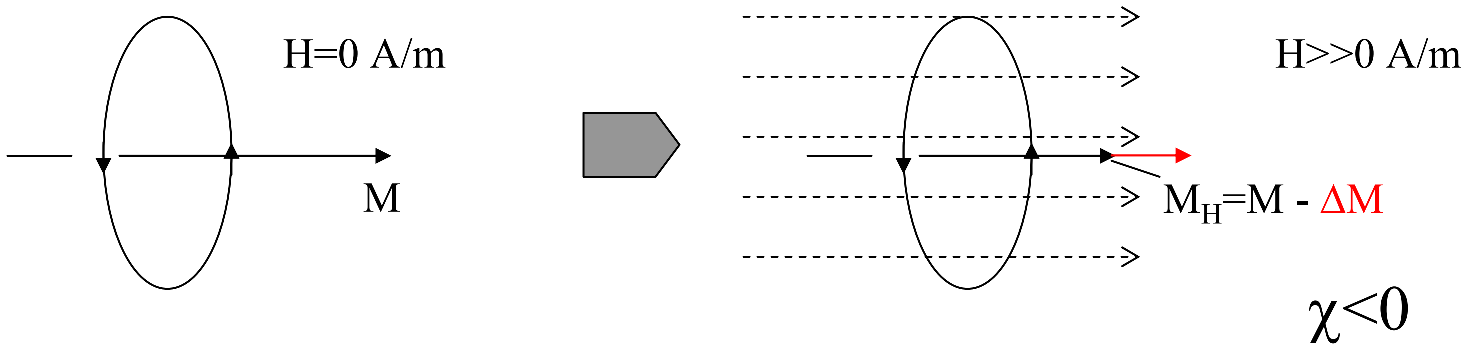
Engineering Theory of Magnetism

A short introduction to magnetics

- Paramagnetism

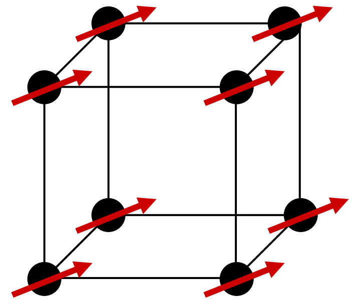


- Diamagnetism

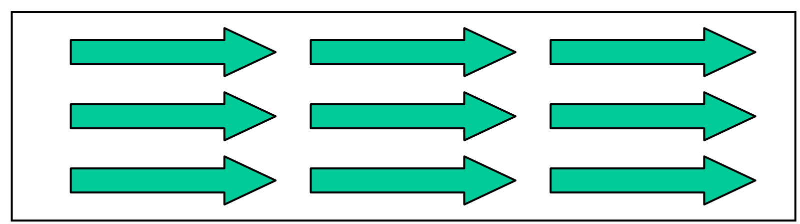


Ferromagnetism

- **Short range** or **exchange** interaction results in spin-spin alignment of neighboring spins in some TM materials

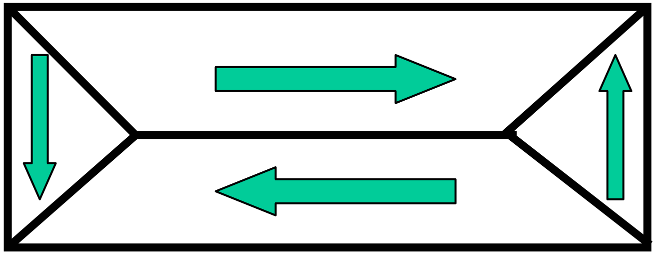


- The spin-spin alignment results in the formation of the so called **ferromagnetic domains**



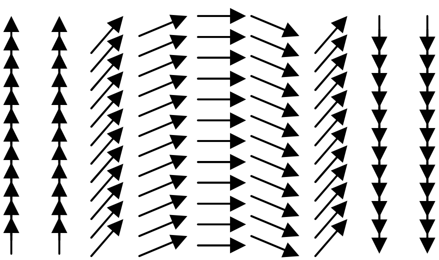
Ferromagnetism

Magnetic domains cannot be extended to infinity
Domain-domain interaction results in magnetic domains separated by **magnetic domain walls**



M=0

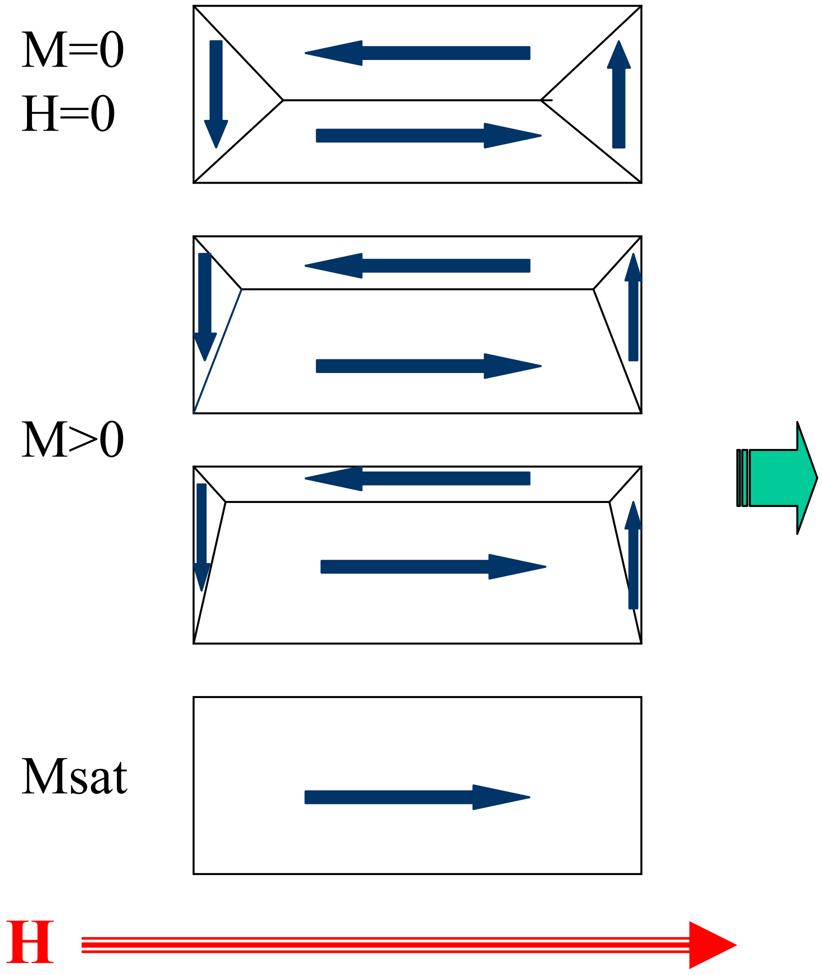
Orientation of dipoles in domain walls changes gradually

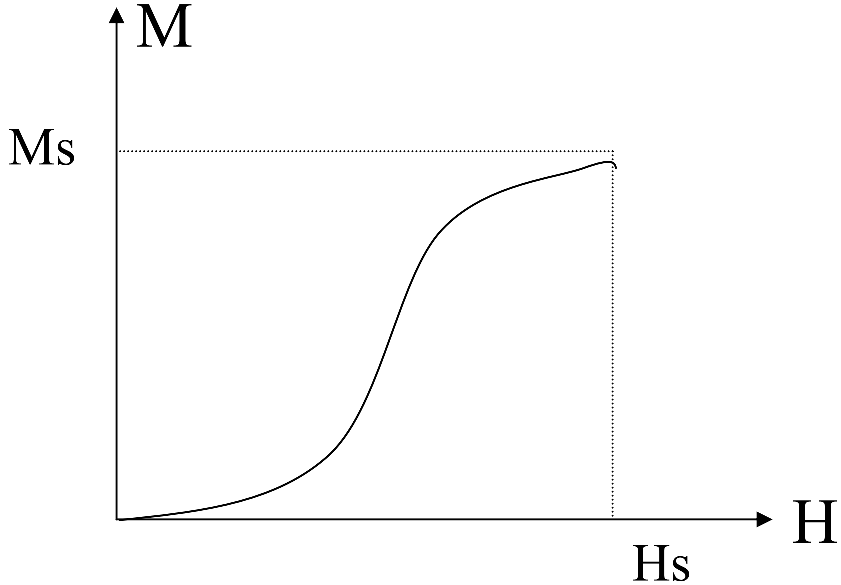


The Basic Mechanisms of Magnetization Process

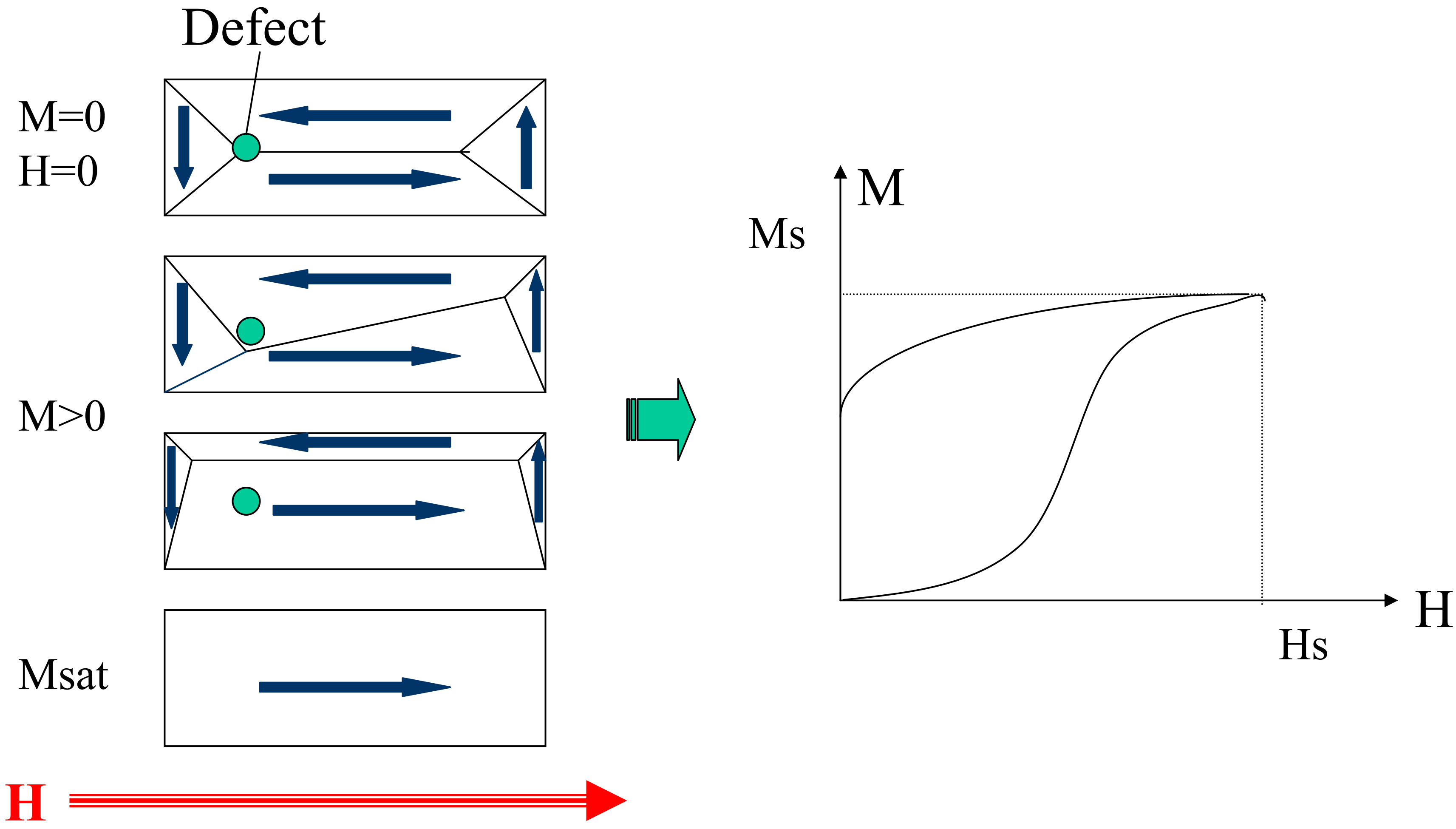
- Domain wall motion:
    - Reversible
    - Irreversible
- Domain rotation:
    - Barkhausen jumps: irreversible effect
    - Small angle rotation: reversible effect

Reversible Magnetic Domain Motion

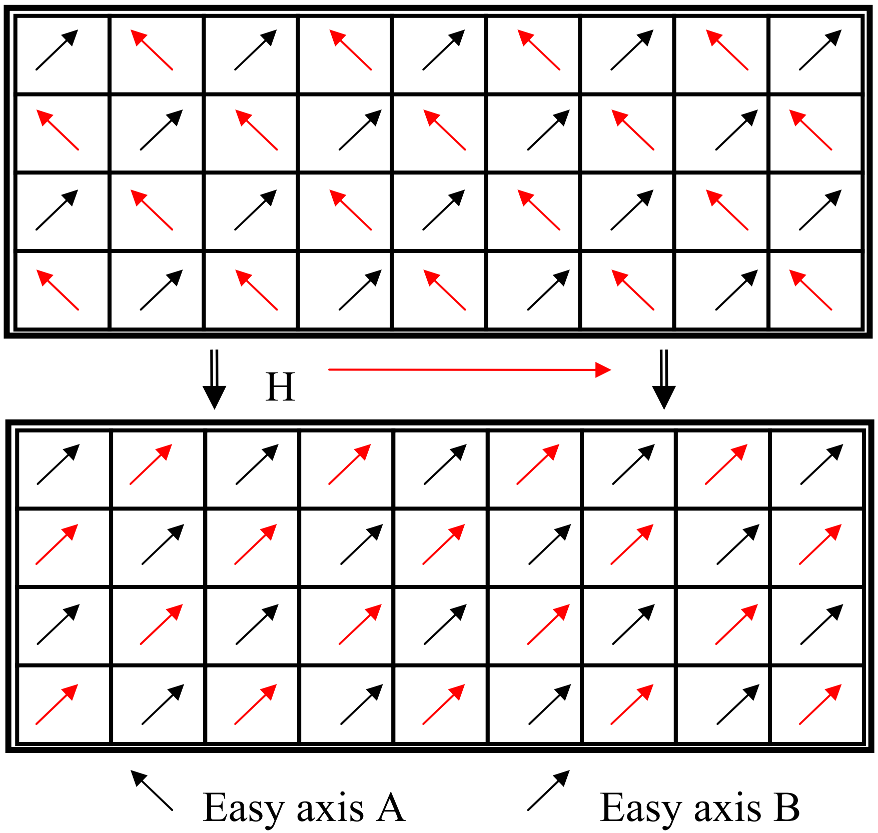




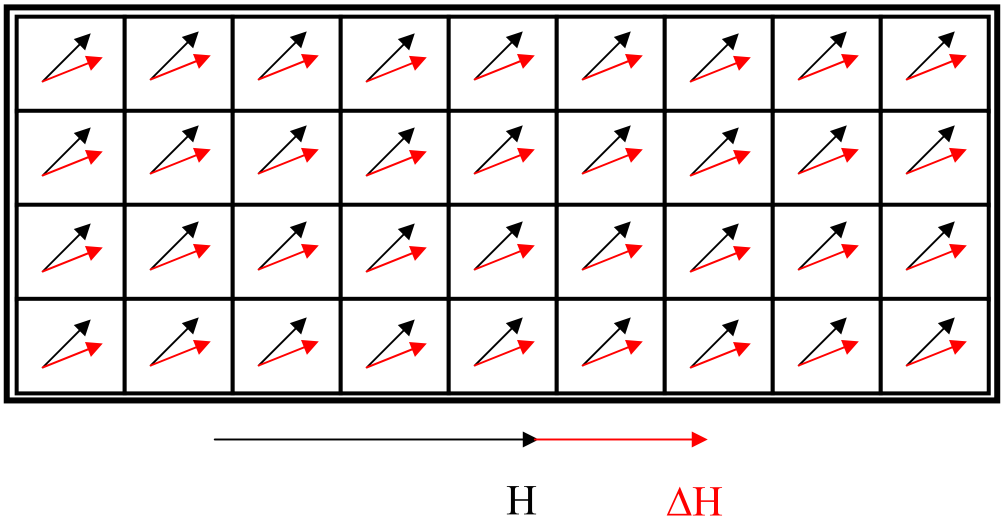
Irreversible Magnetic Domain Motion



Irreversible domain rotation: Barkhausen Jumps



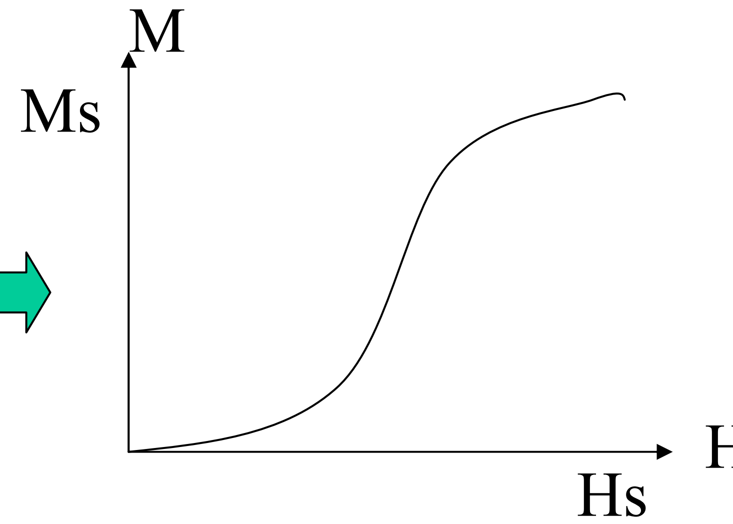
Reversible Rotation of Domains



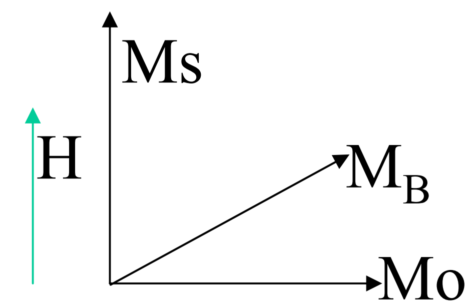
Reversible magnetic domain rotation after the irreversible magnetisation process

The Magnetization Process

- Virgin curve
  - Intrinsic magnetization changes under external field
  - Main curve: three parts
    - Domain wall motion
    - Barkhausen jumps
    - Rotation of magnetization
  - Minor loops



- Saturation Ms
  - Completely oriented dipoles

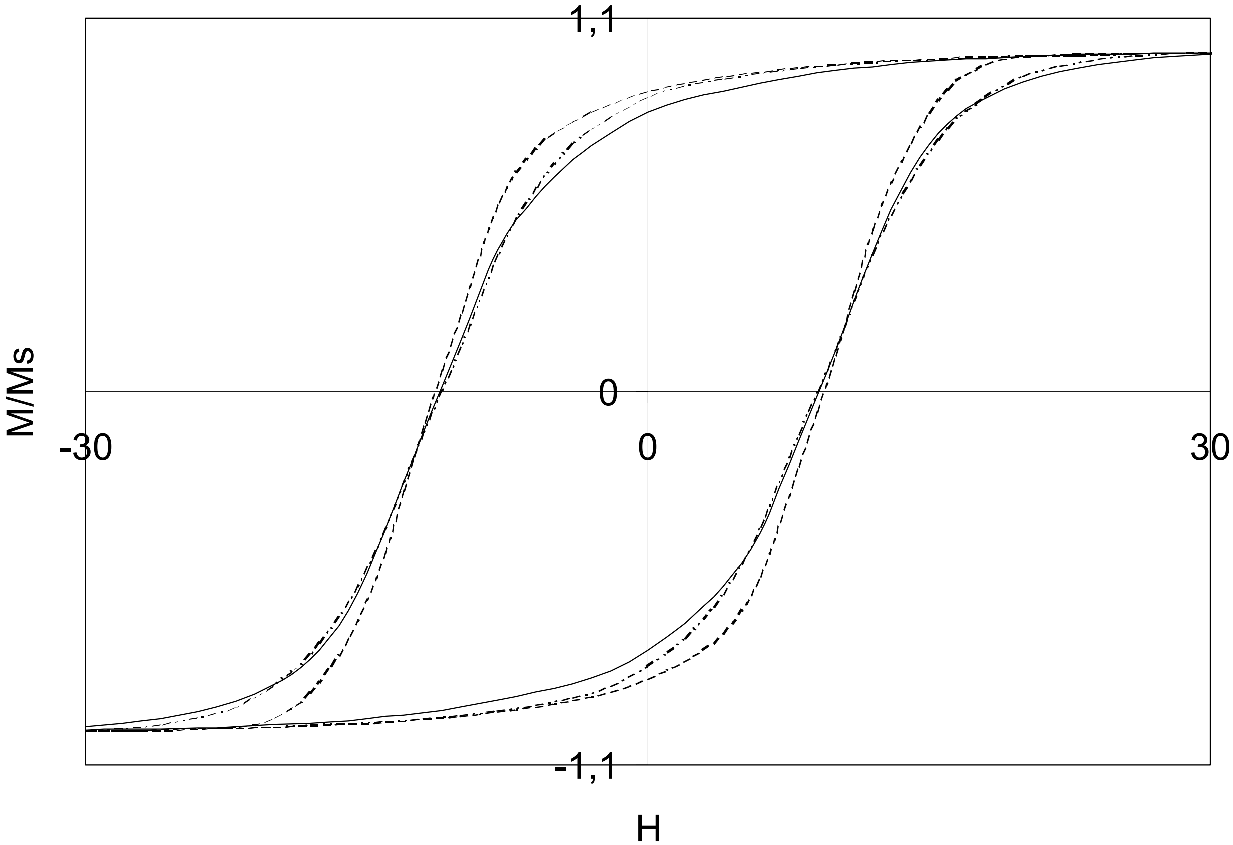


The Magnetization Process

- B-H loop
  - Saturation & back
  - Irreversible process – remanence
  - Coercive force (field) & coercive slope
  - Properties & dynamic properties: f, T, σ
  - Single phase systems have symmetric B-H loops
  - Minor loops: Inside the B-H loop
  - Size of B-H loops: hard - soft - semi
  - Non-single-phase materials may result in asymmetric B-H loop
  - Large Barkhausen Effect: an interesting property

B-H loop

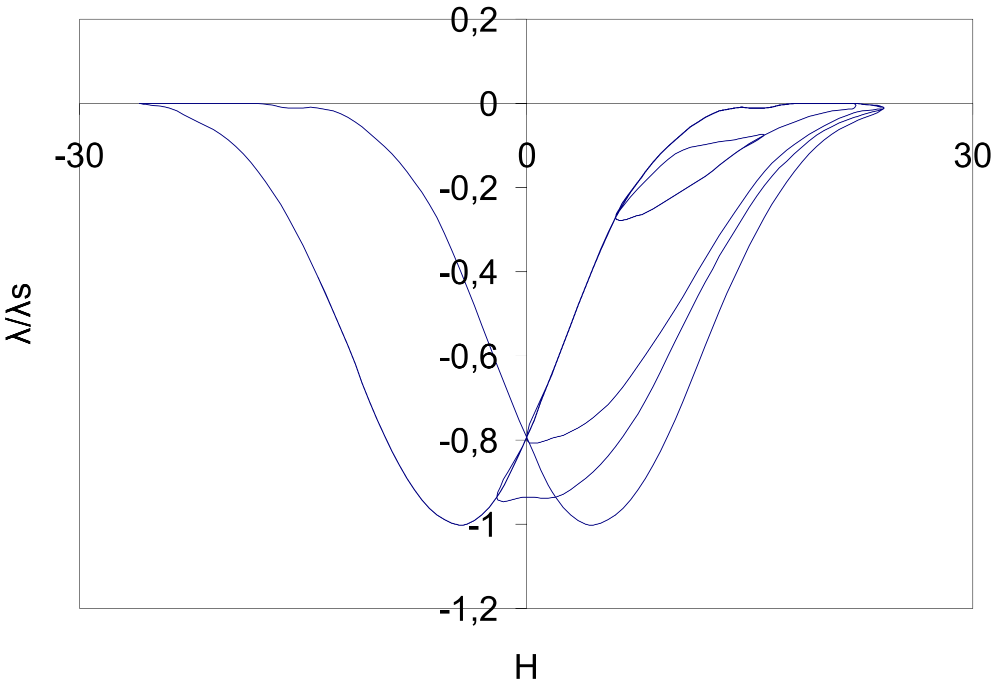
Main parameters: Temperature - Stress - Frequency



Magnetic effects

Magnetostriction:

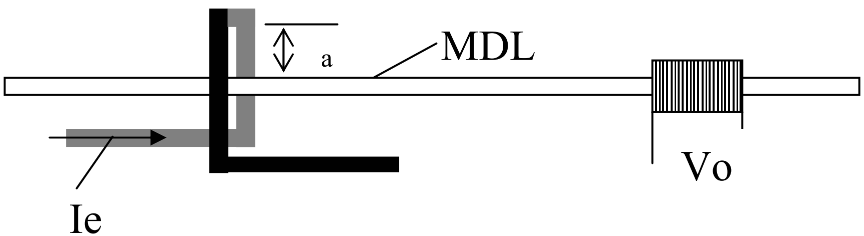
– Magnetic domain rotation (reversible and irreversible)
– $\underline{+}\lambda(H)$: zero, classic, unhysteretic, giant, colossal
– Dynamic properties, hysteresis

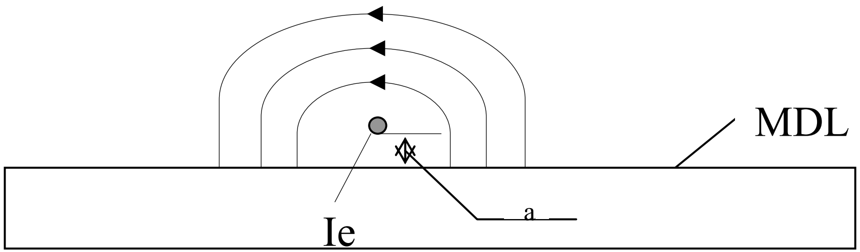


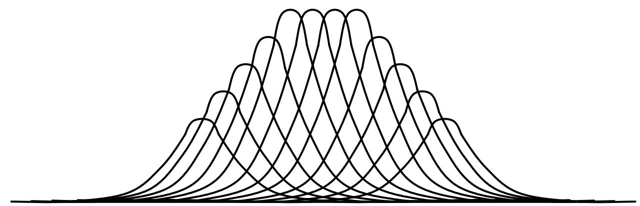
Magnetic effects

Magnetostrictive Delay Lines:

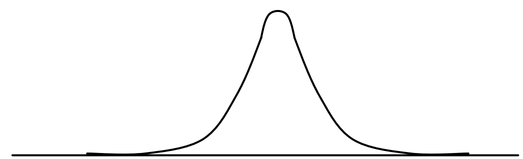
an application of the magnetostriction effect



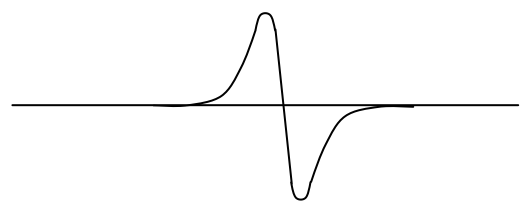




Generated microstrains



Propagating elastic pulse

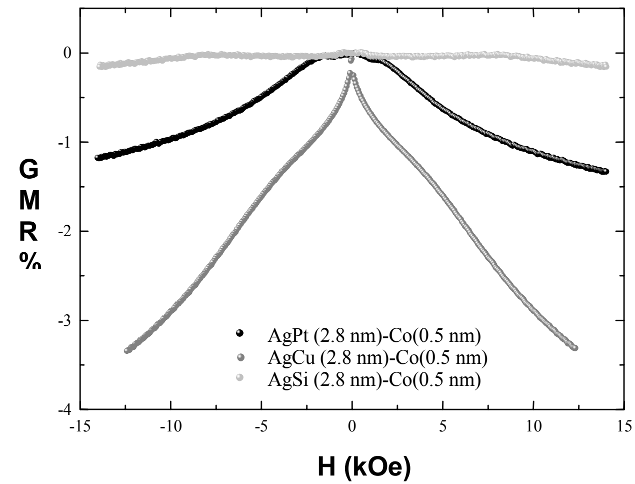


Detectable change of flux density

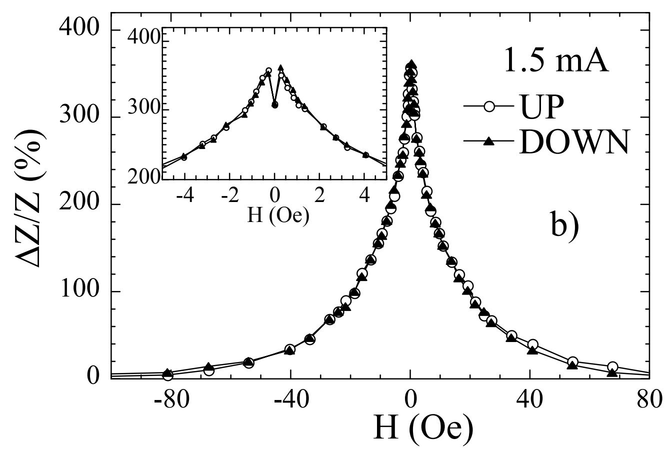
Magnetic effects

Z-H loops

Magnetoresistance
(MR, AMR, GMR, CMR)



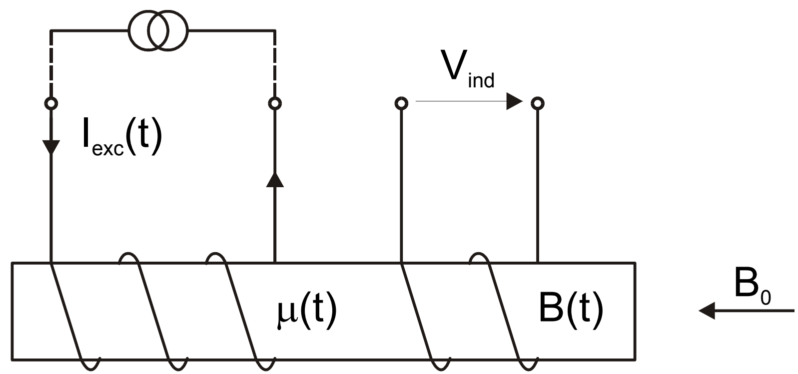
Magnetoimpedance
(MI, SI, GMI)



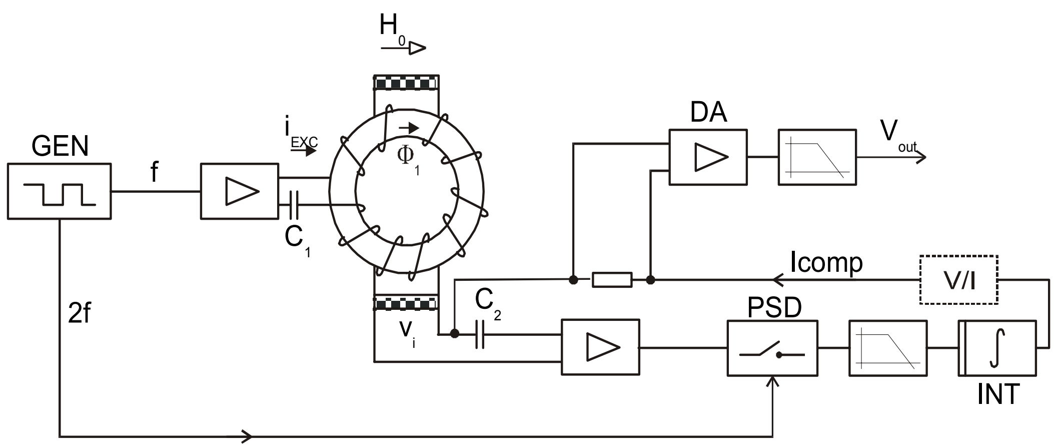
Magnetic effects

Inductive effects

Wiedeman effect



Domain wall nucleation
& propagation



Classic set-ups
(LVDT, fluxgates)

Magnetic effects

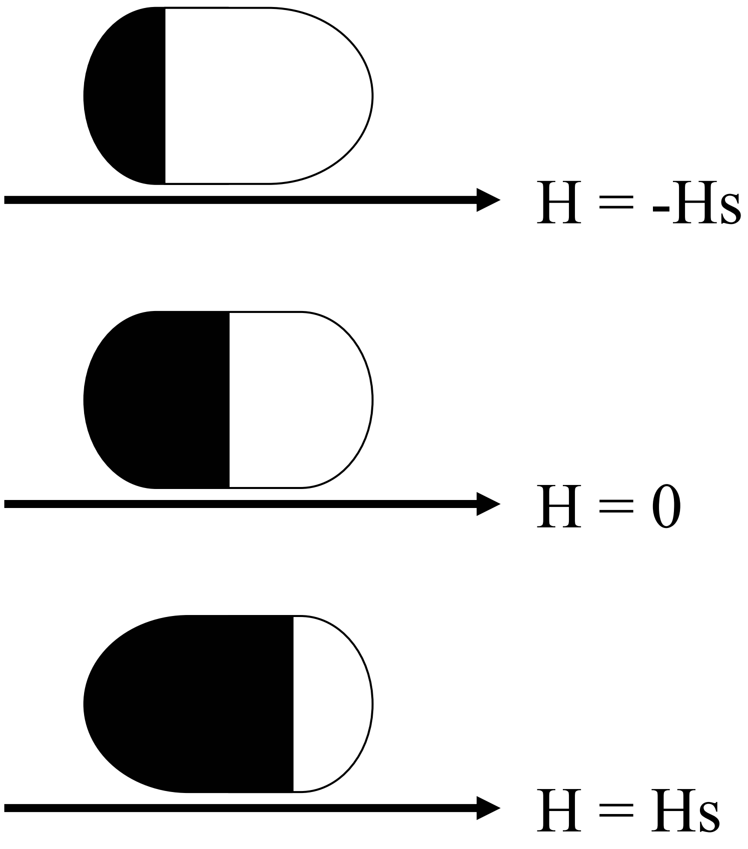
Magneto-optic effects

Bitter, Kerr, Faraday effects

Use of M-O effects

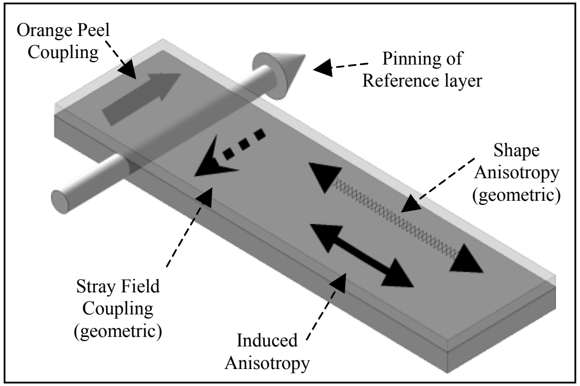
Case study:

displacement sensor

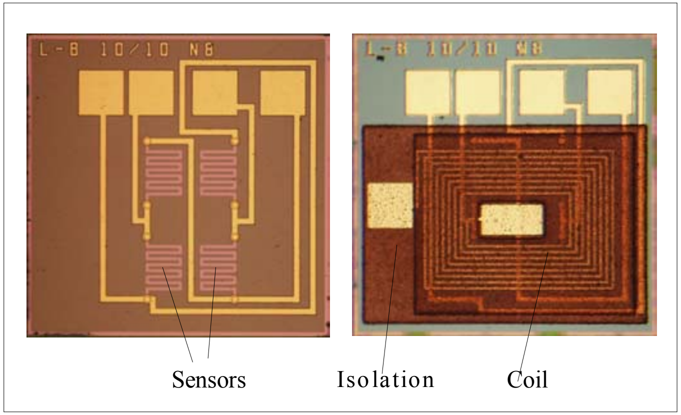


Magnetic effects

Spintronics



Spin valves



Spin tunneling

Magnetic materials

(Fe Co Ni)-(ETM)-(RE)-(NMM)

Bulk	Stress relief
Thin films	Inducing anisotropy
RQ (ribbons & wires)	Tailoring B-λ-Z(H)
Particulate media	Nanocrystallization
Composites	Micromechanics

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Applications of magnetic materials

Applications of magnetic materials

Power

transformers

motors

actuators

Recording

recording media

recording heads

technology

&

Sensors

Magnetic Sensors: An Overview

Part B: Sensors

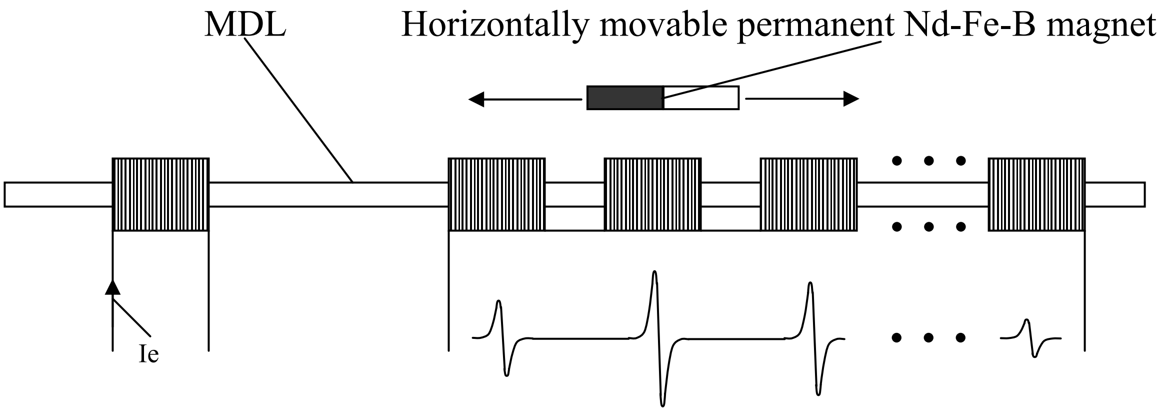
Sensors

- Position
  - Position (tapes, digitizers, 3-d)
  - Dilatometry: LVDT, MDL
  - Speed & vibration: accelaration, …
- Stress
  - Load cells & torque meters
  - Pressure gauges and stress sensors
  - Force/pressure digitizers
- Field
  - NDT applications
  - Recording
  - Compass

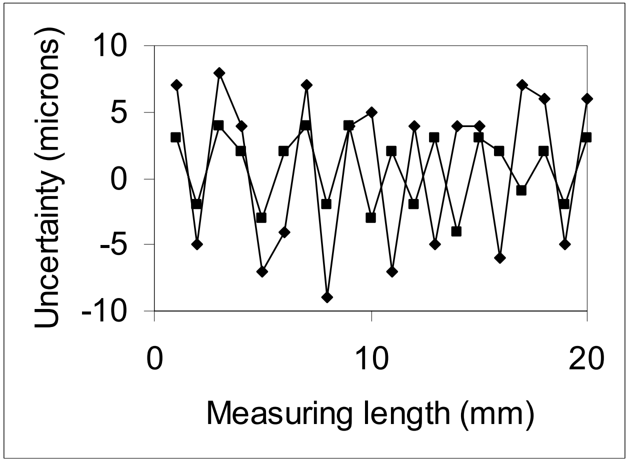
Data from EMSA 2002, Athens, Greece

Position Sensors

- **Position sensor based on the magnetostrictive delay line technique**
  - Sensitivity: 5 μm; Uncertainty: ± 10 μm
  - Drawbacks: ambient field sensitive
  - Characteristics are optimised by using amorphous alloys

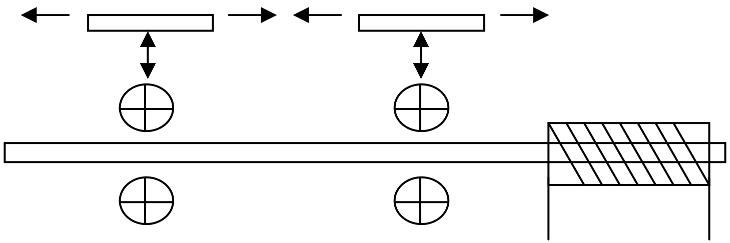


Pulse voltage output train of the in series connected search coils

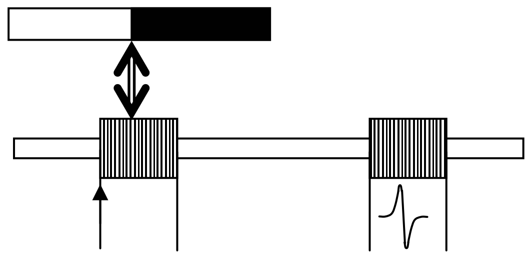


Position Sensors

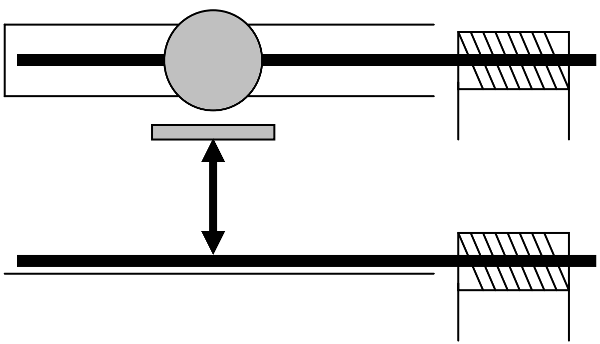
(MDL technique cont.)



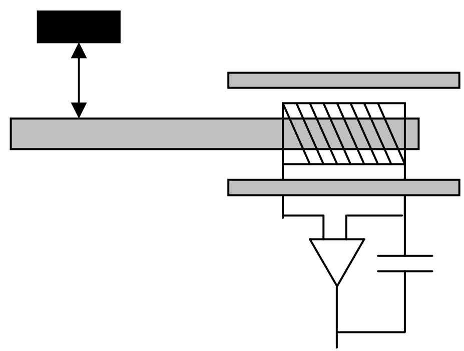
Dilatometer and stress sensor



Moving magnet sensor



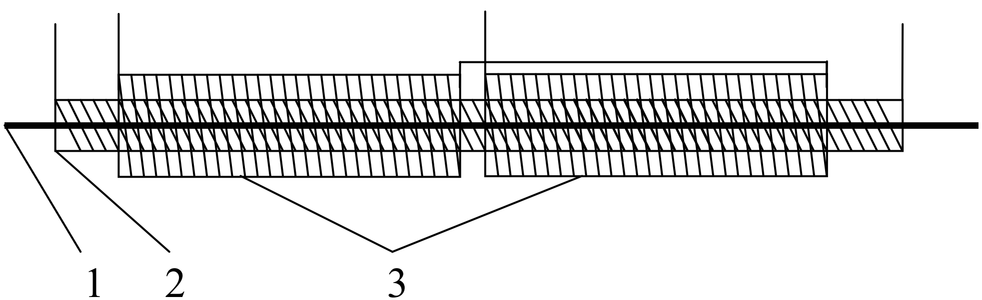
ECT-MDL digitizer

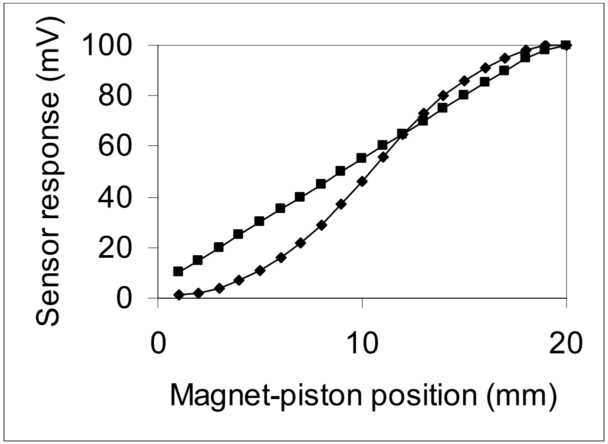


ECT-MDL digitizer

Position Sensors

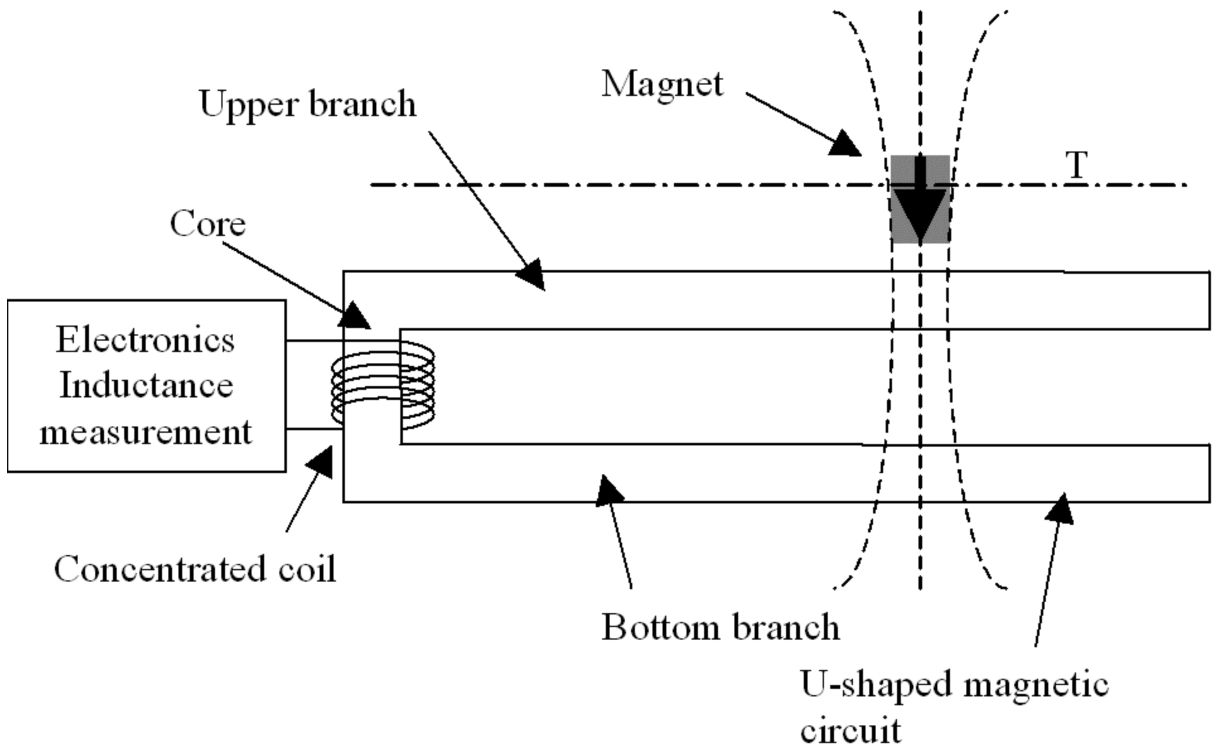
- Position sensor based on the linear variable differential transformer (LVDT) set-up. (1) Soft magnetic material, (2) Excitation coil, (3) In series opposition search coils.
  - Sensitivity: 100 μm
  - Uncertainty: ± 500 μm
  - Repeatable response from -70 C to 150 C
  - Drawbacks: ambient field sensitive
  - Improved characteristics by material tailoring





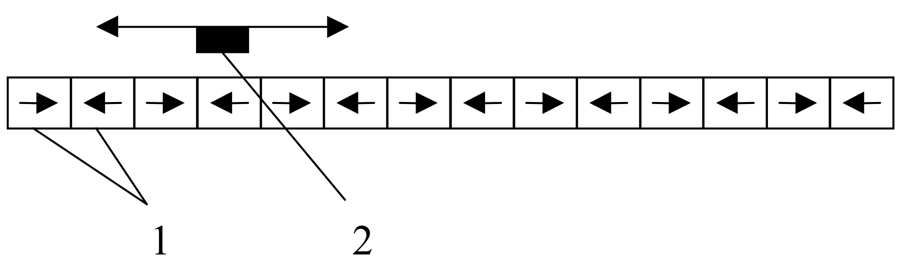
Position Sensors

Position sensor based on an inductive principle



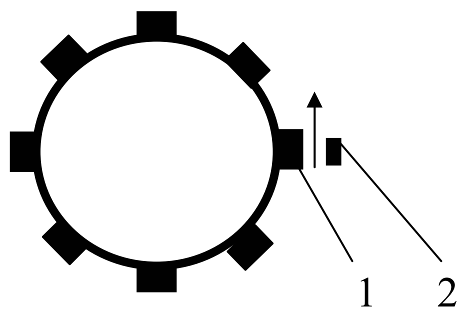
Position Sensors

- Position sensor based on permanent magnet tape. (1) Permanent magnetic thin films, (2) Searching magnetic head.
  - Sensitivity: 100 µm
  - Uncertainty: $\pm$ 500 µm
  - Repeatable response from -70 C to 150 C
  - Drawbacks: ambient field sensitive
  - Characteristics can be improved by material tailoring



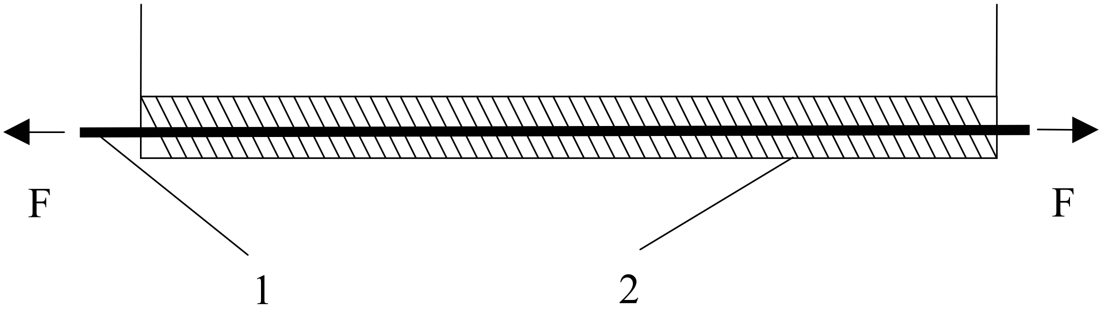
Position Sensors

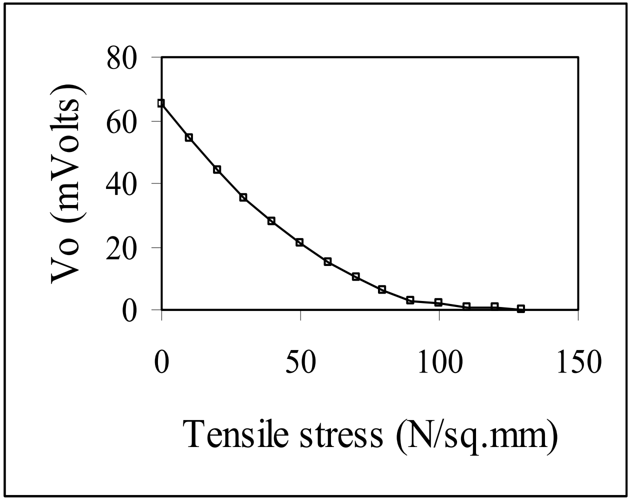
- Angular positioning sensor. (1) Radial permanent magnets in tooth arrangement, (2) Searching field sensor.
  - Repeatable response from -70 C to 150 C
  - Great reproducibility allowed use in automobile industry (ABS)
  - Drawbacks: ambient field sensitive
  - Advantages: no dust sensitive



Stress sensors

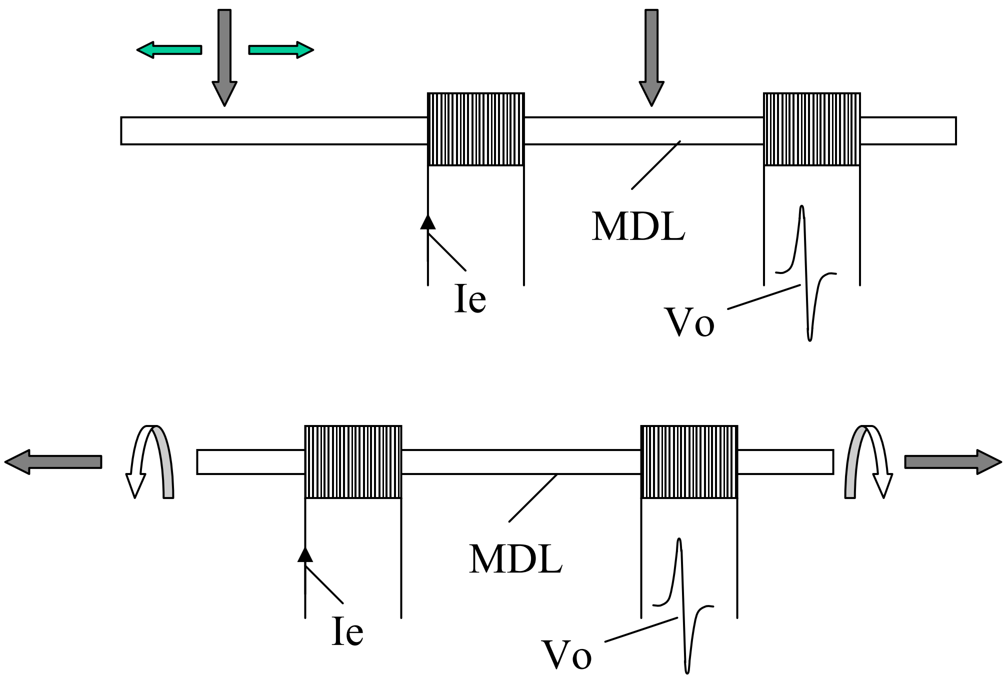
- Stress sensors based on inductive effects. (1) Soft magnetic element, (2) Inductive excitation coil.
  - More sensitive than strain gauges, if amorphous alloys are used
  - Good noise level after heat annealing
  - Good reproducibility after field annealing
  - Ambient field sensitive

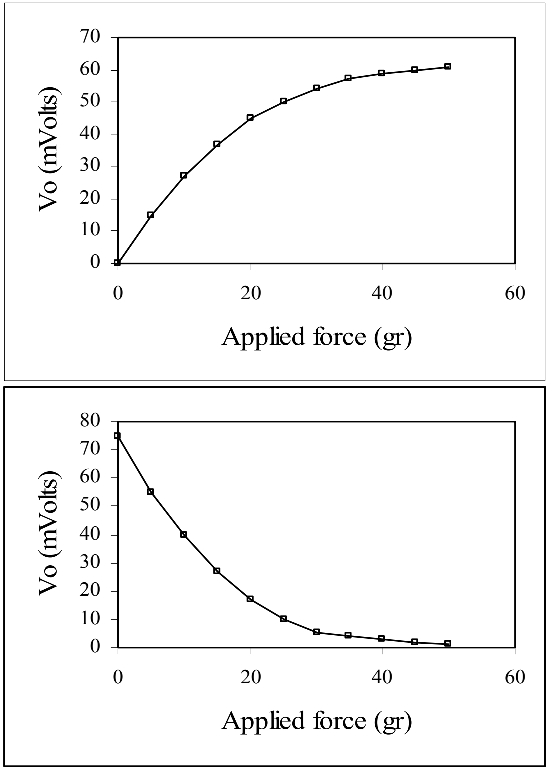




Stress sensors

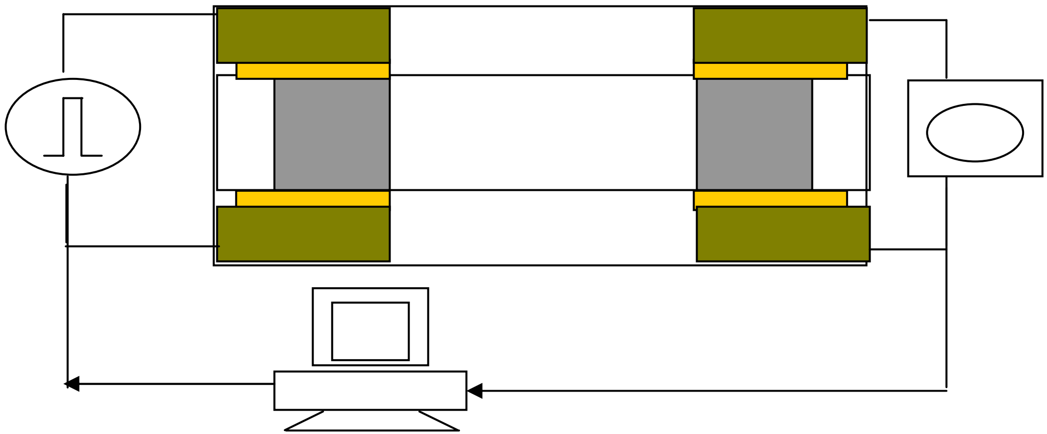
Pressure, stress & torque sensors based on MDLs

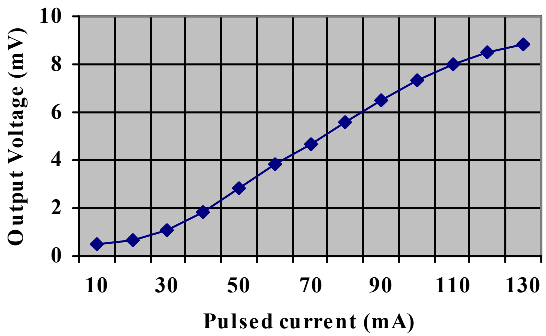


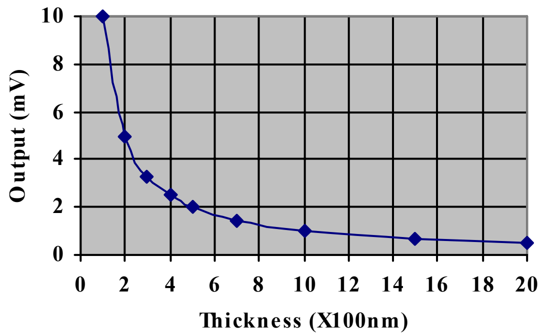


Stress Sensors

Thickness sensor based on a coilless MDL set-up

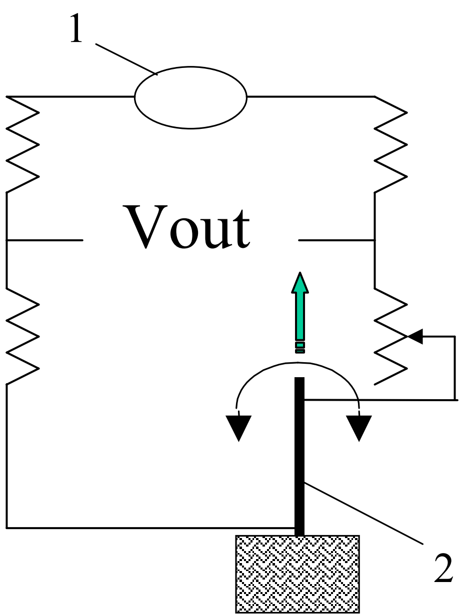


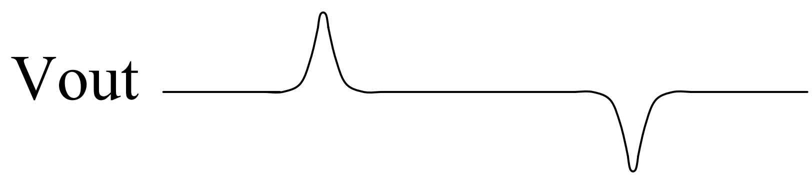


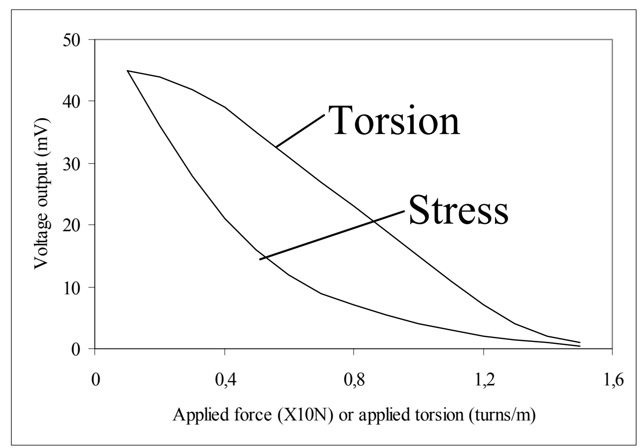


Stress Sensors

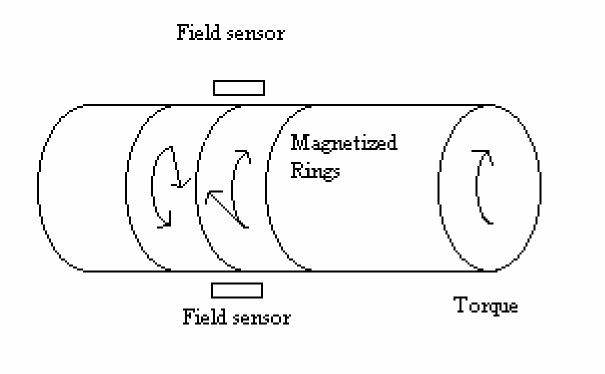
- Magneto-inductive (MI) stress & torque sensors. (1) Sinusoidal excitation circuit, (2) MI element.
  - Very sensitive, especially in high frequencies

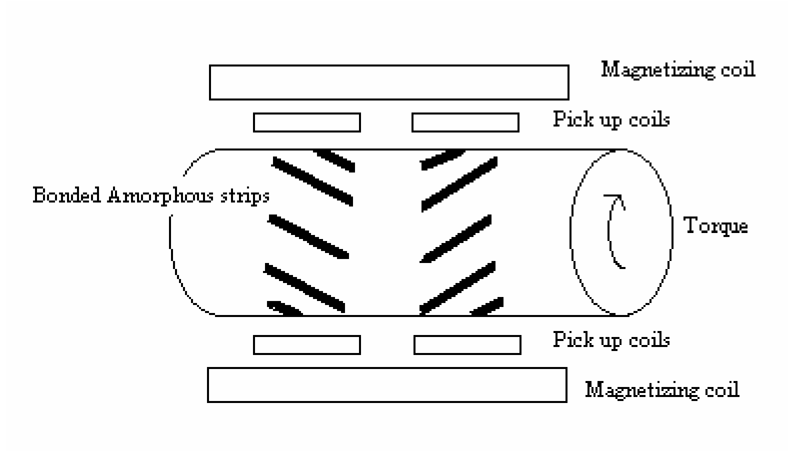


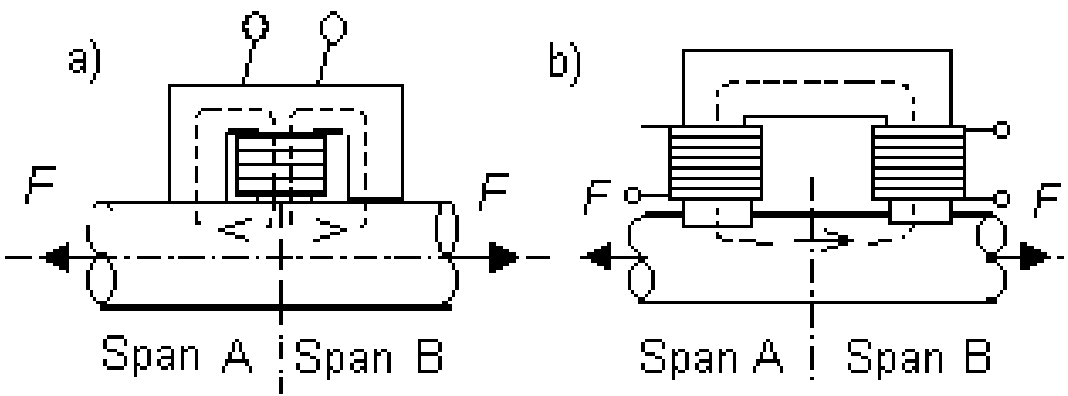




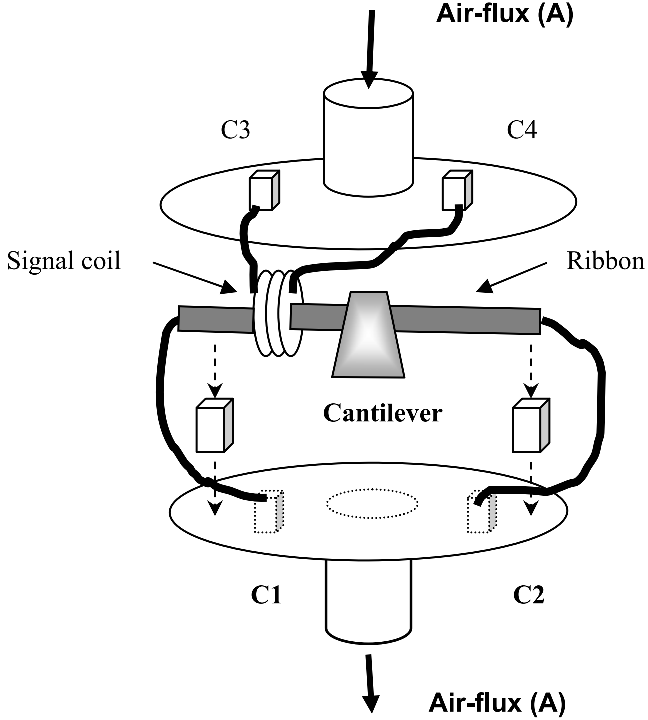
Stress Sensors: Torque Meters

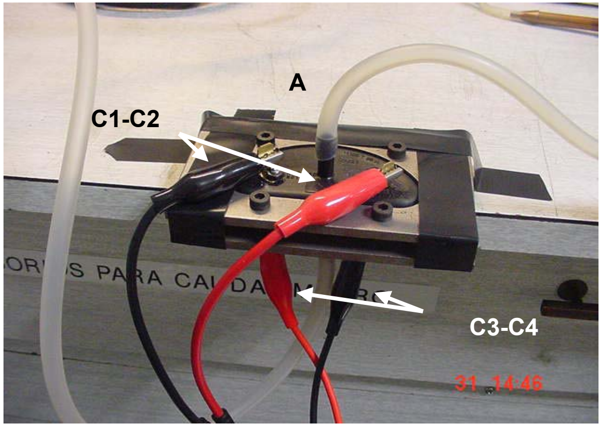






Air-flux Sensors Based on the Inverse Wiedeman Effect



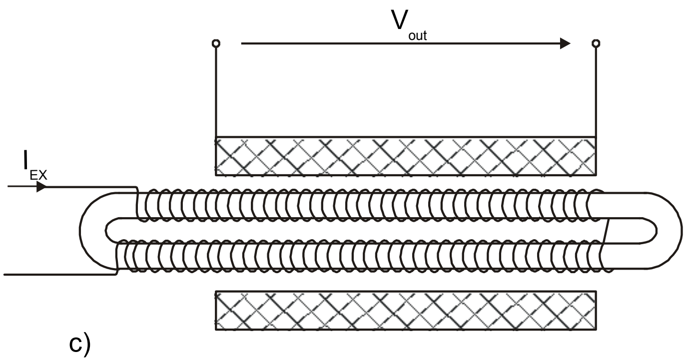


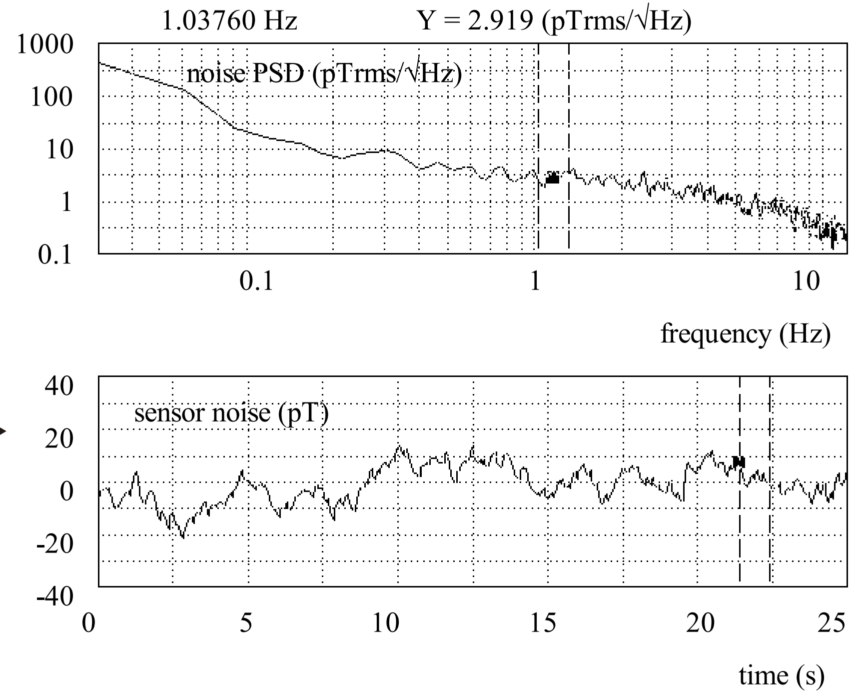
Ambient field dependence

- A serious drawback in mechanical sensors based on magnetics
- There are three solutions:
  - Two axes shielding by nanocrystalline thin ribbons
  - Active compensation by induced field in some cases (MDL and MI set-ups)
  - Smart field sensing

Field Sensors

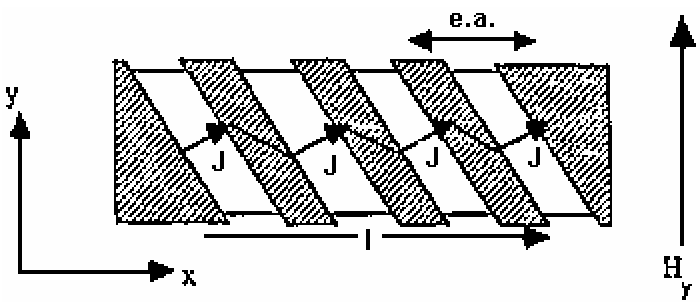
Fluxgates

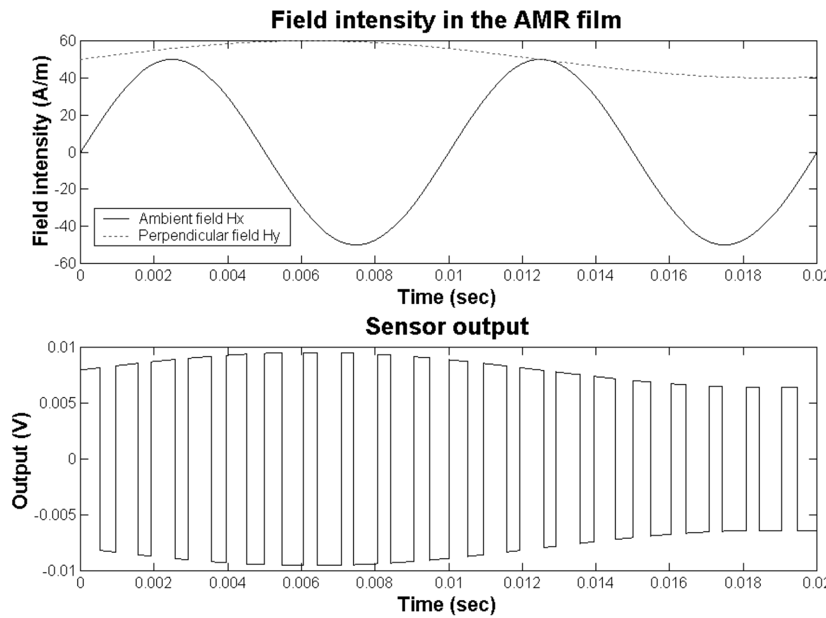




Field Sensors

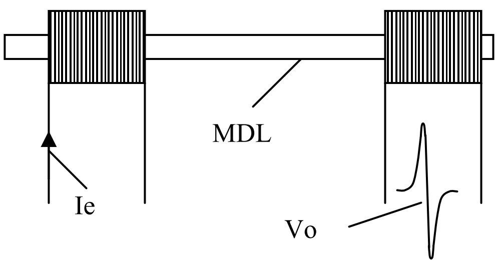
Magnetoresistive heads

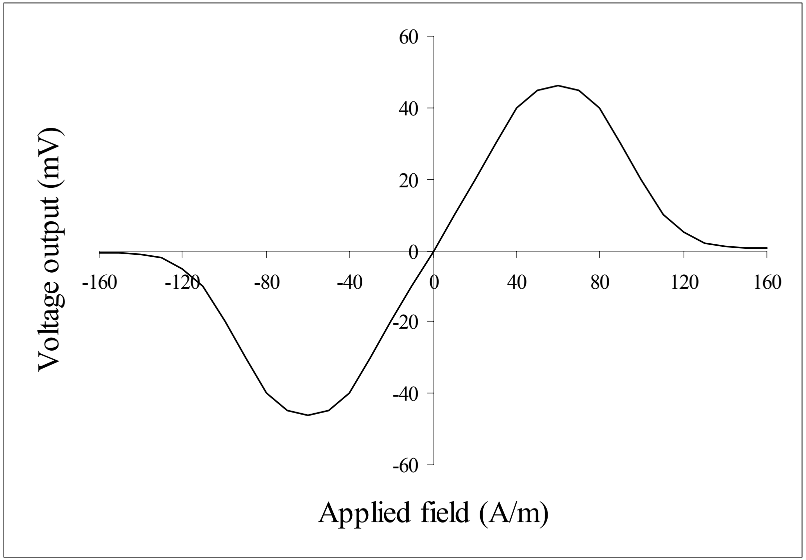




Field Sensors

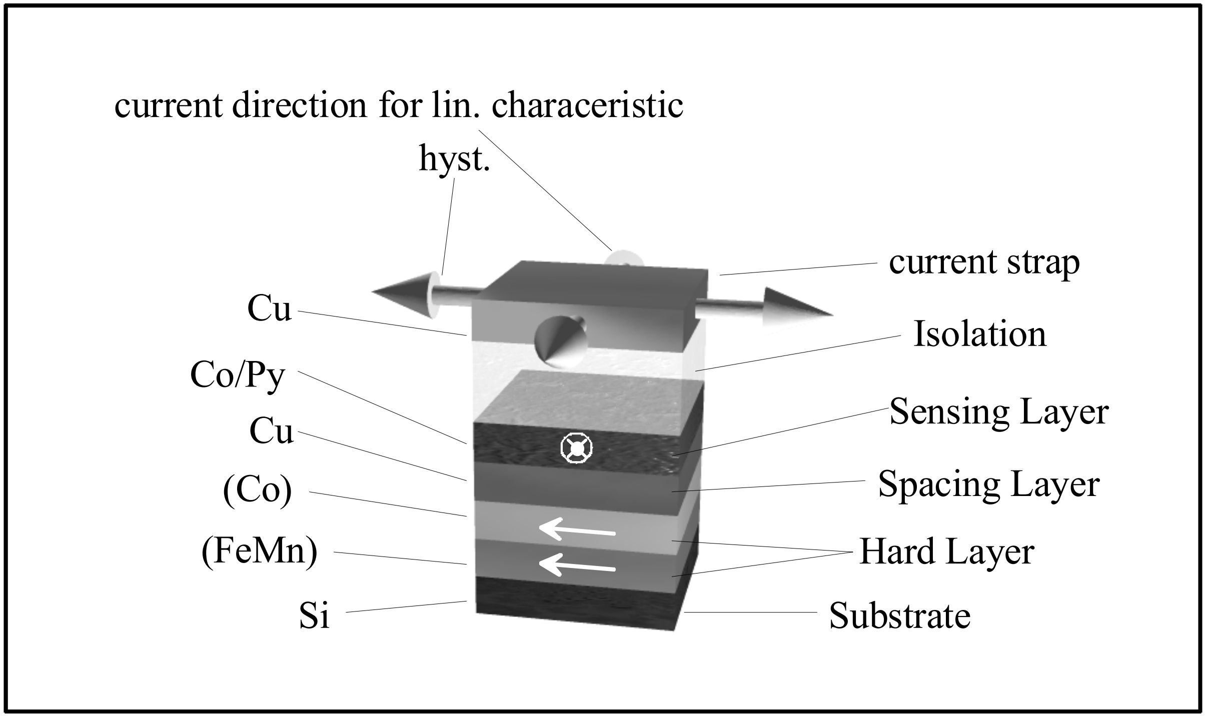
MDLs





Field Sensors

GMR & Spintronics

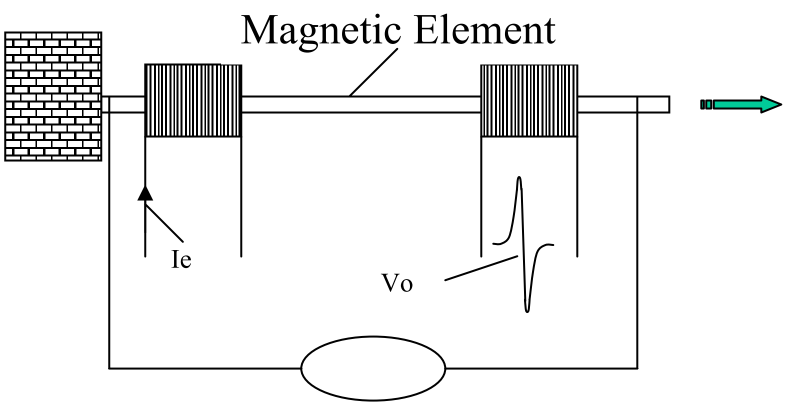


Smart Sensors

Multifunctional system: combination of measurements

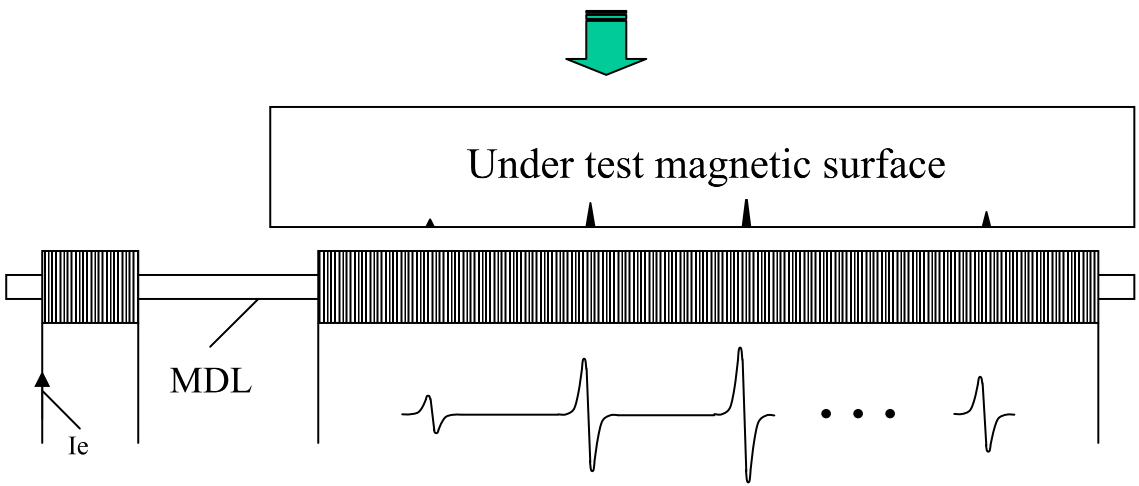
- - Magnetostrictive delay line
- - Magnetoimpedance set-up
- - Domain wall nucleation and propagation set-up

Using three different types of response to determine three different inputs



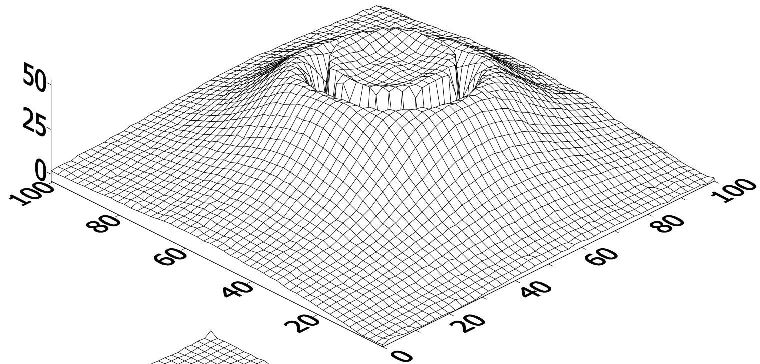
Sensor Applications

- Industrial
  - Sensors in production (piston position, stress monitoring, else)
  - Sensing systems for industry
  - NDT&E using field detection techniques

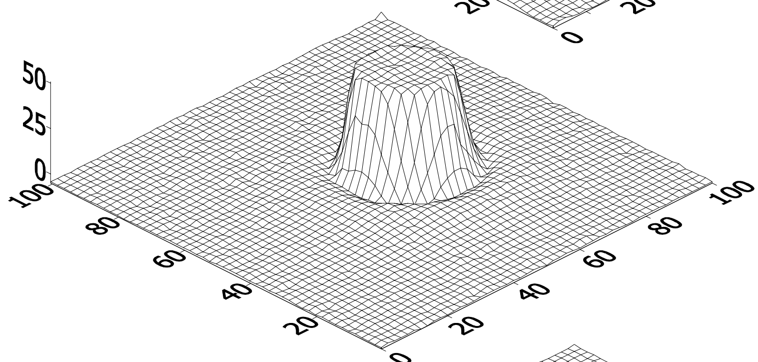


Voltage pulses due to cracks on the magnetic surface

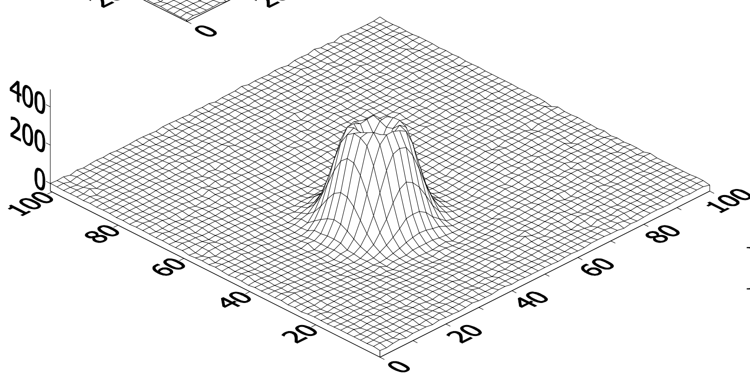
A Comparison Between Hall and GMR Sensors for NDT&E Inspection



GMR Sensor Response

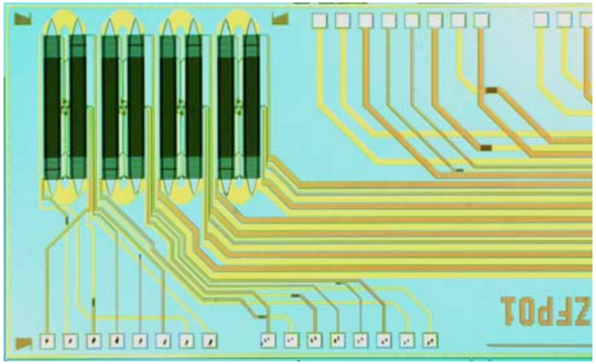


Shielded GMR Sensor Response

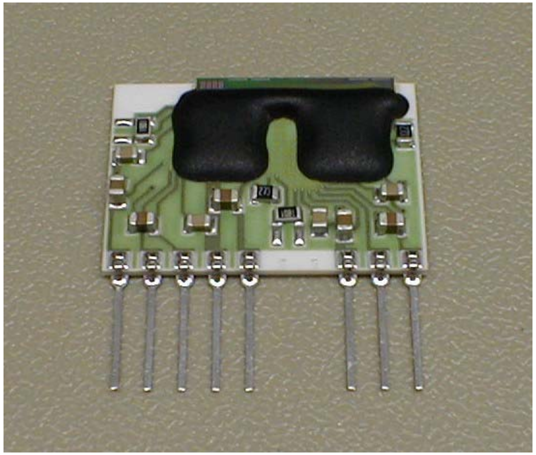


Hall Sensor Response

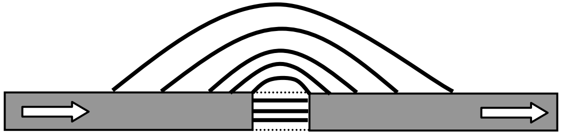
A Micro-Fluxgate Arrangement for NDT&E Inspections



The 4 m-Fluxgate Sensors



The Sensor

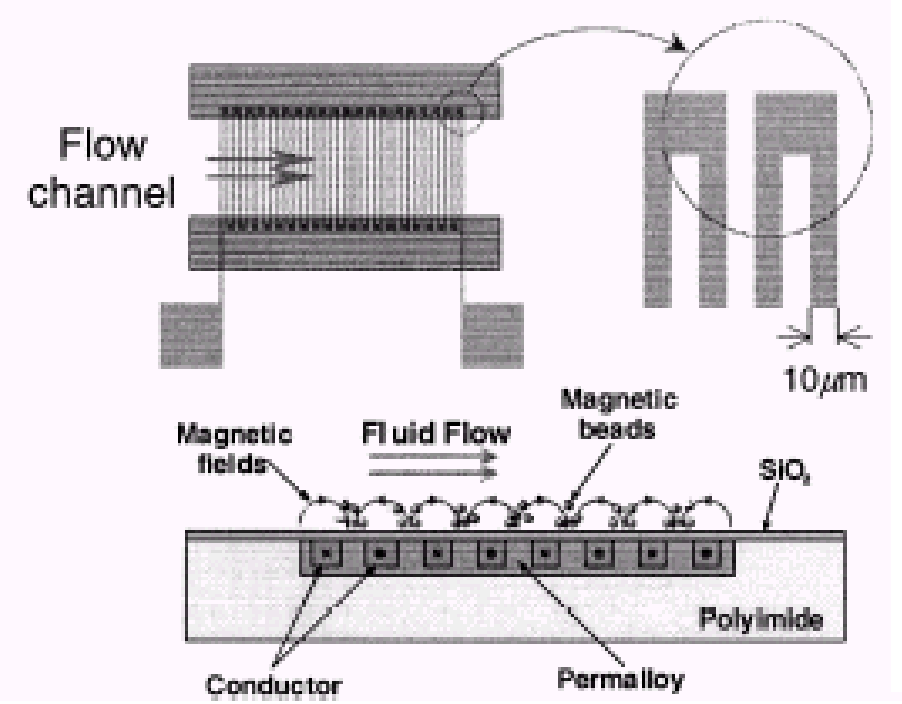


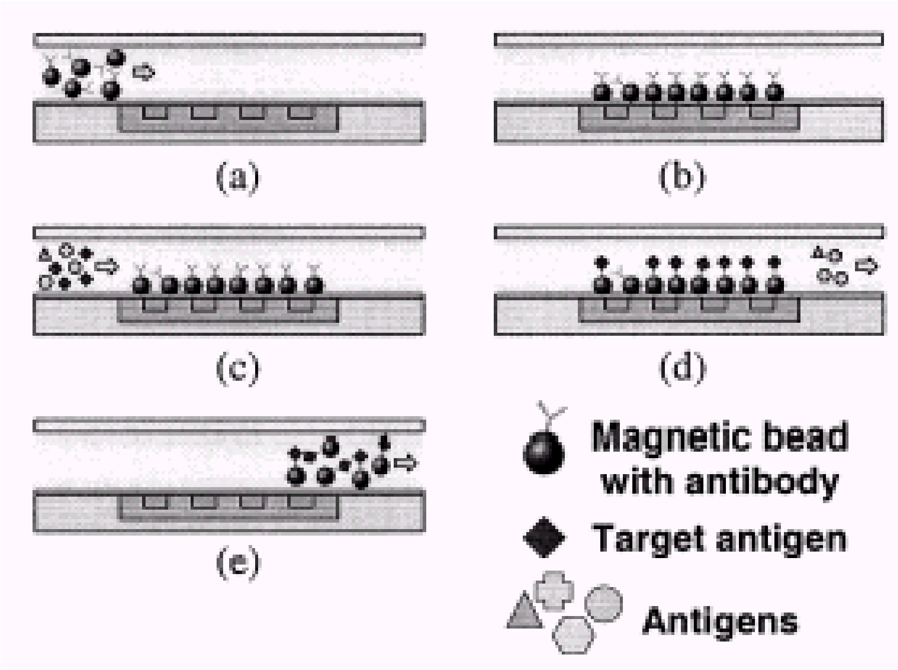
The Under Inspection Magnetic Anomaly

Sensor Applications

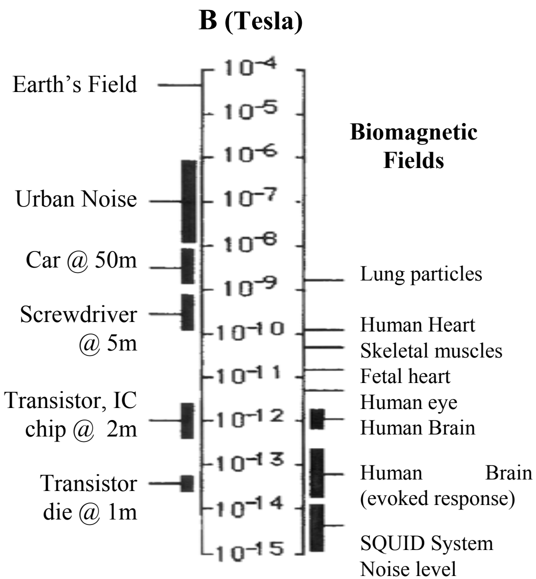
Biomedical

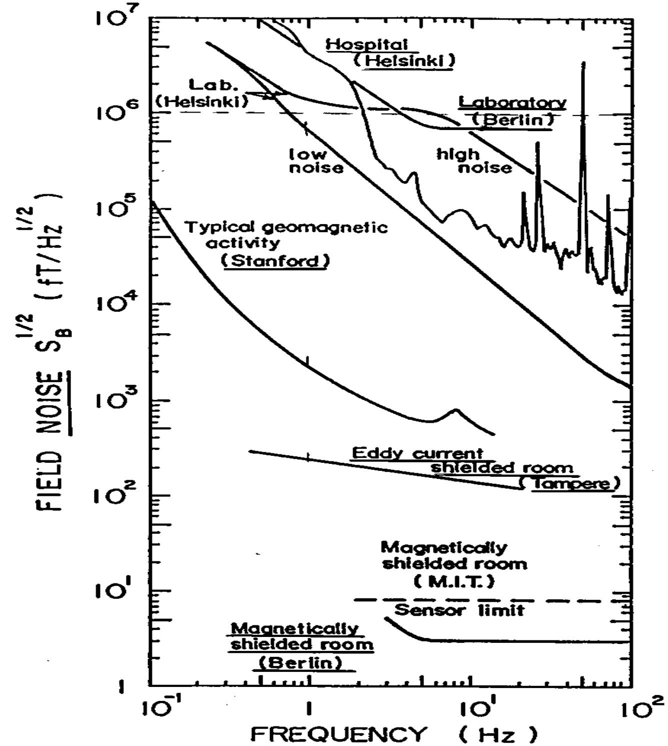
Field monitoring, diabetes & blood monitoring, stress & strain monitoring, cardiac measurements, artificial sphincters

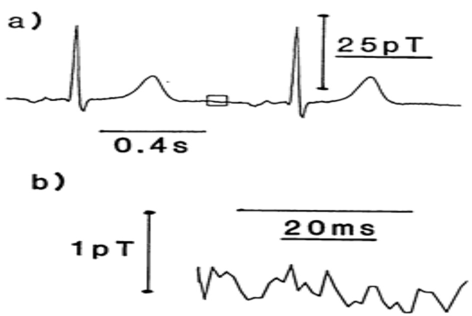




Electromagnetic Measurements in Bio-Engineering





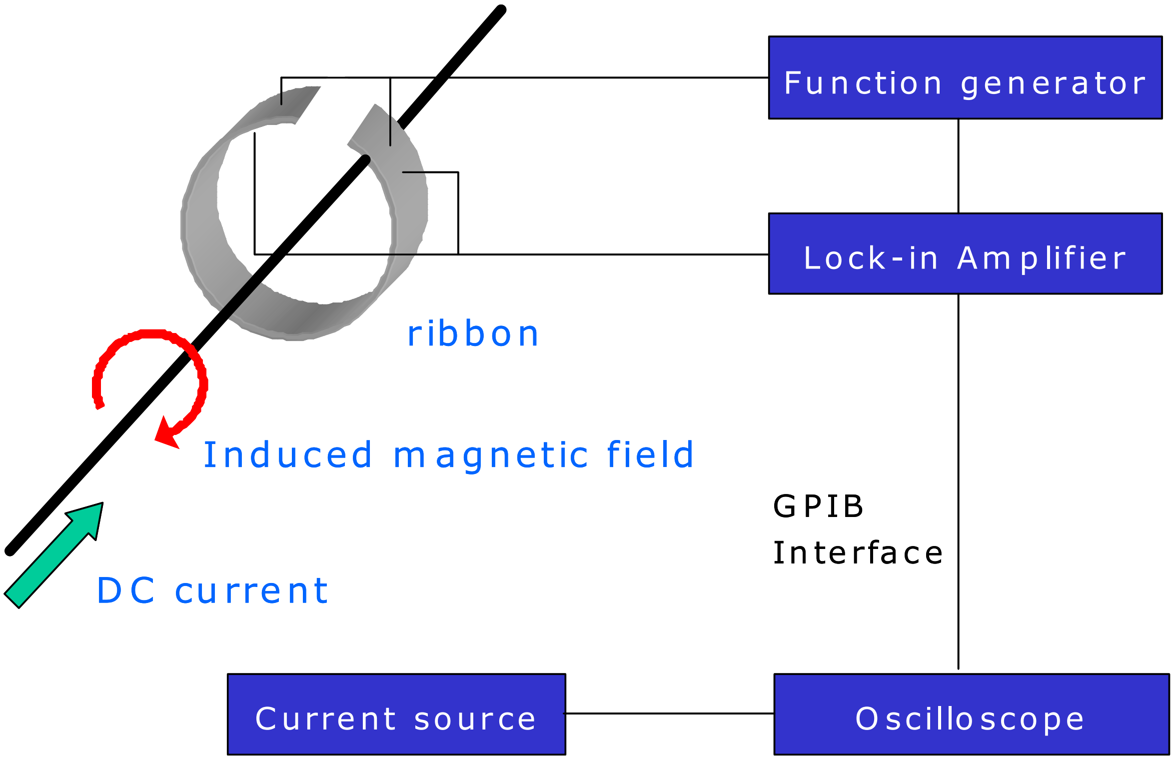


GMI Measurements

Sensor Applications

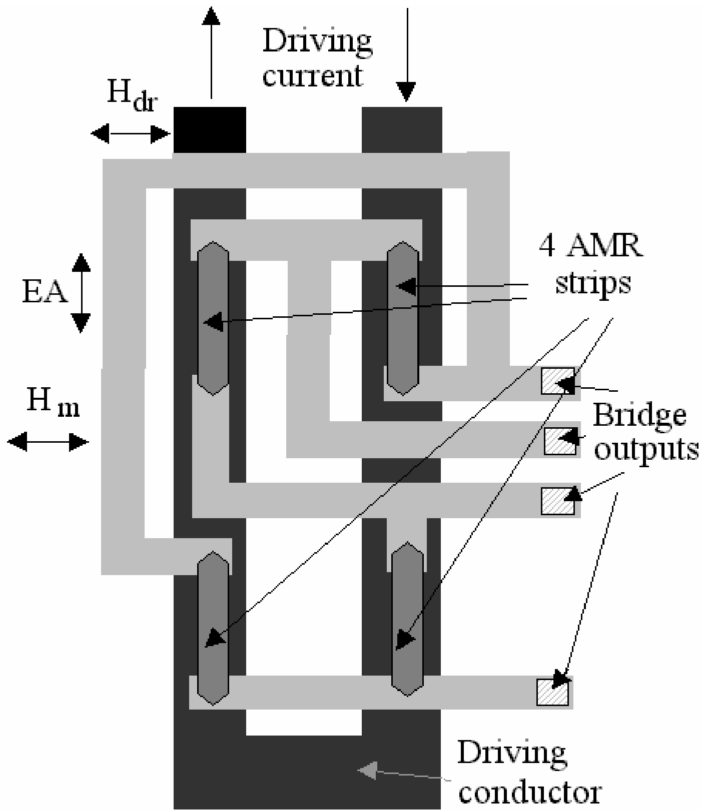
- Military applications
  - Gyroscopes (field)
  - Magnetic signatures (field)
- Automotive
  - Positioning & tracking (field)
  - Torque sensors (stress)
  - On-off- ABS rotation (positioning)
- Other applications
  - Environmental: E/M low frequency
  - Laboratory : characterization techniques
  - Domestic : current path searcher

Sensor Applications



Electric Current Meter

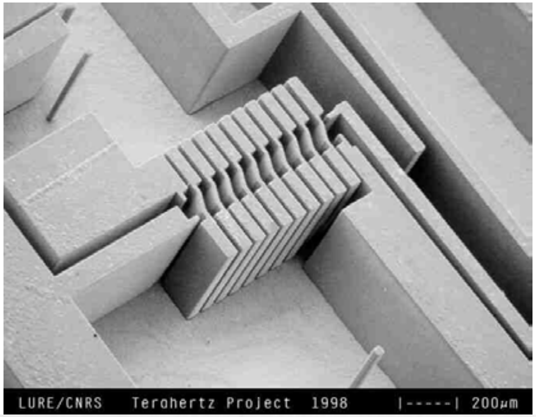
Micromagnetic arrangements

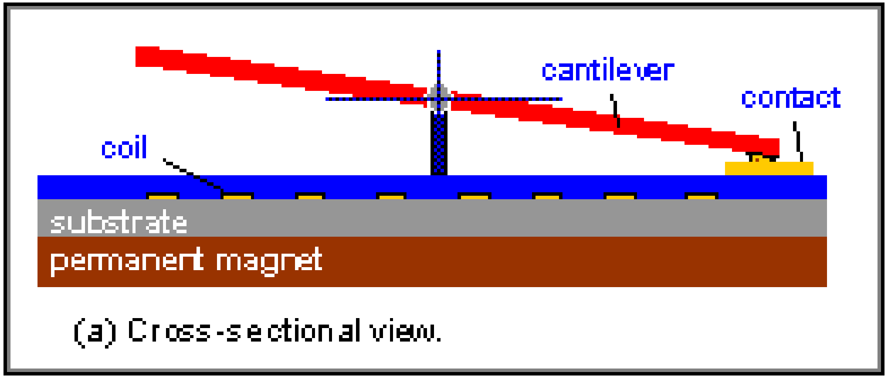


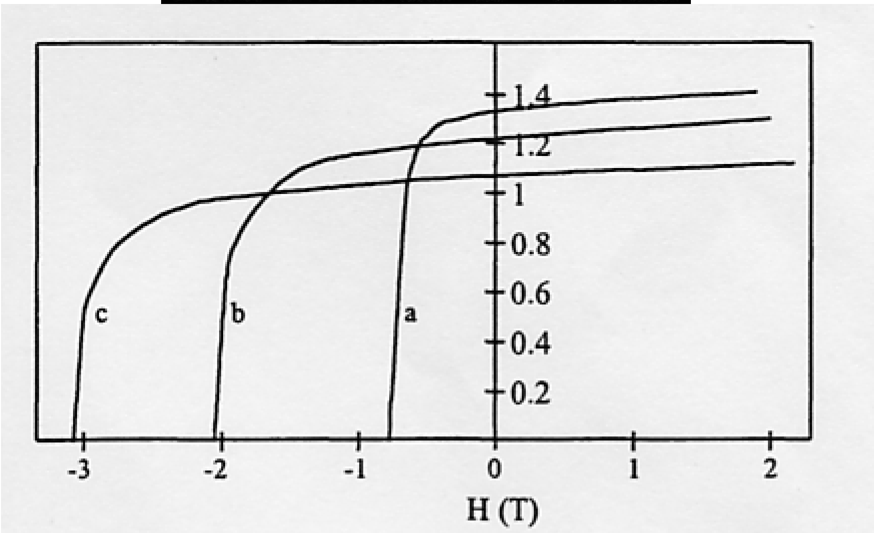
AMR Bridge

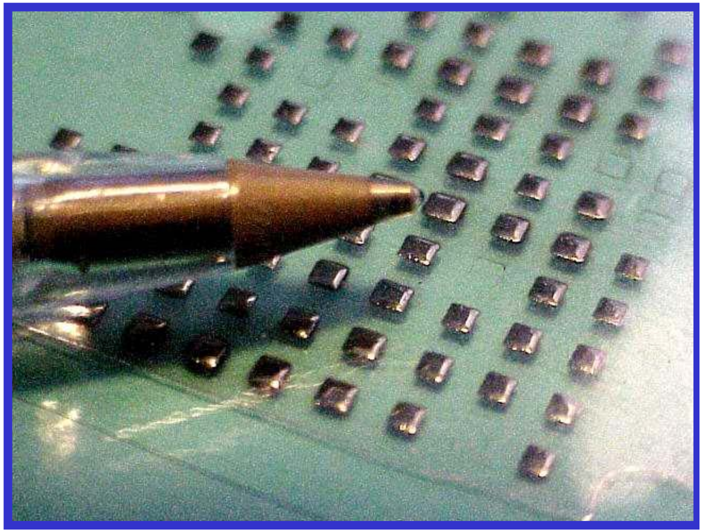
Micro-coils

Micromagnetic arrangements









Developing a sensor

- Facing-up the problem
  - measurement– range – sensitivity
  - Field of use (application)
  - Parameters affecting
- Choice of sensing principle (effect)
  - Taking into account: range – sensitivity – parameters
  - Preliminary experiments: indicative results
  - Scheduling the experiment & and the sensor

Sensor Development

- Sensing element : thin film, RQ, powder, else
- Sensing device: the first prototype
- Sensor electronics &calibration set-up
- Measurements
- Parametric effects: field, stress, temperature
- Design of the sensor housing
- Development of the sensor prototype
- Calibration & Corrective actions
- Final prototype & technical envelop

Designing the future

Is miniaturization a future challenge?

- Nanoscale resolution in writing & reading
- Sensors with secondary standard uncertainty (nanotechnology?)
- Smart multipurpose sensors
- Parametric control (field-temperature- stress)
- Silicon-chip magnetic sensors

Is there any key-parameter in designing magnetic sensors?

- Hysteresis: the key point
- Stability of B-λ-Z(H)
- Parametric effects: field- stress-temperature