Back to the sensor types

Hall sensors:

Advantages:

☐ Wide linearity range, inexpensive, highly integrable.

Drawbacks:

☐ Relatively large detection limit (not suitable for $B < 1\mu T$)

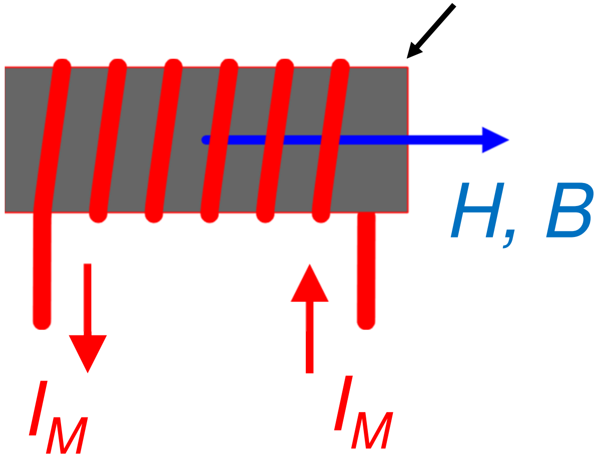
Magnetic sensors for low and ultra-low magnetic fields:

- Anisotropic Magneto-Resistance (AMR sensors)
- Giant Magneto-Resistance (GMR) - Tunnel Magneto Resistance (TMR)
- Flux Gates

Anisotropic Magneto Resistance

A premise on magnetization: ferromagnetic materials

Coil with a solid core



N=number of turns

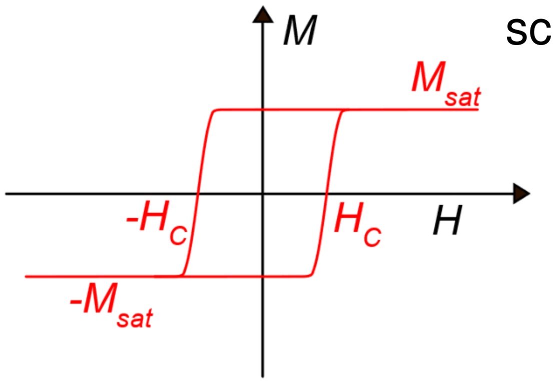
H: Excitation, proportional to NI_M

B: Response to the excitation $B=\mu_0(H+M)$

M: Due to the material.

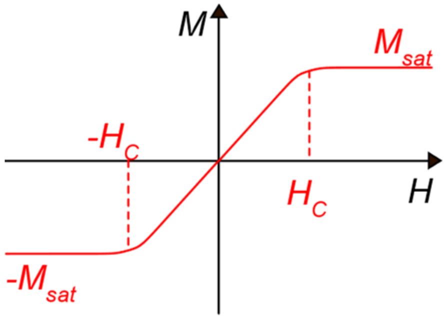
In ferromagnetic materials M>>H

H and M has different scales in these figures



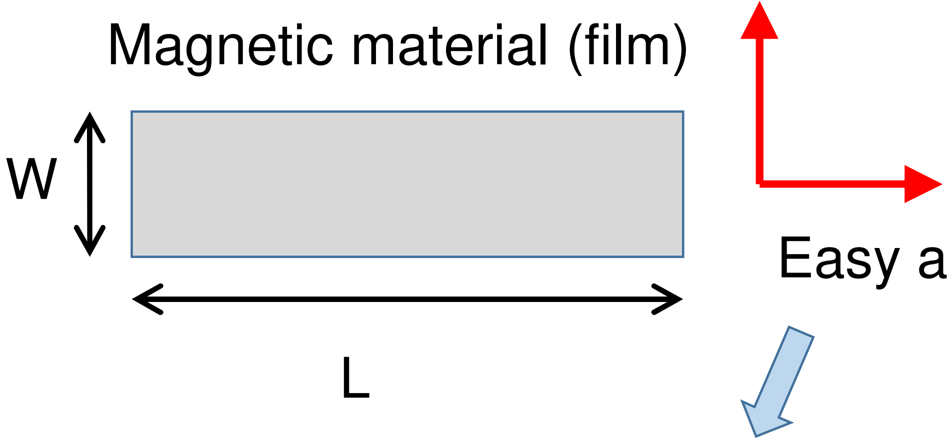
Hysteresis

Hard ferromagnetic



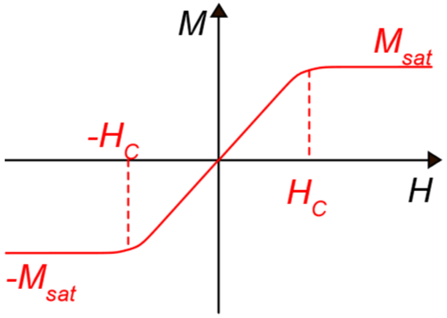
Soft ferromagnetic (idealized)

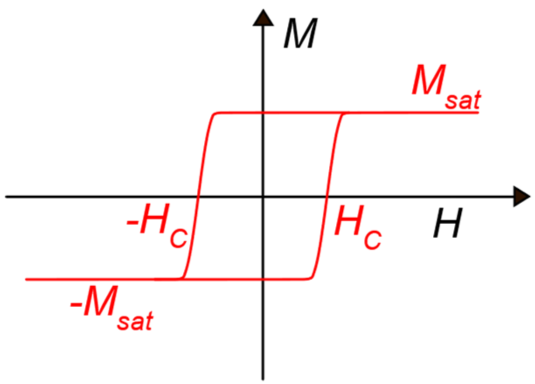
Anisotropic ferromagnetic materials


Magnetic material (film)

Sensitive axis

Easy axis

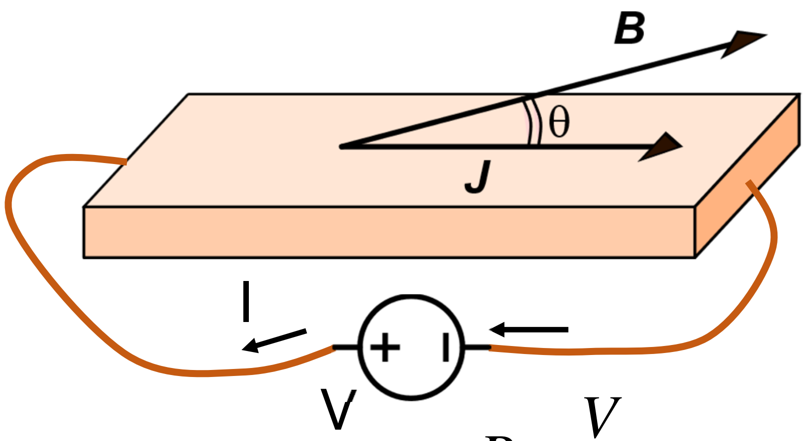




Materials that present this characteristic are, for example Iron-Nickel (Ni_xFe_y) alloys, properly deposited under a magnetic field

The film shape (L >> W) enhance the anysotropy

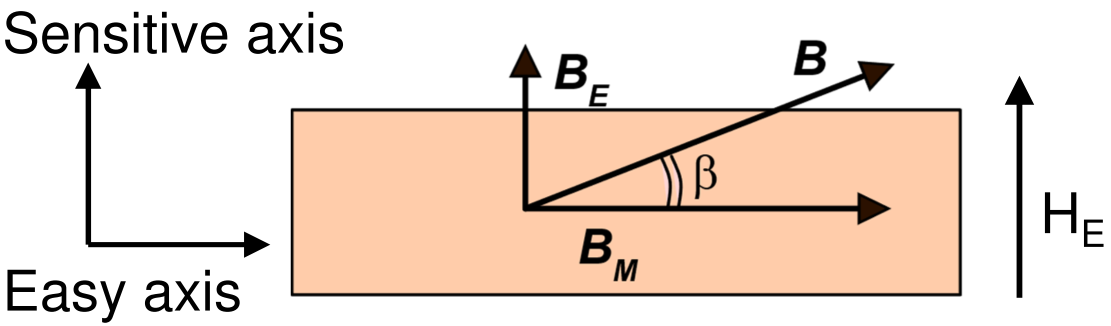
Anisotropic Magneto Resistance (AMR)



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

Material:
Ferromagnetic conductors such as Fe / Ni alloys (Permalloy)
Discovered: 1856 (Lord Kelvin)

$$R = R_\perp + \Delta R \cos^2(\theta)$$



$$\boldsymbol{B} = \boldsymbol{B}_M + \boldsymbol{B}_E$$

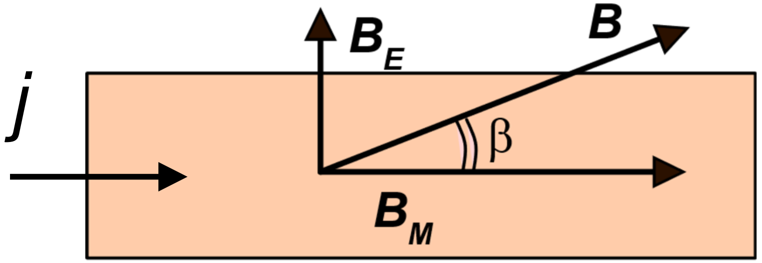
B_M: permanent magnetization (saturated)

B_E: proportional to the external field to be measured (H_E)

$$\beta = \arctan\left(\frac{B_E}{B_M}\right) \cong \frac{B_E}{B_M}$$

$$|B_E| \ll |B_M|$$

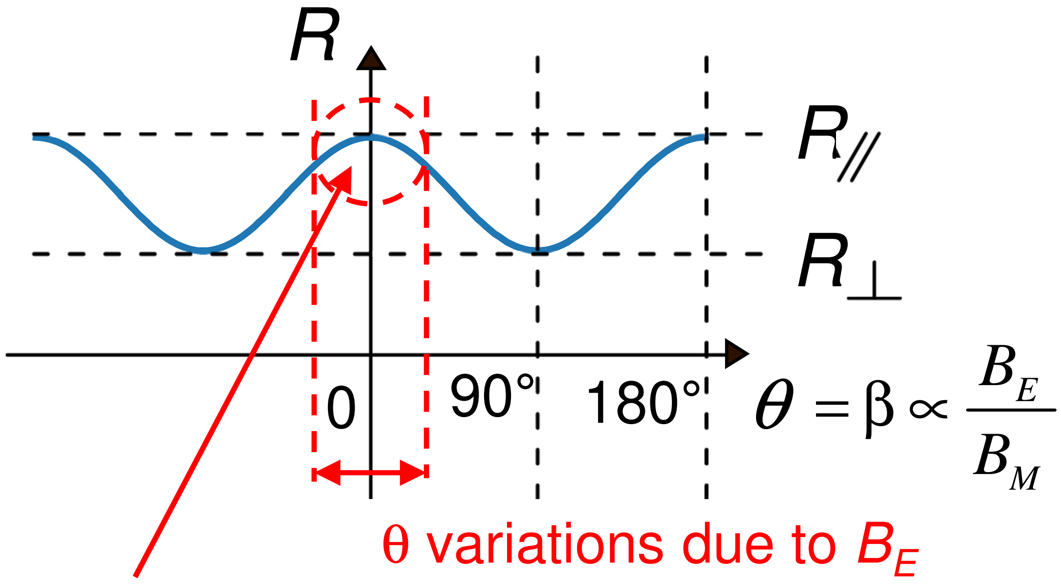
Resistance vs external magnetic field



$$\beta \cong \arctan\left(\frac{B_E}{B_M}\right) \cong \frac{B_E}{B_M}$$

$$R = R_\perp + \Delta R \cos^2(\theta)$$

$$R_{//} = R_\perp + \Delta R$$

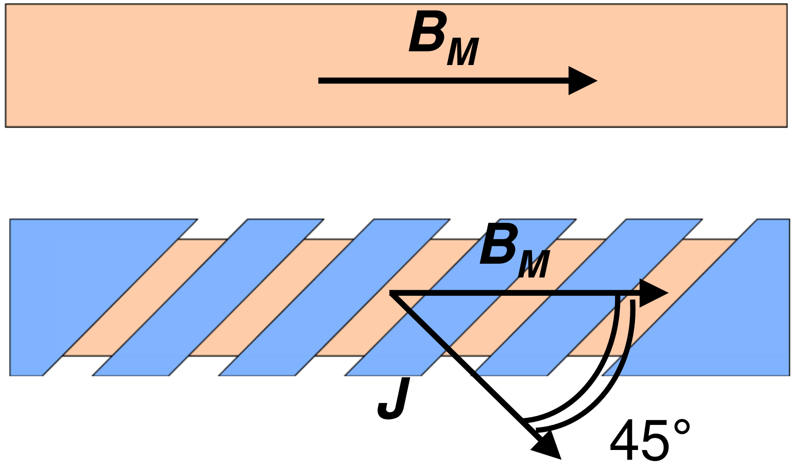


θ variations due to B_E

The derivative is around zero in this region, meaning that the sensitivity to external fields is extremely small

"Barber Pole" approach:

Barber pole



A thin metal film of a ferromagnetic conductor is deposited and magnetized along the easy axis

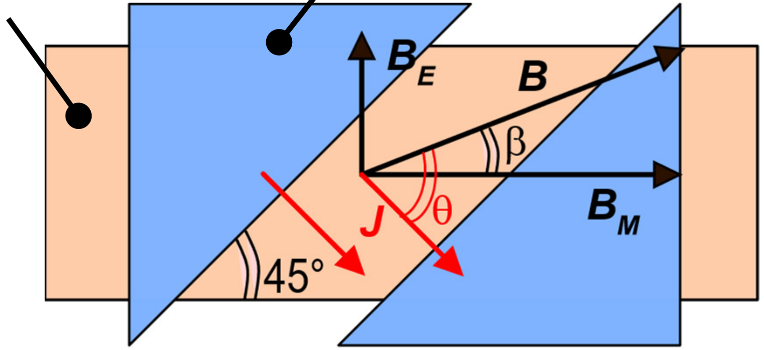
A highly conductive layer (e.g. Al), is deposited on top and patterned in order to form a series of 45 - degrees oriented stripes

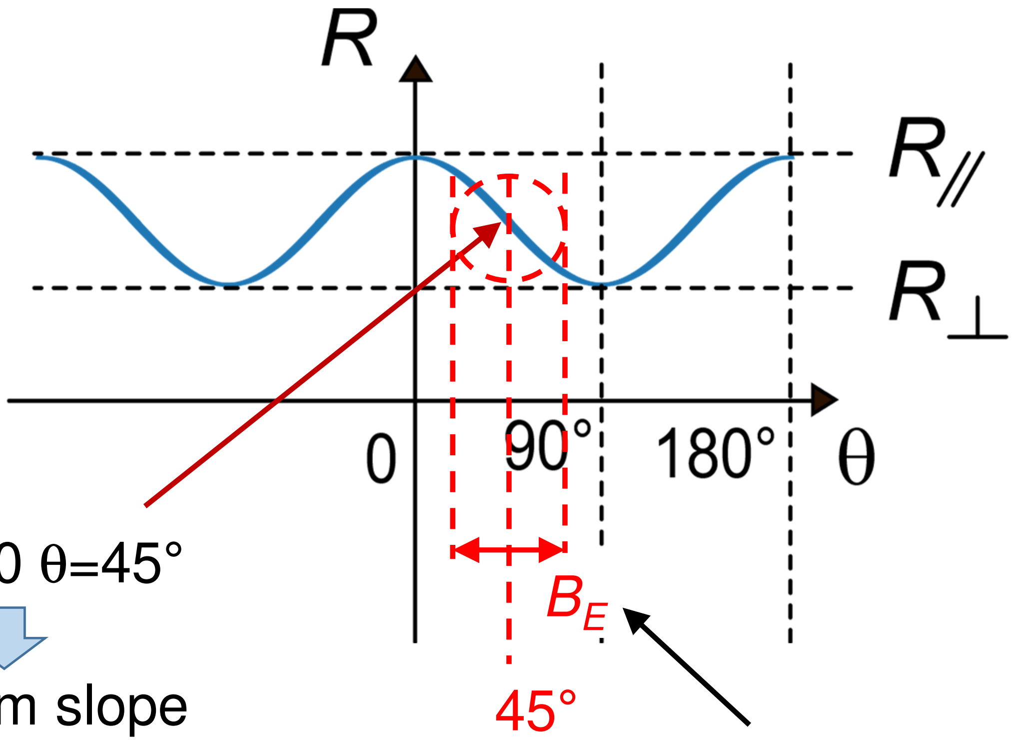
The fact that the Al layer is much more conductive than the underlying magnetic one, forces the current to cross the gaps between the Al stripes along the direction of minimum distance, which is perpendicular to the aluminum stripe edges. Then the current density in the ferroelectric materials between the conducting stripes form a 45° angle with permanent magnetization.

Magnetic field sensor based on AMR

Ferromagnetic
material
(high resistivity)

Aluminum
stripes (very low resistivity)





$$R = R_{\perp} + \Delta R \cos^2(\theta)$$

$$\theta = \frac{\pi}{4} + \beta$$

$$\beta \cong \arctan\left(\frac{B_E}{B_M}\right) \cong \frac{B_E}{B_M}$$

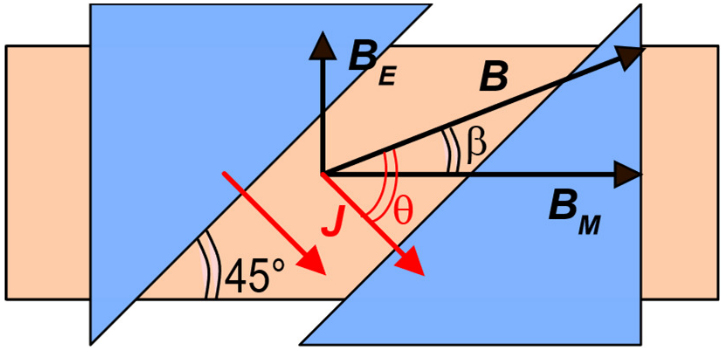
For $B_E=0$ $\theta=45°$

Maximum slope

Maximum sensitivity $\frac{1}{R}\frac{dR}{dH_E}$

Variations produced by the
external magnetic field H_E
oriented along the
sensitive axis

Magnetic field sensor based on AMR



$$\beta \cong \frac{B_E}{B_M}$$

$$\theta = \frac{\pi}{4} + \beta$$

$$R = R_\perp + \Delta R \cos^2(\theta)$$

$$R \cong R_\perp + \Delta R \left(\frac{1}{2} - \frac{B_E}{B_M} \right)$$

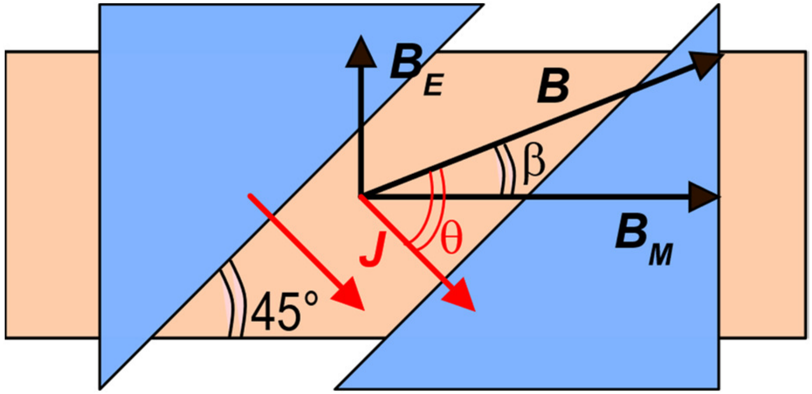
$$\cos^2(\theta) = \left(\frac{1}{2} + \frac{1}{2}\cos(2\theta) \right) = \left(\frac{1}{2} + \frac{1}{2}\cos\left(2\beta + \frac{\pi}{2} \right) \right) =$$

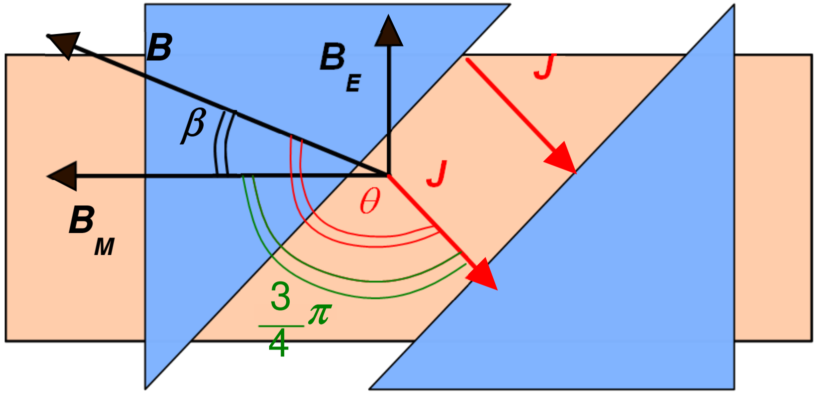
$$= \left(\frac{1}{2} - \frac{1}{2}\sin(2\beta) \right) \cong \left(\frac{1}{2} - \beta \right) \qquad \beta << 1$$

$$R = \underbrace{R_\perp + \frac{\Delta R}{2}} - \Delta R \frac{B_E}{B_M}$$

$$R = R_0 - \Delta R \frac{B_E}{B_M}$$

Effect of reversing the permanent magnetization





$$R = R_\perp + \Delta R\cos^2(\theta) \qquad \theta = \frac{\pi}{4} + \beta$$

$$\cos^2(\theta) = \left(\frac{1}{2} + \frac{1}{2}\cos(2\theta)\right)$$

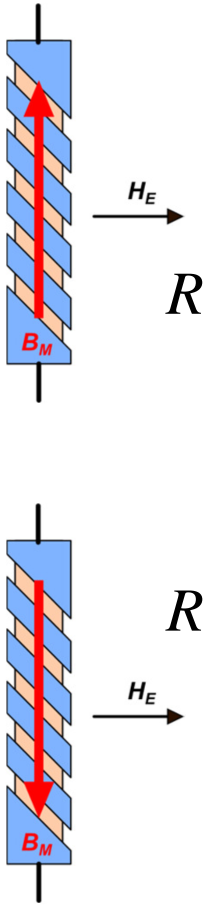
$$2\theta = \frac{\pi}{2} + 2\beta \qquad \cos(2\theta) = -\sin(2\beta)$$

$$\theta = \frac{3\pi}{4} + \beta = \frac{\pi}{4} + \beta + \frac{\pi}{2} \qquad 2\theta = \frac{\pi}{2} + 2\beta + \pi$$

$$\cos(2\theta) = -\cos\left(\frac{\pi}{2} + 2\beta\right) = \sin(2\beta)$$

The sign of the resistance variation caused by B_E is reversed

Wheatstone bridge of AMR resistors

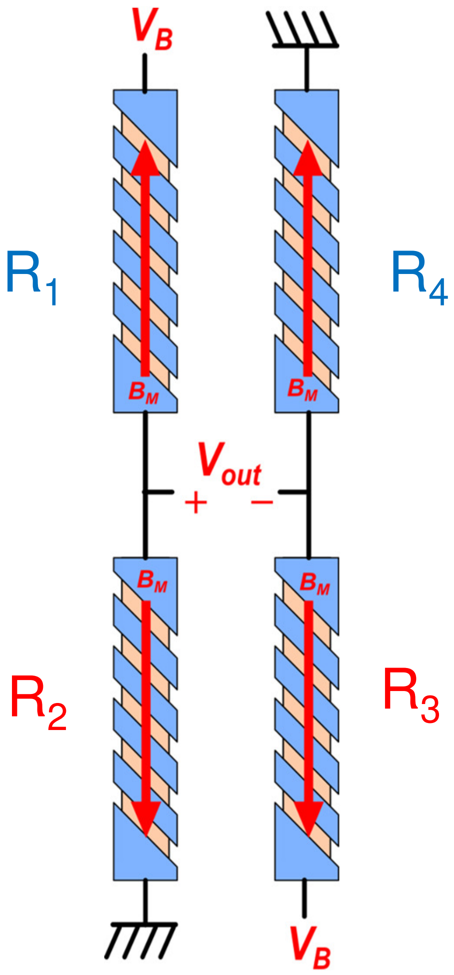


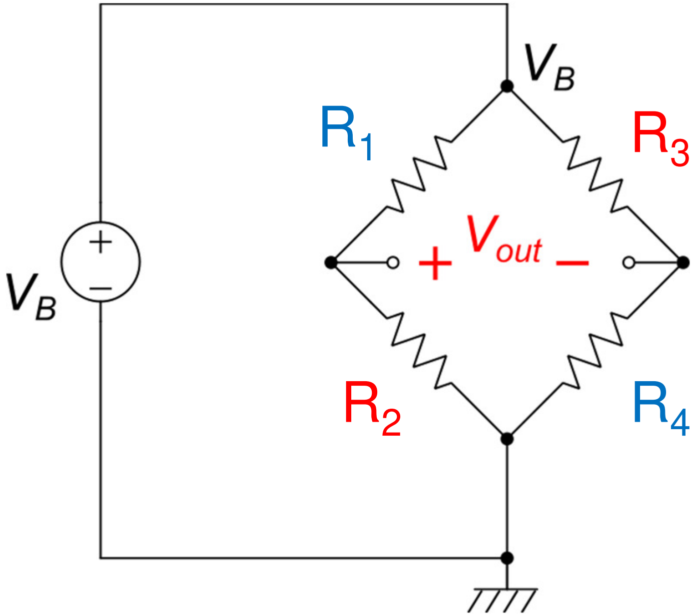
R_1, R_4

$$R = R_0 - \Delta R \frac{B_E}{B_M}$$

R_2, R_3

$$R = R_0 + \Delta R \frac{B_E}{B_M}$$





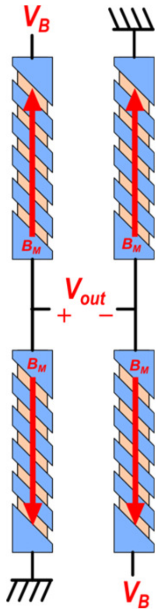
$$V_{out} = V_B \frac{\Delta R}{R_0} \frac{1}{B_M} B_E$$

$$B_E \propto H_E$$

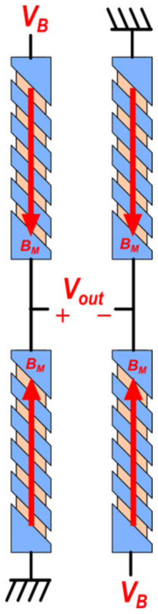
Offset free read cycle

The offset is due to mismatch of the zero-field resistors (R_0) of the Wheatstone bridge

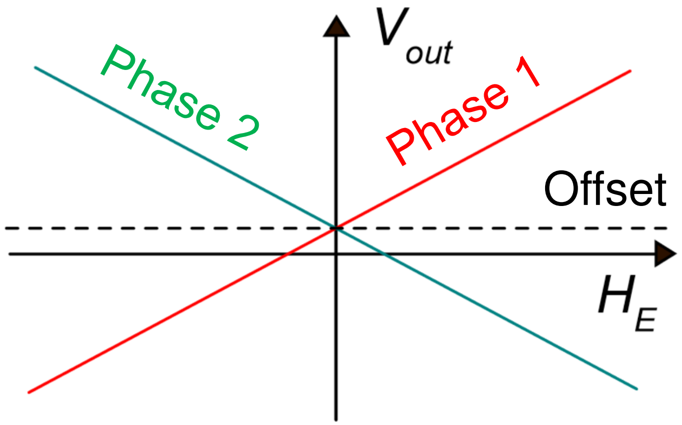
Inverting the magnetization of all AMR resistors change the sign of the output voltage but leaves the offset unchanged

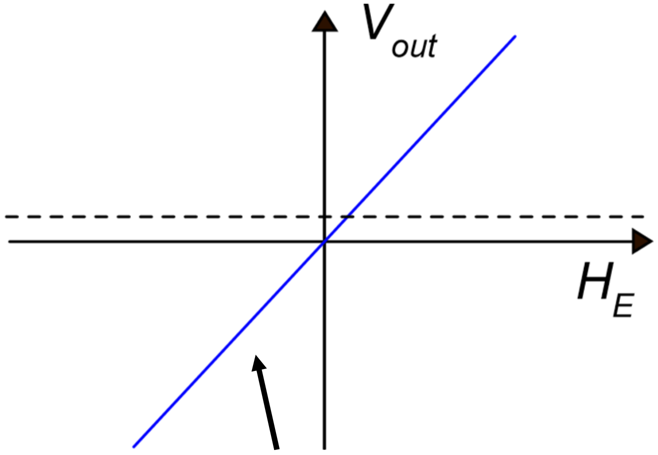


Phase 1



Phase 2

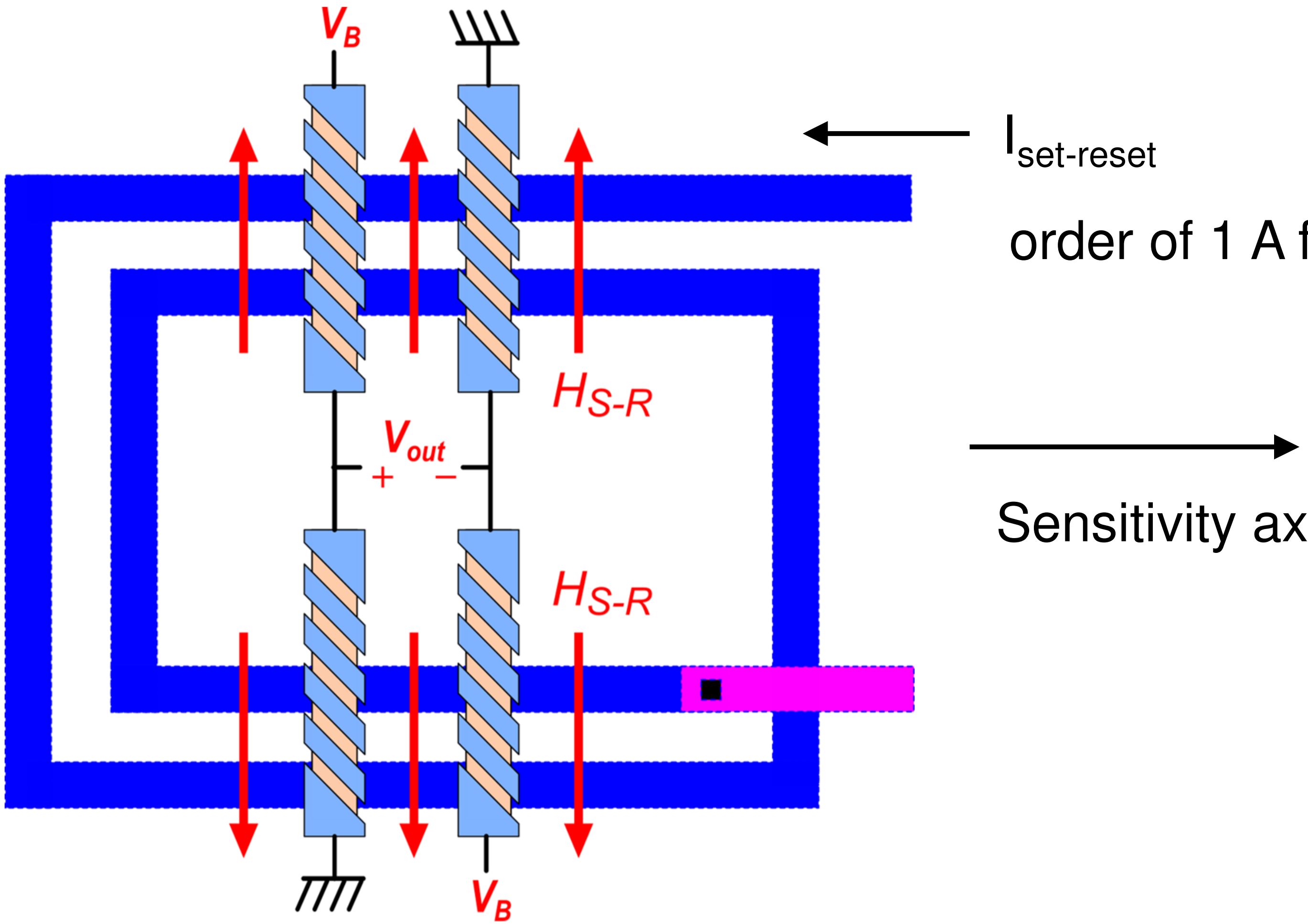




phase 1 - phase 2
(no offset)

$$V_{out} = V_B \frac{\Delta R}{R_0} \frac{1}{B_M} B_E \qquad V_{out} = -V_B \frac{\Delta R}{R_0} \frac{1}{B_M} B_E$$

Integrated AMR sensor with magnetization coil (set-reset coil)



$I_{set\text{-}reset}$

order of 1 A for 1µs

Sensitivity axis

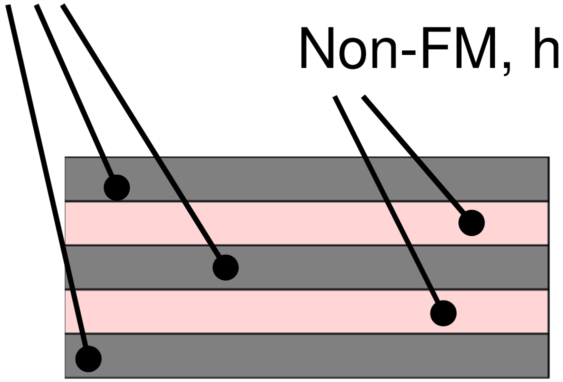
Very sensitive magnetic sensors

- Giant Magneto-Resistance (GMR) sensors
- Tunnelling Magneto-Resistance (TMR) sensors

Applications.

1. Hard Disk Head
2. Solid-State magneto-resistive RAMs (MRAMs)
3. Detection of magnetically-labelled bio-markers

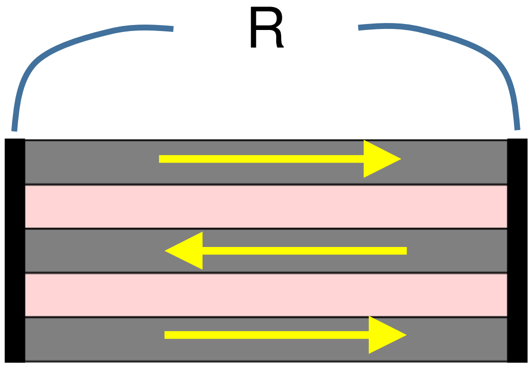
Giant Magneto Resistance (GMR) Sensors



Ferro Magnetic (FM) Layers (medium conductivity)

Non-FM, high conductivity layer (e.g. Cu)

Layer thickness:
a few monolayers



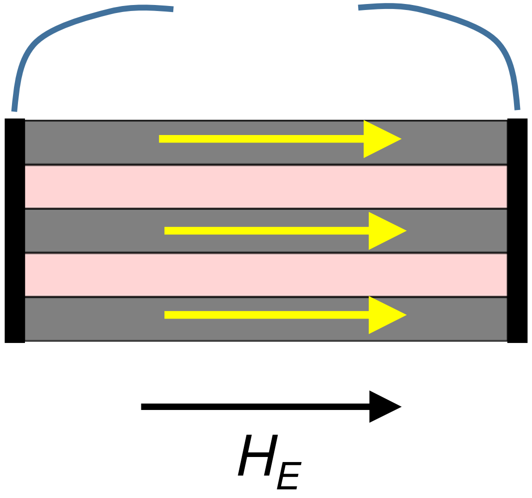
With no external field, magnetization tends to be opposite in adjacent layers

High surface scattering in the conductive layers.

High resistance

Quantum Mechanics principle:
Spin-dependent scattering

Effect of an external field



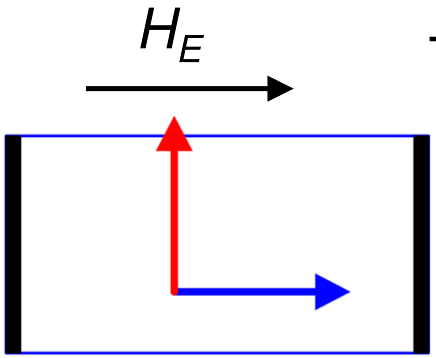
An external field of sufficient strength force all the layers to have parallel magnetization

⇩

Low scattering
Low resistance

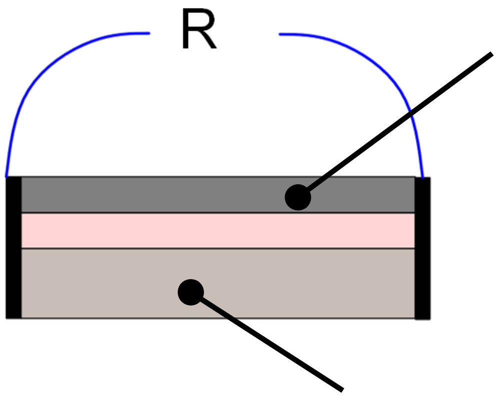
Resistance variations can be much larger than in AMR sensors (up to 100 %), but this is not a linear effect (it is rather a threshold effect).

GMR Spin Valve



Top view

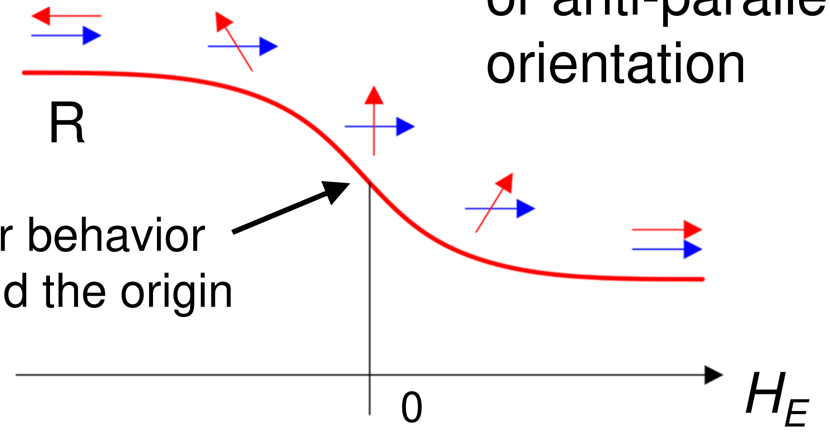
For null external fields, magnetization in the two layers are orthogonal



Top FM layer
(the magnetization is affected by the external field)

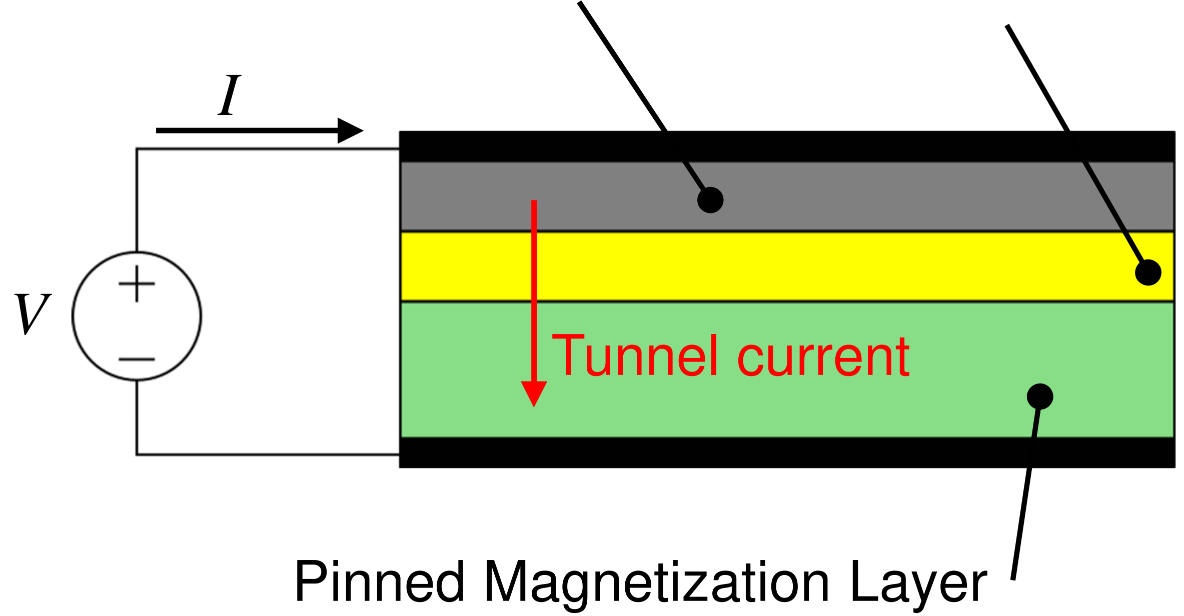
FM layer with pinned magnetization
(does not change with external field)

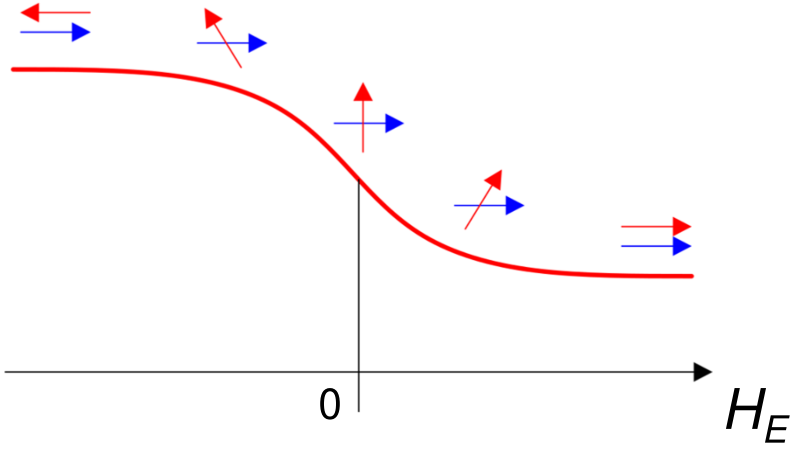
The external field make the two magnetization tend to a parallel or anti-parallel orientation



Linear behavior around the origin

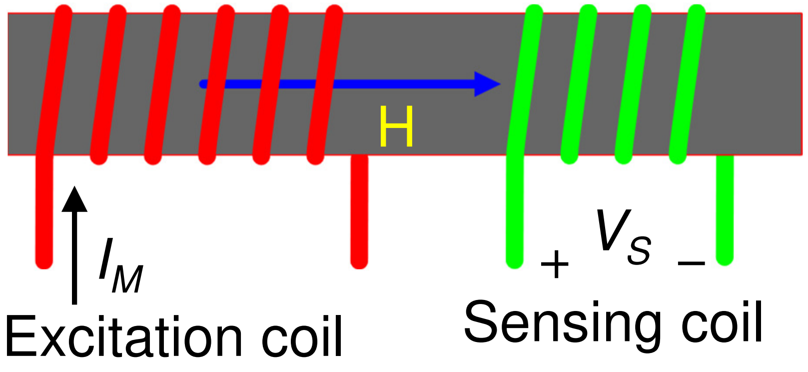
TMR (Tunneling Magneto Resistance)





The resistance curve is similar to that of GMR, but variations are even larger

Flux-Gates Magnetometer : Principle



$$H = H_{IM} + H_{ext}$$

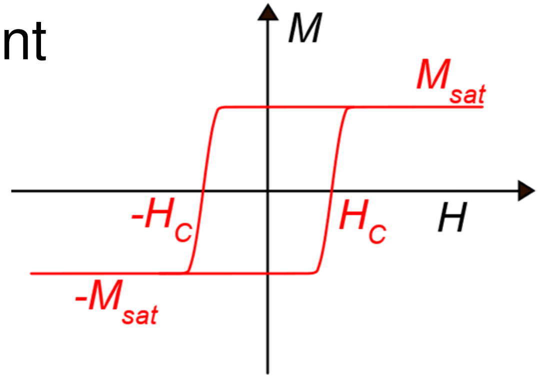
H_{IM}: the excitation field, proportional to I_M

H_{ext}: is the external field, that we want to sense

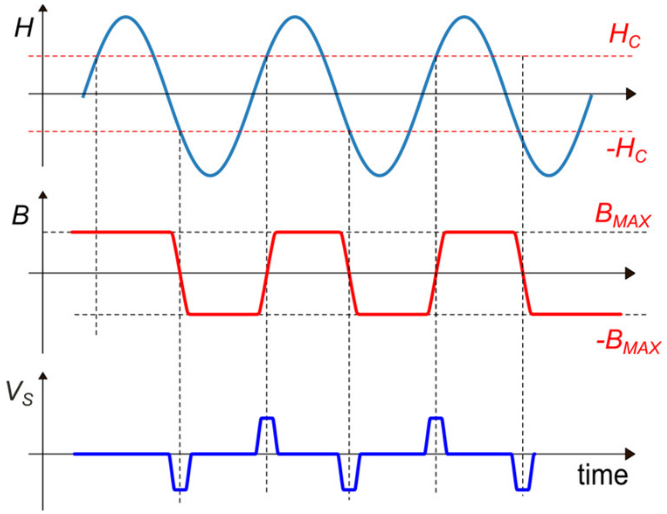
I_M is a sinusoidal current

$$V_S = -\frac{d\Phi}{dt} = -N_S A \frac{dB}{dt}$$

$$B = \mu_0 \left(H + M \right) \cong \mu_0 M$$



For H_{ext}=0

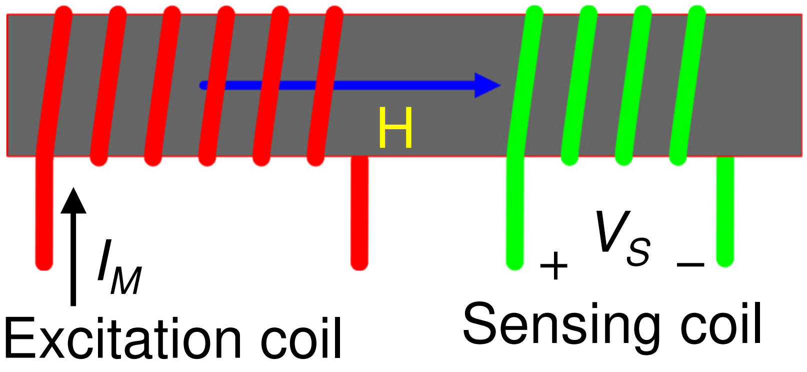


The fluxgate principle is effective also with soft magnetic materials. What is essential is the presence of **saturation.**

In the case of Hext=0, the sensed voltage V_S has the property of half-wave symmetry.

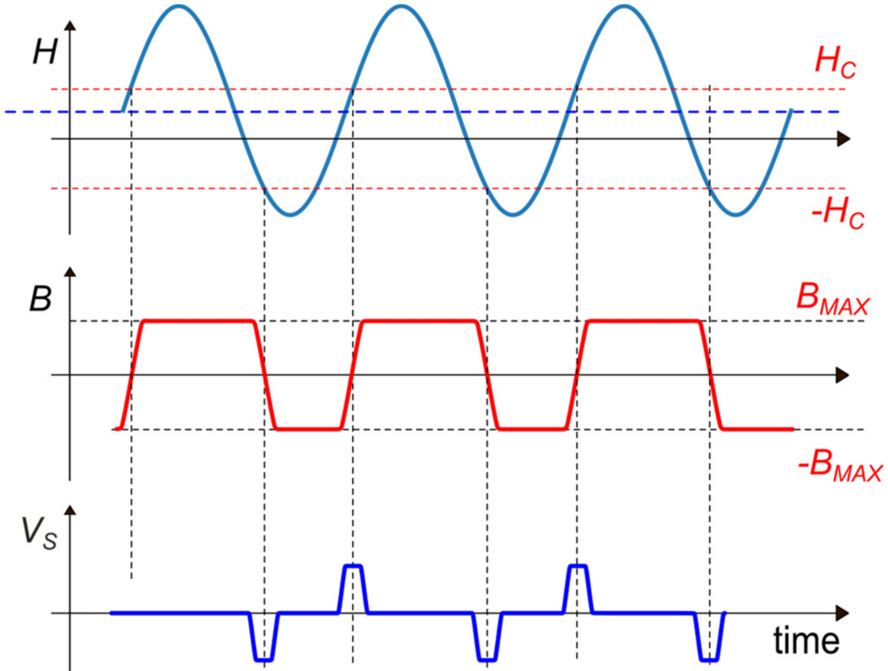
<u>Then it has no even harmonics</u>

Flux-Gates Magnetometer : Principle



The external field H_{ext}, shifts the excitation field H (in the example H is shifted up). As a result, magnetic induction B spends more time in the positive saturation value (B_{MAX}) than in the negative one (.-B_{MAX}).
This introduce an asymmetry that results in the presence of a second harmonic component.

For $H_{ext}=0$



The relationship between the magnitude of the second harmonics and H_{ext} is linear for small values of the field. The sign of H_{ext} is represented by the phase of the second harmonics that can be detected by means of a synchronous demodulator.