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Anizotropní magnetorezistivní jev – od principu k návrhu senzoru

Anisotropic Magnetoresistive Effect – from the principle to the sensor

Summary

The anisotropic magnetoresistive sensors are an attractive alternative to the Hall effect-based sensors, in particular thanks to the comparable level of miniaturization, accompanied by higher sensitivity. These sensors exploit the anisotropic magnetoresistive effect in ferromagnetic metals. The resistance imposed to the flowing current is dependent on the angle of magnetization, the difference between the maximum and minimum resistance reaching units of percent. Sensors based on the anisotropic magnetoresistive effect almost exclusively rely on thin layers of appropriate ferromagnetic alloys. The used material, the way of the deposition and the geometry of the sensor, influencing the magnetoresistive effect itself as well as the range and sensitivity of the sensor, are the decisive parameters for the proper function of the sensor. The characteristic of the magnetoresistive element is linearized and the full-bridge configuration consisting of four elements is mostly used in the sensors. Periodical remagnetizing and feedback compensation mode is often used for improvement of the sensor parameters.

This lecture is dedicated to the anisotropic magnetoresistive sensors, beginning with the explanation of the physical phenomenon they are based on and continuing to the design of the sensors and circuits for their use. Publications that contain own research results are referenced underlined.

The author participated on research and development of this type of sensors during his almost one-year stay at Universidad Nacional Autónoma de México and another one-year stay at Tyndall National Institute in Ireland. Besides that, he performed research on the market-available sensors during his stay at the Czech Technical University in Prague, at the Technische Universität Wien and at his current place, College of Polytechnics Jihlava.

Souhrn

Anizotropní magnetorezistivní senzory představují atraktivní alternativu k senzorům založeným na Hallově jevu zejména díky porovnatelnému stupni miniaturizace při současné vyšší citlivosti. Tyto senzory využívají anizotropního magnetorezistivního jevu ve feromagnetických kovech. Elektrický odpor kladený protékajícímu proudu je závislý na úhlu magnetizace materiálu, přičemž rozdíl mezi maximálním a minimálním odporem dosahuje jednotek procent. Senzory založené na anizotropním magnetorezistivním jevu téměř výhradně využívají tenkých vrstev vhodných feromagnetických slitin. Zásadní pro funkci senzoru je volba materiálu, způsob depozice a geometrie senzoru, která ovlivňuje jak projev jevu samotného, tak i rozsah a citlivost senzoru. Odezva vlastních magnetorezistivních elementů je vhodným způsobem linearizována a senzor pak většinou využívá můstkového zapojení čtyř magnetorezistivních elementů. Pro zlepšení parametrů senzoru se využívá periodického přemagnetování elementů a zpětnovazebního zapojení.

Tato přednáška se zabývá anizotropními magnetorezistivními senzory od popisu samotného fyzikálního principu až po návrh senzoru a obvodů pro jeho použití. Odkazované publikace s výsledky vlastního výzkumu jsou uvedeny podtrženě.

Autor se zabýval vývojem tohoto typu senzorů během téměř roční stáže na Universidad Nacional Autónoma de México a další roční stáže v Tyndall National Institute v Irsku. Kromě toho prováděl výzkum na komerčně dostupných senzorech během svého působení na Českém vysokém učení technickém v Praze, na Technische Universität Wien a na současném působišti, Vysoké škole polytechnické Jihlava.

Klíčová slova

Anizotropní magnetorezistivní jev, anizotropní magnetorezistor, tenké feromagnetické vrstvy, měření magnetického pole

Keywords

Anisotropic magnetoresistive effect, anisotropic magnetoresistor, thin ferromagnetic films, measuring of magnetic field

Contents

1 Introduction

In 1857, an interesting phenomenon appearing in ferromagnetic conductors was described in Proceedings of the Royal Society in London [1], authored by William Thomson, known also as Lord Kelvin, professor at the University of Glasgow. Lord Kelvin reported that „*…iron, when subjected to magnetic force, acquires an increase of resistance to the conduction of electricity along, and a diminution of resistance to the conduction of electricity across, the lines of magnetization.*" He further states that "*…nickel is similarly influenced by magnetism, but to a greater degree.*"

The effect Lord Kelvin observed is a manifestation of the phenomenon known to us today as the Anisotropic Magnetoresistive Effect (AMR). It took more than a century until the origin of AMR has been understood in the full detail. With development of the advanced technologies for deposition of thin films, the AMR effect began to be exploited in reading heads for hard drives and later also in sensors for linear measurements of weak magnetic fields. Various improvement techniques have been developed for linearization of the sensor, for offset and sensitivity stabilization and for elimination of the temperature dependences. Nowadays, AMR sensors for linear and angle measurements form a stable and ever growing segment of the market of magnetic sensors. Current AMR sensors are significantly more sensitive than Hall effect based sensors, allowing their usage in compassing applications. Thanks to their size, weight and price, AMR-based sensors recently find their use also in space research, so far a typical fluxgate sensors domain, in spite of their worse sensitivity, noise and stability parameters.

2 Anisotropic Magnetoresistive Effect

2.1 Origin of the Anisotropic Magnetoresistive Effect

Although its macroscopic manifestation has been known since Lord Kelvins' experiments, the explanation of AMR effect origin was not possible until the mechanism of electric conduction in transition metals (i.e., metals with not fully occupied *3d* orbitals) has been understood, considering the quantum mechanical principles. In his pioneering works [2, 3], N.F. Mott postulates that due to the overlapping of the *4s* and *3d* energy bands in the electron structure of transition metal atoms, an electron scattered off the *4s* shell can undergo two types of transition: transition to another *4s* shell, or transition to an unoccupied state in the *3d* shell. Due to higher effective mass, *3d* electrons are much less mobile than the *4s* electrons. Thus, the s-d transitions contribute significantly to the overall resistivity of the material.

In ferromagnetic metals (Ni, Fe, Co @ room temperature), uncompensated spin magnetic moments align parallel due to the exchange energy. The volume density of the vector sum of all the particular spin magnetic moments is the magnetization vector, ***M***. If all the spin magnetic moments within the ferromagnetic body are aligned, ***M*** reaches its maximum possible value M_s or saturation magnetization (the ferromagnetic body is in the saturated state). An external magnetic field can cause change of direction of ***M*** without changing its value – all the spin magnetic moments react on the magnetic field by the same rotation. This behavior is referred to as *coherent rotation* of ***M***. In a real ferromagnetic body, the parallel alignment of the spin magnetic moments is usually limited to a smaller region – so-called domain.

It has been shown that, owing to the spin-orbit interaction, the probability of an s-d transition in a saturated ferromagnetic material is the highest for the electrons travelling parallel to ***M***, and the lowest for the electrons travelling orthogonally to ***M*** [4, 5]. As the s-d transitions considerably contribute to the resistivity of the material, the overall resistivity of a magnetized ferromagnetic material is the highest when the current flows in the direction of ***M*** and the lowest when the current flows orthogonally to ***M***, in an exact accordance with the Kelvin's finding.

2.2 Macroscopic manifestation of the AMR effect

Let a ferromagnetic body be considered. Designating $\rho_{||}$ the resistivity imposed to the current flowing in parallel to ***M*** and $\rho_{\perp}$ the resistivity imposed to the current flowing orthogonally to ***M***, the theoretical resistivity of a demagnetized sample is [5]

$$\rho_0 \equiv \frac{1}{3}\rho_{\parallel} + \frac{2}{3}\rho_{\perp} \quad (1)$$

and the so-called AMR coefficient is most usually defined as

$$\left(\frac{\Delta\rho}{\rho_0}\right)_{\mathrm{AMR}} = \mathrm{AMR} = \frac{\rho_\parallel - \rho_\perp}{\frac{1}{3}\rho_\parallel + \frac{2}{3}\rho_\perp} \tag{2}$$

being of units of percent in the common ferromagnetic alloys, see table 2 in chapter 5.

Let an electric current with the density ***J*** flow through a saturated ferromagnetic material. It has been found [5, 6, 7] that the general relationship between ***J***, ***M*** and electric field ***E*** in the material can be expressed as

$$\vec{E} = \vec{\vec{\rho}} \cdot \vec{J} \tag{3}$$

with the resistivity tensor being

$$\vec{\vec{\rho}} = \begin{bmatrix} \rho_\perp + \Delta\rho \cdot \cos^2\alpha_x & \Delta\rho \cdot \cos\alpha_x \cdot \cos\alpha_y - \rho_{\mathrm{H}} \cdot \cos\alpha_z & \Delta\rho \cdot \cos\alpha_x \cdot \cos\alpha_z + \rho_{\mathrm{H}} \cdot \cos\alpha_y \\ \Delta\rho \cdot \cos\alpha_x \cdot \cos\alpha_y + \rho_{\mathrm{H}} \cdot \cos\alpha_z & \rho_\perp + \Delta\rho \cdot \cos^2\alpha_y & \Delta\rho \cdot \cos\alpha_y \cdot \cos\alpha_z - \rho_{\mathrm{H}} \cdot \cos\alpha_x \\ \Delta\rho \cdot \cos\alpha_x \cdot \cos\alpha_z - \rho_{\mathrm{H}} \cdot \cos\alpha_y & \Delta\rho \cdot \cos\alpha_y \cdot \cos\alpha_z - \rho_{\mathrm{H}} \cdot \cos\alpha_x & \rho_\perp + \Delta\rho \cdot \cos^2\alpha_z \end{bmatrix} \tag{4}$$

Here,

$\Delta\rho = \rho_\parallel - \rho_\perp$;

ρ_{H} is the Hall coefficient of the material;

$\cos\alpha_x$, $\cos\alpha_y$, $\cos\alpha_z$ are the direction cosines of ***M*** in the choosen orthogonal system of coordinates.

If the system of coordinates is chosen in the way that its *x*-axis coincides with the direction of flowing electric current, i.e., the current density vector is ***J*** = (J_{x}, 0, 0), it can be written for E_{x}

$$E_{\mathrm{x}} = \left(\rho_\perp + \Delta\rho\cos^2\alpha_{\mathrm{x}}\right) \cdot J_{\mathrm{x}} \tag{5}$$

The resistivity imposed to the current, i.e., measured in the current propagation direction, is $\rho_{\text{meas}} = E_{\text{x}} / J_{\text{x}}$ and it is given by the so-called *Voigt–Thomson formula*

$$\rho_{meas}(\alpha_{\text{x}}) = \rho_{\perp} + \Delta\rho\cos^2\alpha_{\text{x}} = \rho_{\parallel} - \Delta\rho\sin^2\alpha_{\text{x}} \tag{6}$$

Many modifications of this basic formula have been developed to better approximate the behavior of the resistivity in a real ferromagnetic film, e.g. [8], but in fact, the presented formula in its basic form represents a sufficiently good model for the ordinary magnetoresistive sensors [9].

3 Thin film AMR stripes

It is possible to design a sensor of magnetic field that employs the described AMR effect. The resistivity of the sensor element is a function of the direction of ***M***, which in turn can be controlled by the external (measured) magnetic field ***H***. One of the crucial assumptions, however, is that the sensor material is saturated and ***M*** undergoes the coherent rotation. This means that the entire volume of the sensor material behaves as a single magnetic domain. Such a behavior can hardly be achieved in bulk forms, but it is relatively easily achievable in thin films (thickness ~ tens of nm) of magnetoresistive material. Additionally, standard technology developed for semiconductor electronics fabrication can be used for fabrication of thin films of magnetoresistive materials. Today, sensors that employ the AMR effect are exclusively based on thin film structures, mostly in the form of narrow stripes.

3.1 Magnetization in saturated ferromagnetic thin films

Direction of saturated magnetization ***M*** in a ferromagnetic thin film exposed to the magnetic field ***H*** is determined by the minimization of the free system energy. In basic considerations, two competing energy terms are taken into account in AMR thin films: the magnetostatic energy, related to the mutual orientation of the external magnetic field ***H*** and ***M*** and being minimal for ***M*** coinciding with ***H***; and energy terms associated with the uniaxial anisotropies in the material.

Uniaxial anisotropy manifests itself by the existence of the so-called easy axis of magnetization, where ***M*** orients to in absence of an external magnetic field. In other words, the energy associated with the uniaxial anisotropy is minimal when ***M*** is oriented along the easy axis (in one of the two possible orientations). The "strength" of the uniaxial anisotropy is quantified by its characteristic field H_k. The higher H_k, the higher energy needed to incline ***M*** out of the easy axis. Magnetic field applied perpendicularly to the easy axis must have the magnitude equal to H_k or higher to rotate ***M*** fully into its direction. Generally, the state with minimal energy in presence of an external magnetic field ***H*** occurs for a direction of ***M*** between the easy axis and ***H*** direction, see figure 1.

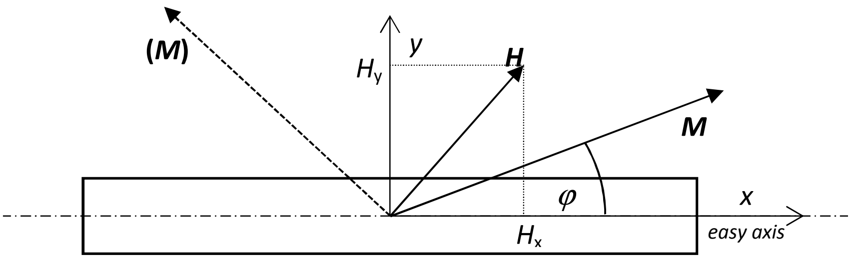

Figure 1: Magnetization ***M*** in thin film ferromagnetic stripe exposed to the magnetic field ***H***. Easy axis is coincident with the longitudinal axis of the stripe. Dotted arrow represents ***M***, if its initial orientation along the easy axis was opposite.

There are several origins of uniaxial anisotropies in magnetoresistive thin films. In the most general view, two main anisotropy sources can be identified:

- inherent material anisotropy (consisting of crystalline anisotropy and anisotropy induced during the manufacturing process);
- shape (form) anisotropy.

3.1.1 Material anisotropy in thin ferromagnetic films

Already during the deposition of the magnetoresistive material, direction usually develops, in which it is easier to magnetize the material, i.e., there exists a uniaxial anisotropy. After deposition, the thin magnetoresistive films intended for the use in sensor applications are annealed in a homogeneous magnetic field for several reasons that will be discussed in chapter 5. This magnetic field is usually applied in the direction of the already existing easy axis. As a result, the anisotropy is further strengthened. Its characteristic field $H_{k,f}$ reaches hundreds of A/m, depending on the particular material (see table 2, chapter 5). Although complicating the sensor design from certain point of view, existence of the material anisotropy is hardly evitable.

3.1.2 Shape anisotropy in thin film ferromagnetic stripes

The shape of a saturated ferromagnetic body heavily influences the behavior of its magnetization. The divergence of $\boldsymbol{M}$ on the surfaces of a spatially limited ferromagnetic body leads to creation of the so-called demagnetization field [10]. Thus it is easier to magnetize the (non-spherical) ferromagnetic body in certain directions compared to other directions and $\boldsymbol{M}$ in a saturated ferromagnetic body has shape-determined preferred directions of orientation. The theory of demagnetization effects has been described thoroughly in the general textbooks on magnetism, e.g., [11]. The demagnetization effects are usually described by the so-called demagnetization factor N for the main directions (usually along the axes of the coordinate system). Unfortunately, only in ellipsoidal specimens the demagnetization field is uniform, resulting in single-number demagnetization factors $N_{x,y,z}$ along the axes [12]. Nevertheless, due to its practical importance, considerable effort has been made to propose suitable models that would allow making a proper estimation of single-number demagnetization factors even in rectangular bodies [13-17].

In the particular case of thin magnetoresistive stripes, an assumption is usually made that the demagnetization factor $N_x \approx 0$, $N_z \approx 1$ and N_y is approximated as $N_y = t / (t + w) \approx t / w$, where w is the width and t is the thickness of the stripe [7, 18, 19].

This means that the demagnetization effects have two important consequences in thin film ferromagnetic stripes [18-20]:

- a uniaxial anisotropy, so-called *shape* or *form anisotropy* is present with the easy axis coincident with the longitudinal axis of the stripe (*x*-axis in fig. 1). Its characteristic field $H_{k,s}$ depends on N_y and saturation magnetization M_s [21]

$$H_{k,s} = N_y M_s \tag{7}$$

- vector of magnetization $\boldsymbol{M}$ does not leave the plane of the stripe under normal conditions due to a huge demagnetization in the perpendicular direction to the film plane (*z*-axis).

In the common AMR sensors, the stripes are designed in the way that the easy axis of the material anisotropy coincides with the easy axis of the shape anisotropy (longitudinal axis of the stripe). The characteristic field of the resultant anisotropy is $H_a = H_{k,f} + H_{k,s}$. While $H_{k,f}$ can hardly be influenced, being rather a material property, the shape anisotropy $H_{k,s}$ can be controlled by the thickness and width of the stripe. However, the stripe thickness cannot be chosen arbitrarily, because thickness bigger than approx. 50 nm can lead to formation of magnetic domains in more than one layer, which leads to degradation of the magnetoresistive effect. Hence, the width of the stripe is a decisive parameter in determination of the strength of the uniaxial anisotropy of the stripe, given by its characteristic field H_a.

3.1.3 Angle of *M* in thin film ferromagnetic stripe

Let us consider a saturated thin ferromagnetic stripe, with a uniaxial anisotropy H_a along its longitudinal axis. $\boldsymbol{M}$ orients itself along the easy axis in one of the two possible orientations. Let an external field $\boldsymbol{H} = (H_x, H_y)$ be applied in an arbitrary direction in the stripe plane – see fig. 1. The external field $\boldsymbol{H}$ disturbs $\boldsymbol{M}$ from its initial position along the easy axis, but due to the anisotropy, $\boldsymbol{M}$ does not rotate fully into the direction of $\boldsymbol{H}$.

Introducing the reduced fields $h_x = \frac{H_x}{H_a}$, $h_y = \frac{H_y}{H_a}$, it can be shown [7] that the angle φ of inclination of ***M*** from the longitudinal axis of the stripe in the state of minimum system energy satisfies the formula

$$h_x \sin\varphi - h_y \cos\varphi + \sin\varphi \cos\varphi = 0 \tag{8}$$

Unfortunately, there is no (simple) analytic solution for φ. It means that there is no simple equation for the angle of ***M*** when the stripe is exposed to an arbitrary external field ***H***. Nevertheless, the angle of ***M*** for an arbitrary ***H*** can be found geometrically, using the so-called Stoner-Wohlfahrt diagram [22, 23]. Recently, works have been published on the topic of analytic solution for φ [33].

There exist simple solutions of (6) for some particular cases, from which the most important one in AMR sensors is that of ***H*** applied in the *y*–axis direction, called in that case the *sensitive axis*. In that case, $h_x = 0$ and for $H_y \leq H_a$, it can be written

$$\sin\varphi = \frac{H_y}{H_a} \tag{9}$$

When $H_y > H_a$, ***M*** is rotated fully to the H_y direction, and further increasing of ***H*** does not change φ, being 90°.

3.2 Resistivity in AMR stripes as a function of the measured field

Let a thin narrow stripe of a magnetoresistive material be contacted on its short edges and let electric current be flowing through the stripe along its longitudinal, or *x*-axis, see fig. 1. The external (measured) field ***H***, applied in the *y*-axis direction, causes inclination of ***M*** given by (9). Combining (9) and the Voigt – Thomson formula (6), and realizing that $\alpha_x = \varphi$, one gets for the resistivity ρ_{meas} imposed to the flowing current

$$\begin{aligned} \rho_{meas}(H_y) &= \rho_{\parallel} - \Delta\rho\left(\frac{H_y}{H_a}\right)^2, \quad &|H_y| \leq H_a \\ \rho_{meas}(H_y) &= \rho_{\perp}, \quad &|H_y| > H_a \end{aligned} \tag{10}$$

Figure 2 illustrates this behavior in theory and measured on a real sample, where hysteresis and smoothening of the characteristic near to the $H_y = H_a$ point are obvious. Both effects are the evidence of the limitation of the single-domain magnetization model. For big angles of $\boldsymbol{M}$, in particular, strong demagnetization effects cause deterioration of the magnetic ordering and creation of multiple domains, which do not rotate coherently anymore.

This leads to the described discrepancy of the model and the real AMR stripe.

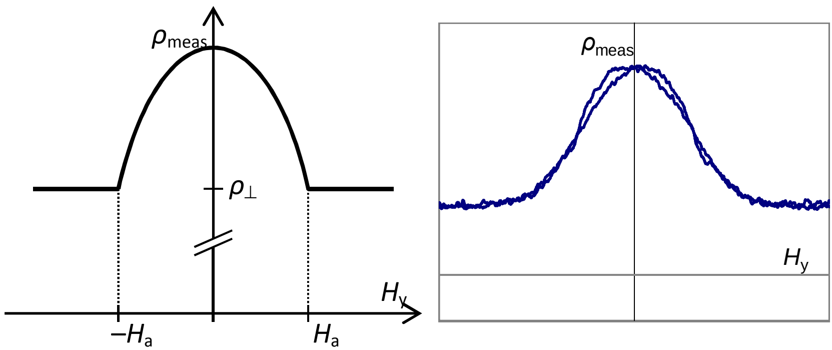

Figure 2: Theoretical (left) and real (right) dependence of the resistivity of an AMR stripe on the field applied in the orthogonal direction.

In practice, the voltage drop across the stripe is usually measured, which is proportional to ρ_{meas} in the case of constant current. Obviously, the dependence of the resistivity ρ_{meas} (or the voltage drop) on the applied field H_y is quadratic and even function, avoiding thus the detection of the polarity of the applied field – reversing the polarity of magnetic field H_y does (theoretically) not lead to a change in ρ_{meas}.

3.4 Linearization of AMR stripes characteristic – Barber poles

Linearization and symmetrical response to the fields of opposite polarity of AMR stripes is usually achieved by depositing shorting bars made of aluminum or gold onto the AMR stripes through the angle of 45°, forming the so-called Barber poles [7]. The conductivity of aluminum or gold is much higher than that of the magnetoresistive material. The current minimizes its path through the more resistive material, flowing from one shorting bar to another in the shortest possible way, i.e., with inclination of 45° to the longitudinal axis (neglecting the effects close to the stripe boundary), see fig. 3.

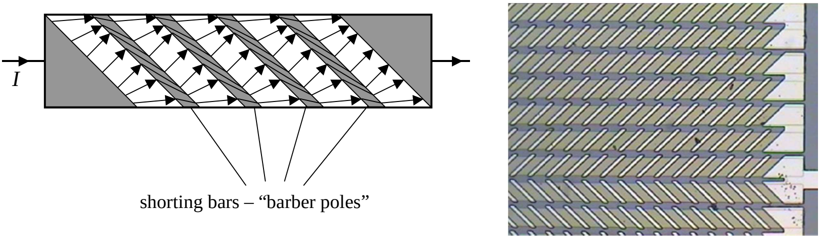

Figure 3: Left: A schematic view of shorting bars function in thin magnetoresistive stripes. Most of the current is inclined through 45° to the longitudinal axis of the stripe. Right: shorting bars in a commercial AMR sensor

Assuming that the easy axis of ***M*** is coincident with the stripe longitudinal axis, the angle between ***J*** and ***M*** is $\varphi \pm 45°$, depending on the concrete orientation of the shorting bars, see fig. 4. Then, after (6) and (9), the dependence of ρ_{meas} on the field H_{y} is given as

$$\rho_{\mathrm{meas}}(H_{\mathrm{y}}) = \frac{\rho_{||} + \rho_{\perp}}{2} \pm \Delta\rho \frac{H_{\mathrm{y}}}{H_{\mathrm{a}}} \sqrt{1 - \left(\frac{H_{\mathrm{y}}}{H_{\mathrm{a}}}\right)^2} \qquad (11)$$

The dependence of ρ_{meas} on the same external field H_{y} for the two possible inclination of shorting bars (+45° and -45°) is opposite, see figure 4. This is very convenient for the design of the full-bridge sensors. It is also worth of notice that the characteristic gets reversed in the same stripe, when the initial orientation of ***M*** along the easy axis is opposite.

It is obvious that using shorting bars, the dependence of resistivity on H_y gets linearized. The theoretical linearity error reaches 1% for approx. $H_y = 0.14 \cdot H_a$ and 5% for approx. $H_y = 0.3 \cdot H_a$. Characteristic field of anisotropy H_a is thus the decisive parameter for setting the sensor range and sensitivity, if planned to be operated in the uncompensated mode.

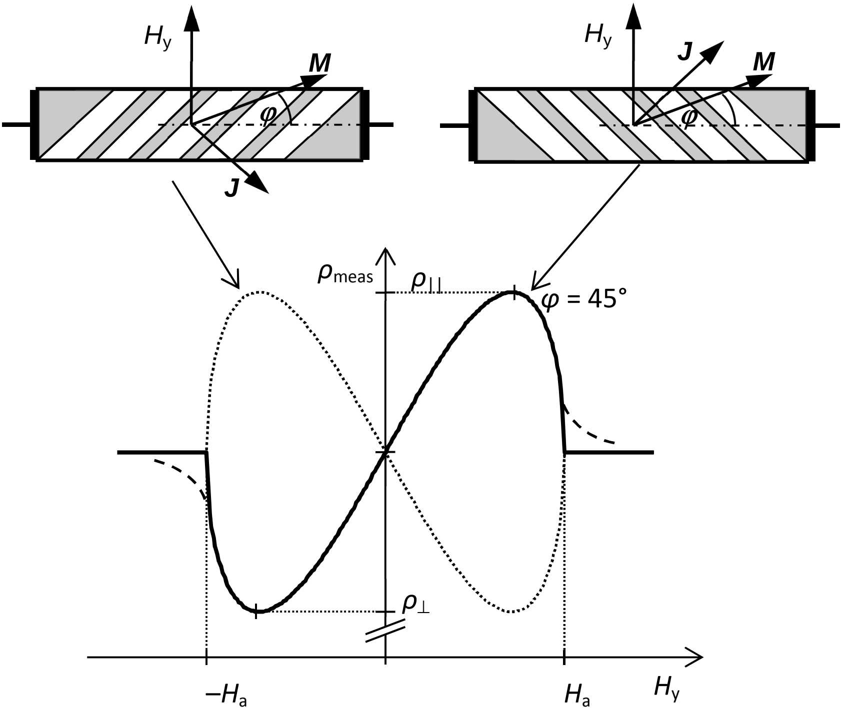

Figure 4: Two possible configurations of the shorting bars in AMR elements and the corresponding characteristics (dashed line – real behavior)

3.5 Configuration of AMR elements in a sensor

A typical AMR sensor for linear field measurements consists of four magnetoresistive elements, linearized using the shorting bars. The zero-field resistance R_0 of all the four elements is ideally identical. Complementary pairs are formed setting different angles of shorting bars in the neighboring bridge elements. Thus the resistance R_0 of one element increases by ΔR while that of the neighboring element decreases by the same amount in response to the applied field, see fig. 5. The output voltage of the bridge is $V_{out} = V_s/R_0 \cdot \Delta R = I_s \cdot \Delta R$.

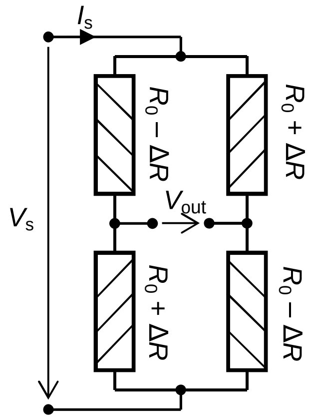

Figure 5: Full bridge configuration of an AMR sensor.

Sufficient length of elements is achieved configuring them in meander-like patterns, providing usually the resistance R_0 in the order of units of kΩ. The AMR meander structures are partly observable in fig. 3.

The alloys used for fabrication of AMR elements exhibit considerable temperature dependence of resistivity [34]. Various methods can be used for the elimination of the consequent temperature dependence of offset and sensitivity [35]. It has been shown by the author of this lecture [24] that the constant-voltage supply of the AMR bridge leads to reduction of the offset temperature drift of the sensor, while the constant-current supply reduces the temperature coefficient of sensitivity, not affecting the offset drift. Since it is easier to compensate the offset temperature drift than the temperature sensitivity variation in a magnetometer device, the use of the constant-current supply is recommendable.

4 Research on improvement techniques in AMR sensors

4.1 Periodical remagnetization - flipping

The described bridge configuration of linearized AMR elements can be used as a sensor for measurement of magnetic fields. However, not talking about the linearity, it suffers of a significant hysteresis. Additionally, its exposition to a strong magnetic field can cause deterioration of the magnetic alignment. This fact is crucial, because if the material is not in the saturated state, the assumption of the single domain-like, coherent rotation of ***M*** is no longer valid. Consequently, the characteristic of such a sensor is unpredictably changed – usually its sensitivity is significantly reduced and its output value in the zero field, i.e. offset, is high and unstable. Fig. 6 shows a characteristic of a commercial AMR sensor, exposed to an excessive field in the sensitive direction. It can be seen that the first quarter of the characteristic corresponds to the theoretical model, but the rest of the curve follows a completely different trend, with much lower sensitivity.

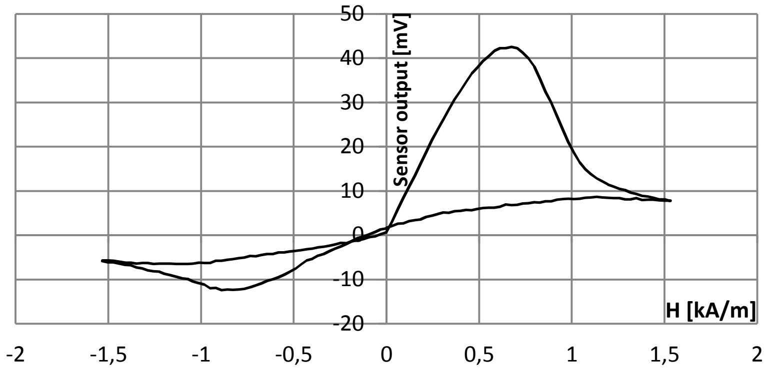

Figure 6: Large-field characteristic of the KMZ 51 AMR sensor without remagnetization (flipping).

Fortunately, it is possible to restore the defined saturated magnetic state of the AMR elements with a strong magnetic field applied along the easy axis. For this purpose, the so-called flipping or set/reset "coil" or strap is integrated into the sensor that can generate high enough magnetic field to set ***M*** to one of the possible orientations along the easy axis, depending on the polarity of the current pulse led through the flipping strap. This reversal is performed simultaneously in all the four bridge elements, usually periodically. The deep saturation of the material increases the immunity of the sensor against field shocks and in addition it significantly reduces the hysteresis and noise.

As reversing of the initial orientation of ***M*** results in reversing of the characteristics of each bridge element, the output characteristic of the bridge also gets reversed. Consequently, a rectangular signal is present on the bridge diagonal when periodical remagnetizing is used, with the amplitude proportional to the measured field. The signal can be restored using the synchronous detection, which allows for easy compensation of the bridge offset, caused by the slight differences in resistances of the particular bridge elements.

Research has been done on the influence of the saturation depth during remagnetization on the noise and offset stability of AMR sensors [25, 26]. The sensor was placed into a magnetic shielding, so that a stable (ideally zero) offset should be present on its output. However, when flipping pulses were not strong enough, there was different offset voltage observed after each flipping pulse, see fig. 7. Also the noise PSD value was influenced by the amplitude of the flipping pulses. It was concluded that the deeper saturation, the better noise parameters / offset stability – see fig.7.

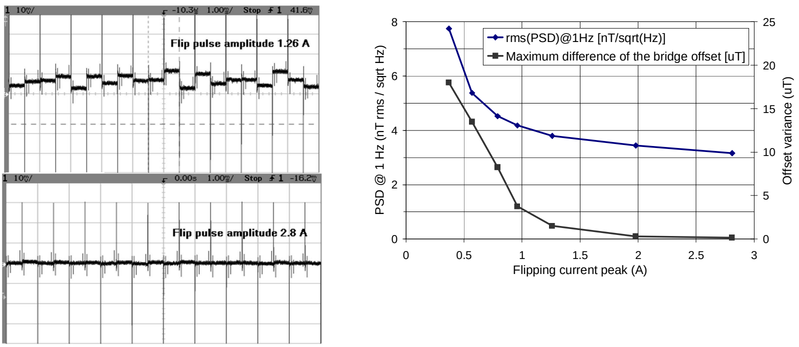

Figure 7: Influence of the saturation depth caused by flipping on the offset stability and noise in KMZ 51 AMR sensor [26].

In practice, remagnetization is accompanied by glitches on the output signal of the sensor, well observable on the waveforms in fig. 7. To avoid the influence of these glitches on the processed output signal in a magnetometer, suitable circuits that ignore short instants of the output signal immediately after the remagnetization have to be used, employing a non-trivial timing (see fig. 8) and a sample/hold circuit in the synchronous detection block. Author of this lecture used such a design of the processing circuits and published this finding [27, 28].

4.2 Feedback compensation mode

To further suppress the temperature dependence of the sensitivity of an AMR sensor and to increase its linearity, it is convenient to operate the sensor in the compensated mode. Magnetic field of the same value as the measured one, but of opposite polarity is generated in the sensor area, maintaining the sensor in virtually zero magnetic field. An integrated compensation strap is usually used for this purpose, which is capable of producing magnetic field in the sensitive axis direction. The demodulated signal from the sensor is integrated and the resulting signal is led back to the compensation coil (strap), see fig. 8. If properly connected, a negative feedback is formed: in presence of the measured field the sensor output voltage is integrated, magnetic field with the opposite orientation to the measured field is generated in the compensation coil, which after stabilizing is of the same value as the measured field. Hence, the sensor acts as a zero indicator, which leads to a significant improvement of linearity (determined by the linearity of the feedback loop in this mode) and reduction of the temperature dependence of the sensor. The current flowing through the compensation coil is proportional to the measured field.

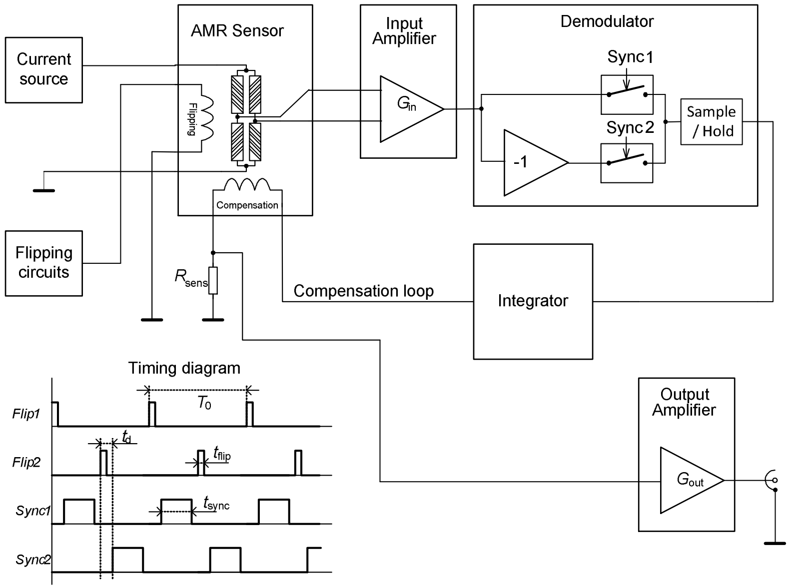

Figure 8: Typical processing chain of magnetometers with AMR sensors.

The compensated mode has another important advantage yet. If the measured field does not act exactly in the sensitive axis direction, it can be decomposed to a component along the sensitive axis H_y and a component along the easy axis H_x of the AMR elements, see fig. 1. The component H_x, however, influences the angle of ***M***, and consequently the response of the sensor to H_y. AMR sensor therefore does not work as an ideal vector sensor – its output is not dependent on the component of the magnetic field in the sensitive axis only. This phenomenon is referred to as *cross-field effect* and represents one of the main problems of AMR sensors, in particular when used in compassing applications, where presence of a field component H_x is inevitable. Feedback compensation highly reduces the cross-field effect, because in the compensated mode, ***M*** is always kept along the easy axis. For that, the compensation field generated strictly along the sensitive axis must have the same magnitude as H_y. Therefore, the compensation current is always proportional to the measured component H_y of the external field, regardless to the component H_x.

The importance of the techniques of periodical flipping and compensation mode of operation can be well illustrated by the achieved parameters. In table 1, example is given for the KMZ 51 sensor.

Table 1: Parameters of KMZ 51 sensor in different operation modes in the range FS = ±300 μT (current supplied if not stated otherwise) [24, 27-29]

	Datasheet value	Measured without flipping / compensation	Measured with flipping	Measured with flipping & compensation
Linearity [% FS]	N/A	0.5	0.5	0.008
Hysteresis [% FS]	2	1.5	0.02	0.008
Offset temp. drift [nT / K]	70	90	N/A	2.1
Temp. coef. of sensitivity [% / K]	0.31	0.23 / voltage supply 0.06 / current supply	N/A	0.002

5 Basic remarks to fabrication of AMR sensor

The practical exploitation of anisotropic magnetoresistive effect in magnetoresistive sensors rely on narrow stripes formed out of a thin film of magnetoresistive material deposited onto an appropriate substrate. In practice, alloy of nickel and iron, NiFe 81:19 (permalloy) is mostly used as the material for fabrication of the magnetoresistive stripes. Its AMR coefficient is high enough to allow its exploitation in sensors (2.2 %). There exist alloys with higher AMR coefficient (see table 2), but a crucial advantage of NiFe 81:19 is its very low magnetostriction, i.e., its magnetic properties are not sensitive to the mechanical stresses.

The width of magnetoresistive stripes is usually in the order of tens of micrometers, the thickness is tens of nanometers, the length reaches hundreds to thousands of micrometers. The stripes are mostly sputtered onto a passivated silicon substrate. To save the space in the sensor, the stripes are almost exclusively realized as meanders [20, 30, 31].

Table 2: Parameters of the ferromagnetic materials @ room temperature (after [7]).

Alloy composition	**$\Delta\rho/\rho_0$ (magneto-resistive coef.)**	**ρ_0 (resistivity of demagnetized material)**	**$H_{k,f}$ (char. field)**	**M_s (saturated magneti-zation)**	**Λ (magneto-striction coef.)**
(%)	(%)	($\times 10^{-8}$ Ω.m)	(A.m^{-1})	($\times 10^{-5}$A.m^{-1})	($\times 10^{-6}$)
NiFe 81:19	2.2	22	250	8.7	0
NiFe 86:14	3	15	200	7.6	-12
NiCo 70:30	3.8	26	2500	7.9	-20
NiCo 50:50	2.2	24	2500	10	0
NiFeCo 60:10:30	3.2	18	1900	10.3	-5
NiFeCo 74:10:16	2.8	23	1000	10.1	0
NiFeMo 87:8:5	0.7	72	490	5.1	0
CoFeB 65:15:20	0.07	86	2000	1.03	0

The AMR coefficient can be affected by high background resistivity ρ_0, caused among others by the charge carrier scattering on the material grain boundaries. The amount of the material grains can be reduced by annealing of the sputtered films, lowering thus ρ_0. Annealing must be done in an inert atmosphere (mostly argon); even a small amount of oxygen present during annealing process can depreciate the anisotropic material due to surface oxidation. A homogeneous magnetic field is usually applied during annealing in the direction of the intended longitudinal axis of the stripes. This measure is performed for reducing the anisotropy dispersion in the material, but it also leads to creation of a uniaxial anisotropy with the easy axis along the direction of the applied field – the above mentioned *induced anisotropy*. The characteristic field $H_{k,f}$ of this anisotropy in NiFe 81:19 is about 250 A/m. Altogether, annealing reduces the background resistivity ρ_0, lowers the mechanical stresses in the material and leads to creation of the induced anisotropy with a low dispersion.

Flipping and compensation straps are deposited beneath or onto the magnetoresistive meanders, separated with a passivation layer. Figure 9 shows a layout of KMZ 51 sensor [30]. The particular bridge legs are composed from more magnetoresistive elements in this design, with appropriate angles of shorting bars, due to the design of the flipping strap and directions of the magnetic field it generates in different sections of the stripes.

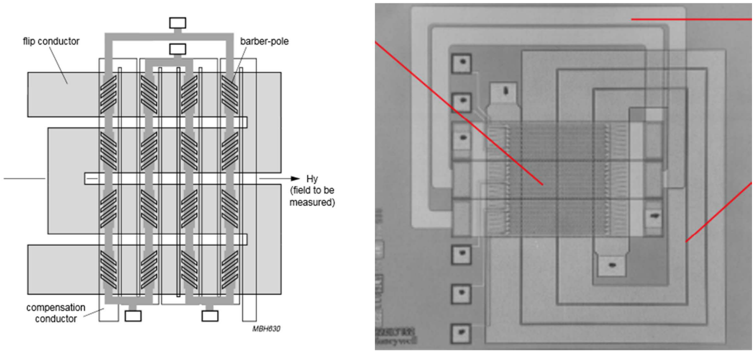

Figure 9: Layout of the market-available KMZ 51 sensor (left) [31], and Honeywell HMC family sensor (right) [32], with shorting bars (barber poles) and compensation and flipping straps

6 Conclusion & Further Research

In this lecture, the anisotropic magnetoresistive effect has been explained from its origins to the sensors that exploit this phenomenon for measurements of magnetic fields. The techniques used for linearization of the sensor response, reduction of hysteresis and temperature dependences of offset and sensitivity have been described.

Periodical remagnetization of the magnetoresistive elements, called flipping or set/reset pulses, serves for restoring the magnetic state of the magnetoresistive structures, leading to increased immunity to strong field shocks, and for reduction of hysteresis. When performed periodically, flipping provides a modulated signal on the sensor output, with the amplitude proportional to the measured magnetic field. Offset of the sensor can be relatively easily eliminated during the processing of such a signal with the synchronous detection.

The sensor can be operated in the compensated mode, when it works virtually in the zero field, as every change in the measured field is quickly compensated with a field of opposite polarity, generated by the on-chip compensation strap. This fact leads to a significant improvement of linearity, reduction of the temperature dependence of sensitivity and elimination of the cross-field effect. Basic remarks to the fabrication of AMR sensors are given.

Further research will be focused on possibilities of digital processing of the sensor signal. If an A/D convertor with the sufficient precision and speed is available, the signal of the sensor can be digitized directly and the synchronous demodulation, offset elimination etc. can be performed by an appropriate digital processing. Although some analog parts, such as the input amplifier or flipping circuits, would remain in the circuitry, the design as a whole would be markedly simplified.

Another field of research is associated with the flipping process. Traditionally, the strong current pulses for flipping are produced by a switched capacitor. Recently, some designers have used rectangular pulses of longer duration, but much lower amplitudes for flipping. There is no work that would compare these two approaches from the point of view of the achievable measurement parameters.

With the fast evolution of wireless sensor grids, consumption of the devices becomes an important issue. In the case of AMR sensors, the main contribution to the consumption is the supply of the sensor bridge and the compensation current. The supply current of the bridge can be lowered by designing sensor elements with higher resistance. The compensation current could be lowered increasing the field factor of the compensation strap. However, the consumption could also be lowered, if the sensor was not working constantly, but rather only for the moment when the measured value is desired. In between readings, the sensor could be set in an “idle” mode, with no supply to the measurement bridge, no flipping and no compensation. Nevertheless, the reading would always have to be preceded with a strong flipping pulse to restore the magnetic properties of the sensor. The main field of investigation here is the repeatability and long-term stability of such systems.

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2012	Organizing Committee of European Magnetic Sensors and Actuators Conference (EMSA)
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Citations (after automatic exclusion of autocitations):
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