Giant Magnetoimpedance Sensors

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Although discovered a long time ago, the magnetoinductance and recently the giant magnetoimpedance (GMI) sensors got a break-through with the development of amorphous wires. But also stripe and thin film structures are utilized for applications with nT sensitivity and MHz bandwidth. A combination with surface acoustic wave technology yields passive and wirelessly interrogable sensors.

1 Magnetoinductance

Magnetoinductive effects in ferromagnetic conductors can be used for various sensors. Although the principle has been known for a long time, the usefulness of these effects for practical applications was recognized recently, and intensive investigations began. Magnetoinductive effects are related to magnetization of a magnetic conductor (wire, strip, thin film, etc.) by a magnetic field, which is produced by an electric current passing through the conductor itself. If the current is varying with time, the magnetic flux in the conductor also varies and induces the electromotive force, which is superimposed to the ohmic voltage between its ends. For instance, in a wire with a circular cross section, the circumferential magnetic field $H$ induced by a constant current with the density $j$ is $H = jr/2$, where $r$ is the distance from the wire axis. For a wire of diameter 1 mm and the current density of 106 A/m², which is low enough so as not to greatly increase the temperature by joule heating, the maximum magnitude of a magnetic field on the wire surface is 250 A/m. To get sufficiently high magnetoinductive voltage, which can be easily detected on the ohmic background signal, the circumferential reversal of the conductor magnetization must take place in magnetic fields of this order or lower. Therefore, good soft magnetic metals with high circumferential permeability are required for such applications.

The systematic study of magnetoinductive effects in soft magnetic conductors started after the technology of amorphous wires had been successfully developed. For example, large magnetoinductive effect has been found in the zero-magnetostrictive amorphous CoFeSiB wire with the circumferential bamboo-like domain structure in the outer shell. When an ac current of 1 kHz was applied to the wire, sharp peaks (about 0.2 V) were induced on the background ohmic signal by the circumferential magnetization reversal in the outer shell. The amplitude of peaks decreased with an increasing external dc magnetic field. With utilization of this effect, a simple magnetic head (Figure 1) was constructed and used for a noncontact rotary encoder and a cordless data tablet.
2 Giant magnetoimpedance

Another magnetoinductive effect observed in soft ferromagnetic metals is giant magnetoimpedance (GMI), which is characterized by a strong dependence of ac impedance on an applied magnetic field (Figure 2). This effect is observed only at sufficiently high frequencies and can be explained by means of classical electrodynamics. It is known that RF current is not homogeneous over the cross section of conductor but tends to be concentrated near the surface (skin effect). The exponential decay of current density from the surface into the interior is described by the skin depth $\delta = \sqrt{2\rho/\omega \mu}$ which depends on the circular frequency of the RF current $\omega$, the resistivity $\rho$, and the permeability $\mu$. In nonferromagnetic metals, $\mu$ is independent of frequency and applied magnetic field; its value is close to the permeability of vacuum $\mu_0$. In ferromagnetic materials, however, the permeability depends on the frequency, the amplitude of the ac magnetic field, and other parameters such as the magnitude and orientation of a bias dc magnetic field, mechanical strain, and temperature. The large permeability of soft magnetic metals and its strong dependence on the bias magnetic field are, in fact, the origin of GMI effect.

According to definition, the complex impedance $Z(\omega) = R + iX$ of a uniform conductor (Figure 3) is given by the ratio of the voltage amplitude $U$ to the amplitude of a sinusoidal current $I \sin \omega t$ passing through it. It is expressed in a ferromagnetic wire (with radius $a$ and length $l$ and for $\delta \ll a$) as $Z = R_{dc}a/2\delta + i\omega L_d 2\delta/a = a R_{dc}/2\sqrt{2\rho}(1 + i)\sqrt{\omega \mu}$. As can be seen, for a uniform current density the impedance is equal to the dc resistance. The definition is valid only for linear elements, that is, when the voltage $U$ is proportional to the current $I$. It should be noted, however, that a ferromagnetic conductor generally is a nonlinear element. That means the voltage is not exactly proportional to the current; moreover, it also contains higher order harmonics of the basic frequency. Therefore, the term impedance should be taken with some precaution.

If the current density $j(r)$ in the conductor is known, the impedance can be calculated. The current density generally can be obtained by the solution of Maxwell equations with the given material relation between $B$ and $H$ for the conductor material.

At high frequencies (above 1 MHz), the domain wall movements are heavily damped by eddy currents, and only magnetization rotations are responsible for magnetic permeability. Then the minimum calculated skin depth is $\delta_m = \sqrt{\alpha\rho/\gamma \mu_0 M_s}$ which is, for soft magnetic amorphous alloys, of the order 0.1 $\mu$m and gives the maximum theoretical values of $|Z|/R_{dc}$ of the order 1000. That theoretical magnitude of GMI can be achieved only in uniaxial materials with the easy direction of the anisotropy exactly perpendicular to the conductor axis and the axial bias field $H$ satisfying the condition $H = H_K + N_z + \omega^2/M_s \gamma^2$, where $N_z$ is the longitudinal demagnetizing factor an $H_K$ is the effective anisotropy field. Any deviation of the easy axis from the perpendicular direction or any fluctuation of $H_K$ leads to a substantial reduction of the GMI effect.
3 Materials

In actual soft magnetic metals, the maximum GMI effect experimentally observed up to now is much lower than the theoretically predicted values. Research in the field is focused on special heat treatments of already known soft magnetic metals and on development of new materials with properties appropriate for practical GMI applications. The GMI-curve $\eta(H)$ is defined as $\eta = 100\%(Z(H)/Z_0 - 1)$ where $Z(H)$ is the impedance for a bias field $H$, measured at a given frequency and constant driving current. $Z_0$ is the impedance for $H \to \infty$, which should be equal to the impedance of a nonferromagnetic conductor with the same cross-section and the same resistivity $\rho$. Practically, for $Z_0$ the value of impedance measured with maximum field $H_{\text{max}}$, available for the given experimental equipment, is used. Some authors use $Z_0 = Z(0)$, but that value depends on the remanent magnetic state, which may not be well defined. The parameters that well characterize the GMI efficiency are the maximum GMI, $\eta_{\text{max}}$, and the maximum field sensitivity, $(d\eta/dH)_{\text{max}}$. Typical values obtained for some soft magnetic conductors are listed in Table 1.

Although GMI was first reported for amorphous metals, some crystalline materials also exhibit large GMI. Sometimes the crystalline metals are even better than the amorphous ones. According to the theory, the largest GMI should be obtained in materials with low resistivity $\rho$, high saturation magnetization $M_s$, and low damping parameter $\alpha$. The crystalline metals have the advantage of lower resistivity, but in amorphous metals, better soft magnetic behavior can be obtained because of the lack of magnetocrystalline anisotropy. Because the magnetoelastic contribution to magnetic anisotropy substantially deteriorates the soft magnetic behavior, the nonmagnetostrictive materials also show the best GMI performance.

Amorphous cobalt-rich ribbons, wires, and glass-covered microwires are good candidates for GMI applications. The low magnetostriction and the easy control of magnetic anisotropy by appropriate heat treatment are the advantages of these materials; the disadvantage is high resistivity. Soft magnetic nanocrystalline metals exhibit GMI behavior similar to amorphous metals. Their somewhat higher $M_s$, and lower $\rho$ can lead to a small improvement. The low resistivity and bulk dimensions of crystalline soft magnetic alloys lead to better performance, especially at low driving frequencies (< 1 MHz). The presence of large magnetocrystalline anisotropy (e.g., in iron-silicon alloys), however, requires a high texture of crystalline grains and proper adjustment of the driving current and dc bias field directions. Excellent GMI behavior was found in combined conductors consisting of a highly conductive nonmagnetic metal core (such as Cu or CuBe) with a thin layer of soft magnetic metal on the surface. An insulating interlayer between the core and the magnetic shell, in sandwich thin-film structures, results in further improvement of GMI behavior. The thin-film structures, which can be used in integrated circuits and the glass-covered microwires, from which simple sensing elements for electrotechnical devices can be easily constructed, seem to be particularly promising for wide exploitation of GMI.

Not only $\mu_{\text{max}}$ and $(d\eta/dH)_{\text{max}}$ but also the particular shape of $\eta(H)$ curve are important for sensor applications. The shape of a GMI curve can be controlled by induced magnetic
anisotropy and/or bias dc current. For wires and ribbons with transversal magnetic anisotropy, the double-peak GMI curve with the maxima close to $\pm H_K$ is observed. If the easy direction is parallel to the conductor axis, the single peak at $H = 0$ is present (as in Figure 2). In this case, however, the $\eta_{\text{max}}$ sharply decreases with increasing anisotropy field. Helical anisotropy, induced in amorphous wires by torque stress or torque annealing, combined with a bias dc current, results in an asymmetric GMI curve. Such a curve can be exploited by a linear field sensor.

4 Sensors

The high sensitivity of magnetoimpedance to external dc or low frequency ac field (here low frequency means the frequency that is at least one order lower than the driving frequency) can be used for magnetic field sensors and other sensors based on the change of a local magnetic field (such as displacement, electric current). The high driving frequency, which must be used to get sufficient sensitivity of sensors, involves many problems like parasitic displacement currents in the circuits connecting the magnetoimpedance (MI) element with the signal source and the measuring unit, impedance mismatching, the presence of reflected signals, and so forth. To avoid those problems, oscillation circuits are used, such as the Colpitts oscillator and the resonance multivibrator, with the MI element as the circuit inductance. Recently, also a combination of surface acoustic wave (SAW) technology with GMI was reported.

4.1 GMI wire in a Colpitts oscillator

Figure 4 illustrates the Colpitts oscillator, utilizing a resonance of the inductance of the MI element and the capacitances $C_1$ and $C_2$. For oscillation frequencies of the order of 100 MHz, the GMI signal can be increased several times. Because the field dependence of the oscillator output signal roughly follows the GMI curve, it is a nonlinear function of the applied field. To get a linear field sensor, a pair of MI elements were used in a multivibrating oscillator circuit, as shown in Figure 5b. The two MI elements, connected in the two symmetric branches of the multivibrator, were biased with opposite dc fields $H_b$ so that in the range of applied fields $-H_b < H_{\text{ex}} < H_b$ the output voltage was nearly linear, as shown in Figure 5a. The bias field $H_b$, however, requires small magnetizing solenoids wound around the MI elements. That complication can be avoided if the asymmetrical GMI effect in twisted wires with dc bias current is used. The bias current in the pair of twisted MI elements flows in the opposite directions with respect to the applied dc field. A linear characteristic similar to Figure 5a is then obtained in a certain range of the applied field.

In a usual field sensor, the MI elements, in the two oscillator branches, are arranged parallel, and the bias fields $H_b$ are opposite. If the bias fields for the parallel elements are in the same direction, or if the elements are arranged in series with the opposite bias fields, a gradient field sensor can be obtained. Because the MI elements may be as short as 50 $\mu$m at 30 $\mu$m wire diameter, very localized weak magnetic fields can be detected.
These types of sensors can be used, for example, for the detection of stray fields caused by cracks in steel sheets and for magnetic rotary encoders of high resolution, but there will be also applications for detection of biomagnetic fields.

Miniature magnetic field sensors based on GMI effect have been used for various applications. They are especially appropriate for medical applications as small permanent magnet movement sensors for the control of human physiological functions. They also can be used for automation and control in industry. Although GMI sensors are quite new and their development is not yet finished, their low prices and high flexibility probably will lead to a wide exploitation in the near future.

5 GMI and SAW

SAW devices are well known for more than tree decades. They apply the propagation of an acoustic wave on the surface of a plain polished piezoelectric substrate. A typical SAW device is sketched in Figure 6. Employing a one-port SAW device and connecting the electrical port to an antenna yields passive, wirelessly interrogable sensor elements. The measurand affects the delay and the resonance frequency, respectively. The sensor is requested by an RF signal, and the information about the measurand can be gained from the RF radio response signal.

Passive SAW radio sensors are characterized to be absolutely free of maintenance and to resist severe environmental conditions like high temperature, high electric and magnetic field strength, even hard radiation. Since the measurand is evaluated from the RF response signal, disturbed by noise and interference, the required signal processing enhances the complexity of such systems. For applications, where a wired connection to the sensor and/or an active radio sensor, containing semiconductor devices, cannot be used due to the conditions stated above, SAW sensors represent a very suitable choice. With the measurand affecting the SAW substrate directly, SAW sensors are capable for the remote measurement of temperature as well as torque, identification, pressure, etc.

A new wirelessly interrogable sensor for magnetic fields can be gained, establishing an alliance of new GMI sensors and the SAW transponder devices. Therefore, the GMI device is coupled to the second port (inter digital transponder 2 in Figure 7) of the SAW transponder. The circuit is adjusted to achieve resonance with the transducer’s capacitance. Tuning the resonance for one octave in frequency by applying the magnetic field to the GMI sensor yields a sufficient effect for a radio request readout. Passive, radio requestable current sensors can be built.

The principle of the prototype sketched in Figure 8 was built and tested. The results, the amplitude $A_{DT2}$ of the affected reflector relative to the reference reflector amplitude $A_{ref}$ are shown in Figure 9. It can be seen, that the principle is best suited for a lot of applications where a magnetic field has to be measured without contact and where a power supply of the sensor is not feasible. The sensitivity (relative signal amplitude / $B_a$) is 80 dB/T in the region of weak fields (up to 30 mT). The development of a sensor for remote electric current measurements is in progress.
Further reading


Figure captions

Figure 1: Simple magnetoinductive head using an amorphous wire

Figure 2: GMI of an amorphous CoFeSiB wire: (a) R resistance and X reactance as functions of the applied field; (b) resistance (open circles) and reactance (solid circles) as functions of frequency

Figure 3: Impedance definition

Figure 4: Colpitts oscillator with an MI element

Figure 5: Linear field sensor with multivibrator; (a) field dependence of the output voltage; (b) circuit diagram

Figure 6: SAW device

Figure 7: Schematic layout of a two port SAW transponder with an external sensor

Figure 8: Wirelessly interrogable passive magnetic field sensor

Figure 9: Amplitude of the impedance affected reflection relative to the reference

Table caption

Table 1: Materials for GMI sensors