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Lock-in amplifiers for AMR sensors

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ABSTRACT

Anisotropic magnetoresistive (AMR) magnetic sensors are often chosen as the magnetic transducer for magnetic field sensing in applications with low to moderate magnetic field resolution because of the relative low mass of the sensor and their ease of use. They measure magnetic fields in the order of the Earth magnetic field (with typical sensitivities of 1‰/G or 10^{-2}‰/μT), have typical minimum detectable fields in order of nT and even 0.1 nT but they are seriously limited by the thermal drifts due to the variation of the resistivity with temperature (∼2.5‰/°C) and the variation of the magnetoresistive effect with temperature (which affects both the sensitivity of the sensors: ∼2.7‰/°C, and the offset: ±0.5‰/°C). Therefore, for lower magnetic fields, fluxgate vector sensors are generally preferred.

In the present work these limitations of AMR sensors are outlined and studied. Three methods based on lock-in amplifiers are proposed as low noise techniques. Their performance has been simulated, experimentally tested and comparatively discussed. The developed model has been also used to derive a technique for temperature compensation of AMR response. The final goal to implement these techniques in a space qualified applied specific integrated circuit (ASIC) for Mars in situ exploration with compact miniaturized magnetometers.

1. Introduction

Anisotropic magnetoresistance (AMR) is the change of electrical resistance due to the variation of the magnetization vector projection on the electrical current direction. It is an effect due to the spin-orbit coupling (Fig. 1). When an electrical current passes through a material, the transport electrons experience a scattering. This scattering is a function of the distribution of the electronic clouds in the material and this distribution is related to the magnetization.

The magnetoresistive effect can be observed in all the materials. However, its intensity is different in the distinct materials. The alloy of niquel and iron named permalloy presents a high magnetoresistive effect in the order of 2–3%, which makes it suitable for magnetic sensors based on this effect. The permalloy has an internal anisotropy, which tends to align the magnetic dipoles in a certain direction called easy axis of magnetization or simply easy axis. In the presence of an external field, the permalloy acquires magnetization against this anisotropy. Let U be the magnetic energy density, K the anisotropy constant, H the magnetic field, M_s the saturation magnetization, φ the angle between the magnetization vector and the easy axis. The expression for the energy density of every permalloy resistor exposed to a magnetic field H has two terms in opposition: one related to the anisotropy energy and another to the magnetostatic energy associated to the effect of the field:

$$U = K \cos^2(\varphi) - M_s H \cos(\varphi) \tag{1}$$

If one derives this expression and equals the derivative to zero, to find the equilibrium orientation of the magnetization vector in the presence of an applied field H, it is found that the equilibrium angles for the magnetization vector respect to the easy axis are:

$$\varphi = 0, \ \arccos\left(\frac{M_s H}{2K}\right).$$

The changes in the electrical resistance are an indirect measurement of the magnetic field because the resistance in the permalloy cores can be expressed as a function of φ:

$$R(\varphi) = R_0 + R_\Delta \cos^2(\varphi) \tag{2}$$

where R is the measured resistance, R_0 is the contribution of the electrical resistance in the absence of a magnetic field and R_Δ is the magnetoresistive contribution. This contribution can be explained as the difference in the resistivity of the material depending on the relative direction between magnetization and current, being

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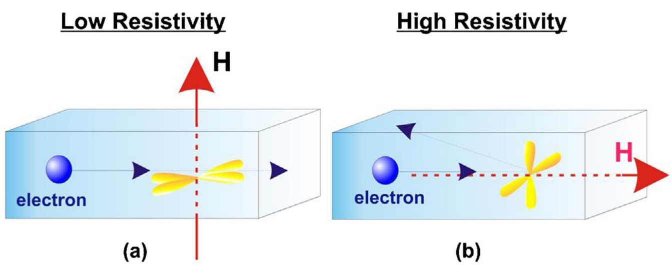

Fig. 1. AMR Spin-orbit coupling.

$\rho_{||M}$ the resistivity of the material when the current flows in the direction of the magnetization and $\rho\perp_M$ the resistivity of the material when the current flows perpendicularly to the magnetization vector (Fig. 2a).

Let the direction between contacts (Fig. 2a) be that of the easy axis (shape anisotropy) of the permalloy core and the perpendicular direction, the sensing direction. Since AMR is an even effect it cannot discern between fields of different signs. To transform the measurement in an odd effect, the permalloy straps usually have a Barber pole biasing, which consists in an array of copper microstraps inserted in the permalloy at 45° (i.e. π/4 rad) respect to the line between the electrical contacts forcing the electrical current to pass through the film at a −45° (Fig. 2a).

The sensors are provided with a coil named set-reset strap to magnetize the permalloy core in such a way that the magnetic spins are firstly aligned in the easy axis direction to linearize the response curve vs. the magnetic field and to avoid Barkhaussen noise due to the energy required to move the magnetic domains walls. This can be performed with a short current pulse of intensity high enough so as to saturate the permalloy core in the easy axis direction. The flipping can be performed in both directions alternatively (set-reset operation) to reduce the offset and the hysteresis.

Following the scheme of Fig. 2a, the resistance of a single permalloy core in the presence of an external magnetic field H would have complementary projections after a set pulse or a reset pulse, applied in the opposite direction:

$$R_{\text{reset}} = R_{\Delta}\ \cos^2\left[\arccos\left(\frac{M_sH}{2K}\right) - \frac{\pi}{4}\right] \quad \text{and}$$

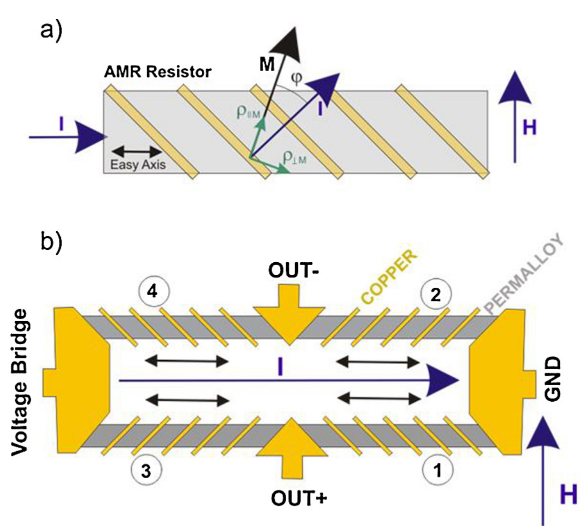

Fig. 2. (a) AMR device indicating current, magnetization directions and the resistivity parallel and perpendicular to the magnetization, (b) Wheatstone bridge of AMRs: Resistors 1 and 3 are magnetically biased in one direction and 2 and 4 in the perpendicular one.

$$R_{\text{set}} = R_{\Delta}\ \sin^2\left[\arccos\left(\frac{M_sH}{2K}\right) - \frac{\pi}{4}\right] \tag{3}$$

The normalized resistance as a function of the magnetic field after a reset pulse is plotted in Fig. 3 (a: simulation, b: experimental curve using a commercial HMC1002 sensor by Honeywell). Note that even though the equations are given as a function of the magnetic field, in the graphs it is represented the magnetic induction since most users usually give sensitivities as a function of Oersteds or Teslas. Also, in our experimental set ups B is proportional to H being the proportionality constant the vaccum permeability μ_0.

The most common way to measure the resistance is by means of a Wheatstone bridge so most of the AMR commercial devices have a Wheatstone bridge with four magnetoresistors (Fig. 2b).

The four permalloy cores in the Wheatstone bridge are trimmed and prepared for being magnetically biased in couples (Fig. 2b).

In the presence of a magnetic field the cores experiment a change in their magnetization state and the differential voltage of the bridge is:

$$V_{\text{set/reset}} = V_+ - V_- = \left[\frac{R_1}{R_1 + R_3} + \frac{R_2}{R_2 + R_4}\right] V_{\text{bridge}} \tag{4}$$

At room temperature this differential voltage for permalloy cores of several tens of nanometers is in the order of 2% of the bridge voltage, which makes them suitable candidates for measuring fields of low to moderate intensity [1,2]. The typical resolutions reported are in the order of nT [3] and some works have achieved tenths of nT resolutions [4].

To achieve the best resolution the sensors are often run in a continuous reset and set mode. This is performed by a set of current pulses of duration in the order of µs and an intensity enough to saturate the cores in their easy axis and both directions alternatively. In set-reset operation the noise of AMR sensors is reduced considerably [5].

In this operation mode the output voltage of the Wheatstone bridge is:

$$V_{\text{OUT}} = \frac{\langle V_{\text{set}}\rangle - \langle V_{\text{reset}}\rangle}{2} \tag{5}$$

where $\langle V_{\text{set}}\rangle$and $\langle V_{\text{reset}}\rangle$ are the averaged measurements after the set and reset pulse respectively. This operation increases slightly the difficulty of use of AMRs and reduces the bandwidth since the acquisition frequency is limited by the time needed to acquire both sets of samples.

Finally, the commercial devices have also another coil with the double purpose of zeroing the bridge, auto-calibration and feedback. In this work a feedback circuitry is not considered in principle on the first hand due to the good linearity of the sensors: better than 0.1% at full scale for fields lower than 100 µT and on the other hand because it does not simplify the circuitry but translates the strong requirements in terms of bits needed to the current source. Other groups have performed very interesting works in this line [6–8].

So far it has been described a typical commercial AMR sensor at a certain temperature but AMR sensors are highly dependent on the temperature. Many properties of the AMR cores are a function of temperature like the saturation magnetization, the resistance, the anisotropy, etc. The AMR output therefore, is influenced by these parameters temperature varying. This is illustrated in Fig. 4 with 10% variations of some of the parameters. This question is especially important if the application implies wide temperature ranges like the daily temperature variations on the surface of Mars (−190 C to 20 C), and these sensors are competitive sensors for magnetic measurements on the surface of Mars because of their low mass and power consumption.

Fig. 4a shows the change in the output signal of an AMR (after a reset) for a 10% change of saturation magnetization (i.e. Ms = 1—red and 0.9 T—green), assuming that the permalloy cores only have