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Effect of electroplated $Ni_{1-x}Fe_x$ composition on the field-induced anisotropy

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Field-induced anisotropy has been proposed as an effective method to produce ferromagnetic rings to produce ferromagnetic rings with radial anisotropy for fluxgate cores.. Compared to stress-induced anisotropy this method easily allows generating a radial anisotropy in electroplated rings. However, it is still not clear what is the source of such anisotropy. It has been suggested that the observed anisotropy could be the effect of magnetocrystalline anisotropy present in the electroplated film because of non-ideal stoichiometry of the alloy. If true this would make impossible to electroplate films with field-induced anisotropy and simultaneously low magnetostriction because this condition occurs at $Ni_{81}Fe_{19}$ composition where the magnetocrystalline anisotropy vanishes. In order to verify this hypothesis we electroplated several rings changing the composition of the alloy, with and without radial magnetic field applied. It turned out that the field-induced anisotropy was to a large extend independent on the composition of the film and it did not show any vanishing trend as we approach $Ni_{81}Fe_{19}$ composition. This suggests it is in fact possible to obtain field-induced anisotropy and simultaneously low magnetostriction. Finally we show how such radial field-induced anisotropy reduced the noise of the fluxgate by almost one order of magnitude.

Index Terms—**permalloy, electrodeposition, anisotropy, fluxgate, noise.**

I. Introduction

One of the main sources of noise in a fluxgate sensor is the magnetic noise originated in the core of the sensor during the periodic transition from one saturated state to the opposite saturation state [1÷3]. Anisotropy orthogonal to the direction of magnetization helps to reduce the noise of fluxgates [4÷5]. In tape-wound cores this is easily achieved by transverse direction of the easy axis. However in planar magnetic cores with ring shape this can be achieved only by radial anisotropy so that the easy axis is orthogonal to the direction of magnetization along the whole circumference of the ring [6].

We have previously presented a method for electroplating Permalloy rings with radial anisotropy by applying a large radial magnetic field by means of a yoke [7]. The anisotropy induced by this method was however not very large; it was therefore suggested that the origin of this field-induced anisotropy had to be found in the non-negligible magnetocrystalline anisotropy of the NiFe alloy.

It is well know that despite Ni and Fe have significant magnetocrystalline anisotropy, when combined in $Ni_{81}Fe_{19}$ composition the magnetocrystalline vanishes [8]. It was then supposed that if the precise stoichiometry of the alloy was achieve the presence of the field during electroplating would not induce any anisotropy due to vanishing magnetocrystalline anisotropy of the alloy. This would indeed make impossible to electroplate a ring with simultaneously low magnetostriction and field-induced anisotropy because the first condition requires $Ni_{81}Fe_{19}$ composition too. In this paper we test this hypothesis by electroplating rings with different current density, thus yielding different composition. If the field-induced anisotropy was really directly connected with magnetocrystalline anisotropy we would expect to see an increment of the effect of the radial field as we move far from $Ni_{81}Fe_{19}$ composition.

II. Manufacturing of the Rings

The rings have been manufactured by electroplating a thin film of $Ni_{1-x}Fe_x$ on a 9μm layer of copper over a 0.25 mm thick fiberglass substrate.

The external diameter of the ring is 48 mm while the inner diameter is 44 mm, giving a 2 mm wide trace. The electroplating was performed using a traditional watt-type bath and a platinum grid as anode. The bath was thermostatically regulated at 55 °C and the stirring was provided by a mechanical pump.

The rings have been electroplated with and without radial field. Such radial field was produced by a yoke with N52 grade NdFeB magnets with magnetization pointing to the center of the ring where a pillar collects the magnetic flux creating a uniform radial field as described in [7]. In this case we newly used arc segments magnets for the yoke instead of square magnets used in to achieve a full magnet ring with no space between magnets. This increases the uniformity of the field and also the amplitude of the radial magnetic field. In the air-gap the magnetic flux density in the proximity of the central pillar was 0.9 T. The rings were electroplated in an ABS container shaped to fit inside the airgap and expose the ring to the magnetic field with only horizontal component.

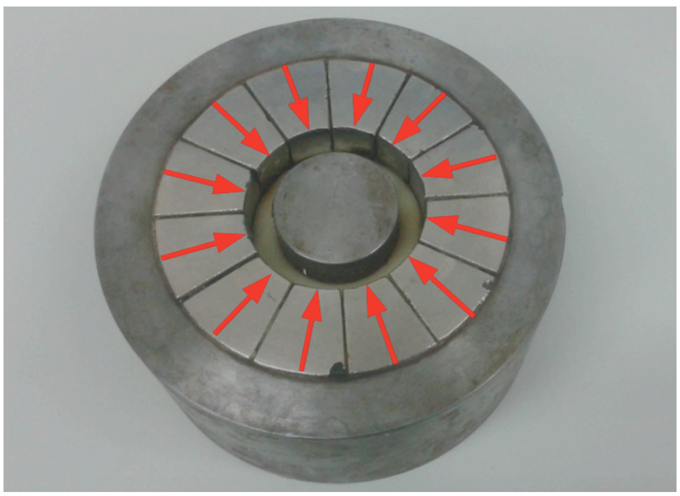

Fig. 1. Yoke with arc segment magnets used for inducing radial anisotropy during electroplating.

The rings electroplated without magnetic field have been manufactured inside a small shielding to cancel most of the Earth magnetic field, even if its amplitude should be negligible.

The current density was changed in order to change the composition of the electroplated film. Current density j_0=16 mA/cm^2 returns an ideal $Ni_{0.81}Fe_{0.19}$ composition, whereas if we increase j the content of iron will increase and vice versa if the current density is decreased the content of nickel increases [9]. In this paper we tested current density up to 3 times larger than j_0 and down to 0.5 times j_0.

However, by changing the current density we also change the deposition rate, that is the amount of material deposited per unit of time. In order to achieve films with a uniform thickness we had therefore to adjust the deposition time: for j_0=16 mA/cm^2 the electroplating time was t=30 minutes to achieve a 6 μm thickness, whereas for other samples we changed the deposition time in inverse proportion to the current density to achieve the same thickness.

Having a uniform thickness is important if we want to compare the samples because the anisotropy induced by magnetic film during electroplating to a certain extend depends on the thickness.

III. Results

In order to evaluate the effect of the magnetic field applied during the electroplating we measured the hysteresis curves of all the samples manufactured by using conventional induction method at low frequency (200 Hz). Both the excitation coil and the pick-up coil were distributed along the whole circumference of the ring to obtain the average hysteresis curve.

In Fig. 2 we can see the B-H curves of rings electroplated at j_0=16 mA/cm^2 with and without radial field applied, while Fig. 3 shows the B-H curve of the rings electroplated at $j=2 \cdot j_0$.

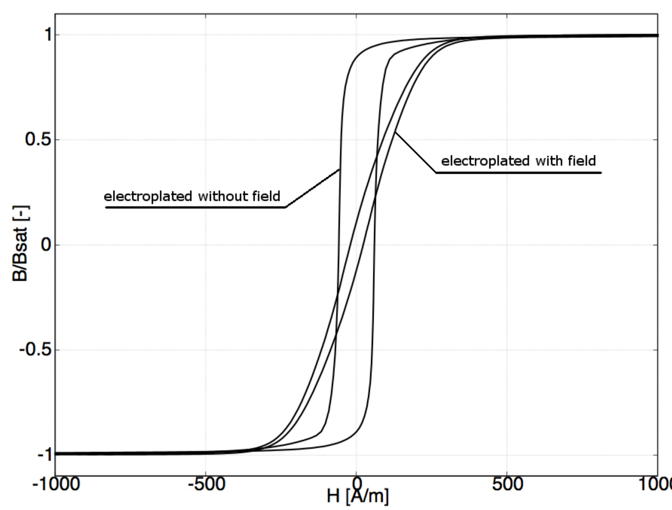

Fig. 2. Hysteresis curve of rings electroplated with and without radial field applied for electrodeposition current density j= 16 mA/cm^2.

The hysteresis curves are very similar in both cases. We can only observe a slight difference in the B-H loop of the rings with field induced anisotropy, where the ring electroplated with at $j=2 \cdot j_0$ has reduced energy in the region close to saturation, indicating that the magnetization rotation begins for lower value of H field, than in the rings electroplated at $j=j_0$.

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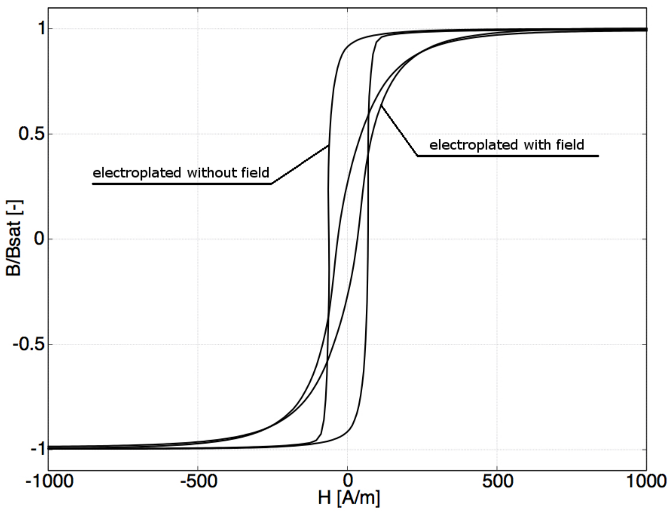

Fig. 3. Hysteresis curve of rings electroplated with and without radial field applied for electrodeposition current density j= 32 mA/cm^2, that is $j=2 \cdot j_0$.

However, this is indeed a minor difference. In both cases the loops are very similar: the coercivity decreases from about 60 A/m for rings electroplated without radial field to about 30 A/m if radial field is applied. But most importantly, the B-H loops are skewed in the very same way. The radial field applied during electroplating modifies the hysteresis loop making the circular axis (direction of the measurement) harder in a similar way, regardless the composition of the magnetic film. We cannot observe any significant difference in the anisotropy induced in the film electroplated at $j=j_0$ and $j=2 \cdot j_0$. The same applies for all compositions we tested, except for the rings electroplated with very low current density ($j<0.7 \cdot j_0$). In that case the coercivity increases by one order of magnitude. This can be seen in Fig. 4, which shows the dependence of coercivity on the current density with and without field applied.

For very low current density the coercivity significantly increases. Therefore, we must exclude rings with high nickel content because their high coercivity does not make them suitable for fluxgate.

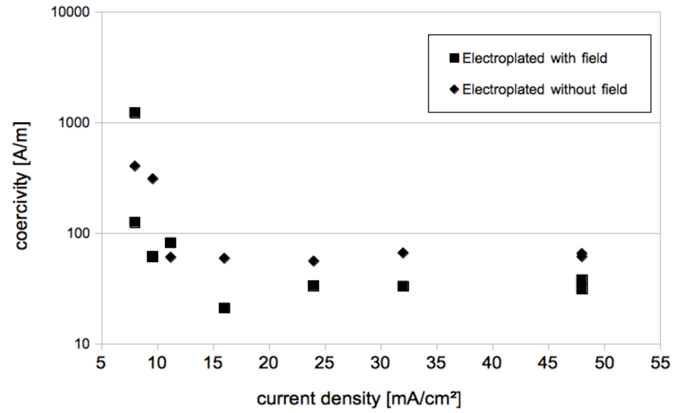

Fig. 4. Dependence of coercivity on the current density of electroplating of rings electroplated with (squares) and without (diamonds) radial field.

Let us now consider the anisotropy induced by the radial field applied during the electroplating. Fig. 5 shows the anisotropy field defined at the field where saturation is achieved (we considered a conventional 90% of saturation) for the rings electroplated with and without magnetic field. We can see that the presence of the radial field during electroplating increases the anisotropy field uniformly for almost all the range of current density and therefore for all the compositions of the NiFe alloy considered (except for very low current density where the saturation occurs at high field not because of a larger anisotropy in orthogonal direction but because of larger coercivity).

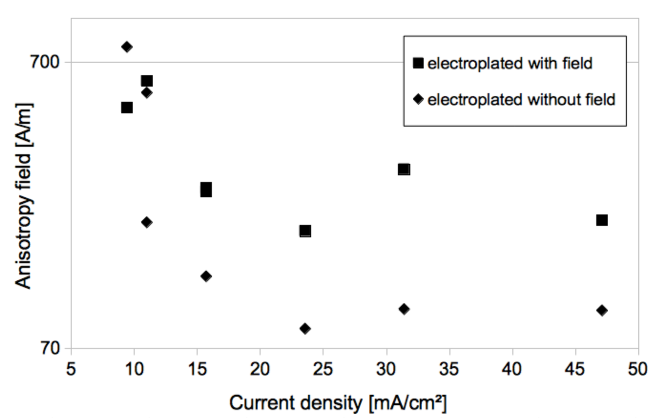

Fig. 5. Dependence of the anisotropy field on the current density of electroplating of rings electroplated with (squares) and without (diamonds) radial field.

We do not observe a significant change of the field-induced anisotropy while changing the composition of the film. There is not a trend of diminishing anisotropy as we approach $Ni_{81}Fe_{19}$

composition (j_0=16 mA/cm^2). This indicates that we could in fact achieve a film with vanishing magnetostriction (by very precisely tunig the ratio of Ni and Fe) and simultaneously obtain a material with radial field-induced anisotropy, as we desire.

IV. Effect of the Anisotropy on the Noise

As we have previously stated the main goal of inducing radial anisotropy in the NiFe rings is to reduce the noise of the fluxgate based on such rings. Therefore, we want to test if eventually the field-induced anisotropy helps in making the noise lower.

We used the rings as cores for fluxgates by winding a 540 turn excitation coil around them, fed by 2.5 $A_{p\text{-}p}$ current at 30 kHz. The pick-up coil was composed of 280 turns and it was tuned by means of an external capacitor to the second harmonic. The output signal was finally derived using a conventional digital lock-in amplifier.

The noise was measured in a 4-layer shielding in a 0.2 Hz – 200 Hz range. Fig. 6 shows the value of the power spectral density of the noise at 1 Hz (commonly used as a reference value for magnetometers) vs. the current density used in electroplating. As we expected [9] the noise is lowest at current density j_0=16 mA/cm^2, where the $Ni_{0.81}Fe_{0.19}$ composition is obtained, and the magnetostriction is the lowest, whereas the noise increases as we reduce or increase the current density and therefore increase the magnetostriction.

Interestingly we note that such behavior is obtained in both rings with and without field induced anisotropy, but even more significantly we observe that the ring electroplated under the influence of the radial field have lower noise than the rings without radial field.

While a ring with field induced radial anisotropy shows 80 pT/√Hz at 1 Hz noise for j=16 mA/cm^2, a ring electroplated with the same current density but without radial field has 800 pT/√Hz noise at 1 Hz, despite larger permeability contributes to larger sensitivity.

This means that noise of fluxgate is indeed very efficiently reduced by the field-induced anisotropy. Moreover, we observed that this effect applies for all rings electroplated at different current density. This means that the mechanism leading to noise reduction by means of anisotropy orthogonal to direction of excitation is independent on the current density of electroplating of the ring and therefore it is beneficial for a wide range of composition of the ferromagnetic film.

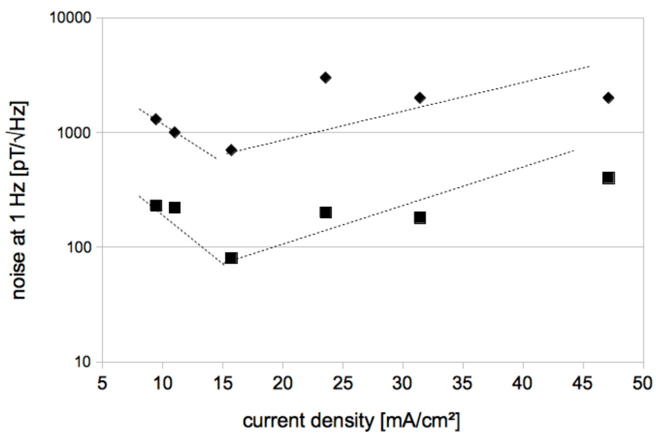

Fig. 6. Power spectral density of the noise vs. electroplating current density for fluxgates based on rings electroplated under radial field (squares) and without radial field (diamonds). The anisotropy induced during the electroplating process reduces the noise of the fluxgate by almost one order of magnitude.

Acknowledgment

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