ISSN 1027-5495. Functional Materials, 26, No.2 (2019), p. 429-435.
doi:https://doi.org/10.15407/fm26.02.429

Multilayer thin films for use as fluxgates cores

L.Z.Lubyaniy, V.N.Samofalov, A.N.Stecenko, I.A.Chichibaba

National Technical University "Kharkiv Polytechnic of Institute",
2 Kyrpychova St., 61002 Kharkiv, Ukraine

Received December 15, 2018

Ways to increase the sensitivity of differential fluxgates based on use of film cores with a certain domain structure are considered. The results of magnetic investigations of multilayer thin permalloy films with uniaxial anisotropy, used as cores of fluxgates, are presented. The performed analysis of fluxgate operation makes possible to calculate its sensitivity from main magnetization curve or hysteresis loop. The magnetization-field dependence for a uniaxial ferromagnet with dispersion of easy magnetization axis was found. It is shown that to increase the signal-to-noise ratio, it is necessary to fabricate film layers in which the magnetization reversal by excitation fields occurs due to reversible rotation of magnetization.

Keywords: fluxgate, core, thin film, anisotropy field, second harmonic.

Рассмотрены способы повышения чувствительности дифференциальных феррозондов, основанные на применении пленочных сердечников с определенной доменной структурой. Приведены результаты магнитных исследований многослойных тонких пленок пермаллоя с одноосной анизотропией, используемых в качестве сердечников феррозондов. Проведенный анализ работы феррозонда позволяет вычислить его чувствительность из основной кривой намагничивания или петли гистерезиса. Найдена зависимость намагниченности от поля для одноосного ферромагнетика с дисперсией осей легкого намагничивания. Показано, что для увеличения отношения сигнал/шум необходимо изготовить пленочные слои, в которых перемагничивание полями возбуждения происходит за счет обратимого вращения намагниченности.

Багатошарові тонкі плівки з одновісною анізотропією для використання їх в якості осердь ферозондів. *В.М.Самофалов, О.М.Стеценко, Л.З.Луб'яний, І.О.Чичибаба.*

Розглянуто способи підвищення чутливості диференційних ферозондів, засновані на застосуванні плівкових осердь з певною доменною структурою. Наведено результати магнітних досліджень багатошарових тонких плівок пермалою з одновісною анізотропією, що використовуються в якості осердь ферозондів. Проведений аналіз роботи ферозонда дозволяє обчислити його чутливість з основної кривої намагнічування або петлі гістерезиса. Знайдено залежність намагніченості від поля для одновісного феромагнетика з дисперсією осей легкого намагнічування. Показано, що для збільшення відносшення сигнал/шум необхідно виготовити плівкові шари, в яких перемагнічування полями збудження відбувається за рахунок зворотного обертання намагніченості.

1. Introduction

Fluxgates are sensors designed to measure weak magnetic fields. They are used for geological exploration purposes, in space fields study, in military medicine, biomedicine, etc., where it is necessary to register fields of intensity 10^{-5} Oe and lower. At present, fluxgate are developed, capable of measuring fields with a lower limit of the order of 10^{-7} Oe. The difficulty of further reduction of lower recorded field level is due to the presence of magnetic noises that arise in fluxgate core during magnetization reversal by excitation fields. To reduce the fluxgate sensitivity threshold, it is expedient to use magnets whose magnetization reversal occurs not due to a motion of domain walls that are the source of Barkhausen noise, but due to reversible magnetization rotation processes. To achieve this, a certain domain structure or magnetic state should be implemented in the core. The most simple way to do this is if as cores are used film layers produced by evaporation and vacuum condensation of magnetically soft materials. Compared to massive cores, this technology allows generating uniaxial magnetic anisotropy, creating multilayer structures from various elements, and obtaining a variety of domain structures.

Previous studies [1–5] have shown that the most suitable for this purpose are sensitive elements that are in a single-domain state or have a multi-domain state with a certain orientation of magnetization in domains. There are many types of such structures, but the difficulty of using them is related to the complexity of implementing the desired magnetic structure. This is due to the fact that such magnetic state should arise spontaneously after the field is turned off and reversibly change with varying field parameters. A stable state, close to equilibrium, can be realized in condensed film layers by creating an induced magnetic anisotropy if the coercive force H_c is sufficiently small. Experience shows that for spontaneous realization of a single-domain state in the layers, the uniaxial anisotropy field Ha should be about 10 times higher than the coercive force. The fulfillment of this condition is usually a rather complex technological task.

In [5] for this purpose thin monocrystalline ferrite-garnet layers were used. The advantage of such cores was that the single-crystal layer had no crystal structure defects and, as a result, an extremely low level of magnetic noise and a low coercive force H_c (~ 0.03 Oe) are provided. In this work, the single-domain state was achieved by including a bias field. According to the authors, a fluxgate with a ferrite-garnet core allowed the detection of weak fields down to $H \sim 10^{-6} - 10^{-7}$ Oe. Apparently, such cores have the lowest level of magnetic noise compared to cores made of other materials. The weakness of single-crystal films cores is the complexity of their fabrication, as well as low values of magnetization.

In [4], it was proposed to use as fluxgate cores multilayer films made of permalloy narrow bands with low coercive force, in which ferromagnetic layers are separated by nonmagnetic spacers. The films were prepared in such a way that easy magnetization axis with uniaxial magnetic anisotropy field $H_a = 2–5$ Oe appeared along short side. Magnetization of samples by excitation fields was carried out in the hard axis direction, i.e. along long side of the strip. With such a magnetization reversal, the level of magnetic noise was reduced by 2–3 orders of magnitude in comparison with the magnetization reversal by a field directed along easy axis, and the signal-to-noise ratio was increased in appropriate number of times. In addition, the magnetization reversal of core in hard axis direction is mainly due to rapid processes of magnetization rotation [6]. This makes it possible to use the excitation field of high frequency $f > 10^6$ Hz during fluxgate operation, which significantly increases fluxgate sensitivity to the field. Of the variety of possible magnetic structures, the most suitable for such purposes is a single-domain state or a single-domain state in each film layer. The solution of this practical task is planned to be realized due to the use various compositions of film materials, as well as the improvement of film layers preparation methods.

Therefore, the purpose of this work is to create fluxgate cores, in which, due to the given magnetic state, a low level of magnetic noise is achieved on the one hand, and on the other hand the signal emf level rises.

2. Calculation of magnetization curve

In this work, we continue the development of our idea [4] — to create fluxgate cores with increased sensitivity to low fields by reducing the level of magnetic noise. This idea requires more detailed experimental and theoretical substantiation. In previous studies [4], multilayer permalloy films with uniaxial magnetic anisotropy were used, and remagnetization in film by excitation fields occurred perpendicular to easy magnetization axis. This was achieved by the magnetization reversal in the layers. It is known [6] that when remagnetization is perpendicular to easy axis, magnetization-field dependence $M(H)$ is linear and therefore the emf of fluxgate signal $e(t)$ must be small. Usually, such materials are not used as cores. Actually, in our cores $e(t)$

takes low values on the linear region of $M(H)$. However, in the field closed to the saturation field, a curvature takes place and in this field region a large signal arises, inversely proportional to the curvature radius of the $M(H)$ dependence. Therefore, for the purposeful increase in the sensitivity of differential fluxgate, it is important to know the nature of curvature on $M(H)$ dependence in the vicinity of saturation field.

The sensitivity threshold of fluxgate is determined by the ratio of signal magnitude S to the noise level N i.e. $(S/N > 1)$. Previously, to increase the signal S, it was proposed to use magnetic materials with high permeability μ. However, in fluxgates with cores of amorphous materials with record values of magnetic permeability, the sensitivity was low. And the point here is not only the level of magnetic noise in amorphous ribbons. In our work [4] it is shown that the value of emf signal equals

$$e(t) = \frac{DB}{dt} \approx 4\pi \cdot A \cdot \left[\frac{d^2M(H)}{dH^2}\right] \cdot \frac{dH}{dt} \cdot 2H, \quad (1)$$

where H_x — measured field, H — excitation field, $M(H)$ — magnetization-field dependence and A — constant, taking into account the core dimensions and the excitation winding parameters.

From this dependence it is seen that the influence of material properties on emf fluxgate signal is manifested through the value of d^2M/dH^2, and by means of the hysteresis loop a conclusion about the degree suitability of material for use as a core can be made. Our further research is related to development of this direction, i.e. searching for materials with high d^2M/dH^2 values (curvature).

The curvature in $M(H)$ dependence near the saturation field can be caused by various factors — dispersion of anisotropy, nonsequential ordering of atomic pairs, and the presence of oriented microstresses. In this paper, we restricted ourselves to an analysis of $M(H)$ curve in the presence of amplitude dispersion of anisotropy. The magnetization curve was calculated in a field perpendicular to easy axis. It was assumed that there is no angular dispersion of magnetic anisotropy. It was also assumed that the probability density f of regions with different values of anisotropy field H_a is uniform, i.e. $f = 1/(Ha_{max} - Ha_{min})$, where Ha_{min} and Ha_{max} are the minimum and maximum values of uniaxial anisotropy field (see Fig. 1). It was also assumed that the difference in the Ha_{min} and Ha_{max} values is small $(Ha_{min} - Ha_{max} < Ha_{max})$, so we did not take into account the possible exchange interaction between phases with different H_a values, i.e. it was assumed that regions with different H_a values are magnetized independently of each other.

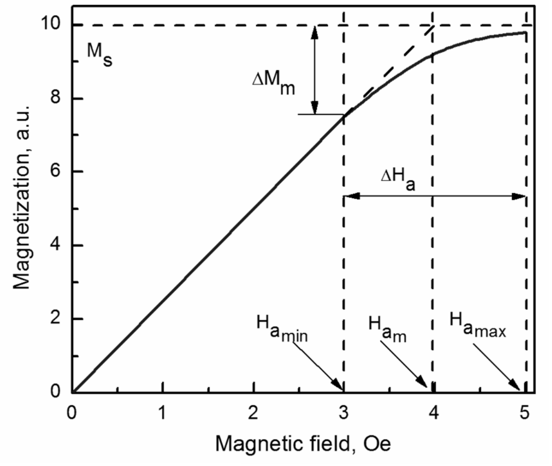

Fig. 1. Calculated field-dependent magnetization curve for a uniaxial film with amplitude dispersion of anisotropy.

The $M(H)$ dependence in the magnetizing field interval from $H = 0$ to $H = Ha_{min}$ will be linear with some mean value of anisotropy field Ha_m. To calculate $M(H)$ for such a case, we obtained the formula:

$$M(H) = M_sH \int_{Ha_{\min}}^{Ha_{\max}} \frac{dHa}{(Ha_{\max} - Ha_{\min})Ha} = \quad (2)$$

$$= \frac{M_sH}{(Ha_{\max} - Ha_{\min})} \ln\left(\frac{Ha_{\max}}{Ha_{\min}}\right),$$

where M_s is the saturation magnetization, Ha_{min} and Ha_{max} are the minimum and maximum values of uniaxial anisotropy field.

From the formula (2) we shall calculate the value of averaged field of anisotropy Ha_m

$$Ha_m = \frac{Ha_{\max} - Ha_{\min}}{\ln(Ha_{\max}/Ha_{\min})}. \quad (3)$$

At $H > Ha_{min}$, the dependence becomes nonlinear and in the field $Ha_{min} > H <$ Ha_{max} will have the form

$$M(H) = \frac{MsHa_{\min}}{(Ha_{\max} - Ha_{\min})} \ln\left(\frac{Ha_{\max}}{H_{\min}}\right) + \quad (4)$$

$$+ \Delta M(H).$$

The first term in (4) is equal to the value of magnetization projection on the field di-

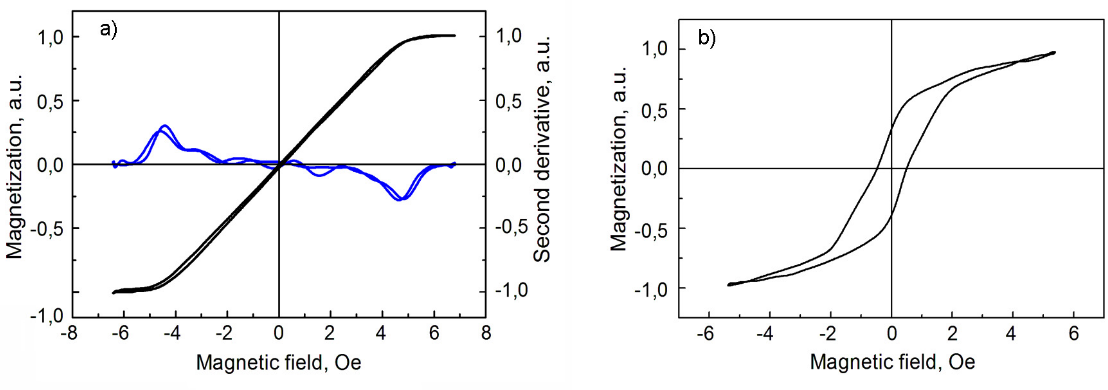

Fig. 2. Hysteresis loop $M(H)$ (black color) and second derivative d^2M/dH^2 (blue color) of permalloy sample 1 mm wide, remagnetized in hard axis direction (a); hysteresis loop of sample 2 mm width (b).

rection at $H = Ha_{min}$, i.e. $M(Ha_{min})$. The second term $\Delta M(H)$ characterizes the change in the magnetization in the field interval $Ha_{min} > H < \mathrm{Ha}_{max}$. The dependence $\Delta M(H)$ can be calculated from the formula

$$\Delta M(H) = \frac{\Delta M_{in}(H_x - Ha_{\min})}{(Ha_{\max} - Ha_{\min})}\left\{1 + \ln\left(\frac{Ha_{\max} - Ha_{\min}}{H_x - Ha_{\min}}\right)\right\}, \quad (5)$$

where $\Delta M_m = M_S - M(Ha_{min})$.

It follows from (5) that for $Hx = Ha_{max}$ the value $\Delta M(Ha_{max}) = \Delta \mathrm{M}_m$, and, consequently, in this case the magnetization $M(H) = M_S$. Fig. 1 shows a graph of calculated dependence of magnetization curve in a field perpendicular to easy axis, calculated from formulas (4) and (5). It consists of two sections: linear in the field interval below Ha_{min} and nonlinear in the interval $Ha_{min} > H < \mathrm{Ha}_{max}$. For clarity in the construction, the values of $Ha_{min} = 3$ Oe, $Ha_{max} = 5$ Oe, and $\Delta M_m \sim 0.1 M_S$ are chosen. From the obtained results it follows that the presence of amplitude dispersion of anisotropy in the films leads to appearance of curvature on $M(H)$ dependence and the second derivative $d^2M/dH^2 \neq 0$. It is important that the difference between Ha_{min} and Ha_{max} be as small as possible. So, the presence of amplitude dispersion of uniaxial anisotropy in the cores contributes to the growth of fluxgate sensitivity. For this purpose, single crystal films or layers in which uniaxial anisotropy is associated with macrostresses can be suitable.

3. Magnetic properties of fluxgate cores

The investigated samples were multilayer ferromagnetic permalloy films in the form of narrow rectangular strips 1 – 3 mm wide, about 20 mm long and 1 – 3 μm thick. Permalloy layers of 80 % Ni composition were separated by nonmagnetic spacers made of SiO, Al_2O_3, or amorphous carbon ~ 0.1 μm thick. Films were deposited in vacuum by magnetron sputtering or electron-beam evaporation. The rectangular shape of samples was reached by dusting through masks or by means of a photolithography. The films were condensed in presence of magnetic field, which was directed along the short side of strip. In this direction, an axis of easy magnetization with an uniaxial magnetic anisotropy field $H_a = 2–5$ Oe appeared.

The magnetic properties of film cores were judged from their hysteresis loops parameters obtained by means of induction device. Device was supplemented with a virtual instrument created in LabVIEW graphical programming environment. The magnetization reversal of samples was carried out by alternating sinusoidal field applied along long side of strip. Computerized digitization made it possible to perform mathematical and statistical processing of hysteresis loops and analysis of their shape, to automatically determine magnetic characteristics such as coercive force, residual magnetization and saturation field. The loops had a weakly pronounced hysteresis and a low coercive force $H_c \sim 0.2$ Oe. The magnetization-field dependence $M(H)$ in field $H < H_a$ was close to linear (Fig. 2a), which is characteristic of magnetically uniaxial materials when they are reversed in hard axis direction. In permalloy films produced by a magnetron method, the coercive force is $H_c > 0.2–0.5$ Oe. This is higher than in the permalloy layers obtained by thermal evaporation [4], where on some films the coercive force was $H_c < 0.1$ Oe.

Comparison the properties of samples with different widths obtained in one experiment showed that narrow (1 mm) sam-

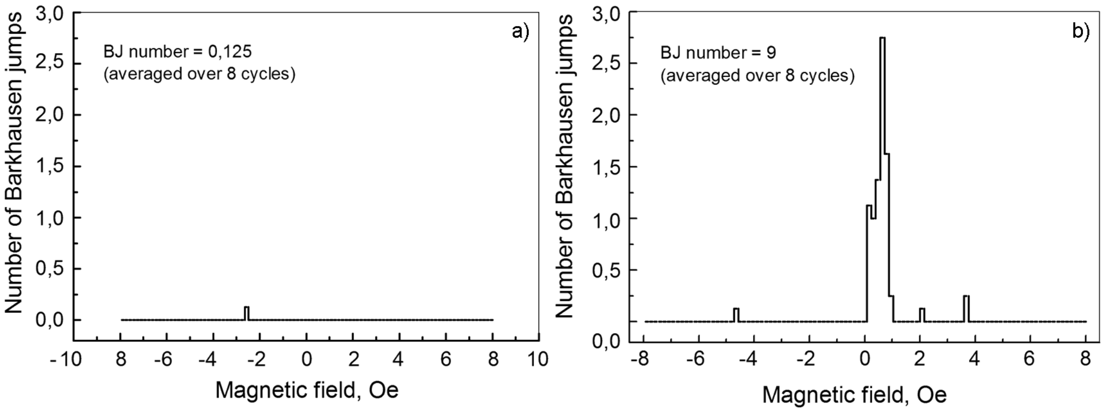

Fig. 3. Distribution of Barkhausen jumps density across the field (dN/dH) for narrow (1 mm) (a) and wide (2 mm) (b) samples.

ples have lower coercive force values (H_c ~ 0.2 Oe) compared with wide (2 mm) ones (H_c ~ 0.5 Oe) (see Fig. 2a,b). It seems that in wide stripes the domain structure with orientation of magnetization parallel of easy axis does not arise across the entire width of the strip due to its relatively large coercive force. The kind of hysteresis loop and large coercive force indicate the heterogeneity of their magnetic state, i.e. in wide samples the equilibrium magnetic state with direction of magnetization parallel to easy axis is not realized. It can be assumed that in the strips with a lower coercive force, for example, $H_c < 0.1$ Oe, the hysteresis loops for wide and narrow strips will be similar. To investigate the domain structure using a magnetic suspension in permalloy layers with a thickness above 0.5 μm it was not possible because of large width of domain walls in permalloy.

Using the experimental $M(H)$ dependence we can estimate the fluxgate sensitivity and find the interval of excitation fields at which the maximum of second derivative and emf is reached. In Fig. 2a the field dependence of second derivative d^2M/dH^2 is shown. It is obtained from digitized experimental hysteresis loops. On line section d^2M/dH^2 it is close to zero, and its maximum is reached at the beginning of curved region at $H=Ha_{min}$ of $M(H)$ dependence. Subsequent tests of fluxgates showed that maximum of emf signal and maximum of second derivative coincide.

4. Magnetic noise characteristics of cores

The most important characteristic of fluxgate, which determines its ability to measure ultralow fields, is a signal-to-noise ratio (S/N). In order to obtain high S/N cores, it is necessary not only to increase the output level of fluxgate signal, but also to minimize its noise. The source of noise in a fluxgate sensors (FS) can serve as noise in electronic circuits, as well as magnetic noise arising in the core itself during magnetization reversal [7]. Therefore, the study of the level of magnetic noise, we gave paramount importance.

Magnetic noise measurements made it possible to identify cores with a minimum noise level. Depending on making conditions, as well as on the shape and size of the samples, the number of Barkhausen jumps (BJ) during magnetization reversal widely varied. In Fig. 3 shows a distribution of Barkhausen jumps number density across the field (dN/dH) for a narrow (1 mm) and wide (2 mm) samples, made by photolithography from a deposited plate. The results are presented taking into account averaging over several cycles of magnetization reversal with an error of about 10 %. The figure shows that Barkgausen jumps level in a narrow strip is significantly lower than in a wide one. The Barkgauzen noise recorded during the magnetization reversal of such cores did not exceed the noise on the measuring equipment wires. The absence of Barkhausen noise along with a hysteresis-free loop (see Fig. 2a) speaks in favor of uniform rotation reversal. At the same time, the wider stripes obtained in the same experiment are remagnetized by several large jumps (see Fig. 2b), which indicates the presence of magnetization reversal by moving the domain walls.

When analyzing the fluxgate noise parameters, fluctuations of a second harmonic of magnetization reversal frequency are of the greatest interest, since it is they that

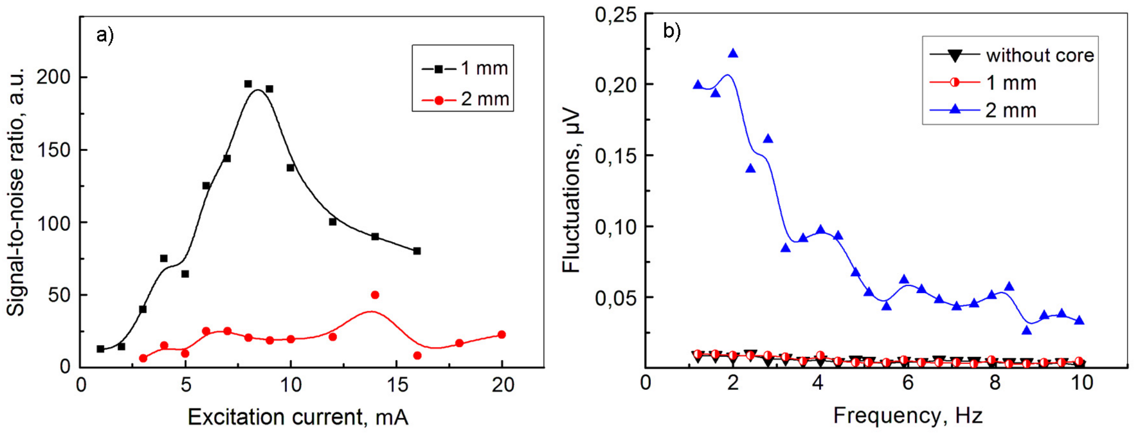

Fig. 4. S/N ratio for a fluxgate with narrow (1 mm) and wide (2 mm) cores (a), spectral distribution of fluctuations of second harmonic, given to FS input, for 1 mm core (red curve), 2 mm cores (blue curve) and without core (black curve) (b).

determine the minimum detectable magnetic field [8]. For testing samples, differential FS were made with excitation frequency 200 kHz.

For all pairs of cores, measurements of fluxgate output signal and fluctuation level near second harmonic were made for different excitation currents. The analysis frequency band was 1–100 Hz. Studies have shown that the maximum output signal falls on the excitation current corresponding to anisotropy field Ha for these cores (taking into account the fluxgate conversion coefficient) where the hysteresis loop has the greatest curvature. It was found that fluxgate with narrow (1 mm) cores have a much smaller fluctuation level than with wide (2 mm) ones (5 – 50 times for different cores). For some narrow samples, the fluctuation level did not exceed the noise of fluxgate without cores (see Fig. 4b).

The fluctuation level of the second harmonic significantly affects the value of signal-to-noise ratio. Fig. 4a shows, for comparison, S/N plots from excitation current for narrow (1 mm) and wide (2 mm) cores. The measurement results have a very good repeat for samples with same width within a limits of one plate. The figure shows that the FS with 1 mm cores have a much higher S/N value than 2 mm ones. At the optimal excitation current, the S/N values, given to the measured field, for cores with different widths differ by an order of magnitude, and are $2{\cdot}10^7$ Oe^{-1} and $2{\cdot}10^6$ Oe^{-1} for narrow and wide strip, respectively (see Table).

The spectral distribution of fluctuations near second harmonic was also studied. It has $1/f$ form (see Fig. 4b). One can see a significant excess the fluctuation level for 2 mm cores in comparison with 1 mm cores in the reduced analysis frequency band.

Table shows the characteristics of FS with some cores. To eliminate the parameters ambiguity, the results were lead to the same volume and similar measurements were carried out under the same conditions. The parameters such as optimal excitation current I_{exc}, fluctuation level U_{fl}, and signal-to-noise ratio S/N, are given. Optimal

Table. Characteristics of fluxgate sensors

Specimens	I_{exc} optimal, mA	U_{fl} at 20 Hz, µV	S/N at 20 Hz, lead to V, $\cdot 10^{-7}$ Oe^{-1}
P1, photolithography, plate 1, width 1 mm	6	7	1.56
P1, photolithography, plate 1, width 2 mm	6	500	0.03
P2 photolithography, plate 2, width 1 mm,	8	3	2.6
P2, photolithography, plate 2, width 2 mm	4	20	0.25
M1, magnetron sputtering, series 1, width 3 mm	26	35	0.31
M2, magnetron sputtering, series 2, width 3 mm	6	250	0.17
E1, electron-beam evaporation, width 1 mm	14	40	0.91

excitation current I_{exc} was determined by the maximum S/N, fluctuation level U_{fl} was given to FS input and signal-to-noise ratio taking into account to trial field and sample volume V.

From Table shows that for cores having different widths, S/N differs by an order of magnitude. Such a pattern is carried out for all investigated plates. The best signal-to-noise ratio S/N have narrow (1 mm) stripes cores, made using photolithography. So, for the FS with P2 cores, the signal-to-noise ratio is equal to $2.6\cdot10^7$ Oe^{-1} for the case of narrow cores and $0.25\cdot10^7$ Oe^{-1} for wide ones. A similar pattern is also performed for cores obtained by other methods through masks (see samples M1, M2, E1). The FS with E1 cores (width 1 mm), obtained by electron-beam evaporation, show a significantly greater S/N than the cores M1 and M2 with a 2 mm width (taking into account the samples volume).

4. Conclusions

It is shown that uniaxial permalloy films in the form of narrow strips with a linear field-dependent magnetization curve $M(H)$ can be used as the cores of differential fluxgate. The linear dependence $M(H)$ is achieved by magnetization by a field directed perpendicular to the easy axis, due to low coercive force films H_c and domain structure with the orientation of magnetization parallel to the easy axis.

The magnitude of emf fluxgate signal is determined by the curvature of $M(H)$ dependence near the saturation field. It is shown that a further increase in the fluxgate sensitivity can also be achieved by studying the nature of curvature and its variation.

It has been established experimentally that in cores with a linear $M(H)$ dependence, the largest emf of fluxgate signal is reached near the saturation field, i.e. where d^2M/dH^2 is the largest. It is shown how the sensitivity of a fluxgate can be determined from the experimental $M(H)$ dependence.

The idea developed by us in [4] to increase the fluxgate sensitivity by reducing the magnetic noise level during reversible rotation of magnetization found here experimental confirmation. At the same time, high values of the signal-to-noise ratio S/N were achieved on samples that are in the multi-domain state. It can be assumed that the implementation of single-domain in layers will lead to an additional decrease in the noise level and thus to a lowering of recorded fields limit to 10^{-8} Oe.

References

1. L.Z.Lubyaniy, V.N.Samofalov, A.G.Ravlik et al., New Magnetic Materials of Microelectronics, Moscow (2006) [in Russian].
2. L.Z.Lubyaniy, V.N.Samofalov, I.A.Chichibaba et al., in: Proc. of Intern. Conf. Functional Materials, Ukraine (2005), p.88.
3. S.I.Bondarenko, L.Z.Lubyanyi, A.G.Ravlik et al., Thin Films in Optics and Electronics, Kharkiv (2003) [in Russian].
4. L.Z.Lubyaniy, V.N.Samofalov, A.N.Stetsenko et al, *Bull. Russ. Acad. Sci., Phys.*, **78**, 142 (2014).
5. P.M.Vetoshko, D.A. Chepurnova et al. *Techn. Phys. Lett.* **42**, 860, (2016).
6. M.Pratton, Thin Ferromagnetic Films, Sudostroenie, St. Petersburg (1967) [in Russian].
7. N.N.Kolachevsky, Magnetic Noise, Nauka, Moscow (1971) [in Russian].
8. Y.V.Afanasyev, Fluxgate Devices, Energoatomizdat, St. Petersburg (1986) [in Russian].