Ultrasensitive core for magnetooptical fluxgate magnetometer with high space resolution

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Abstract

New type of fluxgate magnetometer core on the basis of magnetooptical uniaxial Bi-substituted garnet film was designed, numerically modeled and investigated experimentally. Magnetooptical garnet film with weak magnetization exhibits extremely high sensitivity with relation to external magnetic field. High sensitivity is achieved by single domain wall displacement in film area restricted by potential barriers. High amplitude magnetooptical response was received from garnet film element with special shape in space region 20 - 200 mcm. Magnetic field value for sensitive element saturation and garnet film coercive field were found in the same range 20 – 200 A/m. Used in fluxgate regime garnet film sensitive element can provide space resolution better than one of traditional fluxgate. Presented approach possesses to avoid temperature adjustment and inductive coils application in high sensitive magnetometers.

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Keywords: fluxgate magnetometer; ferrite garnet film; domain wall; Faraday rotation; magnetostatic barrier.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$M$</td>
<td>magnetization of garnet film</td>
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<tr>
<td>$h$</td>
<td>garnet film thickness</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>surface density of domain wall energy</td>
</tr>
<tr>
<td>$H_c$</td>
<td>coercive field of domain wall in garnet film</td>
</tr>
<tr>
<td>$x$</td>
<td>position of domain wall</td>
</tr>
<tr>
<td>$H$</td>
<td>external field value</td>
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1. Introduction

Space resolution of high sensitive magnetometers is of importance due to biological and medical applications. Space resolution of modern types of sensitive magnetometers (SQUID, alkali vapor) is no better than few millimeters [1,2] due to temperature adjustment facilities while GMR-sensors with micrometer dimensions aren’t sensitive enough to feel remote magnetic nanoparticle [3]. Fluxgate magnetometer needs coils and magnetically soft core [4] those are principal obstacles for sensitive elements miniaturization. In addition reduction of core dimensions leads as a rule to saturating field increase and magnetometer sensitivity reduction.

From the other side enhancement of space resolution is necessary to reveal freely flowing magnetic nanoparticle in microchannel and measurement of weak current in tissue *in situ*. Along with high magnetic sensitivity $10 – 100 \text{pT/Hz}^{0.5}$ such magnetometer requires space resolution $10 – 100 \text{mcm}$ and possibility to draw together magnetic object and sensitive element. These parameters seem hardly achievable simultaneously by traditional methods. Suitable way to resolve the problem is to remove temperature facilities or coils and to use optical signal registration.

Few known constructions of magnetooptical magnetometers are based on Bi:YIG monocrystal as a sensitive element [5]. Sensitivity and space resolution of this type magnetometer is no better than of previously mentioned types. The main purpose of present work is creation of magnetooptical sensitive element with magnetization reversal type suitable for fine local magnetic field measurement.

2. Concept and calculation results

An ideal characteristic of high sensitive core for fluxgate magnetometer is step-like dependence between output signal and external field. Continuous Bi-substituted garnet films with low magnetization used for nondestructive evaluation aren’t suitable for fine magnetic sensing due to significant exciting field and random motion of domain walls. Monodomain state of an element etched in such a film is highly coercive. But if garnet magnetization $M$ is small enough to maintain monodomain state of the film (or element size is less than domain dimension but more than domain wall (DW) width) element can be divided into two or more stable domains. This case it can exhibit entirely different behavior in magnetization process. Simultaneously transition to monodomain state can be closed by high energy barrier.

Numerical modeling of magnetostatic stable states of two-domain structure of rectangular elements in external magnetic field normal to film plane was made. Domain wall surface energy is proposed to be high enough to maintain straight form of DW connecting opposite element’s boundaries by shortest way. DW position in element is defined then only by balance of external magnetic field and own stray field created by garnet element boundaries. Stray field was calculated at domain wall center in dependence upon DW position inside element. Element edges were considered vertical in relation of substrate plane. Common view of stray field distributions is shown in Fig. 1.

![Fig. 1. Schemes of own stray field created at the center of domain wall by boundaries of uniaxial garnet film elements: isolated strip, bridge between two half-planes, bridge between two parallel narrow strips. Dashed lines represent DW unstable positions.](image-url)
Isolated strip and strip-like bridge between two opposite normally magnetized infinite half-planes are found to exhibit principally different behavior. Domain wall (DW) inside strip (bridge) suffers increasing repulsion (attraction) from nearest edge when shifted from center. DW position center position is strictly stable in isolated strip but bridge is magnetized spontaneously to one of two saturated states in zero external field. Isolated strip magnetization process occurs reversibly while bridge magnetization occurs by coercive manner. Artificial coercive force is entirely defined by magnetostatic barrier created by garnet film boundary. Strip susceptibility and bridge coercive field are found to be controlled by strip length, width and multiplication of film magnetization by film thickness \( M h \).

Hybrid element made as a bridge between two narrow strips is found to possess an indefinite DW equilibrium position which is highly sensitive to external field. DW repulsion by outer hybrid element vertical boundaries can be compensated in wide region inside bridge by attraction DW by inner element vertical boundaries. Such element seems promising being used in fluxgate or fluxset regime as a magnetometer core.

3. Experimental results

Bi-substituted uniaxial garnet films with magnetization M in the range 25 -50 Gauss were grown on GGG substrate with (111) orientation. Various types of elements were etched chemically in garnet films. Matrix of quadratic elements (a) and bridges between parallel strips (b) are shown in Fig. 2.

Single DW in element was created by garnet film cooling from ~ 200 °C to room temperature in external magnetic field gradient ~ 0.01 Oe/mcm. Microscope remnant and Earth magnetic fields compensation was made by external field. Magnetization process was investigated in quasi-static regime.

Magnetization reversal curves shown in Fig. 2 confirm qualitatively theoretical predictions. Quadratic elements in Fig. 2a are magnetized by almost reversible manner with coercive field ~ 30 A/m which equals to own coercive force of garnet film \( H_c \). Positions of DWs in different quadratic elements and different DW orientations are reproducible so that the spread of reversal parameters well coincide if there is no defect inside element.

Bridge between two half-planes with opposite magnetization directions demonstrates almost rectangular hysteresis loop with highly reproducible artificial coercive field defined by magnetostatic stray field of garnet film boundaries. No stable DW positions were found in between bridge edges.

Magnetization reversal by constant length DW motion occurs at very small external field in the range < 200 A/m. Switching field turned out two orders less than for monodomain state and few times less than predicted. Unlike assumption for theoretical calculation garnet elements edges have very smooth wedge ~ 10 degrees to substrate plane. Epitaxial garnet film wedge is seen as dark element contour in microphotographs in Fig. 2 and Fig. 3. Wedge is formed due to great difference between etching speed values along normal to (111) crystal plane and along other

![Fig. 2. Experimental microphotographs of DW positions and magnetization reversal loops: a - for quadratic elements 40x40 mcm in matrix, \( h = 8.5 \) mcm; b - for 2 rectangular bridges 30x120 mcm and 10x120 mcm, \( h = 3 \) mcm. \( M = 0.005 \) T.](image-url)
Fig. 3. Experimental microphotographs of DW positions at critical points and magnetization reversal loops for rectangular bridges between two parallel strips: a – $H = -160$ A/m, b – $H = 80$ A/m, c – $H = 160$ A/m. Bridges width 30 mcm, garnet magnetization $M = 0.005$ T, $h = 3$ mcm.

crystal directions. Since wedge width exceeds significantly garnet film thickness element boundary stray field is reduced in comparison to calculated value. It is useful effect from one sight since it leads to switching field reduction. From other side large wedge width prevents to create effective compensation of magnetostatic barrier inside bridge.

Nevertheless compensation effect is distinctly visible on hysteresis loop shape dependence upon distance between repulsing and attracting boundaries of hybrid elements shown in Fig. 3. It is clearly seen that element with nearest counteracting boundaries has minimal switching field $\sim 80$ A/m with sharpest borders for DW displacement at bridge edges. DW additional stable positions predicted by graph in Fig. 2 (2, 3) are distinctly visible as well.

4. Conclusion

Two-domain stable state of uniaxial garnet film element with low magnetization exhibits hysteretic properties which can be effectively controlled by element shape. Special element form ensures almost step-like switching characteristic with saturation field less than traditional fluxgate core has and space resolution $\sim 20$ mcm or less.

Due to high Faraday rotation and low stable switching field values uniaxial garnet film elements in two-domain states are promising objects for application in magnetic sensing. It should be noticed that on the contrary to traditional tendency sensitivity increase is accompanied by space resolution increase by approach proposed.

References