Hysteresis loop design by geometry of garnet film element with single domain wall

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Abstract. Numerical modeling and experimental investigation of magnetostatic stable states of two-domain structure in Bi-substituted uniaxial garnet film elements was made. Single domain walls (DW) between two opposite normally magnetized parts in isolated rectangular strip and strip-like bridge are found to exhibit different behavior. DW inside strip (bridge) suffers increasing repulsion (attraction) from nearest edge when shifted from element center. DW position center position is 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 reversal occurs by coercive manner. Strip susceptibility and bridge coercive field are entirely defined by magnetostatic barrier created by element boundary stray field in case of constant DW length during magnetization reversal. Variation of strip and bridge boundary shape along DW trajectory gives the opportunity to create additional controllable potential profile due to DW surface energy modulation by DW length. Garnet elements with high Faraday rotation and low light switching field were developed for fine magnetic sensing and optical data processing applications.

1. Introduction
Bi-substituted epitaxial garnet films (BiLu)3 (FeGa)5 O12 with uniaxial anisotropy and high Faraday rotation are expected for years to be used for optical data processing devices. In most cases garnet film elements in magnetooptical matrix are found in monodomain state which is known to be rather coercive. Magnetization reversal requires external field which is comparable with uniaxial garnet anisotropy field and reaches values and spreads up to few hundred Oersteds which are unacceptable for practical applications [1].

But if garnet magnetization $\mathbf{M}$ is small enough to maintain monodomain state of the film or element size is more than domain wall (DW) width but less than domain dimension element can be divided into two or more stable domains. This case it can exhibit entirely different behaviour in magnetization process. Simultaneously transition to monodomain state can be closed by high energy barrier. Such elements can be fabricated by lithography and etching of uniaxial garnet film with partial mutual compensation of magnetizations of tetrahedral and octahedral iron sublattices.

It is known that compensation of sublattices magnetization isn’t followed by Faraday rotation compensation [2,3]. So such garnet elements could be used for various types of magnetooptical devices.

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The purpose of present work is numerical modelling and experimental magneto-optical investigation of magnetization process of two-domain configurations in uniaxial garnet film elements and estimation of magnetization reversal field possible control and reduction to value suitable for applications.

2. Magnetization by constant length DW motion

2.1. Numerical modeling

Numerical modeling of magnetostatic stable states of two-domain structure in rectangular elements etched in uniaxial garnet film with arbitrary thickness \( h \) was made. DW is proposed straight and connecting opposite element’s boundaries. DW position is defined this case only by balance of external magnetic field and own stray field created by garnet element boundary. 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. Stray field distribution of such an element is calculated as magnetic field created by electric surface currents \( Mh \) flowing along element contour and \( 2Mh \) flowing along DW [4]. Domain wall surface energy is high enough to prevent DW bending.

Common view of stray field distributions is shown in figure 1.

![Figure 1. Stray field distributions scheme in uniaxial garnet film elements with constant DW length during magnetization reversal: isolated strip, bridge between two separated half-planes, bridge connecting two parallel strips. DW stable positions in zero external field are marked by arrows. Dashed line represents DW unstable positions.](image)

Isolated strip and strip-like bridge between two opposite normally magnetized infinite half-planes are found to exhibit different behavior. Domain wall (DW) inside strip (bridge) suffers increasing repulsion (attraction) from nearest edge when shifted from center. DW 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. Coercive force is entirely defined by magnetostatic barrier created by garnet film boundary. Strip susceptibility and bridge coercive field are found to be functions of strip length, width and film magnetization \( M \) and thickness \( h \).

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.

It should be noticed calculation results in figure 1 are represented with 90 degrees rotation in comparison to usual hysteresis loop presentation due to calculation algorithm peculiarities.

2.2. 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 figure 2.

Single DW in element was created by garnet film cooling from temperature exceeding Curie point to room temperature in external magnetic field gradient ~ 0.01 Oe/mcm with microscope remnant and Earth magnetic field compensation. Magnetization process was investigated in quasi-static regime.

Figure 2. Experimental microphotographs of DW positions at critical points and magnetization reversal loops: a - for quadratic elements 30x30 mcm in matrix, b - for rectangular bridges 40x120 mcm and 10x120 mcm. Garnet magnetization $M = 50$ Gauss, thickness $h = 3$ mcm.

Magnetization reversal curves shown in figure 2 confirm qualitatively theoretical predictions. Quadratic elements in matrix in figure 2a are magnetized by almost reversible manner with coercive field ~ 0.4 Oe which equals to own coercive force of garnet film. Positions of DWs in different elements and different orientations are reproducible so that the spread of reversal parameters doesn’t exceed garnet coercive field.

Bridge between two half-planes with opposite magnetization directions demonstrates almost rectangular hysteresis loop with reproducible coercive field defined by magnetostatic stray field of garnet film boundaries.

Magnetization reversal by constant length DW motion occurs at very small external field in the range (1 – 10) Oe. 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 figure 2. Wedge is formed due to great difference between etching speed values along normal to (111) crystal plane and along other 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 sight garnet film wedge restricts space resolution in microelectronics applications. In addition wide wedge reduces stability margin of two-domain element state. This effect is especially harmful for rectangular strip due to irreversible collapse of compressed domain at element edge.
3. Magnetization by variable length DW motion

3.1. Numerical modeling

Variation of DW length during magnetization gives an additional opportunity for hysteresis loop design due to high surface energy of domain wall which is proportional to DW length. So gradient of element width creates constant effective field barrier for DW motion in external field. DW equilibrium position coincides with element width minimum. Effective field barrier value is proportional to inclination angle tangent. Shapes of calculated magnetization curves corresponding to concave and convex elements are shown schematically in figure 3. Calculation was made for straight DW and negligible own coercive force of garnet film.

Hysteresis type of magnetization reversal is obvious in both concave and convex elements. But concave element shows distinct barrier position in demagnetized state. Such construction can be used as a threshold element in optical data processing.

![Figure 3. Scheme of effective field distributions in uniaxial garnet film elements with variable DW length during magnetization reversal. Concave (solid line) and convex (dashed line) elements have equal inclination angles.](image)

3.2. Experimental results

Microphotographs of DW stable positions during concave element magnetization reversal are presented in figure 4. Magnetization curve seems qualitatively similar to calculated shape. Loop slope and narrow hysteresis at low field region are cased by DW bending and garnet film coercive force accordingly. Hysteresis at magnetization curve edge is caused by magnetostatic barrier formed by inclined element boundaries adjacent to element narrowest section. Magnetostatic barrier profile is asymmetrical as it is shown in scheme in figure 3 by dashed parts of magnetization curve for concave element. Local hysteresis loop width is defined by garnet magnetization and inclination angle while critical field value depends upon DW energy as well.

Magnetization reversal of convex rhomb-like elements occurs by rectangular hysteresis loop in accordance with calculated curve. Microphotographs of magnetization states in rhomb-like elements at zero external field and critical external fields $H_{c1}$ and $H_{c2}$ just before and after DW leaps are shown in figure 5. Ratio of critical field values coincides with ratio of elements inclination tangents in accordance with theoretical predictions.
Figure 4. Experimental microphotographs of DW stable positions at critical points and magnetization reversal loop in concave garnet element. \( M = 50 \, \text{G}, h = 3 \, \text{mcm}. \)

Figure 5. Experimental microphotographs of magnetization states in convex rhomb-like garnet elements near critical external field values:
1 – \( H = 0 \, \text{Oe} \), 2 – \( H_{c1} = 4 \, \text{Oe} \), 3 – \( H_{c2} = 5.5 \, \text{Oe} \).
Initial white domain width is 10 mcm. Wedge width is 15 mcm. \( M = 50 \, \text{G}, h = 3 \, \text{mcm}. \)

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. Switching field values are defined by garnet magnetization and element shape and dimensions and can be reduced by two orders of magnitude in comparison with monodomain element switching field. Nonlinear curvature of element contour will ensure additional possibility for design useful properties of magnetooptical elements due to smooth variation of domain wall surface energy.

To improve switching parameters and element space resolution significant reduction of garnet film wedge formed during chemical etching is required.

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 optical data processing and fine magnetic sensing.

5. References
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