Journal of Superconductivity and Novel Magnetism, DOI: 10.1007/s10948-019-05370-8

Electric field-induced nucleation of magnetic micro-inhomogeneities and bubble domain lattices

D.P. Kulikova · E.P. Nikolaeva · W. Ren · A.P. Pyatakov

Received: date 10 Nov 2020/ Accepted: 21 Nov 2020

Abstract The electric field-induced magnetic inhomogeneities nucleation is studied in R-earth iron garnet film grown on a $Gd_3Ga_5O_{12}$ substrate with a (110) crystallographic orientation. The possibility of electric-field-induced generation of bubble domain lattice is demonstrated for the first time.

Keywords Multiferroics · Iron garnet · Bubble domain

1 Introduction

Since the beginning of the century the magnetoelectric and multiferroics media with coupled magnetization and electric polarization has been remained the subject of scientific interest from both fundamental [1, ?] and practical [3] point of view. Recently there were a number of reports on multiferroicity of special type: the ferroelectric polarization localized on the magnetic do- lls in magnetic oxides [4]-[7]. The magnetoelectric properties of the domain walls enable the electric field-induced domain wall motion [4] and transformation [5]. The most prominent manifestation of the domain wall magnetoelectricity is the electric field-induced nucleation of the domain wall in the single domain state that was predicted by I. Dzyaloshinskii [8] and has been experimentally proved recently [9]-[10]: the electric field-induced nucleation of the bubble domain in the gradient electric field from the tip electrode was observed in iron garnet films.

D.P. Kulikova
M.V. Lomonosov Moscow State University, Faculty of Physics, 1-2 Leninskiye Gory, GSP-1, Moscow, 119991, Russia

E.P. Nikolaeva
M.V. Lomonosov Moscow State University, Faculty of Physics, 1-2 Leninskiye Gory, GSP-1, Moscow, 119991, Russia

W. Ren
International Centre of Quantum and Molecular Structures, Materials Genome Institute, Shanghai Key, Laboratory of High Temperature Superconductors, Physics Department, Shanghai University, Shanghai, 200444, China

A.P. Pyatakov
M.V. Lomonosov Moscow State University, Faculty of Physics, 1-2 Leninskiye Gory, GSP-1, Moscow, 119991, Russia
E-mail: pyatakov@physics.msu.ru

Noteworthy, that these magnetoelectric phenomena were observed in iron garnet films grown on gadolinium garnet substrate with (210) crystallographic orientation that are characterized by in-plane orthorhombic anisotropy, while in (111) films the magnetoelectric effects were absent [5]. At the same time the highly symmetrical (111) films are classical object for observation of bubble domain lattice with hexagonal symmetry, while the highly anisotropic (210) films do not support such a structure: the newly born bubble domains are prone to form the stripe domain pattern.

As was shown in [6] the orthorhombic anisotropy is not the necessary condition of the magnetoelectricity in iron garnet films. Therefore, the study of iron garnet films combining the magnetoelectric properties and rich diversity of domain structure not restricted by strong in-plane anisotropy is of special interest. The (110) iron garnet film is chosen as the sample in this paper and it is shown that the electric-field induced generation of magnetic objects demonstrates new interesting features not observed in (210).

2 Experimental setup

The 11.6 μm-thick iron garnet film $(BiLu)_3(FeGa)_5O_{12}$ grown on $Gd_3Ga_5O_{12}$ substrate with crystallographic orientation (110) was studied. The magneto-optical visualization of domain structure was done in Faraday geometry: in transmitted light with crossed polarizer and analyzer (Fig. 1a).

To generate high electric field the voltage was applied between the tip electrode made from 10 μm-diameter molybdenum wire and the film substrate (Fig. 1b). The electrode was in contact with the surface of the film. The voltage 500 V correspond to the electric field strength 1 MV/cm. The absence of the leakage current was controlled with the micro-ammeter.

To enhance the magnetoelectric properties of the domain walls the constant in-plane magnetic field $H_{\parallel}$ = 200 Oe was applied to the sample [5]. Additional magnetic bias field perpendicular to magnetic film $H_{\perp}$ was applied to induce single domain state that is necessary to observe the magnetic bubble domain nucleation at the tip.

For dynamical study of the nucleation process the pulse-probe method was used [5]: the 0,8 μs pulses of electric voltage with repetition rate 24 Hz was applied to the electrodes followed by laser illumination pulses. Varying the time delay between the electric pulse and optical probe enabled to visualize the various phases of magnetic bubble evolution. The voltage pulse rise time and laser illumination pulse time were, respectively, 50 ns and 10 ns that enabled to observe submicrosecond dynamics of the bubble domain generation.

3 Results and discussion

The magnetic film was in the single domain state induced by magnetic bias: constant magnetic field having out of plane $H_{\perp} = 7$ Oe along [110] and in-plane component $H_{\parallel} = 200$ Oe along [001] direction. Then the tip electrode was put in contact with a surface of magnetic film. The mechanical pressure in contact point do not have any effect on the magnetic structure, but when the voltage was applied the nucleation of magnetic domain with a diameter of 5 μm was observed (Fig. 2a). The larger electric bias at the electrode ($V \geq 0.5$ kV) lead to the nucleation of structures with complex shape (Fig. 2c).

The dynamical study of the electric field-induced bubble generation shows that at the moment 100 ns after the step-like voltage pulse the inflating bubble domain become visible under the tip electrode (Fig. 3a), the growth process continues in the following 100 ns (Fig. 3b) and then at 300 ns it transforms to the domain of irregular form with multiple proliferated spinoffs (Fig. 3c). This scenario of magnetic bubble domain inflation differs from the one observed in (210) films. In later case the bubble due to the strong in-plane anisotropy preserves the elliptical shape with one of the axis growing until its transformation to the stripe domain [9].

The series of voltage pulses results in the multiple magnetic bubble domain generation (Fig. 4). Since the pulses were of negative polarity the bubbles nucleated at the rear front of the electric field pulse and collapsed at the forefront. The figures 4 show the picture of the dynamical balance between nucleation and collapsing processes. By gradual decreasing of the out-of-plane component $H_{\perp}$ of magnetic bias field the bubble domains are accumulating in the vicinity of the tip forming the hexagonal lattice of magnetic bubble domains (Fig. 4a-d).

4 Conclusion

Summarizing, the electric-field nucleation of magnetic bubble domains previously observed only in (210) iron garnet films was demonstrated in (110) film. This effect has specific features: irregular shape of the nucleated domains and their proliferation with increasing electric field. The reduced in-plane anisotropy of (110) film compared to (210) one makes possible the hexagonal bubble domain lattice generation by electric field.

This work was supported by Russian Foundation for Basic Researches RFBR grants # 19-02-00828_a, 19-52-53020 GFEN_a and National Natural Science Foundation of China, proposal no.51911530124.

References

1. Spaldin, N. A., Fiebig,M.: The Renaissance of Magnetoelectric Multiferroics. Science. 309, 391-392 (2005)
2. Fiebig, M., Lottermoser, Th., Meier, D., Trassin, M.: The evolution of multiferroics. Nature Reviews Materials. 1, 16046 (2016)
3. Pyatakov, A. P, Zvezdin, A.K.: Magnetoelectric and multiferroic media. Phys. Usp. 55, 557–581 (2012)
4. Logginov, A.S., Meshkov, G.A., Nikolaev, A.V. et al.: Appl. Phys. Lett. 93, 182510 (2008)
5. Pyatakov, A.P., Sergeev, A.S., Nikolaeva, E.P. et al.: Phys. Usp. 58, 981–992 (2015)
6. Veshchunov, I.S., Mironov, S.V., Magrini, W. et al.: Phys. Rev. Lett. 115, 27601 (2015)
7. Yang, Y., Xiang, H., Zhao, H. et al.: Phys. Rev. B. 96, 104431 (2017)
8. Dzyaloshinskii, I.: EPL. 83, 67001 (2008)
9. Kulikova, D.P., Pyatakov, A.P., Nikolaeva, E.P. et al.: Jetp Lett. 104, 197-200 (2016)
10. Kulikova, D.P., Gareev, T.T., Nikolaeva, E.P. et al.: Physica Status Solidi - Rapid Research Letters. 12, 1800066 (2018)

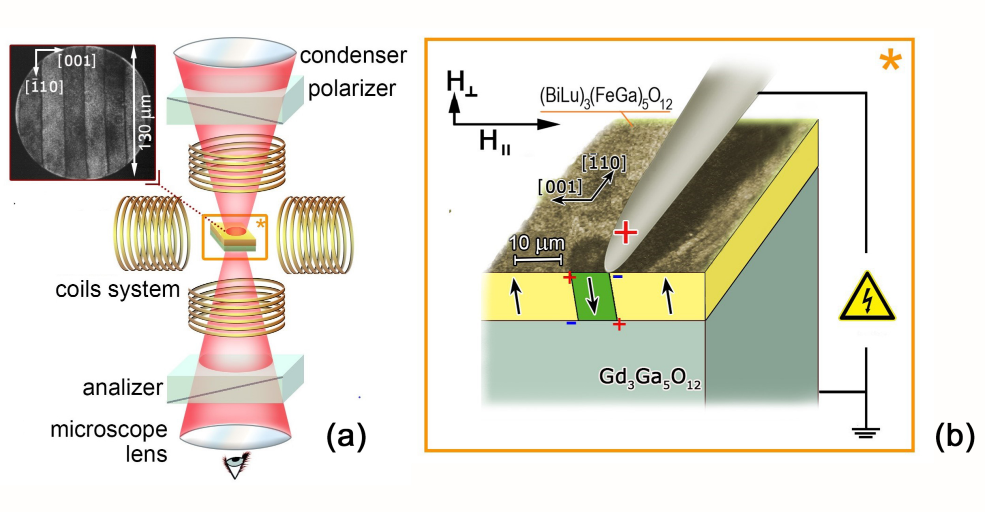

Fig. 1 The schematics of the experiments. (a) the overview of magneto-optical setup. In the inset the typical magneto-optical image of magnetic domain structure in spontaneous state is shown. (b) the zoom of the selected area in Fig. 1a with the combinations of the magneto-optical image (top layer) and schematic picture of the micromagnetic configuration for (110) iron garnet film (cross-section). The bound surface electric charges associated with the electric polarization of the domain walls are also shown [5].

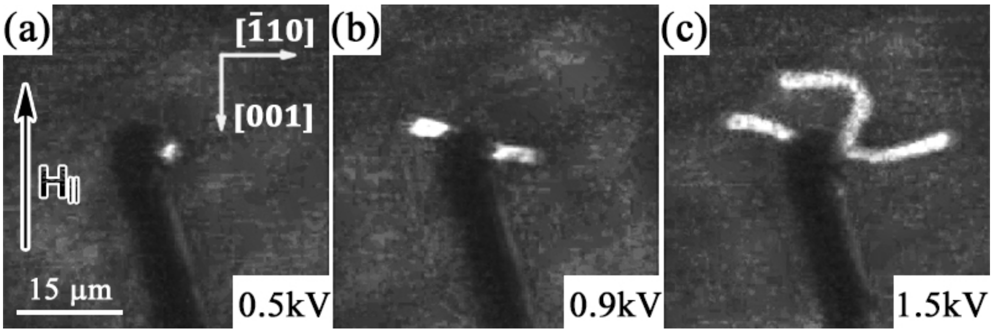

Fig. 2 Typical magnetic domain structures (white objects) nucleated when the electric voltage was applied to the tip electrode. The figures a-c shows the trend for domain proliferation while the nucleating electric voltage was increased from 0.5 kV to 1.5 kV. The magnetic bias field components: $H_\parallel$ = 200 Oe, $H_\perp$ = 7 Oe.

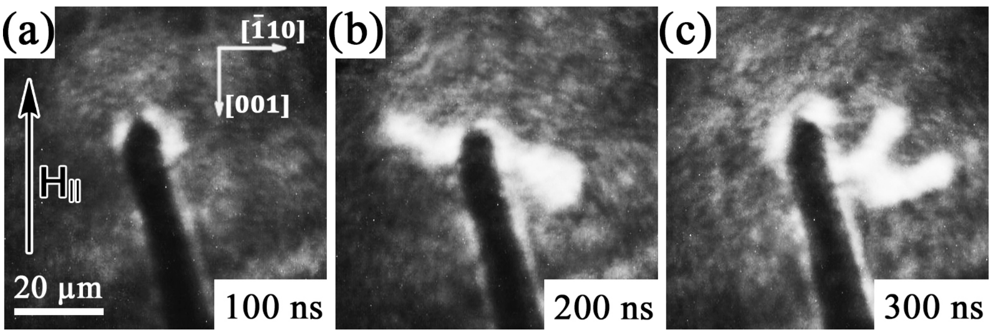

Fig. 3 Dynamical study of magnetic inhomogeneity nucleation and evolution under the influence of step-like voltage pulse with amplitude 130 V. The components of magnetic bias field: $H_\parallel$ = 200 Oe, $H_\perp$ = 7 Oe.

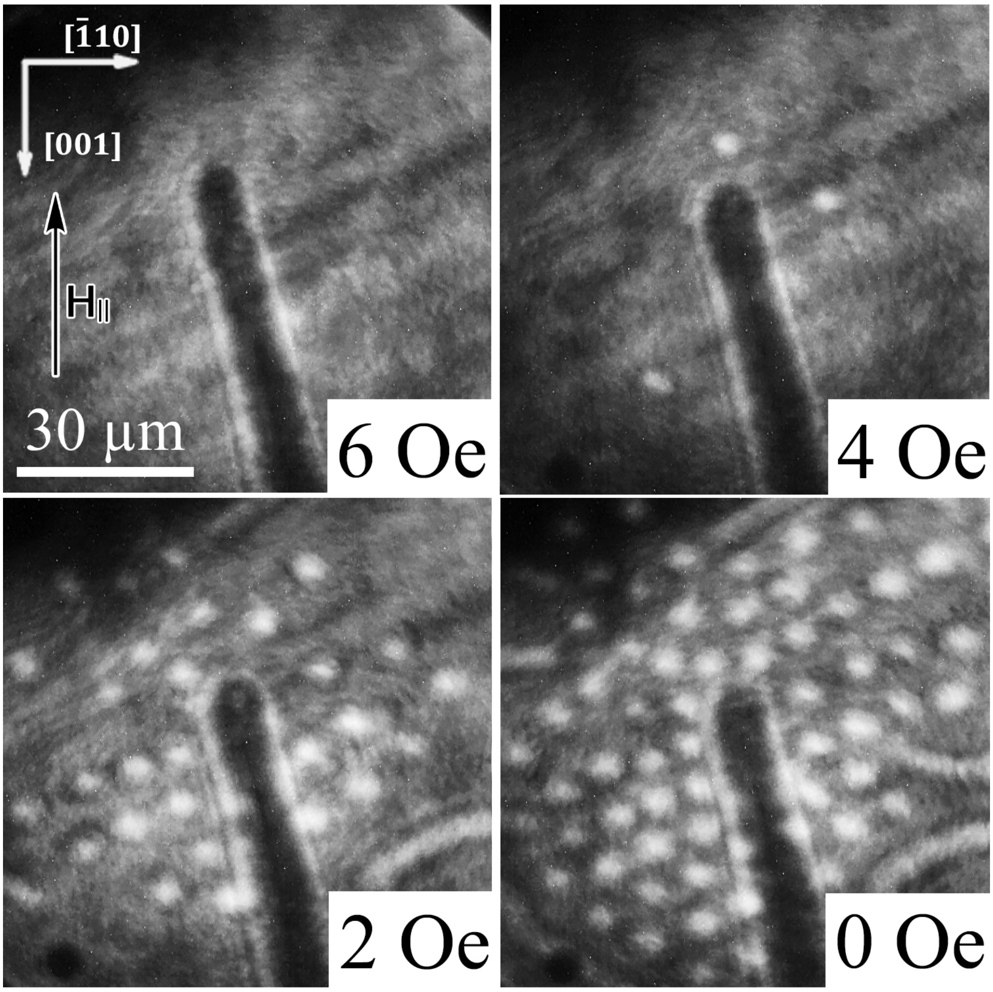

Fig. 4 The bubble lattice generation in AC electric field with rectangular-shaped fronts by gradual decreasing of the magnetic bias component $H_{\perp}$ from 6 Oe to zero (the in-plane component of the magnetic bias remains the same: $H_{\parallel}$ = 200 Oe). The electric pulse amplitude V = 130 V, the duration of the pulse is 800 ns, the pulse to pulse interval is 40 ms.