Concept of using composite multiferroic structure magnonic crystal - ferroelectric slab as memory unit

O Matveev, M Morozova and D Romanenko

Department of Nonlinear Processes, Laboratory “Metamaterials”, Saratov State University, Saratov, Russia

E-mail: olvmatveev@gmail.com

Abstract. In the present work, it is proposed to use as a memory cell with random access a new type of memristor - a multiferroic wave memristor based on structures type magnonic crystal-ferroelectric. Main feature of propagating excitations trough such structure is band gap formation: Bragg band gap that position in spectrum depends on the polarization of ferroelectric. Thus, information from ferroelectric is read as a result of signal transmission / attenuation at frequency of band gap. In present work theoretical model of spin waves propagating in structure magnonic crystal-ferroelectric is developed. Results of an experimental study of the propagation of spin-wave excitations in such structure are given.

1. Introduction
Currently, a promising approach for creating a neuromorphic architecture is the use of memristors as electronic synapses. It is now known that ferroelectric memory has memristor [1] properties and can be considered to create a new architecture of neuromorphic computations. When an electric field is applied to ferroelectric, it changes its polarization, moving to opposite part of the hysteresis loop and can maintain its state. Due to this, it is possible to obtain two states that are well distinguishable in energy, and this is enough to create non-volatile memristor memory based on such cell.

Currently, there are several approaches to creating storage devices based on ferroelectrics. The first is the FRAM [2], created by analogy with DRAM, whose memory cell consists of a transistor and ferroelectric capacitor. The potential applied to the capacitor plates polarizes ferroelectric, thus recording information 0 or 1. For reading potential is re-applied, and memory cell state can be determined by the presence or absence of recharge current. One of the drawbacks of this type of memory is the loss of storage data in the cell when it is read - its destructiveness. Those after any read operation, a data recovery operation should follow. As a result, the cycle of memory access takes more time; significant part of the energy is spent on regeneration and reduces the lifetime of the ferroelectrics. In addition, there are limits for miniaturizing capacitor sizes.

Another type of ferroelectric memory - FeFET uses a different type of cell [3]. In this case, a thin layer of ferroelectric is deposited onto the gate of the field effect transistor. When the polarization of ferroelectric changes, the voltage required to open transistor changes. The disadvantage of this type of memory is that the location of ferroelectric materials on semiconductor in transistor is accompanied by the diffusion of the layers and leads to the effect of charge injection, which can change the direction of pass along the hysteresis loop.
The most new type of memory is ferroelectric tunnel junction (FTJ), based on the ferroelectric tunnel effect [4]. This is a quantum effect, which consists in a change of resistance of the metal–ferroelectric–metal structure in the case of a change in polarization when a coercive voltage is applied to ferroelectric. For reading it is necessary to measure resistance by control current. The ratio of resistances of the “on” and “off” states reaches 100 times in structures based on barium titanate and 10 times in structures based on hafnium oxide, which is not enough to implement a multi-level memristor.

Another approach to creating memristor devices lies in the field of spintronics and is based on the use of spin transfer torque (STT) [5]. The basis of spintronic memristors consists of magnetic structures of two layers of a ferromagnetic with different magnetization. Due to the effect of the magnetic tunnel junction, the resistance can be discretely changed when an electric pulse is applied. The disadvantage of such structures is that to switch between parallel and antiparallel states, different current values are required, which is inconvenient for controlling the memristor or can lead to errors. The ratio of resistances for parallel / antiparallel states in such memristors does not exceed several units. A single line for reading and writing can also lead to errors when, for example, reading causes switching.

The development of spin-wave electronics technology, scalable up to several nanometers, opens up the possibility of using the advantages of spin-wave electronics to improve the performance of ferroelectric memory. The use of spin waves for reading the state of the ferroelectric will solve a number of problems of the ferroelectric memory, such as destructiveness, scaling problems, speed, and also makes such memory insensitive to external radiation. The basis of this type of memory, combining the advantages of ferroelectricity and spintronics, can make a multiferroic spin-wave memristor [6]. This memristor consists of ferroelectric layer and ferromagnetic film with a periodic change of parameters (of magnonic crystal).

2. Main part

In multiferroic spin-wave memristor in contrast to the previously known principles of ferroelectric memory, another principle of operation is used, based on wave interactions of different physical nature: spin-wave excitations in magnonic crystal and electromagnetic waves in ferroelectric film. With this approach, the polarization of ferroelectric affects the characteristics of spin-wave excitations in magnonic crystal. Reading information recorded on ferroelectric is carried out by analyzing the spin-wave signal at the output of the structure.

The proposal of a ferromagnetic layer as a readout layer is explained by the possibility of a spin wave propagating in such a layer, the characteristics of which are sensitive to the state of ferroelectric, and for the excitation of which low energy costs are required. With this approach, when reading, the state of polarization of ferroelectric does not change and the bit is not erased after each reading. Thus, the problem of memory destructiveness can be solved.

As a reading layer in such a structure, it is proposed to use a periodic ferromagnetic layer - a magnonic crystal (MC). The choice of a periodic layer is explained by the presence of band gaps in the spectrum of waves in such structure - non-transmission bands. Bits 0 (or 1) will correspond to the fall (or not fall) of the control frequency in the band gap.

Consider the features of the formation of band gaps in the propagation of waves in the structure of magnonic crystal-ferroelectric.

The simplest multiferroic structure based on ferromagnetic films is the structure of the ferromagnetic film-ferroelectric. With tangential direction of external magnetic field in ferromagnetic film, the surface magnetostatic wave (MSW) will propagate. The distribution of the electromagnetic field of surface MSW and electromagnetic wave (EMW) is the same and at the point of phase synchronism of surface MSW and EMW, the dispersion characteristics push apart: magnetostatic and electromagnetic waves are hybridized and a hybrid spin-electromagnetic wave (HSEW) is formed.

In figure 1a shows the theoretical dispersion characteristics of HSEW in structure magnonic crystal-ferroelectric calculated using the dispersion equation obtained from solving Maxwell's
equations and matching the components of electric and magnetic fields at the interfaces of the media, as well as the method of coupled waves.

In magnonic crystal-ferroelectric structure, the periodicity of the structure leads to the formation of waves reflected from inhomogeneities. In figure 1a shows dispersion characteristics of the following types of waves in isolated layers: direct and reflected EMW in ferroelectric layer in the absence of coupling between these waves (dashed curves), direct and reflected MSW in magnonic crystal in the absence of coupling between these waves (dashed curves).

Dispersion characteristics in figure 1a shows that there are 5 points of intersection of the curves presented (points $A$, $C$, $A'$, $C'$, $B$). Hybridization at point $A$ (the point of intersection of the dispersion characteristics of the direct MSW and the direct EMW) occurs due to the interaction of these waves and is similar to the hybridization for structure ferromagnetic film – ferroelectric. As a result, two branches of HSEW are formed (branches 3 and 4). Hybridization at point $A'$ (the point of intersection of the dispersion characteristics of the reflected MSW and reflected EMW) has a similar nature. As a result, two branches of the HSEW are formed (branches 3' and 4').

![Figure 1. (a) Theoretical dispersion characteristics of HSEW in the structure of magnonic crystal - ferroelectric. (b) Experimental frequency responses of surface MSW in magnonic crystal (black curve) and HSEW in the structure of magnonic crystal - ferroelectric (orange curve). (c) Fragment of the frequency response shown in figure (b) in the region of hybrid band gap at $U = 0$ V (curve 1), 300 V (curve 2), 600 V (curve 3), 800 V (curve 4).](image)

At points $C$, $C'$ and $B$, two band gaps are formed. The main band gap (area b) is formed near point B. This band gap is formed also in single magnonic crystal. The central frequency of the main band gap $f_1$ almost corresponds to the central frequency of the band gap for waves in single magnonic crystal $f_B$, and the width of the main band gap $\Delta f_1 = \Delta f_B$, where $\Delta f_B$ is the width of the band gap for waves in single magnonic crystal.

Hybrid band gap is formed near points $C$, $C'$ due to the formation of hybrid branches 5 and 6 and branches 5' and 6' (area c). This band gap is formed in the presence of ferroelectric layer. Hybrid band gap is located higher in frequency than band gap for waves in single magnonic crystal ($f_2 > f_B$, where $f_2$ is the central frequency of hybrid band gap) and has a smaller width $\Delta f_2 < \Delta f_1$.

With an increase dielectric constant of ferroelectric $\varepsilon$, the center frequency of the main band gap shifts to the lower border of the MSW bandwidth. In turn with an increase $\varepsilon$ the hybrid band gap are broaden and shifts down in frequency, and the central frequency of hybrid band gap tends to the central frequency of the main band gap (to point C). The width and position of the main band gap does not depend on $\varepsilon$.

In figure 1b black curves show the experimental frequency response of the surface MSW in a single magnonic crystal. Magnonic crystal was a yttrium iron garnet film with a thickness of 12 μm, a length of 7 mm, a width of 2 mm, and a saturation magnetization of 1750 G, on the surface of which a
periodic system of grooves with a period of 200 μm, a groove width of 100 μm, and a groove depth of 1 μm was created. The magnitude of external magnetic field was 860 Oe. One can clearly see two minima corresponding to the band gaps of the first and second Bragg resonance in the magnonic crystal. The minima are observed at frequencies $f_1 = 4.4$ GHz (main band gap (1)) and $f_12 = 4.52$ GHz (main band gap (2)). To form magnonic crystal - ferroelectric structure on the surface of magnonic crystal, an ferroelectric plate of barium strontium titanate with a thickness of 500 μm and a dielectric constant of 4000 was placed. The frequency response of the HSEW in the magnonic crystal - ferroelectric structure is shown in orange in figure 1b. It can be seen that in this case, between the first and second Bragg band gaps (marked with blue ellipses) at the frequency $f_1 = 4.49$ GHz, an additional band gap is formed (marked with a red ellipse). This additional band gap can be interpreted as a hybrid band gap. Dispersion characteristic for HSEW in the structure of magnonic crystal - ferroelectric with the parameters of the experiment is shown in figure 1a.

When a voltage is applied to the ferroelectric layer, its dielectric constant changes and the hybrid band gap shifts, as shown in figure 1c.

This effect can be used as a basis for the operation of a spin-wave memristor based on structure magnonic crystal - ferroelectric (figure 2a). To read information from ferroelectric layer, the signal is fed at the frequency in band gap (reference frequency $f_0$). Because the control frequency lies in band gap, signal is attenuate (figure 2b). That signal does not pass through such structure, which corresponds to state 0 (figure 2c). With a different state of ferroelectric, i.e. another dielectric constant band gap is at a different frequency (figure 2d). The signal at the control frequency $f_0$ passes without attenuation, which corresponds to state 1 (figure 2e). The principle of such a reading is given in the form of a table in figure 2f.

To read the n-level state of ferroelectric, it is necessary to set n control frequencies, each of which corresponds to band gap positions for each polarization state. With this approach, the contrast (i.e., the ratio of the signal power at frequency of band gap and frequency outside band gap) does not depend on the number of intermediate levels of ferroelectric.

Using magnonic crystal in memory cell allows reading information from two ferroelectric layers located above and below magnonic crystal (figure 3a). In this structure, the formation of two band gaps takes place. Moreover, the position of the first band gap (BG-1) at frequency f1 is determined by
the state of the top ferroelectric layer, and the position of the second band gap (BG-2) at the frequency $f_2$ is determined by the state of the bottom ferroelectric layer. In this case, the signal at frequency $f_1$ will allow reading information from top ferroelectric layer (figure 3b, d), and the signal at $f_2$ - from bottom ferroelectric layer (figure 3c, e). With this method, it becomes possible to compact the placement of information by 2 times.

Figure 3. (a) Scheme of a multiferroic spin-wave memristor based on the structure of ferroelectric - magnonic crystal - ferroelectric. (b) Schematic representation of the HSEW frequency response in the region of hybrid band gaps (BG-1 and BG-2) with dielectric constant of the bottom ferroelectric $\varepsilon_1$ and the dielectric constant of the top ferroelectric $\varepsilon_0$ (red curve) and $\varepsilon_0^*$ (black curve). (c) Schematic representation of the frequency response of the HSEW in the region of the hybrid band gaps with dielectric constant of the bottom ferroelectric $\varepsilon_1$ and the dielectric constant of the top ferroelectric $\varepsilon_0$ (red curve) and $\varepsilon_0^*$ (black curve). (d, e) The principle of reading data.

3. Conclusions

Thus, shown features of the spin wave and electromagnetic excitations in periodic layered structures based on magnonic crystals and ferroelectrics allow us to consider such structures as a cell of nonvolatile memory that functions as linear and nonlinear synapses in the architecture of neuromorphic networks. This memory cell is not destructive, allows to multi-bit reading of information, the expected transmission / attenuation ratio does not depend on the number of read bits. When scaling such a cell into the nanometer region, its parameters can be comparable the similar characteristics of known types of ferroelectric memory.

Acknowledgments

This work was supported by the Russian Foundation for Basic Research, project № 19-29-03049 MK.

References

[1] Strukov D B, Snider G S, Stewart D R and Williams R S 2008 Nature 453 80-3
[2] Scott J F and De Araujo C A P 1989 Science 24 1400-5
[3] Böcke T S, Müller J, Bräuhaus D, Schröder U and Böttger U 2011 Appl. Phys. Lett. 99 102903
[4] Chanthbouala A et al 2012 Nature materials 11 860-4
[5] Sengupta A and Roy K 2018 Applied Physics Express 11 030101
[6] Morozova M A, Grishin S V, Sadovnikov A V, Romanenko D V, Sharaevskii Yu P and Nikitov S A 2015 IEEE Trans. on. Magn. 51 7126980