Magnetic properties, spin waves and interaction between spin excitations and 2D electrons in interface layer in $Y_3Fe_5O_{12}/AlO_x/GaAs$-heterostructures

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Abstract

We describe synthesis of submicron $Y_3Fe_5O_{12}$ (YIG) films sputtered on GaAs-based substrates and present results of the study of ferromagnetic resonance (FMR), spin wave propagation and interaction between spin excitations and 2D electrons in interface layer in YIG/AlO$_x$/GaAs-heterostructures. It is found that the contribution of the relaxation process to the FMR linewidth is about 3.6%–6.6% of the linewidth $\Delta H$. The main contribution to the FMR linewidth of sputtered YIG films is given by a magnetic profile inhomogeneity. Transistor structures with two-dimensional electron gas (2DEG) channels in AlO$_x$/GaAs interface governed by YIG-film spin excitations are designed. An effective influence of spin excitations on the current flowing through the GaAs 2DEG channel is observed. It is found that the light illumination results in essential changes in the YIG-film FMR spectrum of transistor structures—an increase of the 2DEG current induced by light leads to an inverse effect, which represents essential changes in the FMR spectrum.

Keywords: YIG/GaAs-heterostructures, spin waves, 2D electrons in interface layer

(Some figures may appear in colour only in the online journal)

1. Introduction

Integration of ferrites with semiconductors offers many advantages and new possibilities in microwave applications such as high-speed wireless communications, auto radars, astronomy systems, active phased array antennas, space electronics and satellite navigation [1]. This integration gives significant advantages in miniaturisation, speed, bandwidth, radio reception selectivity and the production costs of monolithic microwave integrated circuits (MMICs). Ferrite film growth on semiconductor substrates is very important for development of new types of spintronic and spin-wave devices such as microwave filters, delay lines, and spin-polarized field-effect transistors (spin-FETs).

Nowadays, spin-wave devices have been realized on the basis of $Y_3Fe_5O_{12}$ (YIG) films grown on gadolinium–gallium garnet (Gd$_3$Ga$_5$O$_{12}$, GGG) substrates [2, 3]. Narrow-band filtration can be achieved in YIG-based one-dimensional magnonic crystals [4–6]. The pulsed laser deposition technique has been used to grow submicron YIG films on GGG substrates for microwave spin-wave band pass filter [7]. Construction of spin-wave devices on the basis of YIG films directly deposited on semiconductors is the next stage in the development of spin-wave devices. The recent progress in
synthesis of nanometer YIG films of high quality on semiconductor substrates [8, 9] and low relaxation of long-wavelength spin waves in nanoparticle magnetic films [10, 11] give the possibility to construct spin-wave devices on semiconductor chips operating at microwave frequencies.

Active control and manipulation of spin degrees of freedom in spin-FETs is one of the main problems in spintronics [12–20]. The spin transport in two-dimensional electron gas (2DEG) and large spin–orbit interaction are essential for realizing spin transport devices. However, the noneffective spin injection and weak influence of the gate on electron current flowing through the transistor channel are known difficulties in spin-FET design. Modulating the channel conductivity by using an electric field to induce spin precession is performed at low temperatures and has remained elusive at higher ones [19, 20]. Furthermore, the poor crystal quality of ferrite films sputtered on GaAs substrates has a detrimental effect on the device performance [1, 21]. At the same time, it is worth noting that YIG films are regarded as perspective materials in spintronics [22].

At present, there is observed extensive studies of insulator YIG film/nonmagnetic metal (Pt) structures, in which spins in the YIG film and electrons in the metal are coupled by a strong spin–orbital interaction [23–27]. The spin–orbital interaction gives spin waves the opportunity to influence the current flowing in the metal and to generate spin waves by the direct electric current [23]. It is noted that in nanosized YIG/Pt structures the spin-wave damping can be completely compensated by the spin–orbit torque [25]. A strong enhancement of the spin-current emission is observed at low frequencies, showing the appearance of nonlinear phenomena [24]. In the absence the spin–orbital interaction, for example, in structures Pt/STO/ YIG, spin-wave excitations do not influence on the current [26]. Nevertheless, it is noted that the microwave electromagnetic interaction between ferrites and stripline conductors are effectively used in magnetoelectronic devices such as bandpass filters [28, 29]. If the insulator nonmagnetic layer in YIG/insulator layer/semiconductor heterostructures is nanosized, then one can expect that at ferrite resonance frequencies the influence on the 2DEG current at the semiconductor interface induced by the electromagnetic interaction between spin excitations in the YIG film and the 2DEG current can be high.

Table 1. Properties of YIG films sputtered on GaAs-based substrates.

| #  | Thickness $d$ (nm) | Main layer $4\pi M - H_{asso}$ (Oe) | Sublayers $4\pi M - H_{asso}$ (Oe) | FMR linewidth | $\Delta H_{\perp}$ (Oe) | $\Delta H_{||}$ (Oe) | Spin-wave damping parameter $\delta_0 (\times 10^{-3})$
|----|--------------------|---------------------------------|---------------------------------|-------------|----------------|----------------|---------------------------------|
| 1  | 40                 | 1180                           | 1464                           | 155         | 106            | 4.5             |
| 2  | 40                 | 1209                           | 1372                           | 143         | 129            | 4.1             |
| 3  | 40                 | 990                            | 1278                           | 245         | 207            | 7.2             |
| 4  | 250                | 1454                           | 1320                           | 73          | 155            | 2.1             |
| 5  | 97                 | 651                            | 901                            | 554         | 651            | 16.0            |
| 6  | 964                | 666                            | 402                            | 175         | 221            | 5.0             |

Taking into account the above-mentioned, one can conclude that YIG film growth on semiconductor substrates and investigation of spin waves and interaction between spin excitations and electrons in semiconductor are of great importance for many applications.

In this paper, synthesis of YIG films deposited on GaAs substrates with AlO$_x$ layers by ion-beam sputtering is described. We present results of the characterization of YIG films/AlO$_x$/GaAs heterostructures and their interfaces (see section 2). Magnetic characteristics of deposited films are deduced from the FMR X-band spectroscopy (section 3). Spin wave propagation are described in section 4. In section 5, we consider the influence of spin excitations in YIG films on the electron current flowing through the 2DEG channel formed at the AlO$_x$/GaAs interface. It is found that a high interaction between spin excitations and the current in the 2DEG channel in GaAs-based substrates can be achieved at the ferromagnetic resonance (FMR) frequency of YIG films. The inverse effect, the influence of the electron current on the FMR spectrum, is described in section 6. This interaction is studied by a detection of $S$-parameters of the transistor channel at microwave frequencies under the light exposure and without light illumination. The interaction is enhanced with the light exposure of the AlO$_x$/GaAs interface and with the microwave power increase. It is found that above the spin-wave instability threshold the increase of the 2DEG density induced by light results in essential changes in the FMR spectrum and in the $S_{21}$-parameter of the channel.

2. YIG film preparation and characterization

YIG films were deposited in Ar + O$_2$ atmosphere on GaAs substrates by the two-stage ion-beam sputtering [30, 31]. The $n$-GaAs substrates with the thickness of 0.4 mm had the (1 0 0)-orientation. Electrical resistivity of GaAs chips was measured by the dc four-probe method at room temperature.
and was equal to $0.9 \times 10^5 \, \Omega \cdot \text{cm}$. In order to suppress the diffusion of Ga ions into the YIG films, to reduce the elastic deformation and to form 2DEG layers in GaAs substrates, the deposition process was produced on the amorphous-like nonstoichiometric aluminium oxide layer $\text{AlO}_x$ with the thickness of 8–20 nm ion-beam sputtered previously on GaAs. The 2DEG layer was formed at the $\text{AlO}_x$/GaAs interface [32, 33].

At the first stage of the ion-beam sputtering, a thin (30 nm) buffer YIG layer was grown. After annealing of YIG/$\text{AlO}_x$/GaAs heterostructure, the sputtered buffer YIG layer had a polycrystal structure. Annealing was performed in the quasi-impulse regime during 5 min at 590 °C in $\text{N}_2$ (samples #3, 5, 6, table 1) and air (samples #1, 2, 4) atmospheres with the pressure of 0.1 Torr. After the deposition and annealing processes, the buffer YIG layer was polished by a low-energy (400 eV) oxygen ion beam. The polish procedure decreased stress tension and dislocations and smoothed areas of intercrystallite boundaries. The thickness of the buffer YIG layer was reduced to 10–16 nm. After this operation, the surface of the buffer layer was suitable to deposit a thicker (main) YIG layer without stress tension and lattice mismatch.

At the second stage, the main YIG layer was deposited. After annealing during 5 min at 550 °C in $\text{N}_2$ (samples #3, 5, 6) and air (samples #1, 2, 4) atmospheres with the pressure of 0.1 Torr the sputtered main YIG layer obtained a polycrystal structure. Cross-section of the YIG film sputtered on GaAs-based substrate (sample #5) is presented in figure 1(a). Cross-section of deposited heterostructure has been made by ion-beam cutting on the FIB Helios NanoLab 600 Station (FEI Company, USA). YIG film surface (figure 1(b)) exposes the roughness caused by large-scale crystallites of the main YIG layer. The size of crystallites was in the range of 50–100 nm.

The structure of YIG films was studied by the x-ray diffraction (XRD $\text{CuK}_\alpha$) method and by the energy-dispersive x-ray spectroscopy. The XRD spectrum confirms the existence of the YIG phase in the sample (figure 2). It is found that YIG films are polycrystal and are of homogeneous phase structure. The spectroscopy methods have shown that the interface layer of GaAs is enriched with Ga due to the volatility of As ions, however, the deposited YIG films are not degraded and are not exfoliated from the GaAs substrates.

3. Magnetic characteristics of sputtered YIG films

Ferromagnetic resonance of sputtered YIG films was studied by the X-band electron spin resonance technique. Relating to samples, applied magnetic field had in-plane and perpendicular orientations. Using magnetic field sweeping at stabilized frequency $F = 9.41 \, \text{GHz}$, we have read the first derivative of the FMR curve with respect to the magnetic field $H$. FMR spectrum of the YIG film with the thickness of 40 nm (sample #1, table 1) at perpendicular and at in-plane magnetic fields are presented in figure 3. Arrows correspond to FMR peaks of YIG sublayers.

In order to find magnetic characteristics of the main YIG layer and sublayers, we use the Lorentzian fitting of experimental curves. Experimental curves are fitted by the sum of first derivatives of Lorentzian curves

$$A(H) = \sum_i^n C_i \frac{\partial L_i(H)}{\partial H},$$

where $i$ is the peak number ($i = 1$ is the number of the main YIG layer and $i = 2, 3, 4, \ldots$ are numbers of sublayers), $C_i$ is the amplitude,
is the Lorentzian curve, $H_0^{(i)}$ is the peak position, $\Delta H^{(i)}$ is the FMR linewidth. From the Lorentzian fitting (1) we find peak positions $H_0^{(i)}$ and the FMR linewidth $\Delta H^{(i)}$.

Differences between magnetization and uniaxial anisotropy field $4\pi M - H_a$ (effective magnetization) of the main YIG layer and YIG sublayers are found from the FMR peak position $H_0^{(i)}$ of the corresponding layer at the in-plane magnetic field [34]

$$ F = \gamma \left[ H_0^{(i)} \left( H_0^{(i)} + 4\pi M - H_a \right) \right]^{1/2} \tag{2} $$

and from the FMR peak position $H_0^{(\perp)}$ at the perpendicular field

$$ F = \gamma \left[ H_0^{(\perp)} \left( H_0^{(\perp)} - 4\pi M - H_a \right) \right]^{1/2} \tag{3} $$

where $\gamma = 2.83$ MHz Oe$^{-1}$ is the gyromagnetic ratio. Taking into account equations (2) and (3), values of the effective magnetization $4\pi M - H_a$ of main YIG layers and YIG sublayers are found. Effective magnetizations and FMR linewidths $\Delta H_{\perp}$ and $\Delta H_{\parallel}$ of main YIG layers are presented in table 1.

We note that samples #1, 2, 4 annealed in the air atmosphere have higher values of the effective magnetization and lower values of the FMR linewidth than samples #3, 5, 6 annealed in the N$_2$ atmosphere. The reason for the YIG sublayer formation is not well clear up to now and it is planned to be clarified in the next study.

4. Spin waves

The FMR linewidth measurement is not sufficient for the determination of spin-excitation relaxation losses. The linewidth $\Delta H$ is formed by relaxation of spin excitations and by magnetic inhomogeneity of a magnetic film. In order to
find the relaxation parameters, one should study spin wave propagation directly. We studied the amplitude–frequency characteristics and the relaxation of the Damon–Esbach surface spin waves [35] in the in-plane oriented magnetic field. The setup is presented in figure 4(a). The spin-wave measurement cells contain antennas connected with microstrip lines. The samples are placed on the antenna structure. Antennas generate and receive spin waves propagated in YIG films. The studied samples are irregular trapezoidal with sizes of 2 × 6 mm. The distance \( l \) between antennas in the one of the cells was set to 1.2 mm and in the other was equal to 0.4 mm. The thickness of antennas is of 30 \( \mu \)m. The antenna length is equal to 2 mm. The measurement setup contains the Rohde–Schwarz vector network analyzer (VNA) ZVA-40. The VNA generates the current flowing in the generating antenna and detects the current induced by spin waves in the receiving one. We measure amplitude–frequency characteristics which are the transmission coefficient \( S_{21} \) (the scalar gain) in the frequency range of 3.0–4.8 GHz. Only for sample \#4 could we detect the transmission coefficient \( S_{21} \) in the cell with the distance \( l = 1.2 \text{ mm} \) between antennas (figure 4(b)). For other samples, the spin-wave relaxation appeared to be much faster and in the cell with the distance \( l = 1.2 \text{ mm} \) we could not detect the spin-wave signals on the receiving antenna. Spin waves propagated in these samples were detected in the cell with the distance \( l = 0.4 \text{ mm} \) between antennas.

Noises in figure 4 and in the following figures are the sum of noises caused by the VNA generator, the VNA detector section, and by environmental electromagnetic pollution. In order to reduce these noises, the microwave study has been carried out in the averaging regime with 400 repetitions. In addition, it is need to note that connectors of the cells are not perfect and, therefore, the voltage standing wave ratio of the cells is greater than 1. This results in standing wave resonances in cables, which have been taken into account in the calibration procedure and have been subtracted.

Measuring the \( S_{21} \)-parameter, we can estimate the spin-wave relaxation time \( \tau \), the spin-wave damping parameter

\[
\delta = \frac{\Delta \omega}{\omega} = \frac{1}{2\pi F \tau},
\]

where \( \Delta \omega = 1/\tau \), \( \omega = 2\pi F \) is the circular frequency, \( F = \gamma |H(H + (4\pi M - H_0))|^{1/2} \), and the contribution of the relaxation process to the FMR linewidth \( \Delta H_{|I|} \). According to the theoretical model developed in [9], one can estimate the lower bound \( \tau_0 = \min \tau (\tau > \tau_0) \) of the spin-wave relaxation time. For example, the lower bound \( \tau_0 \) of the spin-wave relaxation time and the higher bound \( \delta_0 \) of the spin-wave damping parameter \( \delta (\delta < \delta_0) \) for sample \#4 at the frequency \( F = 4.07 \text{ GHz} \) are \( \tau_0 = 18.2 \text{ ns} \) and \( \delta_0 = 2.1 \cdot 10^{-3} \), respectively. Calculations have been done for the maximum value of the amplitude–frequency characteristic \( S_{21} \) (figure 4(b)). The spin-wave damping parameter \( \delta_0 \) for other samples at the frequency \( F = 4.0 \text{ GHz} \) is presented in table 1.

One can note that the spin-wave damping parameter of samples is of high values. It is supposed that the cause of the fast relaxation is the presence of ions with strong spin-orbital coupling. In order to rule out the possibility of relaxation caused by rare-earth ions, the target for the YIG-film deposition was constructed using a standard technique of producing ferrites from the blend containing oxides Y2O3 and Fe2O3 of special purity grade (higher than 99.999%). Owing to this, one can conclude that Fe2+ ions can be regarded as the main ions with strong spin-orbital coupling and high values of the spin-wave damping parameter can be explained by relaxation processes caused by the Fe2+ ion presence [36, 37]. The appearance of Fe2+ ions with high value of the spin-orbital interaction can be likely associated with structural defects as well as nonstoichiometric composition of the films. Fe2+ ions can be introduced during growth. According to [34, 38], for the ion relaxation the FMR linewidth \( \Delta H \) is proportional to \( \omega^2 \tau(i)/(1 + \omega^2 \tau(i)^2) \), where \( \tau(i) \) is the relaxation time and is independent of frequency for confluence processes. Therefore, we can assume that the damping parameter \( \delta \) does not grow with frequency increase. Taking into account this assumption and the ratio

\[
\Delta \omega = 2\pi \frac{\partial F}{\partial H} \frac{\Delta H_{|I|}^{(rel)}}{\omega},
\]

we find that for the samples (table 1) at the frequency \( F = 9.41 \text{ GHz} \) the contribution \( \Delta H_{|I|}^{(rel)} \) of the relaxation process to the FMR linewidth \( \Delta H_{|I|} \) is about 3.6%–6.6% of the linewidth. It is worth to note that even the roughest lower bound \( \tau_0 \) for \( \tau \) explains only a few percent of the FMR linewidth. High values of the FMR linewidth is due to magnetic inhomogeneity of YIG films through their thickness. The analogous magnetic inhomogeneity has been observed in YIG films sputtered on GaN substrates [9].

5. Influence of spin excitations on the 2DEG current

Two-dimensional electron gases are formed at oxide interfaces [32, 33]. In order to study interaction between spin excitations in the YIG film and 2DEG in GaAs at the AlO3/GaAs interface, we have performed the transistor structure with 2DEG channel on samples \#3 and \#6 (figure 5(a)). Electrical contacts have been formed after etching by using the silver paste. The distance \( L \) between contacts is equal to 2 mm. The distance \( L \) was chosen greater than the distance \( l \) between antennas in the spin-wave study to avoid signals on contacts induced by propagating spin-waves. We have not observed any conductivity between contacts in the case when the contacts do not touch GaAs. Only the case when the contacts touch the GaAs interface was studied.

We measure amplitude–frequency characteristics of transistor structures, which are the transmission coefficient \( S_{21} \) and the voltage reflection coefficient \( S_{11} \) in frequency range of 3.5–5.5 GHz and in applied magnetic fields \( H \) up to 6 kOe with the in-plane orientation. The S-parameter matrix for the 2-port network is defined as \( U_j^{(out)} = S_{ik} U_k^{(in)} \), where \( U_j^{(out)} \) is the voltage wave reflected from the i-contact and \( U_k^{(in)} \) is the incident wave at the k-contact [39]. The electrical resistivity of YIG films is considerably higher than the resistivity of the
GaAs substrate (0.9 × 10^5 Ω · cm), consequently, the channel conductivity between contacts is due to the GaAs 2DEG interface region. In the FMR frequency band, the YIG-film spin excitations influence on the current flowing through the GaAs channel. The measurement setup contains the VNA ZVA-40, which generates the current flowing through the 2DEG channel and detects reflected (S_{11}) and passed (S_{21}) signals. Normalized S-parameters measured in sample #3 in the magnetic field H = 1.107 kOe and at the microwave power P = 10 dBm.

It is need to note that the maximum of the S_{21}-parameter is shifted to higher frequencies with respect to the S_{11}-parameter curve. Taking into account values of the magnetic field and the frequency of the maximum of the S_{21}-parameter and using equation (2), we can conclude that the effective magnetization of the S_{21}-maximum corresponds to the sublayer with 4\pi M = H_a = 1278 Oe (table 1). Consequently, the value of the effective magnetization of the YIG interface region is higher than the effective magnetization of the main YIG layer.

According to [28, 29], the observed interaction between spin excitations and 2D electrons is of the electromagnetic nature. At resonance frequencies the alternating magnetic field of spin excitations induces an alternating electrical field, which influences on 2D electrons. The observed influence of spin excitations on the 2DEG current results in modulation of the current flowing in the 2DEG channel and, in this sense, one can say that this modulation is analogous to the action of a gate electrical potential in FET-structures.

6. Inverse effect. Influence of the current on spin excitations

In order to observe the inverse effect— influence of the current on spin excitations and to enhance this inverse effect, we have carried out the experiment under the following conditions: (1) high channel conductivity, (2) low values of the microwave frequency, at which the three-magnon decay occurs, and (3) high values of the microwave power. Increase of the 2DEG...
current caused by the growth of the channel conductivity leads to the increase of an alternating magnetic field acting on the YIG film and at high microwave powers results in essential changes in the FMR spectrum. According to [34], at the three-magnon decay of the FMR excitation at high microwave powers this influence can be rather high. In the in-plane magnetic field, spin excitations can decay into backward volume spin waves.

In order to increase the channel conductivity in the transistor structure formed on the sample #6, the channel was exposed by a light beam ($\lambda = 650 \text{ nm}$, $\epsilon = 1.907 \text{ eV}$) with the photon energy $\epsilon$ greater than the GaAs energy band gap of 1.424 eV and less than the YIG band gap of 2.85 eV [40] and the AlO$_2$ band gap of 6.5 eV [41]. The light beam was linearly polarized with the intensity $W = 81 \text{ mW cm}^{-2}$. The light exposure leads to electron density increase in the GaAs 2DEG channel and it is analogous to an action of electric field in FET structures. Resistance of the channel is reduced from the FET structure formed on the sample #6 at the AlO$_2$/GaAs interface and with microwave power growth. The local microwave intensity at neighbouring YIG/AlO$_2$ interface region increases. This leads to the three-magnon decay of the FMR excitation in the YIG interface layer. The magnon instability process appears in the magnetic field of the in-plane orientation at the frequency $F < 1.8 \text{ GHz}$ and at the microwave power $P > 10 \text{ dBm}$. The normalized $S_{21}$-parameters measured in sample #6 at the frequency $F = 1.8 \text{ GHz}$ and at the microwave power $P = 14 \text{ dBm}$ under the light exposure and without light are shown in figure 6. Dependencies are normalized by the maximum value of the $S_{21}$-parameter measured under the light exposure. The increase of electrons in the 2DEG channel induced by light leads to essential changes in the FMR spectrum and in the $S_{21}$-parameter. One can see that an additional FMR peak $b$ appears in applied magnetic field of 1 kOe. One can observe a decrease in the height of the peak $a$ and a growth in the amplitude of the peak $b$, while decreasing frequency of the incident microwave signal and keeping the microwave power constant and equal to 14 dBm. Therefore, one can conclude that this leads to an increase of the thickness of the YIG layer $b$, where the magnon instability process occurs.

7. Summary

In summary, we described synthesis of YIG films sputtered on AlO$_2$/GaAs substrates, determined their magnetic characteristics, studied properties of the spin wave propagation and the influence of spin excitations in YIG films and 2DEG formed at the AlO$_2$/GaAs interface. It is found that the contribution of the relaxation process to the ferromagnetic resonance (FMR) linewidth is about 3.6%–6.6% of the linewidth $\Delta H$. It is supposed that increasing of the FMR linewidth is due to magnetic inhomogeneity of YIG films. High interaction between spin excitations and the electron current flowing through the 2DEG channel formed at the AlO$_2$/GaAs interface is achieved at the YIG-film FMR frequency. On the other hand, above the spin-wave instability threshold the growth of the channel conductivity induced by the light illumination results in essential changes in the FMR spectrum of transistor structures and in the $S_{21}$-parameter of channels. It is found that the interaction between the spin excitations in YIG films and 2DEG channel currents is increased with the light exposure of the AlO$_2$/GaAs interface and with microwave power growth. The observed interaction is of great importance for active control and manipulation of spin degrees of freedom in field-effect transistors at microwave frequencies.

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