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Stochastic spontaneous magnetization switching of a synthetic antiferromagnet GdFeCo/Ir/Gd Fe Co with perpendicular anisotropy

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Statistical patterns of spontaneous magnetization reversal of a synthetic GdFeCo/Ir/GdFeCo ferrimagnet with perpendicular anisotropy in the ranges of magnetic fields close to, but not equal to, the critical switching fields of four stable magnetization states P^+, AP^+, AP^- and P^- corresponding to two parallel (P^+, P^-) and two antiparallel (AP^+, AP^-) the mutual directions of magnetization of the thick and thin layers of GdFeCo. Instead of a sharp switch between the AP^+ and AP^- states in the critical field, in our experiments there is a spontaneous switching of magnetization delayed by a time interval that varies stochastically from experience to experience. Statistical analysis of a series of time dependences of magnetization revealed a decrease in the average delay duration as it approaches the critical field.

Keywords: dynamics of magnetization reversal, synthetic ferromagnets, magnetic relaxation.

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1. Introduction

Thin magnetic films comprising two bound by exchange interaction ferromagnetic layers are widely used in magnetic memory devices and magnetic sensors [1–3]. Dynamics of magnetization reversal in these systems is object of great interest and intensive studies for last several decades. Structures FM/NM/FM with antiferromagnetically bound ferromagnetic layers and perpendicular magnetization are of special interest as simplify the magnetic recording of information. Depending on the material and thickness of ferromagnetic layers in such structures different modes of magnetization reversal can be achieved [4–6]. It is necessary to distinguish magnetization reversal of individual films, from which the synthetic ferrimagnetic is made, and magnetization reversal as a whole of the multifilm sample, in which exchange interaction between layers occurs. Even in case of only two ferromagnetic layers the interactions occur between domains in neighboring layers, which can result in non-monotonic relaxation of magnetization [7,8].

The magnetization reversal mechanism of single film plays decisive role in the practical application of heterostructures. Each type pf magnetization reversal corresponds to definite time dependence of magnetization of single layer in external magnetic field [9]. The coherent magnetization reversal occurs very quickly and facilitates to Barkhausen noise cecreasing [10]. It permits use of heterostructure in magnetoresistive sensors, where coherence of magnetization reversal results in improved sensitivity to weak magnetic field. If magnetization reversal of single films as part of multilayer device is not coherent, and magnetization reversal occurs due to nucleation of magnetic domains, these systems also have promising applications in biodetection platforms [11]. In particular, existence of local magnetization reversal, which does not cover the entire area of thin film of synthetic antiferromagnetic, makes easier use in platforms of biodetection „lab-on-chip" [11]. Domain wall structures have many potential applications in fast magnetization switching devices and memory devices, where information can be stored locally on a specific region of film, and the resulting domain configuration can be transferred from any other selected region of the film via magnetic, electrical and optical controlled domain propagation. [12,13].

Major of relaxation processes in single thin films can be described by logarithmic [14], exponential [15] and power-exponential laws [16]. In particular, systems with competing nucleation and propagation of domains can be described by Avrami–Kolmogorov power-exponential relaxation law [17] and Labrun–Fatuzzo equations [18]. Depending on ration of contribution of domains nucleation and propagation of domain walls during magnetization reversal the dynamics of magnetization reversal can be described by modified exponential laws. The obtained indices of exponents and parameters of exponential law in Labrun–Fatuzzo approximations give the quantitative approach to description

of competition between domain nucleation and propagation, being sensitive to domain shape and domain boundary fractality in most existing synthetic ferrimagnetics.

Some synthetic ferrimagnetics demonstrate non-linear magnetic excitations, which can not be described using above mentioned models [19,20]. In particular, this occurs in structures with large Dzyaloshinski–Moriya contribution resulting in specific spin configurations on domain boundaries [19]. Another system that exhibits nonlinear magnetization reversal dynamics is a synthetic ferrimagnetics subjected to such temperature and magnetic field, that more than two types of magnetic domains, bound by exchange interaction, are simultaneously propagated in the system [20]. Increased interest in these systems in recent years resulted in more in-depth studies of magnetization reversal in synthetic ferrimagnetics, accompanied by identification of multipole types of nonlinear magnetic relaxations in interface-coupled magnetic nanostructures. In particular, [7] showed that transitions between states P^+, AP^+, AP^- and P^- can occur in such sequence that excludes intermediate metastable state. Potential barriers of these transitions can be adjusted by temperature such that even under conditions of the external magnetic field, insufficient to overcome the potential barrier, transition between states still occurs under the influence of thermal fluctuations, which have a certain waiting time.

In present paper we study the dynamic magnetization reversal in synthetic ferrimagnetics GdFeCo/Ir/GdFeCo, containing to ferromagnetic layers GdFeCo, antiferromagnetically coupled with each other via the layer of nonmagnetic metal Ir. Ferrimagnetics GdFeCo are rather perspective objects of study as they have compensation point near the room temperature, this ensures implementation in them the all-optical magnetization switching by femtosecond laser pulse and makes them necessary for optical magnetic recording of information [21]. Note that thermal optical record on CD-discs also uses alloy GdFeCo as active ferromagnetic material demagnetized by laser heating.

The paper objective is determination of patterns of magnetization reversal of this structure depending on set magnetic field, not coinciding with switching field, i. e. in such conditions when the thermal fluctuations with definite waiting time switch the system in another stable state.

2. Procedure and samples

Multilayer heterostructure $Pt(5.6\,nm)/Cu(4\,nm)/Gd_{0.25}[Fe_{0.9}Co_{0.1}]_{0.75}(5.2\,nm)/Ir(0.6\,nm)/Gd_{0.25}[Fe_{0.9}Co_{0.1}]_{0.75}(4.2\,nm)/Cu(5.6\,nm)/Ta(5\,nm)$ was obtained by method of magnetron sputtering on substrate Si/SiO_2 with thermally grown oxide layer 100 nm thick. Substrate surface before sputtering was etched by high-frequency plasma Ar 50 W at pressure $1 \cdot 10^{-2}$ mbar for 5 min. To obtain homogeneous thin film the sample holder was rotated with speed $\sim 10-30$ rpm. The seed layer Ta was necessary for buffering the substrate defects and making easier the formation of texture Cu (111) favourable for amorphous layer GdFeCo formation. Over all layers Pt was sputtered to prevent oxidation of structure lower layers. Copper was necessary for additional improvement of the perpendicular magnetic anisotropy GdFeCo.

The time dependences of the magnetic moment were registered using magnetometric system MPMS-3 SQUID-VSM Quantum Design. Sequence of magnetic field switching is shown in Figure 1, *a*. To keep same initial state of sample before recording of each time dependence of the magnetic moment the sample was initially held in field $H_1 = +4$ kOe for 2 min, this resulted in same orientation of layers magnetization and their saturation (Figure 1, *b*). This field exceeds the saturation field 3.5 kOe (Figure 2).

Then magnetic field was switched with linear speed 100 Oe/s maximum to field H_2, which located in range from +2.7 to −2.7 kOe (Figure 1, *b*). In this field the thin layer GdFeCo was in waiting mode of magnetization switching, its jump in our experiments was indicator of occurred transition (Figure 1, *c*). For this jump registration, after field H_2 achievement we started recording of the time dependence $M(t)$ for 100 min. After waiting during this time period the measurements were stopped, and field $H_3 = -4$ kOe was set, it corresponded to reverse magnetization of both layers and maintained switched on for 2 min (Figure 1, *c*). Further magnetic field was switched off. Sample saturation in fields $H_1 = +4$ and $H_3 = -4$ kOe was performed to unify the initial magnetic state of the sample before each measurement $M(t)$, and to exclude effects of residual field in superconducting magnet SQUID.

3. Experimental findings and discussion

First of all wee obtained the magnetic hysteresis loop $M(H)$ to determine structure switching fields GdFeCo/Ir/GdFeCo in light axis of magnetization. The hysteresis loop $M(H)$ contains four transitions: $P^+ \to AP^+$ in field +2200 Oe (*1*), $AP^+ \to AP^-$ (*2*) and reverse to it $AP^- \to AP^+$ in field 720 Oe and $AP^- \to P^-$ in field −2200 Oe (*3*) (Figure 2).

Then we determined field $H_1 = +4$ kOe, switching it to value $H_2 = +2700$ Oe and recorded time dependence of magnetic moment of sample for 100 min. Further in each next iteration we gradually decrease the applied field H_2 and again write the time dependence for next 100 min. Result of such experiment with different fields H_2, close to critical fields of transitions P^-, AP^-, AP^+ and P^+, is shown in Figure 3. Generally the experiment took 94 h and 53 dependences $M(t)$ were written.

It is obvious that transitions $P^+ \to AP^+$ and $AP^- \to P^-$ are accompanied by magnetic moment changes, which depend on time (Figure 3, *a* and *d*). But these changes do not exceed several percents of full difference of magnetizations in P^- and AP^- states, and correspond to magnetic relaxation in single ferromagnetic layers, but not to mutual

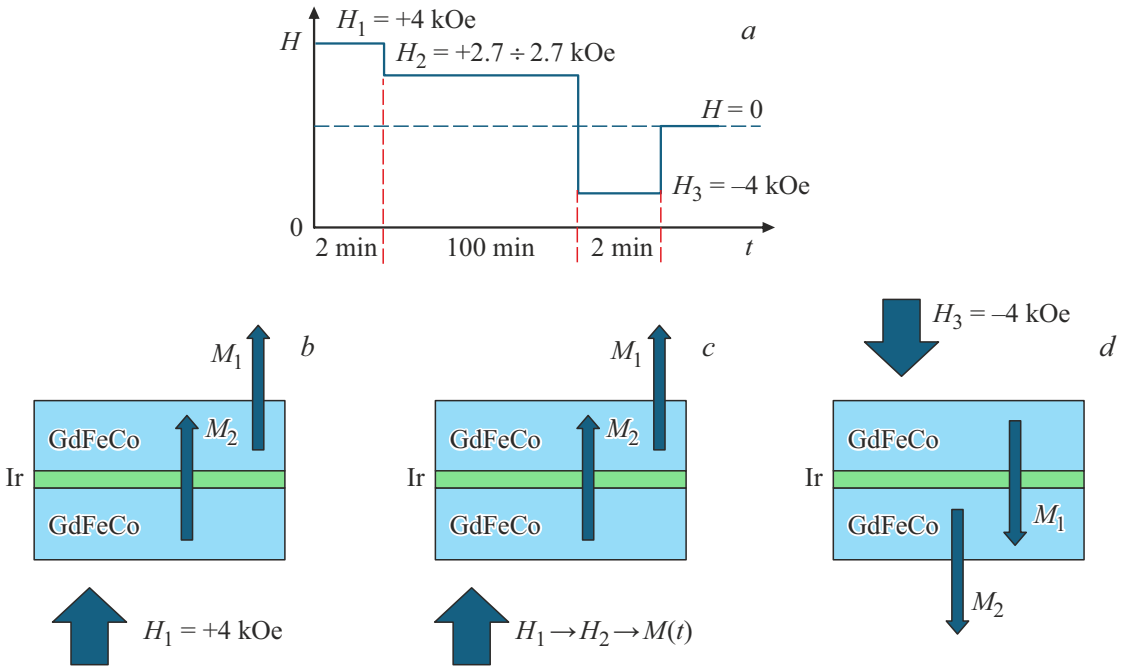

Figure 1. Field switching diagram in single cycle of experiment on preparation of time dependences of magnetic moment (a). Sample saturation in field $H_1 = +4$ kOe (b). Field switching from H_1 to H_2 in range from +2.7 to −2.7 kOe, and recording of time dependence of magnetic moment (c). Sample saturation in reverse field $H_3 = -4$ kOe (d). The external magnetic field was then reduced to zero before the start of the next cycle.

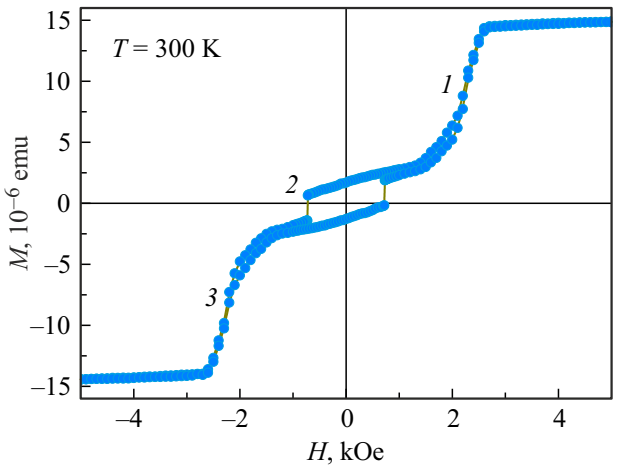

Figure 2. Magnetic hysteresis loop $M(H)$ at $T = 300$ K. Digits *1, 2* and *3* designate transitions $P^+ \rightarrow AP^+$, $AP^+ \rightarrow AP^-$ and $AP^- \rightarrow P^-$.

switching of their magnetizations. Transition from state AP^+ to AP^- occurs abruptly and each time (Figure 3, b). We determined amplitude of switching ΔM for each time dependence of magnetic moment $M(t)$ on applied field H_2. The dependence $\Delta M(H_2)$ is shown in Figure 4. It is obvious that significant changes in magnetic moment equal to those that are expected during transitions $AP^- \rightarrow AP^+$ and $AP^+ \rightarrow AP^-$ are observed in field near 720 Oe only.

Then field H_2 becomes equal to switching field (−720 Oe) the transition occurs immediately. But, when field switches to $H_2 = -700$ Oe, initially magnetization does not changes with time. After some delay there is abrupt switching between states AP^+ and AP^- occurs, so magnetization changes between two values corresponding to these states, during time period lower than time of data recording of each experimental point (~ 10 s). Registration of several series of dependences $M(t)$ in same field H_2 shows that delay time is accidentally distributed value. To characterize this stochasticity during delay time the magnetization reversal $AP^+ \rightarrow AP^-$ the series of 27 dependences $M(t)$ was registered in critical field $H_2 = -720$ Oe and in fields −700 Oe and −680 Oe, close to the critical field (Figure 5). All dependences $M(t)$ are registered for 30 min.

Further we plotted distribution of probability of switching from state AP^+ to AP^- by delay time t_{SWITCH} (Figure 6) in fields $H_2 = -720$, −700 and −680 Oe.

In field $H_2 = -720$ Oe, which coincides with critical field, the transition occurs always, and it is observed during first seconds of time dependence of magnetic moment without delay (Figure 6 a). Upon field H_2 removal from critical value to lower side, i.e. upon its setting to $H_2 = -700$ Oe, on all dependences $M(t)$ transitions occur at different values of time delay from moment of field switching (Figure 6, b). At more removal from critical field $H_2 = -680$ Oe in major dependences $M(t)$ transitions do not occur, apparently, because their monitoring requires more waiting time (Figure 6, c). When field H_2 is set above

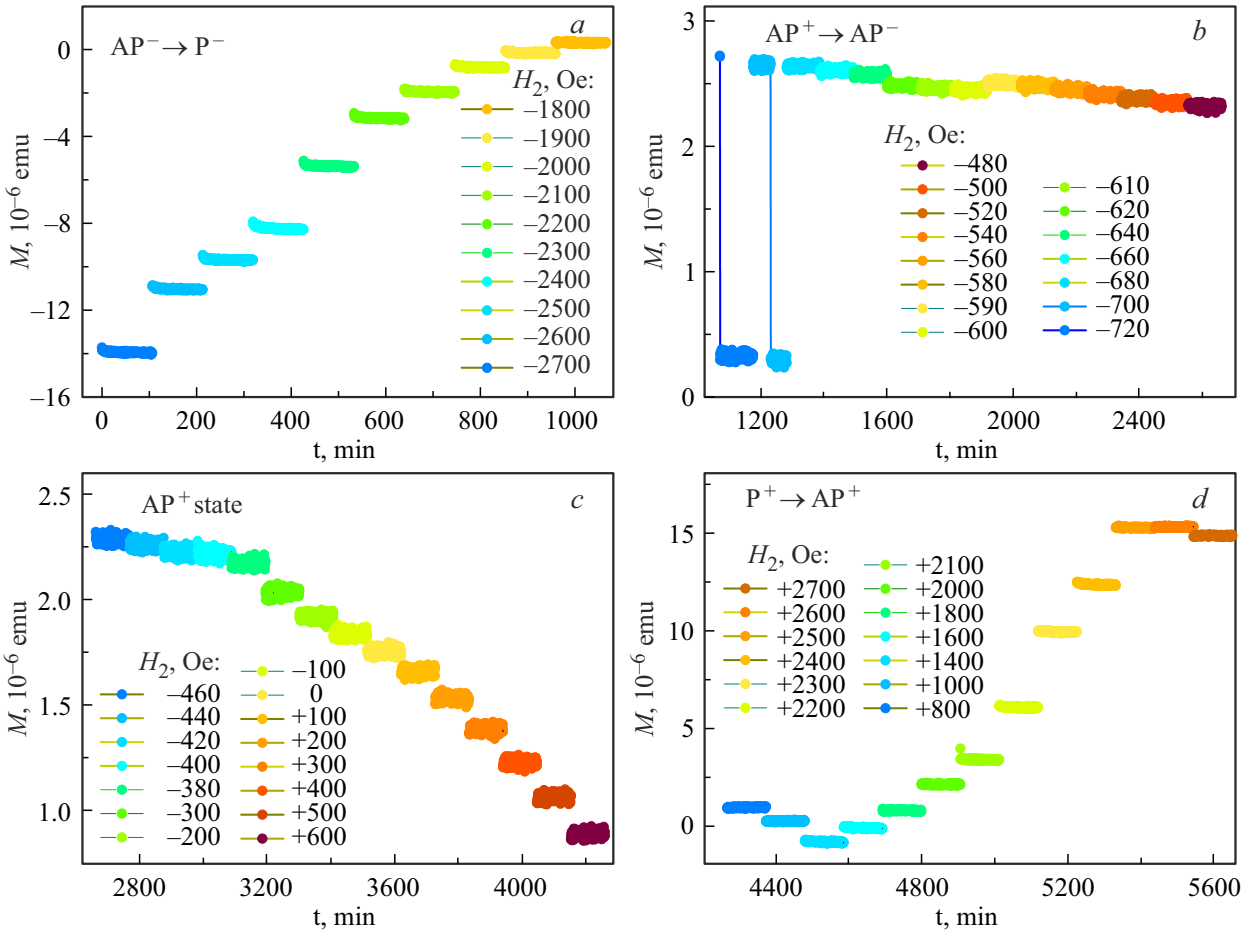

Figure 3. Set of dependences $M(t)$ for transitions $AP^- \rightarrow P^-$ (*a*), $AP^+ \rightarrow AP^-$ (*b*), AP^+ (*c*) and $P^+ \rightarrow AP^+$ (*d*).

the critical value ($H_2 > 720$ Oe) the registered dependence $M(t)$ always starts in point AP^- and, hence, during time of recording the dependence $M(t)$ on one transition occurs (in Figure not shown).

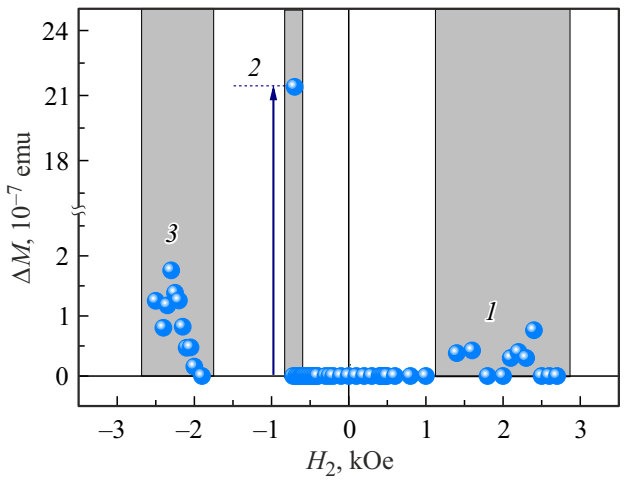

Figure 4. Changes on magnetic moment of sample ΔM, obtained from curves $M(t)$ in Figure 3, on applied field H_2.

It can be assumed that there are at least two alternative paths of transition between states AP^+ and AP^-, similar to that theoretically shown for structures CoFeB/Ta/CoFeB in [8]. The first path is direct, for which there is sufficiently high potential barrier, and the second path is through the state P^-, where the system occurs quicker. As a result of such competition the time delay depends on the thermal fluctuations, such activated behaviour of magnetization switching via one energy barrier is described by Arrhenius–Neel formula:

$$\tau = \tau_0 e^{E_M/k_B T}, \qquad (1)$$

Where τ — average time of switching of thermally activated event via one energy barrier (E_M) at set temperarure (T), k_B — Boltzmann's constant and τ_0 — characteristic magnetization time. The observed behaviour of magnetization reversal during transition $AP^+ \rightarrow AP^-$ indicates new class of behaviour of magnetization reversal in synthetic ferrimagnetics, when the system has rather high energy barrier resulting in nucleation of the magnetic domain, but at that the barriers for domain spreading are significantly lower, this ensures practically instantaneous spreading of the domain boundaries. In such approximation the waiting time is

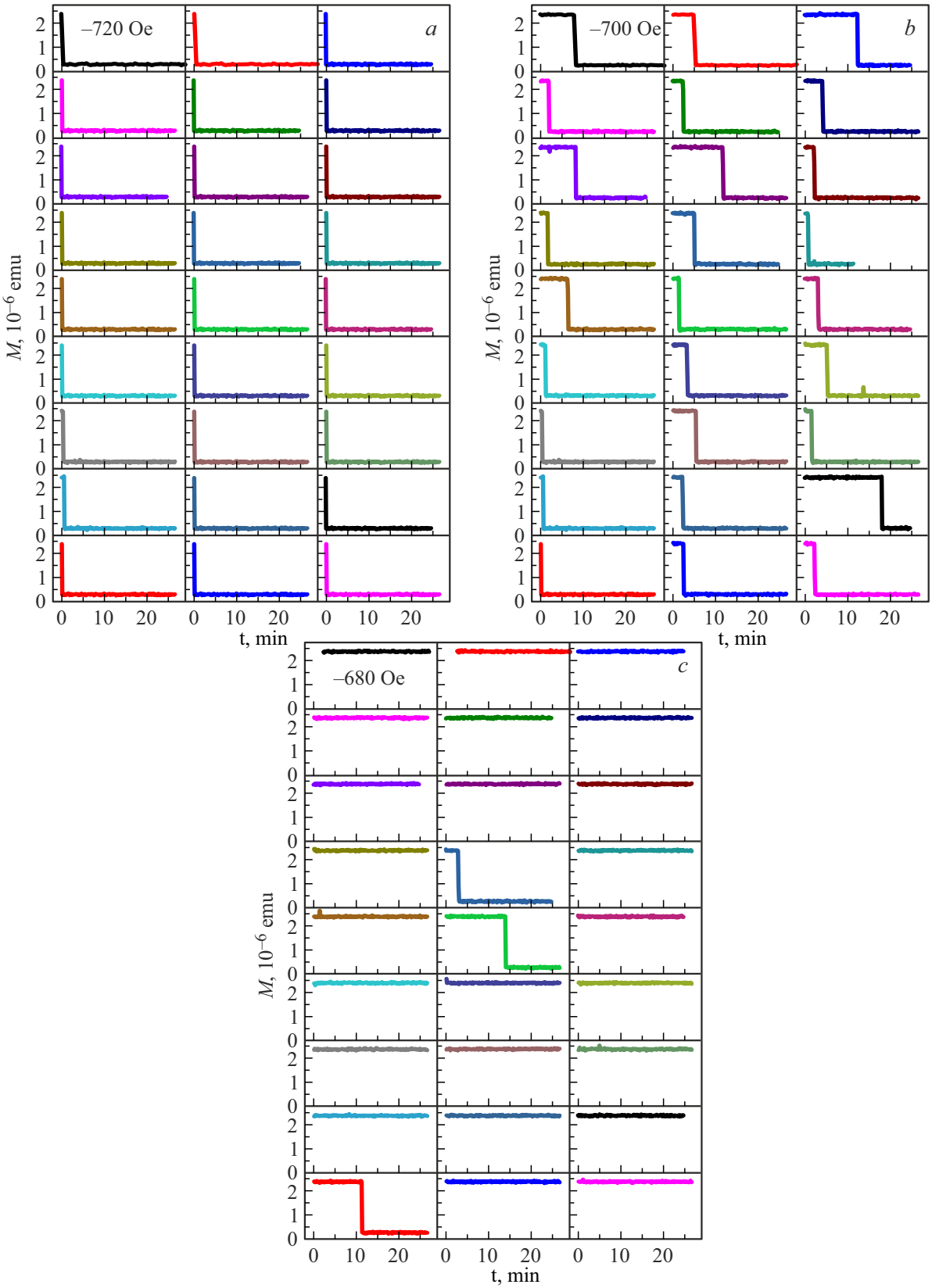

Figure 5. Set of time dependence of magnetic moment at $H_2 = -720$ Oe (a), 700 Oe (b) and -680 Oe (c) for transition $AP^+ \rightarrow AP^-$.

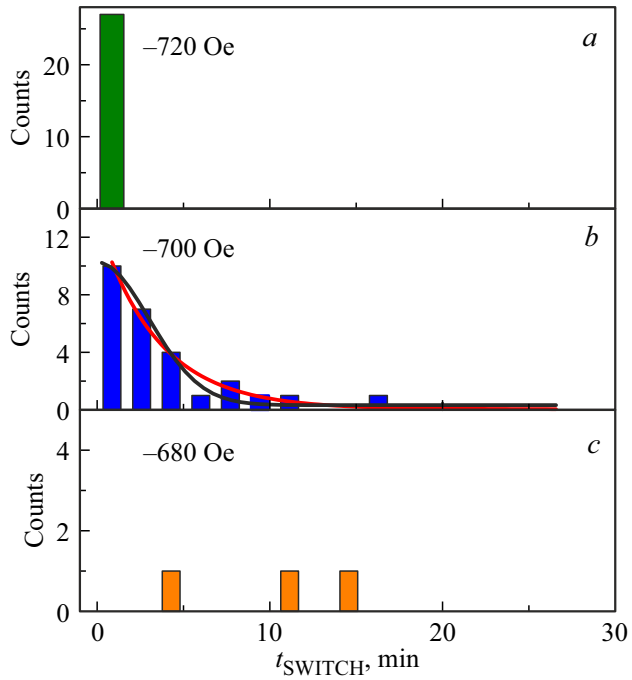

Figure 6. Distributions of probability of switching from state AP^+ to AP^- by delay time t_{SWITCH}, obtained in fields $H_2 = -720$, -700 and -680 Oe. Figure 6, *b* by lines shows approximation by normal (green line) and exponential (red line) distributions. For normal distribution average time of event is ~ 3 min, and for exponential ~ 4 min.

determined by value of magnetic field which reduces value of the barrier E_M and appropriate waiting time depends on field $\tau(H)$.

4. Conclusion

The stochastic switching of magnetization is determined at transition $AP^+ \rightarrow AP^-$ in system GdFeCo/Ir/GdFeCo, located in field close to switching field. Switching between states is manifested in a sharp change in magnetization, which occurs with a delay after the value of the switching field is set. The time delay is distributed according to the exponential law. In this case, the value removal of the switching field from its critical value leads to increase in the average delay time. The stochastic switching of magnetization is explained by waiting time of thermal fluctuation, able to result in occurrence of magnetization nucleus which quickly spreads over full film. As field approaches the critical value the waiting time of such nucleus appearance becomes shorter.

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Conflict of interest

The authors declare that they have no conflict of interest.

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