05,04

Impact of the mutual direction of Polarizer and Free Layer on the auto-oscillation mode of magnetic tunnel junctions (MTJs) of different geometry

© *V.R. Kikteva*[1,2], *K.V. Kiseleva*[1,3], *G.A. Kichin*[1,4], *P.N. Skirdkov*[1,4,5], *K.A. Zvezdin*[1,4,5]

[1] New Spintronic Technologies LLC, Moscow, Russia
[2] Bauman Moscow State Technical University, Moscow, Russia
[3] Skolkovo Institute of Science and Technology,
Moscow, Russia
[4] Moscow Institute of Physics and Technology,
Moscow, Russia
[5] Prokhorov General Physics Institute of the Russian Academy of Science,
Moscow, Russia

E-mail: kiktevavera@mail.ru

Received April 17, 2023
Revised April 17, 2023
Accepted May 11, 2023

In this work we studied the auto-oscillation mode of structures based on magnetic tunnel junctions. During the experiment we studied how different values and orientation of the magnetic field affect the efficiency of the auto-oscillations regime for samples of various shapes. The auto-oscillation mode in samples was observed near the transition from one state of magnetization of the free layer to another. It was found that the maximum value of the power spectral density and its position relative to the frequency axis can be controlled by changing the magnitude and orientation of the external magnetic field.

Keywords: Magnetic tunnel junction (MTJ), auto-oscillations, power spectral density, nanooscillator.

DOI: 10.21883/PSS.2023.06.56097.03H

1. Introduction

Spin-transfer nano-oscillators based on magnetic tunnel junctions (MTJ) are one of the most promising developments in nano-electronics and nano-photonics. These devices are nanosystems capable of generating high-frequency electromagnetic waves, ranging from a few gigahertz to terahertz, while consuming a minimal amount of energy. The auto-oscillation mode makes spin-transfer nano-oscillators potentially useful for creating high-frequency generators

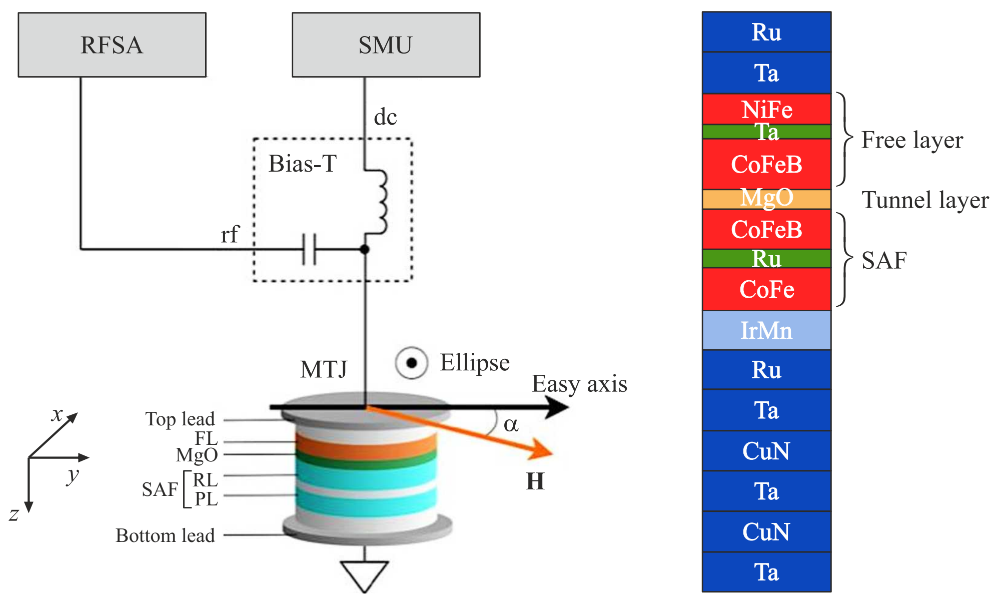

Figure 1. Schematic of the experimental setup and MTJ structure.Current was transmitted through the sample using a source-measurement units (SMU). The characteristic current value varied from −2 to +1 mA.

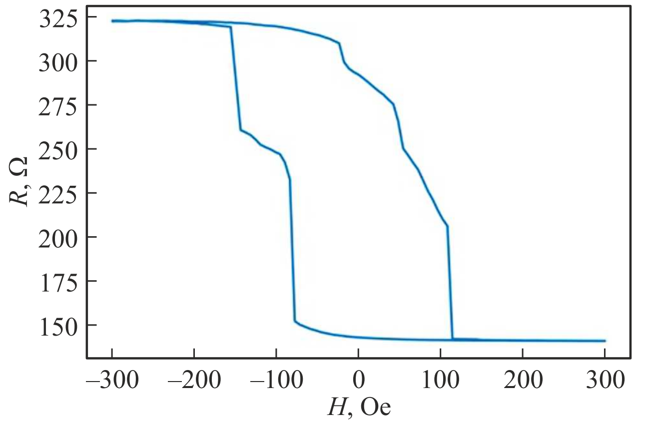

Figure 2. Magnetoresistance diagram for sample size 250 × 300 nm.

with low power consumption. Such devices can be used in a variety of applications, including wireless communication, radar, microwave electronics and many others.

The study of spin-transfer nano-oscillators and their properties is an active research area in the scientific and engineering fields [1–3], as these devices have many potential applications and can become a key element of future electronic devices [4–5]. Spin-transfer oscillators are also known to be used as a true random number generator due to the possibility of stochastic switching of the free-layer magnetization [6].

In this paper, we have studied the auto-oscillation mode dependence on the orientation and magnitude of the external magnetic field. Nano-oscillators were studied in samples of different geometries and layer structures under different conditions.

2. Experiment description

In this paper we studied the dependence of the sample geometry, relative field direction of the magnet, polarizer and free layer on the auto-oscillation mode. Samples consisting of the following layers were examined: IrMn (6)/CoFe30 (2.6)/Ru (0.7)/CoFe40B20 (1.8)/MgO/CoFe40B20 (2.0)/Ta (0.21)/NiFe (3) (Fig. 1). The CoFe/Ru/CoFeB structure is an antiferromagnetically bonded three layers: (SAF) acts as both reference (RL) and pinned layer (PL) [7]. MgO acts as a tunnel barrier, and the top layer of CoFeB is a free layer (FL), in which magnetization precession can be excited by a spin-

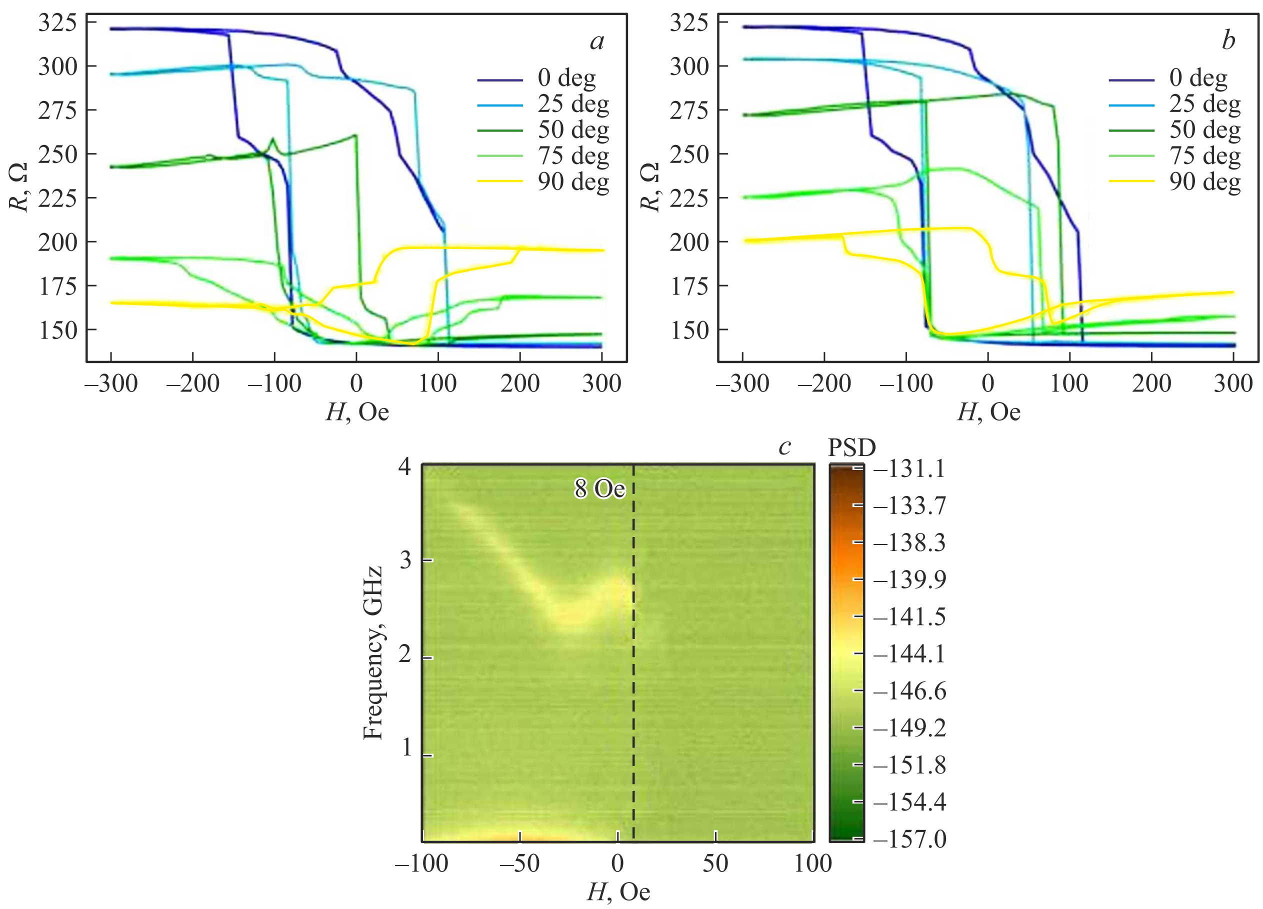

Figure 3. *a*), *b*) Diagram of the typical experimental behavior of the magnetoresistance curve of elliptical samples. *c*) The power spectral density (PSD) diagram as a function of frequency and external field at 25° of rotation relative to SAF.

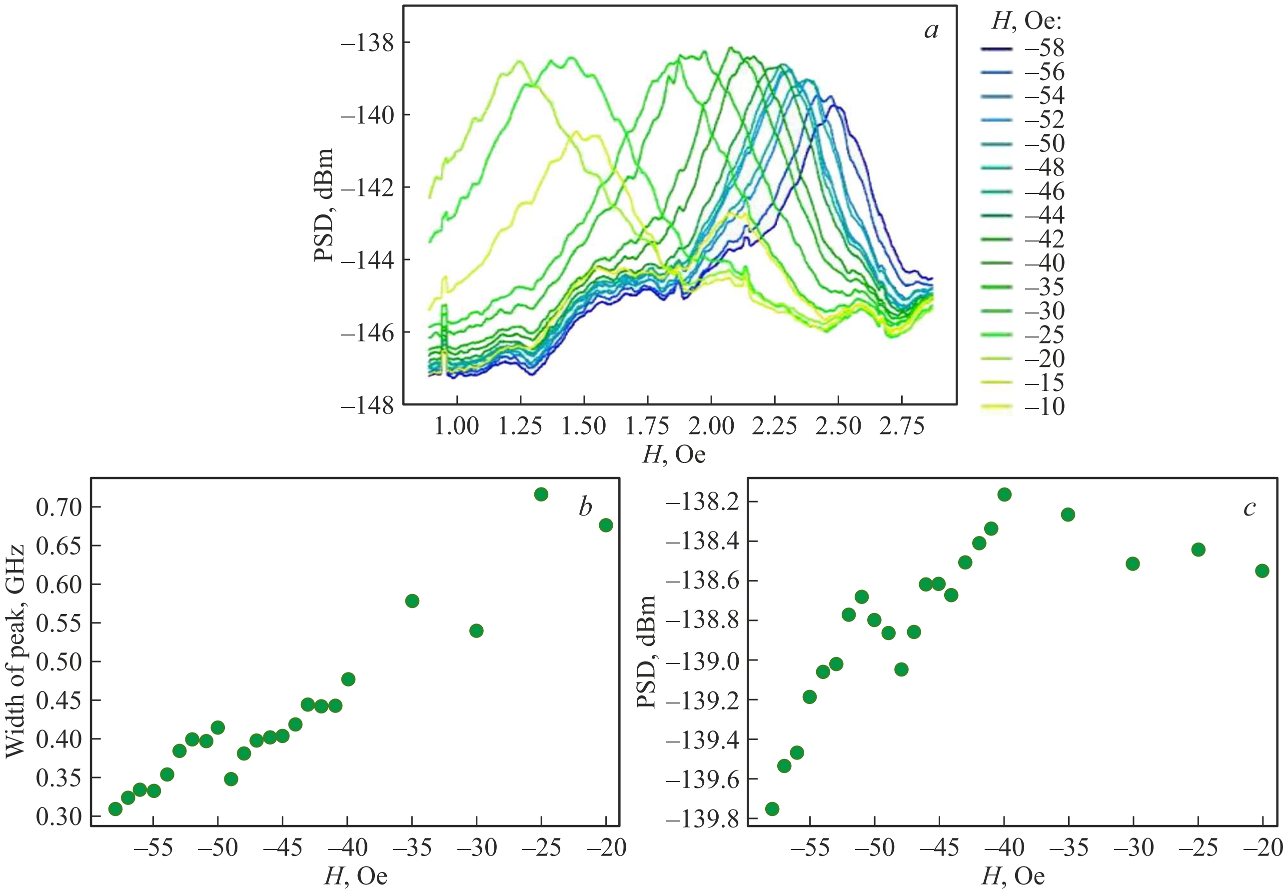

Figure 4. *a*) Dependence of the PSD value on the frequency, at which the generation peak was observed at a fixed magnetic field value (25°). *b*) Diagram of the generation peak width dependence on the field values. *c*) Diagram of the PSD value against field values.

polarized current (spin transfer tor STT [8]). In this paper, measurements were carried out on samples with sizes 100×300 nm, 200×300 nm and 250×300 nm. Elliptical shaped samples at angles 0, 15, 30, 90° with respect to the pinned layer were considered. The schematic diagram and sample structure are shown in Fig. 1.

The frequency averaged signal power distribution (PSD) was recorded with a spectrum analyzer (RFSA). The signal was studied in the frequency range $f = 100$ MHz$-$4 GHz. The external magnetic field was created by an electromagnet, which could be rotated. The field range was ± 300 Oe.

3. Discussion

The samples under study have a complex magnetization structure. From the magnetoresistance diagram (Fig. 2), it can be seen that besides the antiparallel and parallel states of the free layer, there are some additional complex states in the field range $H_{ext} = [0, 120]$ Oe.

Among the samples studied, attention should be paid to samples where the ellipse is directed at an angle 90° with respect to the SAF, since in these samples, the auto-oscillation mode was observed in general more frequently than in all other samples. Among these samples, generation was observed, on average, more frequently on samples of size 250×300 nm than on elongated samples of size 100×300 nm. Thus, for an elliptical sample with a given geometry, the maximum value of the power spectral density is observed at the orientation of the magnetic field relative to the SAF in the range $[0°, 55°]$. Maximum value of auto-oscillations was observed at 25° and in the range of external fields $H_{ext} = [-58; -10]$ Oe.

The magnetoresistance values in the antiparallel state for angles $[0°, 20°]$ are relatively comparable and are ± 300 Ohm, but by $\sim 50°$ the maximum value drops to ± 260 Ohm (Fig. 3, *a*). As the rotation angle is further increased, there is a gradual remagnetization of the sample, which finally occurs at 90° relative to the major axis of the ellipse. A similar trend is observed for negative field angles, except that a larger angle is required for remagnetization (Fig. 3, *b*).

The diagram of PSD versus frequency and external field (Fig. 3, *c*) shows a wide range of fields, where the auto-oscillation effect is clearly observed in negative and small positive fields and for frequencies above 2 GHz. The maximum PSD values were observed at low frequencies. After applying a field $H < -10$ Oe, the PSD value decreased to -144 dBm, which coincides with the values found when

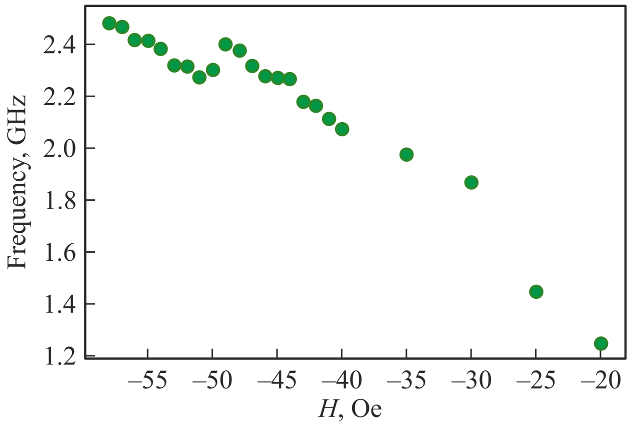

Figure 5. Diagram of the frequency at which the maximum power spectral density was observed for different magnetic field values.

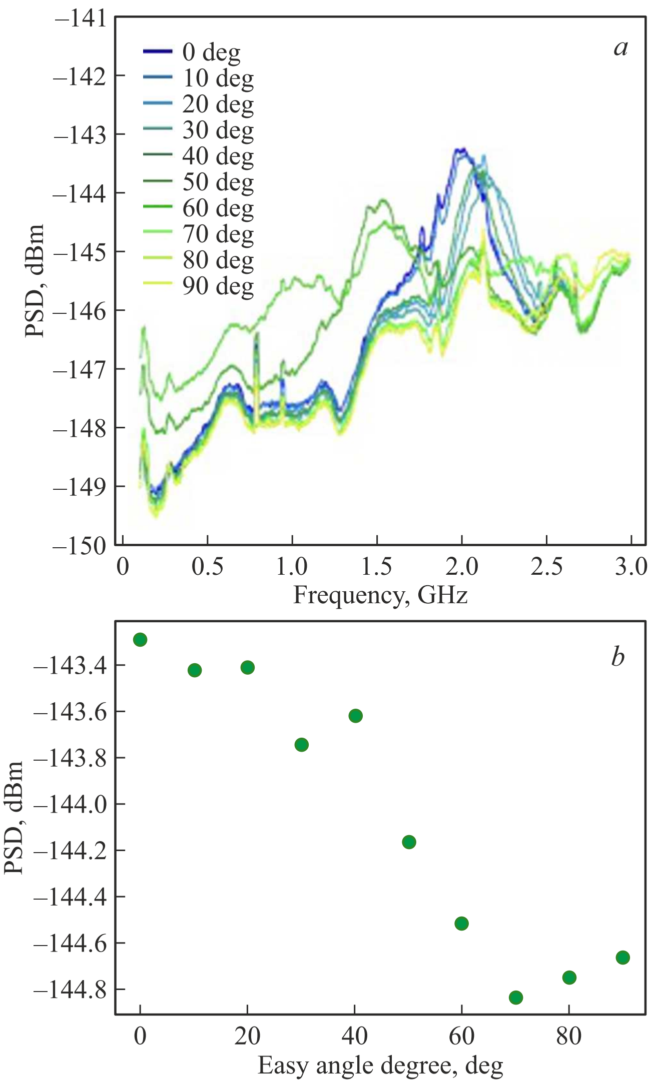

Figure 6. *a*) PSD dependencies of auto-oscillation mode PSD on frequency at a fixed magnetic field value −45 Oe. *b*) Dependence of maximum PSD value on the angle.

studying the spectra for each magnetic field value at 25° fixed field orientation (Fig. 4, *a*).

It can be seen from the diagram in Fig. 4, that the oscillations peak changed its width and shifted towards higher frequencies as the magnetic field value increased. The maximum value of auto-oscillations was observed at field value −40 Oe. As the field was subsequently reduced, the auto-oscillations peak shifted towards the low frequencies and the peak width increased. After field value −20 Oe, the generation peak disappears.

In the field range [−50, −48] Oe the peak generation width (Fig. 4, *b*), maximum PSD value (Fig. 4, *c*) is observed to abruptly change. In the hysteresis diagram for 25° (Fig. 3, *a*), this area of the fields corresponds to the boundary between the transition from one state to another.

The maximum value of the power spectral density was observed at the frequency defined by Kittel's formula for ferromagnetic resonance [9]:

$$f = \gamma \sqrt{\begin{aligned} &\big(M(N_z - N_x) + B_0 \cos(\theta_{\text{ext}})\big) \\ &\quad \times \big(M(N_y - N_x) + B_0 \cos(\theta_{\text{ext}})\big) \end{aligned}}. \quad (1)$$

Here, γ — is the gyromagnetic ratio, M — is the magnetization of the free layer, B_0 — is the value of the external magnetic field. N_x, N_y, N_z — demagnetization coefficients, for the measured elliptical sample with 250×300 nm they are 0.024, 0.042, 0.934, respectively [10]. The auto-oscillations peak shifted towards the low frequencies as the field value decreased (Fig. 5).

By changing the orientation of the external magnetic field and a fixed magnetic field value at −45 Oe the auto-oscillation mode was observed in the frequency range $f = [1.8{-}2.2]$ GHz. The maximum PSD = −143.5 dBm remained constant at field angles smaller than 45°, at larger angles, the generation peak shifted towards the low frequencies and disappeared at 70°. Fig. 6 shows power spectral density diagrams for different magnetic field orientations relative to the easy axis.

4. Conclusion

In this paper, the mode of auto-oscillation in elliptical MTJs of different geometries at different magnetic field values and orientations has been studied. The generation was most often observed on samples of size 250×300 nm, where the ellipse is rotated at an angle 90° with respect to SAF. The auto-oscillation mode was observed at the moment of transition from one state of the free layer to another, regardless of the orientation of the magnetic field. It is also found that in a linear distribution of magnetoresistance from the field, minimum PSD values are observed. The maximum PSD value was observed near switching, after which the oscillations peak disappeared. There is an abrupt change in the oscillations peak at the moment of MTJ switching. When the magnetic field orientation is fixed, the generation frequency decreases as the field magnitude decreases. The most significant and stable auto-oscillation effect was observed in the negative field area at magnet rotation angle 25° relative to the major axis of the ellipse. At a fixed magnetic field value, the generation peak did not change its position when the magnetic field orientation was less than 45°. At higher angles, the peak shifted towards the low frequencies and disappeared near 90°.

Funding

The study was performed with the support of RSF grant (No. 19−12−00432).

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] T. Wada, T. Yamane, T. Seki, T. Nozaki, Y. Suzuki, H. Kubota, A. Fukushima, S. Yuasa, H. Maehara, Y. Nagamine, K. Tsunekawa, D.D. Djayaprawira, N. Watanabe. Phys. Rev. B **81**, 104410 (2010).
[2] S. Bonetti, P. Muduli, F. Mancoff, J. Åkerman. Appl. Phys. Lett. **94**, 102507 (2009).
[3] M. Tarequzzaman, T. Böhnert, M. Decker, J.D. Costa, J. Borme, B. Lacoste, E. Paz, A.S. Jenkins, S. Serrano-Guisan, C.H. Back, R. Ferreira, P.P. Freitas. Phys. Commun. **2**, 20 (2019).
[4] S. Ning, H. Liu, J. Wu, F. Luo. Fund. Res. **2**, 535 (2022).
[5] A. Helmer, S. Cornelissen, T. Devolder, J.-V. Kim, W. van Roy, L. Lagae, C. Chappert. Phys. Rev. B **81**, 094416 (2010).
[6] D. Vodenicarevic, N. Locatelli, A. Mizrahi, J.S. Friedman, A.F. Vincent, M. Romera, A. Fukushima, K. Yakushiji, H. Kubota, S. Yuasa, S. Tiwari, J. Grollier, D. Querlioz. Phys. Rev. Appl. **8**, 054045 (2017).
[7] P.N. Skirdkov, K.A. Zvezdin. Ann. Phys. **532**, *6*, 12 (2020).
[8] M.D. Stiles, A. Zangwill. Phys. Rev. B **66**, 014407 (2002).
[9] C. Kittel. J. Phys. Rad. **12**, *3*, 291 (1951).
[10] O. Kohmoto. Jpn. J. Appl. Phys. **42**, 6875 (2003).

Translated by Ego Translating