JOINT INSTITUTE FOR NUCLEAR RESEARCH
Bogoliubov Laboratory of Theoretical Physics

Magnetization reversal in S/F/S Josephson junctions on a 3D topological insulator

-student report-

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I would like to express a special gratitude to my supervisor, Prof. Dr. Yuri M. Shukrinov, for helping me to uncover unusual and amazing world of theoretical condensed matter physics. His patience, motivation and immense knowledge were very helpful during my research. Besides my supervisor, I would like to thank Dr. Ilhom Rahmonov for his continious support and last, but not least, I am very grateful to Joint Institute for Nuclear Research for giving me an opportunity to be part of Summer Student Programme and Organising Committee for great guidance.

Elena, Daniel, thank you for making our stay in Dubna amazing and unforgettable.

Contents

Chapter 1

Introduction

Superconducting spintronics based on the interaction of superconducting current with magnetic moment in Josephson superconductor-ferromagnet structures attracts much attention today due to possibility of controlling magnetism by superconductivity and due to a perspective of applications in memory elements and quantum computer technologies.

By adding current pulse signal, dynamics of magnetic moment components has been simulated and the full magnetization reversal at different parameters of the junction has been demonstrated.

In this report one can find just a short, but concise description of used model and a few interesting results which were obtained during my stay in Joint Institute for Nuclear Research as a summer student. Most important results and discussions will be presented in a form of scientific paper.

Chapter 2

Magnetization dynamics generated by a Josephson current in S/F/S junction on a 3D TI

2.1 Model system

The sketch of the system under consideration is presented in Figure 1. Two conventional s-wave superconductors and a ferromagnet are deposited on top of a 3D topological insulator (TI) to form a Josephson junction. Ferromagnet can be as metallic, so as insulating. The magnetization of the ferromagnet is supposed to be spatially homogeneous. Electric current travelling via TI surface states along the x-direction exerts a torque on the ferromagnet magnetization [1–3]. This is matter of fact, does not depend of ferromagnet having metallic or insulating characteristics.

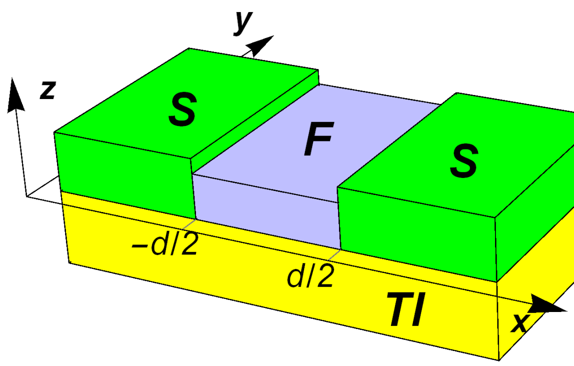

Fig.1: Sketch of the system under consideration. Superconducting leads and a ferromagnetic interlayer are deposited on top of the topological insulator (TI).

However, for insulating ferromagnet, all the current flows via the TI surface states. On the other hand, for metallic ferromagnets, the current partially travels via the ferromagnet. In that case, efficiency of the torque is reduced [4–7]. There is an interaction between the spin densities on the two sides of the S/F interface. Hamiltonian which describes TI surface states in the presence of the effective exchange interaction is given as:

$$\begin{aligned}\hat{H} &= \hat{H}_{TI} + \hat{H}_{int}, &(2.1)\\ \hat{H}_{TI} &= \int d^2\boldsymbol{r}\hat{\Psi}^\dagger(\boldsymbol{r})\Big[-iv_F(\boldsymbol{\nabla}\times\boldsymbol{e}_z)\cdot\hat{\boldsymbol{\sigma}} - \mu\Big]\hat{\Psi}(\boldsymbol{r}), &(2.2)\\ H_{int} &= -\frac{1}{2}\int d^2\boldsymbol{r}\hat{\Psi}^\dagger(\boldsymbol{r})J_{ex}\boldsymbol{S}\cdot\boldsymbol{\sigma}\hat{\Psi}(\boldsymbol{r}), &(2.3)\end{aligned}$$

where $\hat{\Psi} = (\Psi_\uparrow, \Psi_\downarrow)^T$, v_F is the Fermi velocity, $\boldsymbol{e}_z$ is a unit vector normal to the surface of TI, μ is the chemical potential and $\hat{\boldsymbol{\sigma}} = (\sigma_x, \sigma_y, \sigma_z)$ is a vector operator with a Pauli matrices as a components in the spin space. $\boldsymbol{S}$ is spin operator localized in ferromagnet interlayer, J_{ex} is the exchange constant. It should be noted that integration is performed over the 2D interface. Electric current $\boldsymbol{j}$ flowing via the TI surface states, induces a stationary electron spin polarization, due to full spin-momentum locking of the TI surface states [8–11]. This is inevitable and it does not depend if it is normal current or supercurrent.

$$\langle\boldsymbol{s}\rangle = -\frac{1}{2ev_F}[\boldsymbol{e}_z\times\boldsymbol{j}]. \tag{2.4}$$

2.2 Magnetization dynamics

Landau-Lifshitz-Gilbert (LLG) equations are used to describe dynamics of ferromagnet magnetization:

$$\frac{\partial\boldsymbol{M}}{\partial t} = -\gamma\boldsymbol{M}\times\boldsymbol{H}_{eff} + \frac{\alpha}{M}\boldsymbol{M}\times\frac{\partial\boldsymbol{M}}{\partial t} + \frac{J_{ex}}{d_F}\boldsymbol{M}\times\langle\boldsymbol{s}\rangle, \tag{2.5}$$

where $\boldsymbol{M}$ is the saturation magnetization, γ is the gyromagnetic ratio, $\boldsymbol{H}_{eff}$ is the local effective field in the ferromagnet and α is Gilbert damping constant. The last term in previous equation represents the torque, averaged over the ferromagnet thickness d_F along the z-direction. Current is flowing along x-direction. Unit vector $\boldsymbol{m} = \boldsymbol{M}/M$ should be introduced and will be used in following text.

The ferromagnet is an easy-plane magnet. Hard axis is directed along the z-axis. A weaker in-plane uniaxial anisotropy along x-axis is also assumed. Taking into account all that, local effective field in the ferromagnet can be written as follows:

$$\boldsymbol{H}_{eff} = -\frac{K}{M}m_z\boldsymbol{e}_z + \frac{K_u}{M}m_x\boldsymbol{e}_x, \tag{2.6}$$

where K and K_u are hard axis and easy axis anisotropy constants, respectively.

Chapter 3

Magnetization reversal and detection

3.1 Magnetization reversal

It is numerically considered magnetization reversal by the electric current pulse. The LLG equation (2.5) in dimensionless form can be written as follows:

$$\frac{\partial \boldsymbol{m}}{\partial \tilde{t}} = -\boldsymbol{m} \times \tilde{\boldsymbol{H}}_{eff} + \alpha \boldsymbol{m} \times \frac{\partial \boldsymbol{m}}{\partial \tilde{t}} + \tilde{N}\tilde{j}[\boldsymbol{e}_y \times \boldsymbol{m}], \tag{3.1}$$

where we have introduced the dimensionless quantities $\tilde{t} = \gamma t K_u/M$, $\tilde{\boldsymbol{H}}_{eff} = -(K/K_u)m_z\boldsymbol{e}_z + m_x\boldsymbol{e}_x$, $\tilde{j} = j/j_{c0}$ and $\tilde{N} = rE_J/8E_M$, which is a product of the dimensionless $r = 2h_{eff}d/v_F$ and the ratio of the Josephson and magnetic energies $E_J = j_{c0}\Phi_0/2\pi$ (j_{c0} is the critical current density at $m_x = 0$ and Φ_0 is the flux quantum) and $E_M = K_u d_F d/2$ per unit length of the junction.
Basing on previous equation, it was investigated dynamics of the magnetization numerically. Before changing diferent parameters to get dependences of interest, equation (3.1) should be written as:

$$\begin{aligned}
\frac{\mathrm{d}m_x}{\mathrm{d}t} &= \frac{1}{1+(m\alpha)^2}(-m_y h_z - m_z h_y + \alpha[h_x m^2 - m_x(\boldsymbol{mh})] - \alpha N j m_x m_y + N j m_z) \\
\frac{\mathrm{d}m_y}{\mathrm{d}t} &= \frac{1}{1+(m\alpha)^2}(-(m_z h_x - m_x h_z) + \alpha[h_y m^2 - m_y(\boldsymbol{mh})] + \alpha N j(m^2 - m_y^2) \\
\frac{\mathrm{d}m_z}{\mathrm{d}t} &= \frac{1}{1+(m\alpha)^2}(-(m_x h_y - m_y h_x) + \alpha[h_z m^2 - m_z(\boldsymbol{mh})] - \alpha N j m_z m_y - N j m_x) \\
\frac{\mathrm{d}\varphi}{\mathrm{d}t} &= \frac{1}{\beta}(j - j_c \sin(\varphi - r m_y) + \beta r \frac{\mathrm{d}m_y}{\mathrm{d}t},
\end{aligned} \tag{3.2}$$

where $h_x = m_x$, $h_y = 0$ and $h_z = -km_z$.

3.2 Results

3.2.1 dt-dependence

First, an effect of time duration of rectangular current pulse to magnetization reversal was investigated. Before pulse action, magnetization is directed along the x-axis, i.e. m_x=1. It was considered that the value of magnetization m_x at the end of current pulse may clarify the question if full magnetization reversal would happened. Using fixed initial conditions, model and numerical parameters, different regions where full magnetization reversal occurs were obtained, as it can be seen in Figure 2. Those regions are shown with different colours. Points marked with an empty circles correspond to the values of dt for which magnetization reversal is absent. Used fixed parameters are: T_{max}-time domain for one step of current, T_{P}-step of time, A_s-amplitude of current signal, t_0-mathematical expectation, α and β-damping parameters, k-ratio of hard axis and easy axis anisotropy constants, r-effective exchange parameter, while N is proportional to the ratio of Josephson and magnetic energy.

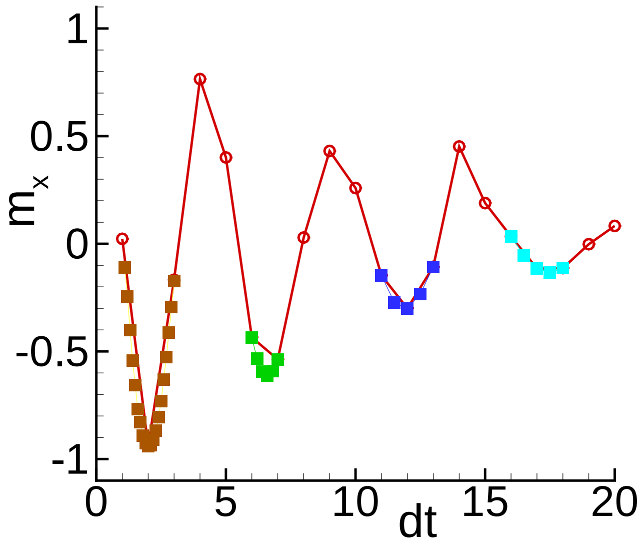

Fig.2: Magnetization value m_x taken at the end point of the rectangular current pulse as a function of time duration of pulse, for the following values of parameters: $T_{\max} = 100$, $T_{\mathrm{p}} = 0.005$, $A_{\mathrm{s}} = 1.5$, $t_0 = 25$, $\alpha = 0.1$, $k = 1$, $N = 1$, $\beta = 1$, $r = 0, 5$, $d = 0.3$.

One can notice some minimum values of m_x around which magnetization reversal occures. Full magnetization reversal occures if value of m_x at the end of sumulation is -1. It has to be mentioned once again that this dependence was observed at the end of current pulse. This periodicity, which can be noticed in figure above, will appear also at the larger values of dt, but then values of m_x at the end of current pulse will be larger.

3.2.2 α-dependence

Using the same, mentioned, parameters, m_x as a function of Gilbert damping constant was investigated. This dependence is presented in Figure 3. It should be noted that values of m_x are values at the end of current pulse.

One can notice almost the same behaviour as in dt dependence. Coloured circles represent values of m_x for which magnetization reversal appears, while in the empty ones is absent. Periodicity and minima are present, but this minima show for larger values of m_x, in comparison with dt dependence.

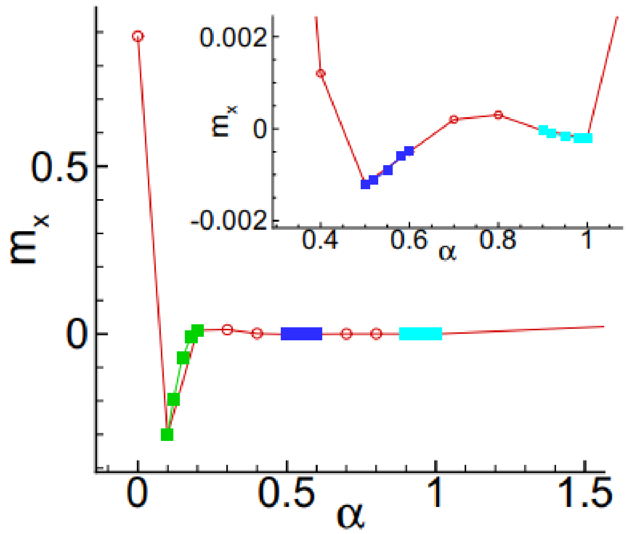

Fig.3: Magnetization value m_x taken at the end point of the rectangular current pulse as a function of Gilbert damping constant ,for the following values of parameters: $T_{\max} = 100$, $T_{\mathrm{p}} = 0.005$, $A_{\mathrm{s}} = 1.5$, $t_0 = 25$, $dt = 12$, $k = 1$, $N = 1$, $\beta = 1$, $r = 0, 5$, $d = 0.3$.

Some general behaviour that value of m_x at the end of current pulse is almost constant and oscilates around zero, for values of α larger then 0.4 is easily visible.

Chapter 4

Conclusion

As it can be seen, possibility of magnetization reversal depends on the model and pulse parameters. The observed features might find an application in different fields of superconducting spintronics. They can also be considered as a fundamental basis for memory elements.

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