Moscow International Symposium on Magnetism
July 1-5, 2017

SPIN-TORQUE DIODE SENSITIVITY IN MAGNETIC NANOWIRE WITH A MAGNETIC TUNNEL JUNCTION

G.D. DEMIN[1,2*]

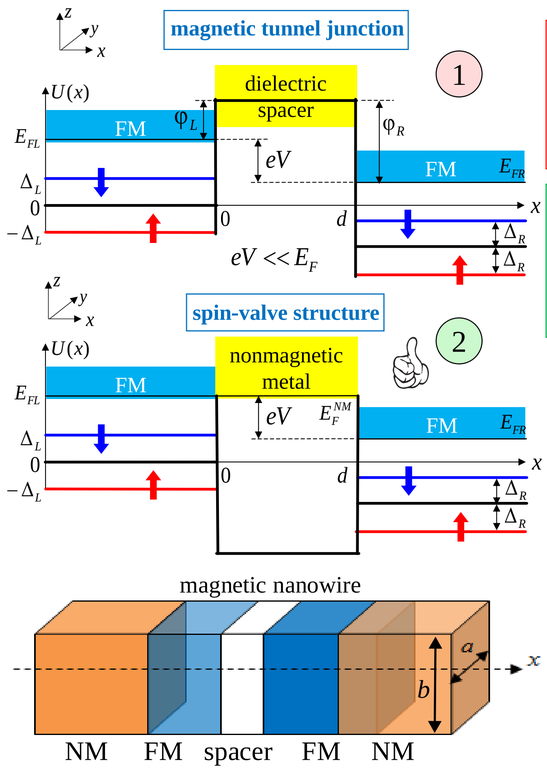
[1] Moscow Institute of Physics and Technology (MIPT), Moscow,141700, Russian Federation
[2] National Research University of Electronic Technology (MIET), Moscow, 141700, Russian Federation

*corresponding author, e-mail: gddemin@gmail.com

BACKGROUND AND MOTIVATION

Nowadays much attention in the field of spintronics is paid to the consideration of so-called spin-torque diodes based on magnetic tunnel junctions (MTJ). Microwave alternating current in such structures generates dc voltage appeared at the resonant frequency of spin oscillations which are induced by the spin-transfer torque effect in the free magnetic layer [1]. The effect of rectification of the microwave signal by the MTJ makes it possible to use it as a highly sensitive microwave detector [2]. In a number of studies it has been shown that in the presence of a bias current, the sensitivity of the spin diode can exceed the sensitivity of a Schottky diode by an order of value [3,4], which makes this detector attractive for practical applications in the microwave vision techniques. On the other hand, the critical value of the current density, in the vicinity of which there is a sharp increase in the sensitivity of the spin diode, is very large and this creates the problem to use MTJ biased by the critical current in practice. In this connection, an alternative way of increasing the sensitivity of a spin diode is of interest by reducing lateral dimensions of the magnetic tunnel structure. In this work we performed an analysis of the microwave sensitivity of the magnetic nanowire with a magnetic tunnel junction as a spin-torque diode depending on the bias current and the radius of its cross section. We also consider possible effects of quantization of the magnetoresistance and spin torque transfer in the nanowire based on a spin-valve structure with a nonmagnetic spacer which can be good alternative to tunnel junctions in the case of scalability to 10 nm and beyond.

THEORETICAL MODEL OF SPIN TRANSFER IN MAGNETIC NANOWIRES TAKING INTO ACCOUNT THE QUANTIZATION PHENOMENA DUE TO CONFINED GEOMETRY



Unfortunately, in the simulation we did not find the quantization steps in spin-transfer torques and conductance in dependence from the lateral size of magnetic nanowire based on magnetic tunnel junction!

The solution:

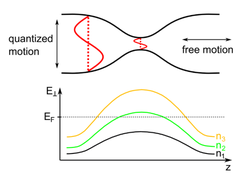
Spin-valve structure with the metal spacer can behave like the magnetic nanocontact with the domain-wall and demonstrates the quantization effects!

Quantum of spin- and current densities in magnetic nanowires:

$$\begin{cases} \dfrac{dJ_e}{dV} \propto \dfrac{e^2}{h} \\ \dfrac{dJ_{\mu(s)}}{dV} \propto \dfrac{e}{4\pi} \end{cases}$$

quantization effect

$$E_{\perp mni} = \frac{\hbar^2\pi^2}{2m_e}\left(\frac{m^2}{a^2}+\frac{n^2}{b^2}\right) \quad (m,n = 1,2,3...)$$

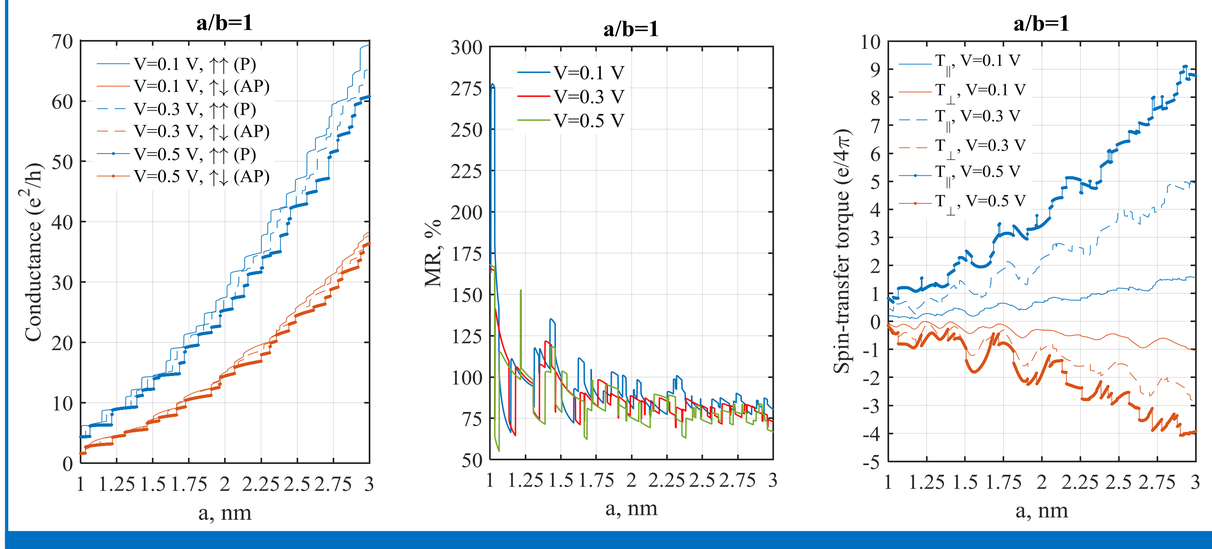


Thermodynamically averaged spin and current densities in a magnetic nanowire

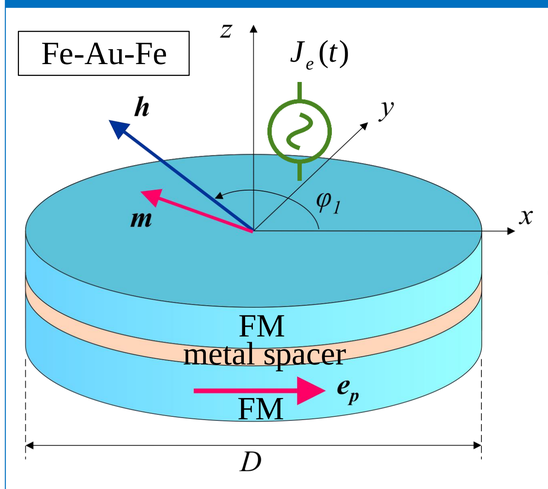
$$< J_e >= \frac{e}{2\pi\hbar^2}\sum_{\sigma,\sigma'=\uparrow,\downarrow}\left(m_{L^*}\cdot\sum_{m,n}\int_0^{+\infty}\frac{1}{k_{xL}^{\sigma}}\,j_{LR\sigma\sigma}^{(TR)}F_{LR}dE - m_{R^*}\cdot\sum_{m,n}\int_0^{+\infty}\frac{1}{k_{xR}^{\sigma'}}\,j_{RL\sigma'\sigma}^{(TR)}F_{RL}dE\right)$$

$$< J_{\mu(s)} >= \frac{1}{2\pi\hbar^2}\sum_{\sigma,\sigma'=\uparrow,\downarrow}\left(m_{L^*}\cdot\sum_{m,n}\int_0^{+\infty}\frac{1}{k_{xL}^{\sigma}}\,j_{LR\mu\sigma\sigma}^{(TR)}F_{LR}dE - m_{R^*}\cdot\sum_{m,n}\int_0^{+\infty}\frac{1}{k_{xR}^{\sigma'}}\,j_{RL\mu\sigma'\sigma}^{(TR)}F_{RL}dE\right) \quad \mu = x,y,z$$

QUANTIZATION OF CONDUCTANCE AND SPIN-TRANSFER TORQUES IN MAGNETIC NANOWIRES BASED ON SPIN-VALVE STRUCTURES WITH THIN METAL SPACER



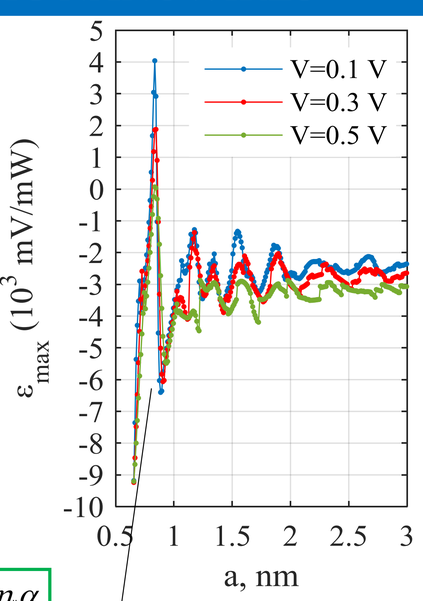
ENHANCEMENT OF SPIN-TORQUE DIODE SENSITIVITY IN MAGNETIC NANOWIRES



Microwave sensitivity of the spin-torque diode based on magnetic nanowire:

$$\varepsilon \approx -\varepsilon_{MAX}\frac{\omega^2+\left(\omega_0^2-\omega^2\right)\eta_\perp k_{eff}/\left(2k_{eff}-k_b\right)\eta_\parallel\alpha}{\omega^2+\left[\omega_0^2-\omega^2\right]^2/\left(2k_{eff}-k_b\right)^2\alpha^2}$$

$$\varepsilon_{MAX} = \varepsilon_p\rho\eta_\parallel/\left(\alpha\cdot\left(2k_{eff}-k_b\right)\right)$$



Enhancement of spin-torque diode sensitivity!

The simulation parameters:

$E_{FL(R)}^{(Fe)} = 2.786eV$
$E_{FNM}^{(Au)} = 5.51eV$
$\Delta_{L(R)}^{(Fe)} = 1.0241eV$
$d_{ML}^{(Au)} = 0.2355nm$
$d_{NM}^{(Au)} = 2\cdot d_{ML}^{(Au)}$
$\varepsilon_P = 85.5mV/mW$
$\alpha = 0.01$
$k_{eff} = 0.6$
$k_b = 0.3$

Spin-transfer torque efficiency

$$\eta_{\parallel(\perp)} = \frac{2e}{\hbar}\left(\frac{T_{\parallel(\perp)}(\pi/2)}{< J_e >}\right)$$

Modified MR

$$\rho = \frac{R_{AP}-R_P}{R_P+R_{AP}} = \frac{MR}{2+MR}$$

Eff. anisotropy coefficient

$$k_{eff} = \frac{2K_u}{M_S^2} - 4\pi N_Z + 4\pi N_Y$$

Shape anisotropy coefficient

$$k_b = 4\pi\left(N_Y - N_X\right)$$

Resonant frequency

$$\omega_0 = \left(k_{eff}-k_b\right)k_{eff}$$

RESULTS AND DISCUSSION

The analysis of the conductance and spin-transfer torques in magnetic nanowires shows that, unfortunately, there is no quantization effects in the case of magnetic tunnel junction due to small tunneling probability but the quantization of these values occurs in the case of a spin-valve structure with metallic spacer. A decrease of cross-section lateral sizes to several nm makes it possible to obtain an increase in the microwave sensitivity in the absence of a bias magnetic field and a direct bias current of the spin diode by more than two order of value. The results obtained can be useful for future development of high-sensitivity microwave detectors for microwave imaging and other practical applications.

REFERENCES AND ACKNOWLEDGMENTS

References: [1] S. Miwa et. al., Nature Materials. – V.13. – pp. 50–56 (2014); [2] X. Li, Y. Zhou, P.W.T. Pong, Journal of Nanotechnology. – № 8347280. – p. 1-11 (2016); [3] S. Miwa et. al., Nature Communications. – V. 7. – p. 11259 (2016); [4] A.F. Popkov, N.E. Kulagin, G.D. Demin, Solid State Communications. – V. 248.– pp. 140–143 (2016)

Acknowledgments: The work was supported by the Russian Science Foundation project № 16-19-00181.