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TITLE OF THE DOCTORAL DISSERTATION:

Dynamika i przełączanie magnetyzacji indukowane prądami spinowymi w heterostrukturach metal ciężki/ferromangetyk

Dynamics and spin-current induced switching in heavy metal/ferromagnet heterostructures

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1. Introduction

This doctoral thesis examines the dynamics and magnetization switching phenomena in magnetic tunnel junctions and spin Hall heterostructures for potential applications in magnetic random access memory - MRAM. Currently, a contemporary MRAM cell uses spin-transfer torque (STT) effect and consists of two thin ferromagnetic layers separated by the non-magnetic insulating layer which is a tunnel barrier. The spin polarized electrons from the first ferromagnetic layer tunnel to the second ferromagnetic layer, ,which due to the STT effect leads to magnetization switching. Changes in the relative magnetization direction of the ferromagnetic layers results in resistance changes (due to the magetoresistance effect), allowing information to be read at low currents going through the MTJ. The challenge is to record information, as high current density may lead to the risk of breaking the tunnel barrier because of the potential degradation, while designing the free ferromagnetic layer for too low current density leads to thermal instability. Optimization is a fundamental problem in the techniques of MTJ produced on an industrial scale. MTJ parameters are affected not only by the magnetically active layers included in its composition, but also by the layers beneath them - buffer layers. Changes in the material, its thickness, annealing parameters or deposition of buffer layers can influence the magnetic parameters of MTJ, among others, field anisotropy, saturation magnetization or damping parameter. Even small roughness, crystallographic texture, doping, or mixing at the interface of individual layers are important for layers weighing several to a dozen atomic layers.

For spin Hall effect heterostructures, spin currents are generated by non-magnetic heavy metals is characterized by high spin-orbit coupling. Spin-orbit scattering of electrons leads to spin accumulation transverse to the direction of charge current flow and causes the magnetization vector to move, leading to the precessions in the ferromagnetic layer. Thanks

to this, it is possible to eliminate the necessity of current flow through the MTJ barrier during information recording from the classic MRAM memory and replace it with a planar current used for recording, coming from the spin-orbital interaction in the heavy metal layer.
The use of the spin-orbital polarization effect is still in the phase of intensive research, which focuses mainly on obtaining the highest possible spin-to-charge interconversion rate of the so-called spin Hall angle, which is the ratio of the spin current density to the charge current density.

2. Theses of work

Main aim of the conducted research are the following:

- optimizing multilayer structure for high spin-charge interconversion
- fabricating prototypical devices for precise determination of the spin-Hall angle
- development of the experimental methods for spin-charge interconversion
- designing devices for magnetic-field-free magnetization switching with spin-orbit torque effect

3. Proposed methodology

DIfferent multilayer struture systems were designed, deposited using the magnetron sputtering and experimentally tested using various experimental methods. In order to determine the actual thicknesses of individual layer and the crystal structure (such as phase analysis, crystallite size, texture, mixing at the interfaces of the layers), XRD diffraction measurements and XRR measurements were carried out. In addition, a vibrating sample magnetometer was used in the ferromagnets continuous layers to estimate the spontaneous magnetization, saturation and magnetization hysteresis loop.

Dynamic measurements, initially for continuous ferromagnetic layers, were carried out using a vector network analyser ferromagnetic resonance VNA-FMR method. Next, dynamic measurements of the structured samples were carried out using the spin-diode ferromagnetic resonance method SD-FMR with stepper motor driven by a dedicated linear controller controlled the mechanical rotation of the stage. Current switching with and without the use of an external magnetic field was carried out using the four-point method. Moreover, in order to check the samples neuromorphic like behaviour, impulse wave generator was used. The measurements to calculate the spin Hall angle were carried out using the methods of harmonic Hall voltage with mechanical rotation of the stage.

Micro and nano-fabrication of MTJs and multilayers was at the Laboratory of Laser Ablation and Nanolithography in Academic Centre of Materials and Nanotechnology AGH.

4. Key results

The first experimental section shows how to characterize the dynamic properties of samples that have not been subjected to the patterning process - samples with continuous layers of ferromagnetic material. The two types of pMTJ were investigated with varying thicknesses of FM and MgO (capping layer). Signals from the two layers were observed and characterized by the VNA-FMR method. The thermal stability was determined and the field free current induced switching achieved.

The second paper presents a system in which SOT-induced switching in the Co/Pt/Co structure with in-plane and perpendicular anisotropy of Co layers coupled ferromagnetically by the Pt spacer with varying thickness is investigated. Here the spin Hall angle and spin-diffusion length are determined using the SOT FMR method, the results of which are analysed using the dedicated theoretical model. In this case, the coupling between two Co layers is tuned by the Pt spacer thickness, where field-free SOT-induced switching of the perpendicularly magnetized Co layer is observed. Moreover, for a specific range of Pt, gradual magnetization change with in-plane current is obtained.

In the third paper, the investigation of the dynamics and the switching process in CoFeB/Ta/CoFeB trilayers with in-plane and perpendicular magnetic anisotropies of the two ferromagnets were done. Interesting behaviour of IEC, determined by the SOT-FMR technique was discovered. IEC tuned by varying Ta spacer thickness and changes from ferromagnetic (t_{Ta} < 1.3 nm) to antiferromagnetic (1.3 nm < t_{Ta}). In an antiferromagnetic regime, a small external magnetic field is required for SOT switching to be achieved. However, in the ferromagnetic regime the field-free SOT switching is obtained, but the resistance change range is slightly reduced.

In the last section, an energy efficiency measurement protocol for spin orbit torque was proposed based on low frequency hall voltage measurement and RF ferromagnetic resonance analysis. The protocol has been verified in Pt- and Pt-Ti-based devices, yielding an intrinsic spin-hall angle of up to 0.35 and a spin-hall conductivity of up to 3.3 x10^5 S/m, resulting in one of the highest values reported. The dynamic parameters was investigated by SD-FMR technique. The spin Hall efficiencies as a function of the HM layer were obtained. The evaluation of the spin Hall angle (spin current to charge current ratio) was done by harmonic Hall voltage measurement with controlled mechanical rotation stage. The summary for interface transparency, spin Hall angle and spin Hall conductivity in Pt and PT/Ti interfaces were showed.

5. Publications incorporated in the doctoral thesis

[P1] W. Skowroński, **S. Łazarski,** P. Rzeszut, S. Ziętek, J. Chęciński and J. Wrona, Influence of a composite free layer structure on thermal stability of perpendicular magnetic tunnel junction, **Journal of Applied Physics** 124, 063903 (2018). DOI: doi.org/10.1063/1.5032148

[P4] S. Łazarski, W. Skowroński, J. Kanak, Ł. Karwacki, S. Ziętek, K. Grochot, T. Stobiecki and F. Stobiecki, Field-Free Spin-Orbit Torque Switching in Co/Pt/Co Multilayer with Mixed Magnetic Anisotropies, **Physical Review Applied** 12, 014006 (2019).

DOI: 10.1103/PhysRevApplied.12.014006

[P7] S. Łazarski, W. Skowroński, K. Grochot, W. Powroźnik, J. Kanak, M. Schmidt and T. Stobiecki, Spin-orbit torque induced magnetisation dynamics and switching in CoFeB/Ta/CoFeB system with mixed magnetic anisotropy, **Physical Review B** 103, 134421 (2021). DOI: 10.1103/ PhysRevB.103.134421

[P9] W. Skowroński, K. Grochot, P. Rzeszut, **S. Łazarski,** G. Gajoch, C. Worek, J. Kanak, T. Stobiecki, J. Langer, B. Ocker and M. Vafaee Angular Harmonic Hall Voltage and Magnetoresistance Measurements of Pt/FeCoB and Pt-Ti/FeCoB Bilayers for Spin Hall Conductivity Determination, **IEEE Transactions on Electron Devices** 68, no. 12, p. 6379-5385 (2021). DOI: 10.1109/TED.2021.3122999