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Self-report · Autoreferat

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Static and dynamic characterization of magnetic tunnel junctions with perpendicular anisotropy.

Statyczna i dynamiczna charakteryzacja magnetycznych złącz tunelowych z anizotropią prostopadłą.

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INTRODUCTION

The main scope of the PhD thesis was application of magnetic tunnel junctions (MTJ) in novel electronic devices and components such as radio frequency and neural platforms components, investigation of synchronization and coupling between adjacent elements. The main focus was to demonstrate practical applications of MTJs as elements of multi-state storage cells and their use for neuromorphic computing, as well as work towards using electrical synchronization between MTJ-based spin torque oscillators (STO). Also a comprehensive description of research methods, fabrication processes and tools used was included to allow for reproducing of the results.

The first novel concept presented was a multi-state magnetic random access memory (MRAM) cell, obtained by serially (head-to-tail) connecting multiple MTJs with a perpendicular anisotropy, a fixed layer at the bottom and a free layer at the top. Such a connection allows for gradual and quantized resistance increase of the system, instant decrease of the resistance level to minimum value and a wide range of positive and negative voltages not resulting in any change of the system state. Systems of up to seven serially connected MTJs were experimentally tested and exhibited up to eight stable states, which allows for storage of three bits of data in a single device. Considering the fact that usually cell-driving transistor size is greater than size of actual MRAM cell and is related to switching current needed, such a solution provides a way to increase data density in future MRAM devices. In addition, other electrical properties of single and multiple MTJs connected were determined, what allowed for a better analysis of their behavior as such memory cells.

Based on the previous research, and considering challenges in producing multi-state MRAM cells with small parameter variance, another application of such cells was emerging: artificial neural networks. First, a behavioral model of single MTJ was prepared, that allowed to perform simulations of serially connected elements. The basic type of characterization involved MTJ resistance vs. field (R-H) and resistance vs. applied voltage pulse amplitude (R-V). The R(V) curve for a multi-bit cell was then simulated using a behavioral model. After successful parameters optimization and determination, an architecture of voltage feed-forward artificial neural network involving such elements was presented, and designed in standard CMOS technology of UMC 180 nm. Combining all the data a full simulation of such a neural network was performed, proving that results of such computing idea are promising and might replace other solutions in the field, as they prove to be energy efficient.

The success in designing the artificial neural network led to further interest in the area. As other researchers examined artificial neural networks working in pulse or frequency domains it is assumed that some interconnections of spin torque oscillators may lead to an interesting solution too. On the path towards such solutions experiments were made to check on how spin torque oscillators might synchronize their signal to an external signal and signal generated by other elements of the same type. For this purpose another set of MTJ was utilized with an in-plane magnetized reference layer and perpendicularly magnetized free layer. experiments performed in the radio-frequency regime lead to a very clear and strong synchronization of STO precession at around 4 GHz to external signal of 2f, therefore use of such components as frequency dividers is possible. Also mutual effects between two serially (head-to-tail) connected elements were observed, including synchronization of their oscillation. Such results are promising and serve as a good starting point for further research in the field of using spin torque oscillators in artificial neural networks.

Overall a few practical applications of magnetic tunnel junctions were proposed and proven to work. Research towards the development of new circuits involving spintronic devices was done. The whole research process was very complicated, as fabrication of MTJs as nanodevices was challenging and very time-consuming. Also sometimes the fabrication process was not successful, even due to slightest variation of fabrication parameters. What is more the measurement process posed other types of challenges, such as practical inability to reproduce exact connection characteristics between experiments separated in time as well as often losing unprotected and sensitive bare MTJs to various kind of electrical spikes in the measurement system, that occurred despite proper shielding and grounding of all the equipment. It is hoped that outcome of the research will lead to significant applications of magnetic tunnel junctions in radio frequency and neural computing as well as will extend overall knowledge in this area by being a starting point for future studies in the matter.

THESES OF WORK

The main aim of the conducted research were following:

- Optimize fabrication procedure of serially connected chains of magnetic tunnel junctions with perpendicular magnetic anisotropy
- Characterize magnetic tunnel junctions under static conditions, examining spin transfer torque and current induced magnetization switching
- Develop the measurement protocol of spin torque oscillators and their synchronization to external and internal signals
- Characterize dynamic behavior of magnetic tunnel junctions in radio-frequency regime
- Propose industrial applications of magnetic tunnel junctions, such as multi-state MRAM and quantized weight for neural networks

METHODOLOGY

A number of multilayer magnetic tunnel junction structures deposited using magnetron sputtering by partners in Singulus AG (Germany) and AIST Tsukuba (Japan) were used as a base for experiments. These structures were subjected to a process of nanostructurization and lithography in the Academic Centre for Materials and Nanotechnology at AGH. The techniques used involved electron beam or optical UV projection lithography and e-beam lithography processes, followed by ion beam etching and magnetron sputtering in order to create the junctions (with sizes of around 100 nm each) and electrical contacts for measurement.

Fabricated samples were subjected to a series of electrical measurements in the presence of variable external magnetic fields. Using automated and semi-automated probe stations a series of measurements were taken, which allowed the characterization of behavior of elements under the test in a complex and precise way. The measurements included measurements of:

- Resistance while varying external magnetic field with fixed voltage
- Resistance while varying amplitude of pulsed voltage (millisecond-range) with fixed magnetic field
- Resistance while varying angle of external magnetic field with fixed amplitude and fixed voltage
- DC voltage produced by the element while powered with RF signal with varying frequency and constant magnetic field and RF power
- RF signal produced by the element while varying applied voltage or external magnetic field

Also various series and modifications of such measurements were possible to perform using sophisticated measurement software and scripting. Also automation and scripting was used to process and analyze the measurement data.

The neural network was designed and simulated using Cadence Virtuoso software. Non-electrical simulations were performed using Matlab scripting language with Deep Learning Toolbox package.

KEY RESULTS

The key results of the thesis are:

- Fabrication of a multi-bit magnetic random access memory cell with a potential industrial application, where the cell might increase data density in the memory type
- Preparation of the behavioral model of a single and multi-bit magnetic random access memory cell
- Introducing a neuromorphic computing scheme involving multi-bit cells and demonstrating simulation of operation of such device performing handwritten digits recognition
- Demonstrating ability of synchronization of oscillations of magnetic tunnel junction to an external signal as well as with each other

PUBLICATIONS INCORPORATED IN THE PHD THESIS

- P. Rzeszut, W. Skowroński, S. Ziętek, J. Wrona, and T. Stobiecki, “Multi-bit MRAM storage cells utilizing serially connected perpendicular magnetic tunnel junctions,” Journal of Applied Physics, vol. 125, no. 22, p. 223907, 2019.
- P. Rzeszut, J. Chęciński, I. Brzozowski, S. Ziętek,W. Skowroński, and T. Stobiecki, “Multi-state MRAM cells for hardware neuromorphic computing,” Scientific Reports, vol. 12, no. 1, pp. 1–11, 2022.
- P. Rzeszut, J. Mojsiejuk, W. Skowroński, S. Tsunegi, H. Kubota, and S. Yuasa, “Towards mutual synchronization of serially connected Spin Torque Oscillators based on magnetic tunnel junctions,” arXiv preprint arXiv:2306.11608, 2023.