Development of spin electronics devices for hardware implementation of neuromorphic computing platforms

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INTRODUCTION:

Within the project, we studied potential applications of spintronic devices in hardware implementations of neuromorphic platforms such as neural networks, with an emphasis on optimizing the control of magnetic devices using spin currents from spin-orbit coupling. We proposed neural networks based on memristive elements made of magnetic tunnel junctions (MTJ) and developed software for the simulation of macrospin spintronic devices. Spintronic devices are a class of electronic devices that use electron spin in addition to charge. They have the potential to enable the creation of new types of computing and information processing systems with increased performance and energy efficiency. The project investigated the use of spintronic devices in the context of neural networks, which are computational models inspired by the structure and function of the brain.

RESEARCH METHODOLOGY:

One aspect of the project was to optimize the control of magnetic devices using spin currents. Spin currents are generated in a material with high spin-orbit coupling (exhibiting spin-orbit torque (SOT)); the system was optimized so that its properties could be controlled by the SOT effect. By optimizing the use of the spin-orbit current in magnetic nano-devices, we hoped to improve the energy efficiency and performance of spintronic devices in neural networks. This part of the project involved two PhD students – Krzysztof Grochot and Stanisław Łazarski.

Another aspect of the project was to design of neural networks based on memristive elements made of magnetic tunnel junctions. Memory cells are usually binary units that store a single bit of information. It has been shown that several bits of information can be stored in series connections of magnetic tunnel junctions, which can be a quantized element of the neural network balance, which can change its resistance in response to the applied voltage – work done mainly by Piotr Rzeszut. The elements were proposed and simulated as a whole system as a way to implement synaptic weights in neural networks. The use of memristive elements made of magnetic tunnel junctions enables the development of new types of neural networks with better efficiency and energy efficiency.

In addition, another doctoral student, Jakub Mojsiejuk, developed a dedicated software for the simulation of magnetic elements using the macrospin method, which is a model of single-domain magnetization of ferromagnetic material. The simulation software developed by the team is intended to help understand the behavior of spintronic devices in neural networks and to facilitate the design and optimization of these devices.

An important aspect of the project was the stay of one of the PhD students, Piotr Rzeszut, in a the Spintronic Research Centre at AIST in Japan, where he worked on the coupling and synchronization of oscillators based on magnetic tunnel junctions.

A part of the experimental research was possible thanks to the use of a strong electromagnet, which was purchased with the IDUB funds.

RESULTS:

The research results were described in the following publications:

- Sławomir Ziętek, Jakub Mojsiejuk, Krzysztof Grochot, Stanisław Łazarski, Witold Skowroński, Tomasz Stobiecki: Numerical model of harmonic Hall voltage detection for spintronic devices, Phys. Rev. B 106, 024403 (2022)
- Piotr Rzeszut, Jakub Chęciński, Ireneusz Brzozowski, Sławomir Ziętek, Witold Skowroński, Tomasz Stobiecki, Multi-state MRAM cells for hardware neuromorphic computing, Scientific Reports 12, 7178 (2022)
- Jakub Mojsiejuk, Sławomir Ziętek, Krzysztof Grochot, Witold Skowroński, Tomasz Stobiecki: A comprehensive simulation package for analysis of multilayer spintronic devices, npj Computational Materials 9, 54 (2023)
- Jakub Pawlak, Witold Skowroński, Piotr Kuświk, Félix Casanova, Marek Przybylski: Spin Hall induced magnetization dynamics in multiferroic tunnel junction, Adv. Electron. Mater. 2300122 (2023)

DISCUSSION:

During the project, a number of new spintronic devices were designed that can be used to build novel platforms for neuromorphic computing. The research was based on two systems – multilayer systems exhibiting strong spin-orbit coupling, where magnetization orientations can be controlled by spin-polarized current coming from a layer of, for example, a heavy metal. The second system are magnetic tunnel junctions which can be the basis of a multicell, which can act as a quantized weight in a neural network. Alternatively, it is the basis for the construction of a spintronic oscillator where a degree of synchronization can be used, for example, in reservoir computing.

SUMMARY:

IDUB project was realized in Spin Electronics group at the Institute of Electronics at AGH the University, mainly by four PhD students. To date, the results were published in a number of well recognized high impact factor journals (the work in Scientific Reports was selected as the Top 100 paper in Engineering). In addition, parts of the research were presented in several international conferences, such as Physics of Magnetism 2023 in Poznań, JEMS 2022 in Warsaw, IEEE NAP 2022 in Kraków. The team was also successful in receiving a funding for another project – a Polish-Chinese joint research grant, Sheng.

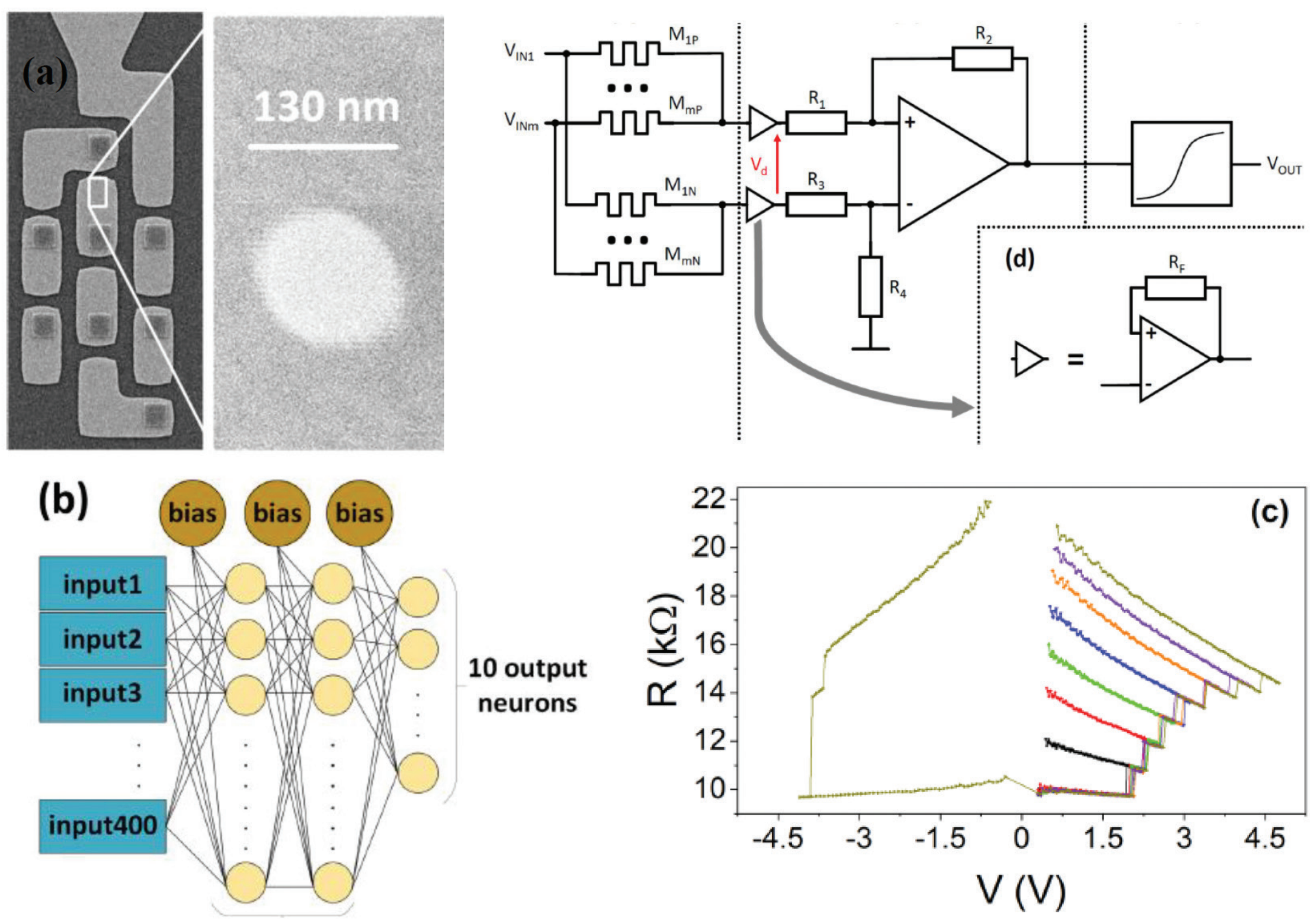

Figure 1. Serial connection of 8 MTJs comprising a multicell (a). Schematics of neural network utilizing multicell as a quantized weight (b), experimental dependence of the resistance as a function of the applied switching voltage, showing 7-level states (c) schematics of the artifical neuron (d).

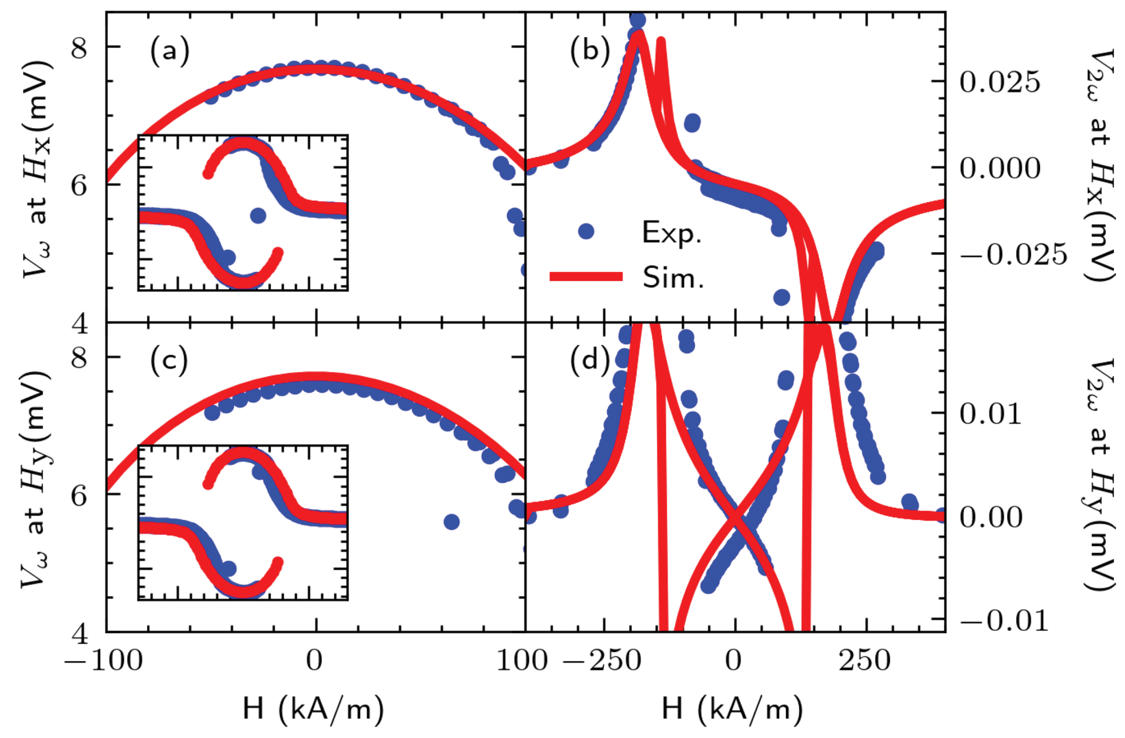

Figure 2. Comparison between experimental data of the effective fields and simulations based on the developed software in ferromagnet/heavy metal bilayers.

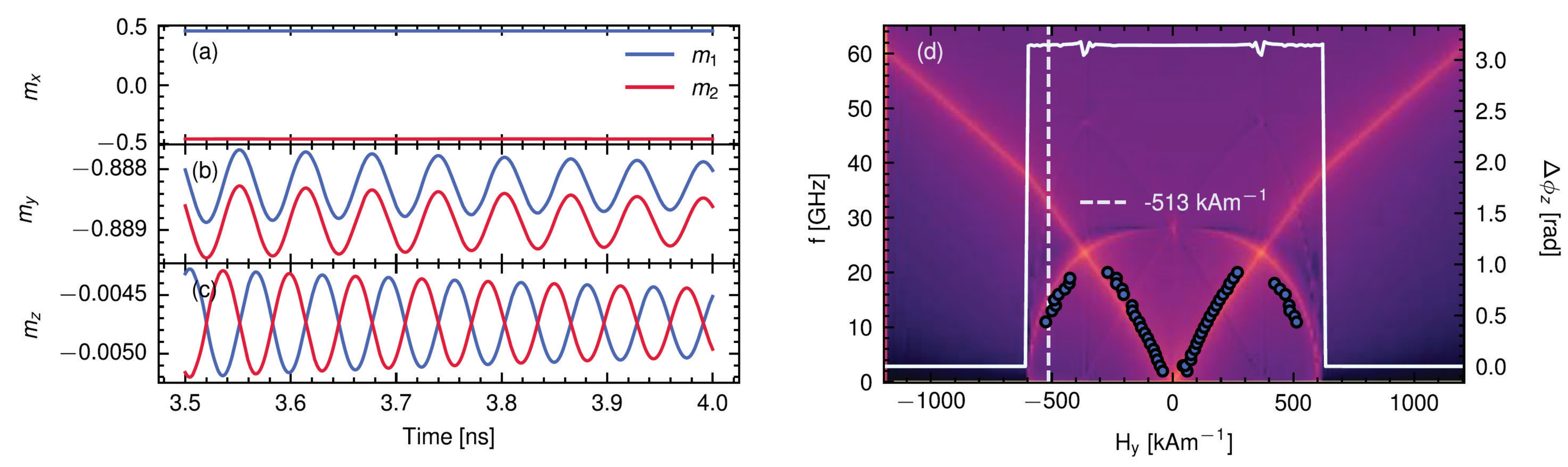

Figure 3. Simulations data of the precession of the magnetization in a multilayer system consisting of ferromagnet and heavy metals. Oscillations up to 20 GHz were observed with a good agreement between optical and acoustic modes.

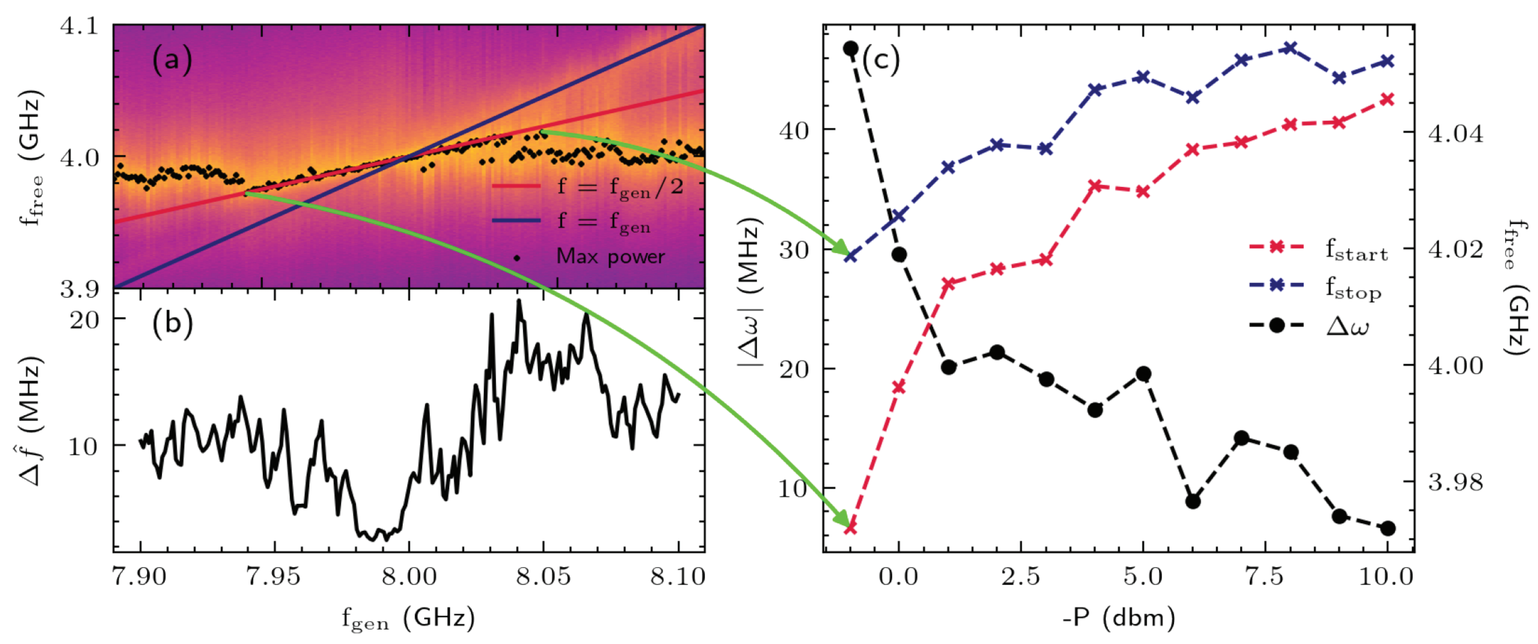

Figure 4. Synchronization of the MTJ oscillations to a double frequency of the external generator resulting in a frequency lock-in and a reduction of the oscillations linewidth.

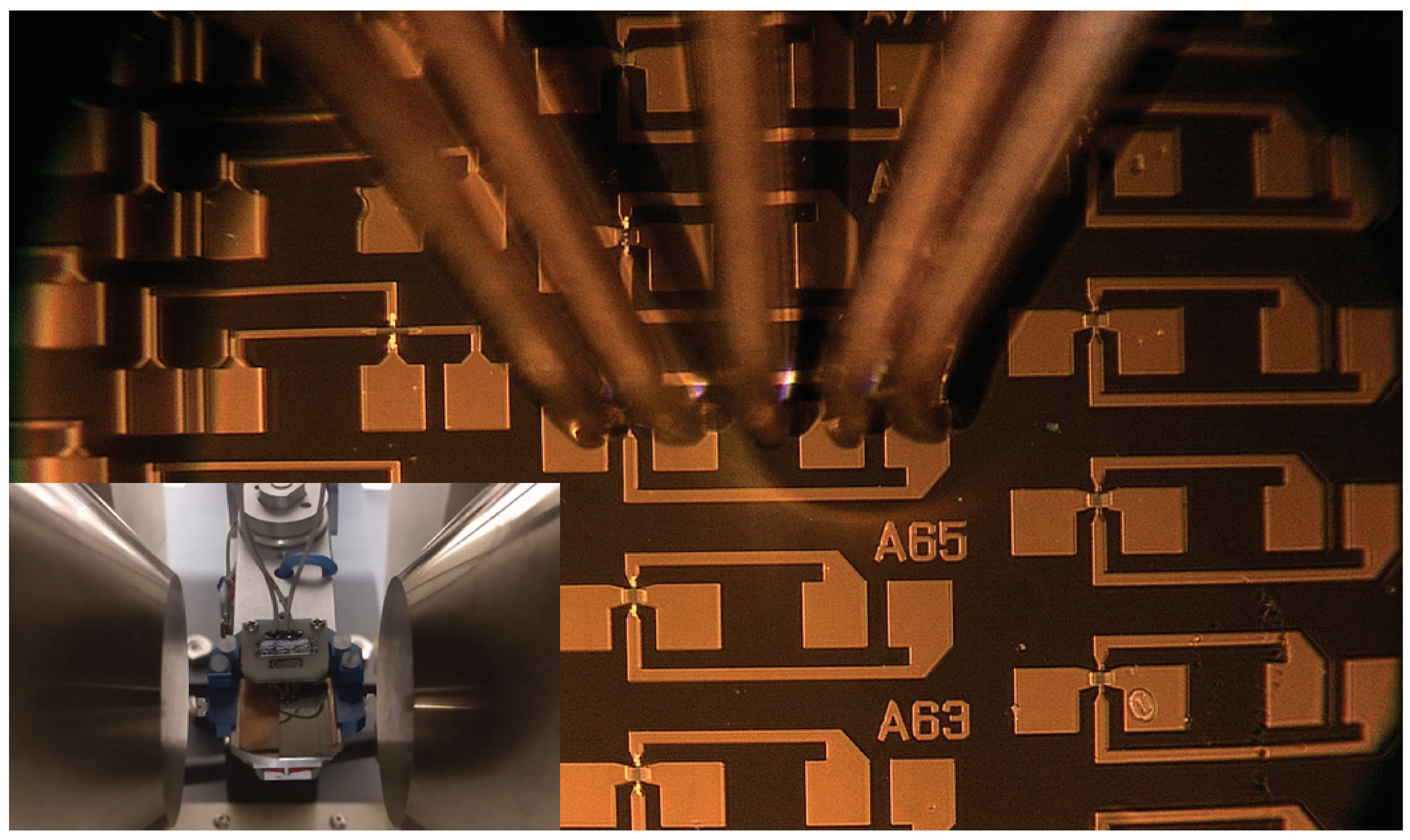

Figure 5. Matrix of ferromagnets/heavy metal Hall bars used for spin orbit torque determination. Inset shows a rotating probe station mounted in an electromagnet.