First Symposium

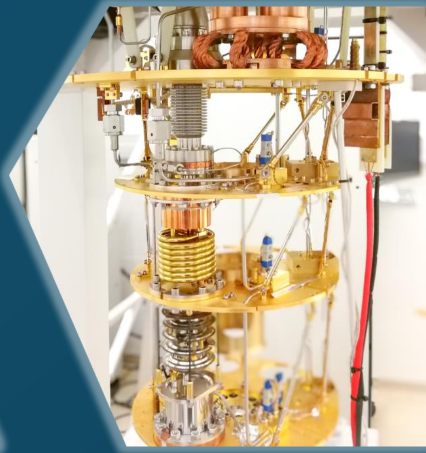
on

Physics and Chemistry for Unconventional Computing

Book of Abstracts

AGH University of Krakow
Academic Centre for Materials and Nanotechnology

June 11-13, 2025
Krakow, Poland



- ✓ QUANTUM COMPUTING
- ✓ SPINTRONICS AND ORBITRONICS
- ✓ NEUROMORPHIC COMPUTING
- ✓ RESERVOIR COMPUTING
- ✓ BIOCOMPUTING AND MOLECULAR COMPUTING

ACADEMIC CENTRE FOR MATERIALS AND NANOTECHNOLOGY
FACULTY OF PHYSICS AND APPLIED COMPUTER SCIENCE
FACULTY OF COMPUTER SCIENCE, ELECTRONICS AND TELECOMMUNICATIONS

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Reconfigurable Logic-in-Memory Based on Magnon Torque

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In-memory computing, utilizing non-volatile memories capable of performing both information storage and logic operations within the same device, holds the promise for empowering artificial intelligence with significantly reduced energy consumption. Existing logic-in-memory devices that have been implemented operate mainly based on charge transport, a process that inevitably gives rise to joule heating. On the other hand, information processing and transmission using magnons as information carriers is a promising route for developing spin-based logic and memory devices with low-dissipation, since magnons can transport spin in ferrimagnetic and antiferromagnetic insulators without involving moving electrons. For practical applications, the implementation of magnon logic operations using gate voltages is necessary. Current technology to manipulate magnon current transport at room temperature mainly relies on magnetic fields that can reorientate the magnetic ordering or modulate the magnetic domain structure. It remains challenging to develop a magnon-based logic due to the lack of efficient electrical manipulation of magnon transport. We presented a magnon logic-in-memory device in a spin-source/multiferroic/ferromagnet structure, where multiferroic magnon modes can be electrically excited and controlled. In this device, magnon information is encoded to ferromagnetic bits by the magnon-mediated spin torque. We showed that the ferroelectric polarization can electrically modulate the magnon spin-torque by controlling the non-collinear antiferromagnetic structure in multiferroic bismuth ferrite thin films with coupled antiferromagnetic and ferroelectric orders. By manipulating the two coupled non-volatile state variables—ferroelectric polarization and magnetization—we further demonstrate reconfigurable logic-in-memory operations in a single device. These findings highlight the potential of multiferroics for controlling magnon information transport and offer a pathway towards room-temperature voltage-controlled, low-power, scalable magnonics for in-memory computing.

Hybrid structure based on soft ferromagnetic film and multilayer nanodots as a platform for spin wave computing

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Materials with perpendicular magnetic anisotropy and antisymmetric exchange interactions have been widely explored in spintronics, but have been of limited use in magnonics due to high attenuation. We propose a hybrid structure that exploits a mutual skyrmion-ferromagnetic film interaction and the rich dynamical properties of skyrmions to control skyrmion dynamics in a ferromagnetic multilayer and spin-wave propagation in a low-damping ferromagnetic strip [1]. The proposed hybrid system consists of skyrmions confined in a strip or circular multilayer above a permalloy film. Numerical results show improved stability of the skyrmion and complex spin-wave spectra with several key features for magnonics: dispersive bands with Bragg band gaps, anti-crossing gaps related to a coupling between two magnon modes of different origin; the flat bands and bound states related to the skyrmion azimuthal modes with frequencies below and above the ferromagnetic resonance frequency of the permalloy strip, respectively. In addition, the system offers reprogrammability due to two stable magnetisation states in the nanodots, a single domain state and a skyrmion state. With these properties, the proposed hybrid structure has multiple functionalities useful for magnonics, overcoming the damping limitations of materials with perpendicular magnetic anisotropy and antisymmetric exchange interactions, opening up potential applications in spin-wave filtering, spin-wave generation and analogue computing, in particular in the realisation of magnonic neural networks.

Acknowledgment
We acknowledge the financial support from National Science Centre, Poland, grants no. UMO-2020/39/I/ST3/02413 and UMO-2021/41/N/ST3/04478.

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Spin-Orbit Computing Devices

C. K. Safeer[1]

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As transistor-based computing devices face challenges such as power dissipation, volatility, and scaling bottlenecks, spintronic devices are emerging as strong candidates to replace CMOS technology. Among them, spin–orbit-based devices such as Spin-Orbit Torque Magnetic Random Access Memory (SOT-MRAM) and Magnetoelectric Spin-Orbit (MESO) logic have shown compelling potential due to their non-volatility, high speed, and energy efficiency. SOT-MRAM operates by utilizing spin–orbit torques generated in heavy metals or topological insulators to switch the magnetization of a ferromagnetic free layer, with separate read and write paths that enhance endurance and reliability [1–3]. MESO logic builds on similar spin to charge interconversion (SCI) mechanisms and introduces voltage-driven magnetoelectric switching, enabling ultra-low-energy logic operations [4].

For both technologies, efficient SCI mechanisms is critical for minimizing energy loss and ensuring scalability. This includes both bulk mechanisms (e.g., the spin Hall effect) and interfacial effects (e.g., the inverse Rashba–Edelstein effect), which have been demonstrated in various material systems. Spin–orbit torque switching without external magnetic fields has been achieved through symmetry engineering in heterostructures[3], or by using low-symmetry two-dimensional (2D) materials [5-7], while efficient SCI in 2D systems such as graphene and transition metal dichalcogenides shows promise for low-power, room-temperature, gate-tunable operation [8-10]. These advances not only pave the way for practical device architectures but also highlight the feasibility of ultra-thin, reconfigurable spin-based logic and memory, key to unlocking the full potential of post-CMOS technologies for in-memory computing and artificial intelligence.

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Interlayer Dzyaloshinskii– Moriya interactions in epitaxial Co/Ir/Co/Pt multilayers

Anna Kozioł-Rachwał[1], Edyta Oleś[1], Piotr Dróżdż[1], Artur Kwiatkowski[1], Michał Ślęzak[1] and Tomasz Ślęzak[1]

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The Dzyaloshinskii–Moriya interaction (DMI) is an antisymmetric exchange interaction that arises in systems lacking inversion symmetry.[1] Initially demonstrated in ferromagnetic (FM) thin films, DMI describes the coupling between spins mediated by an adjacent paramagnetic heavy metal layer. As DMI favors a specific rotational sense of spin alignment within the FM layer, is inherently chiral in nature.

More recently, theoretical predictions[2] and experimental studies[3] have confirmed the presence of a significant interlayer DMI between neighboring FM layers separated by a non-magnetic spacer. This type of interlayer DMI opens up new avenues for tailoring magnetic textures and improving the functional capabilities of magnetic multilayer structures.

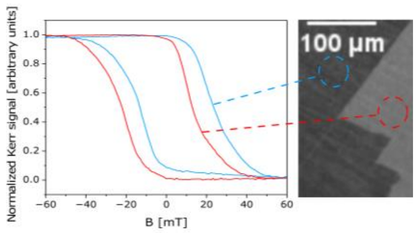

Figure 1. Right: PMOKE microscopy image registered at B_z=-16mT for Co(3nm)/Ir(0.4nm)/Co(1.7nm)/Pt, left: PMOKE hysteresis loops measured for regions of the sample with two antiparallel in-plane domains of top layer.

In our study we investigated the magnetic properties of epitaxial Co(3nm)/Ir(t_{Ir})/Co(d_{Co})/Pt multilayers grown by molecular beam epitaxy on MgO(111). The top FM layer exhibited in-plane magnetization, while variation of the d_{Co} enabled control of perpendicular magnetic anisotropy in the bottom Co layer. For a specific range of Co layer thickness and Ir spacer thickness, where strong antiferromagnetic RKKY interaction is expected, we observed unique magnetic behavior of the bottom Co layer that is sensitive to the magnetic state of the top Co film. Figure 1 (right) shows the polar magnetooptic Kerr effect (PMOKE) microscopy contrast obtained under a perpendicular magnetic field of −16 mT. Prior to the PMOKE measurement, the sample was demagnetized using an in-plane magnetic field to induce the formation of in-plane magnetic domains in the top Co layer. Remarkably, the domain pattern was preserved during magnetization reversal under the perpendicular field. PMOKE hysteresis loops measured in two regions—corresponding to antiparallel in-plane domains—are shifted in opposite directions (Figure 1, left), providing clear evidence of interlayer DMI in the system. In my presentation, I will demonstrate how the magnetic properties of Co(3nm)/Ir(t_{Ir})/Co(d_{Co})/Pt multilayers evolve with changes in t_{Ir} and d_{Co}.

Acknowledgment

Research project was supported by program "Excellence initiative – research university" for the "AGH University of Science and Technology".

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Modification of topological magnon gap in CrI_3 monolayer

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The topological magnonics opens up a new way to create novel information carrier devices like spin-wave diodes, spin-wave beam splitters, and spin-wave interferometers[1] as an alternative to their electronic counterparts. A good candidate for the realisation of those devices is a CrI_3 monolayer, a ferromagnetic van der Waals crystal with a honeycomb lattice arrangement and the existence of a band gap, along with the topological edge states at Dirac points. There have been many debates about the origin of the topological magnon band gap in these materials since two main models with distinct characteristics, i.e., Dzyaloshinskii-Moriya (DM) and Kitaev, provided possible explanations with different outcome implications[2,3]. Here we investigate the angular magnetic field dependence of the magnon gap of CrI_3 using stochastic atomistic spin dynamics simulations together with linear spin wave theory to determine the main differences between Kitaev and DM models. We observe three distinct magnetic field dependencies between these two gap opening mechanisms[4]. First, we demonstrate that the Kitaev-induced magnon gap is influenced by both the direction and amplitude of the applied magnetic field, while the DM-induced gap is solely affected by the magnetic field direction. Second, the position of the Dirac cones within the Kitaev-induced magnon gap shifts in response to changes in the magnetic field direction, whereas they remain unaffected by the magnetic field direction in the DM-induced gap scenario. Third, we find a direct-indirect magnon band-gap transition in the Kitaev model by varying the applied magnetic field direction. These differences may distinguish the origin of topological magnon gaps in CrI_3 and pave the way for exploration and engineering topological gaps in other van der Waals magnetic materials.

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Multiferroic Perovskite Heterostructures for Data Storage Applications

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Heterostructures composed of layers with different ferroic orders enable both the optimization of individual layer properties and the coupling between them, with great potential for applications in data storage. Particularly interesting are systems based on complex oxides such as perovskites, which exhibit properties including ferromagnetism, ferroelectricity, high spin polarization, and strong sensitivity to different stimuli (strain, temperature, voltage etc.).
We present studies on multiferroic tunnel juntions of Fe/$BaTiO_3$ (BTO)/$La_{0.67}Sr_{0.33}MnO_3$ (LSMO) and Pt/Co/BTO/LSMO, grown epitaxially on $SrTiO_3$ (STO) substrates using pulsed laser deposition (PLD) (Fig. 1 a and b), and fabricated using ion-etching-free lithography. We observed presence of tunneling electroresistance (TER) and tunneling magnetoresistance (TMR) effects (relative change of resistance depending on the voltage/magnetic field) at room temperature [1]. Furthermore, spin-orbit torque ferromagnetic resonance (SOT-FMR) measurements in Pt/Co/BTO/LSMO structures demonstrate the excitation of magnetization dynamics in both the Co and LSMO layers (Fig. 1 c), which indicates efficient spin current transport through the BTO barrier via the spin Hall effect (SHE) in Pt [2]. These findings highlight the potential for controlling the magnetic properties using purely electrical current. The coupling of ferroic orders in epitaxial perovskite layers is currently being investigated as a pathway to control spin properties via voltage.

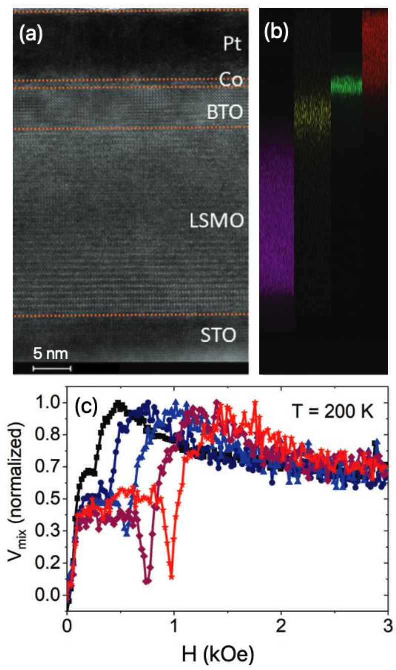

Figure 1. HR-TEM of the multilayer is presented in (a). EDX maps of Mn (purple), Ba (yellow), Co (green), and Pt (orange) are shown in (b). The measurements of the SOT-FMR spectra at T=200 K performed at different excitation frequencies (c).

Acknowledgment

The research project is partially supported by the Excellence initiative-research university (IDUB) programme of the AGH University of Krakow.

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Properties of $L1_1$ CuPt/CoPt deposited on Si and STO substrates

Piotr Jabłoński[1], Jakub Pawlak[2], Maciej Czapkiewicz[2], Jarosław Kanak[2], Jakub Czerski[2], Krzysztof Grochot[2], Anna Kozioł Rachwał[3], Witold Skowroński[2], Marek Przybylski[1,3]

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The total energy expenditure for computing is continuously increasing, and predictions alarm that around 2040 it could exceed the world's energy production [1]. In reference to the necessity of reducing energy consumption, modern magnetic-memory technology focuses on low energy devices. In response to that requirement, magnetic random access memory (mRAM) considers using the Spin-Orbit Torque (SOT) effect for magnetization switching and the perpendicular magnetic anisotropy (PMA) that enhances thermal stability of a nanomagnet. The SOT effect occurs in heavy metal/ferromagnet (HM/FM) heterostructures, however, deterministic switching of perpendicualrly magnetized magnets requires an additional symmetry breaking mechanism, such as an additional in-plane field, coupling to another magnet, or out-of-plane damping like torque. It was reported that in the CuPt/CoPt bilayer with broken inversion-symmetry, thanks to the 3m1 point group, specific 3m torque enables field-free SOT-switching [2]. Following that idea, we present structural and magnetic studies of CuPt/CoPt bilayers of different thicknesses deposited by magnetron sputtering on Si and STO(111) substrates. The PMA in CoPt, measured using Anomalous Hall effect (AHE) – Fig.1., is observed for a CoPt layer thinner than 3 nm. The system is characterized by varying sizes of the magnetic domains depending on the CoPt thickness. . Field-free current-induced switching of magnetic domain was observed by means of magneto-optic Kerr effect microscope and photoelectron emission microscopy with X-ray circular dichroism contrast. Spin-Torque Ferromagnetic Resonance (ST-FMR) measurements – Fig.2. allowed for the determination of the Gilbert damping α=0.15, indicating magnetic losses in the CoPt alloy. We demonstrate the influence of the substrate on the CuPt/CoPt structure, and consequently, on its magnetic domain structure and damping properties.

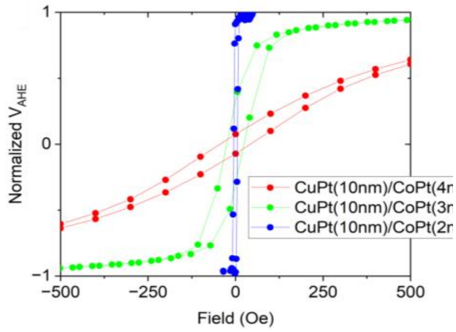

Figure 1. *AHE voltage of CuPt/CoPt with different thicknesses on Si.*

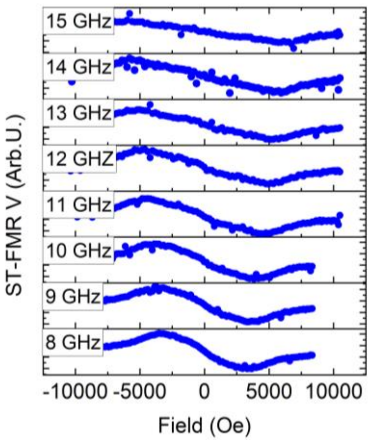

Figure 2. *ST-FMR signal voltage for different frequency of the alternating current of the CuPt/CoPt(2nm) sample.*

Acknowledgment

We acknowledge National Science Centre, Poland project no. 2021/40/Q/ST5/00209 (Sheng) and the Excellence initiative-research university (IDUB) programme of the AGH University of Krakow.

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Synchronization and desynchronization of electrically coupled spin torque connected in series.

Jakub Mojsiejuk[1], Piotr Rzeszut[1], Sumito Tsunegi[2], Kay Yakushiji[2], Hitoshi Kubota[2], Shinji Yuasa[2], and Witold Skowroński[1]
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The use of spin torque oscillators (STO) has gained traction in recent years due to potential application in radio frequency (RF) devices and pattern recognition [0]. The challenge there lies in a reliable way to control their synchronization [1, 2]. We explore the electric coupling of two magnetic tunnel junctions (MTJs) connected in series acting as STOs, which upon DC supply generated the RF signal. Both synchronized and de-synchronized state were observed, in which the individual oscillating frequencies of the STOs diverged. This result is replicated in numerical simulation using a macrospin LLGS equation with a coupling modification [3]. A parameter dispersion analysis was conducted to demonstrate how a relative change in the anisotropy of the second MTJ connected in series can affect the synchronization. This fact is then leveraged to propose an STO with voltage controlled magnetic anisotropy (VCMA) that can achieve synchronization and desynchronization on a small temporal scale, on demand.

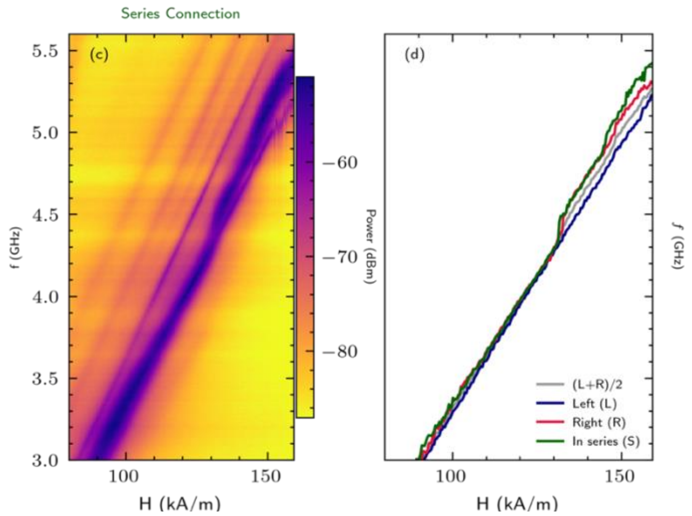

Fig.1 Frequency desynchronization of the STOs connected in series. Left, oscillation spectrum of two MTJs connected in series. Right, extracted max power frequency lines from in-series (S) setup, and left MTJ (L) and right MTJ (R) when they were measured separately. As reference, an averaged signal (L+R)/2, of individual oscillations of L and R in gray.

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Can we build a topological qubit in 2025?

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Recently a lot of attention has been given to the prospects of a realization of a topological qubit based on Majorana Zero Modes. In relation to this, I will critically examine the so-called topological gap protocol (TGP). I will demonstrate that the TGP is not a reliable diagnostic tool for the presence of topological superconductivity and associated Majorana Zero Modes. Moreover, I will show that this protocol is also an unreliable method to detect a superconducting gap, a prerequisite for readout of a well-defined parity in a superconductor and the proposed basis of a putative topological qubit. Based on these insights, I will show that any kind of topological qubit is not possible in the near term.

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Superconductor-quantum dot hybrid chains for quantum technologies

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Majorana zero-modes (MZMs) are predicted to be hosted at the edges of one-dimensional p-wave superconductors. MZMs can be characterized as spinless, chargeless and zero-energy excitations. Interest in MZMs has been driven by their potential applications in quantum computing, where high-fidelity gates are expected to be achieved, and quantum information can be protected from decoherence. Various platforms where MZMs might be hosted have been proposed, including topological insulators, semiconducting nanowires with strong spin-orbit interaction, iron-based superconductors, and fractional quantum Hall systems. A bottom-up approach has recently been introduced, wherein quantum dots in semiconductors with strong spin-orbit coupling have been coupled through superconductors to create a unit cell of the Kitaev chain[1,2]. Pairs of fine-tuned MZMs can be generated even in such minimal units, through which their properties can be studied [3]. In this talk I will present an experimental approach to the engineering of basic Kitaev chain components in a semiconductor/superconductor hybrid based on InSb nanowires with aluminum half-shells. I will discuss results on chain scaling [4] along with future experiments through which quantum information applications might be implemented using this platform.

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Superconducting Quantum Interference Devices based on InSb Nanoflag Josephson Junctions

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High-quality III-V narrow bandgap semiconductor materials with strong spin-orbit coupling and large Lande g-factor provide a promising platform for next-generation applications in the field of high-speed electronics, spintronics, and quantum computing. InSb stands out due to its narrow bandgap, high carrier mobility, and small effective mass, making it very appealing for these applications. In fact, this material has attracted tremendous attention in recent years for the implementation of topological superconducting states.

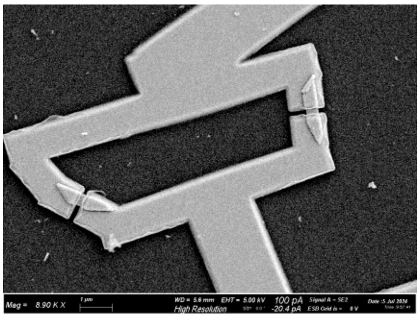

Figure 1. Top-view scanning electron microscopy image of a SQUID in symmetric geometry.

In this context, the simultaneous breaking of time-reversal and inversion symmetry can lead to peculiar effects in Josephson junctions, such as the anomalous Josephson effect or supercurrent rectification, which is a dissipationless analog of the diode effect. Due to their potential impact in new quantum technologies, it is important to find robust platforms and external means to manipulate the above effects in a controlled way. We demonstrate that hybrid Josephson junctions made of high-quality InSb nanoflags [1] constitute a promising platform for supercurrent rectification due to its strong spin orbit coupling. The high quality of the devices enabled the observation of the diode effect in these Josephson junctions [2]. When subjected to an in-plane magnetic field, these devices enter a non-reciprocal transport regime, manifesting an asymmetry between positive and negative critical currents.
Furthermore, we fabricated and investigated superconducting quantum interference devices (SQUIDs) based on InSb nanoflag Josephson junctions [3]. We measured interference patterns in both symmetric and asymmetric geometries. The interference patterns in both configurations can be modulated by a back-gate voltage, a feature well reproduced through numerical simulations. The observed behavior aligns with the skewed current-phase relations of the Josephson junctions, demonstrating significant contributions from higher harmonics. Finally, we assess the flux-to-voltage sensitivity of the SQUIDs to evaluate their performance as magnetometers.

Acknowledgment

We acknowledge support from project PRIN2022 2022-PH852L(PE3) TopoFlags-"Non-reciprocal supercurrent and topological transition in hybrid Nb-InSb nanoflags" funded by the European Community-Next Generation EU within the program "PNRR Missione 4- Componente 2-Investimento 1.1 Fondo per il Programma Nazionale di Ricerca e Progetti di Rilevante Interesse Nazionale (PRIN)" and by PNRR MUR Project No. PE0000023-NQSTI.

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Beyond-classical computation in quantum simulation

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Quantum computers hold the promise of solving certain problems that lie beyond the reach of conventional computers. However, establishing this capability, especially for impactful and meaningful problems, remains a central challenge. Here, we show that superconducting quantum annealing processors can rapidly generate samples in close agreement with solutions of the Schrödinger equation. We demonstrate area-law scaling of entanglement in the model quench dynamics of two-, three-, and infinite-dimensional spin glasses, supporting the observed stretched-exponential scaling of effort for matrix-product-state approaches. We show that several leading approximate methods based on tensor networks and neural networks cannot achieve the same accuracy as the quantum annealer within a reasonable time frame. Thus, quantum annealers can answer questions of practical importance that may remain out of reach for classical computation.

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Signatures of a gate-controlled superconducting diode effect in LAO/STO 2DEG

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The superconducting diode effect (SDE), which allows current to flow without resistance in only one direction, has significant potential for quantum computing. Gate-tunable SDE devices can serve as low-power, directionally controlled components that improve qubit readout, enable non-reciprocal signal flow, and help scale quantum circuits by reducing heat and complexity in cryogenic setups.
We chose the transtion metals oxide heterostructutre $LaAlO_3/SrTiO_3$ (LAO/STO), in which the presence of SDE is predicted theoretically [1]. This system hosts a superconducting two-dimensional electron gas (2DEG) at the LAO/STO interface. The combined effect of spin-orbit coupling and an external in-plane magnetic field give rise to a non-zero total momentum of Cooper pairs in 2DEG in superconducting state, enabling the emergence of the SDE. This would manifest as a dependence of the critical current I_c on the direction of the magnetic field. Our goal is to experimentally detect this effect.
We performed current-voltage I(V) measurements at temperatures ranging from 50 to 500 mK and in-plane magnetic fields up to 2 T. A superconducting transition at zero gate voltage was observed at T_c = 240 mK, consistent with previous reports. The temperature dependence of both the I(V) characteristics and I_c follows the Berezinskii–Kosterlitz–Thouless (BKT) model, which is characteristic of unconventional 2D superconductivity.
We observed signatures of the SDE in our LAO/STO structures (Fig. 1) after comparing the critical current for opposite orientations of the magnetic field and current flow. With no gate voltage, our 2DEG system shows only small changes in I_c. Given the highly tunable nature of the LAO/STO interface – particularly in terms of 2DEG carrier concentration and mobility – we applied gate voltage to probe the SDE under various conditions.

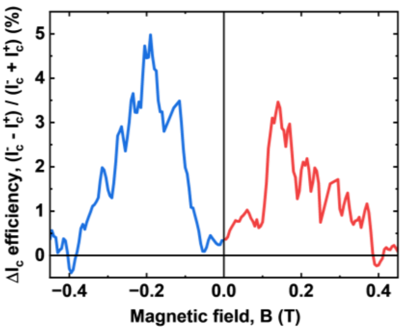

Figure 1. The difference in critical current ΔI_c for opposite orientations of the magnetic field B, as a signature of SDE.

Acknowledgment
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Feature Maps in Quantum Neural Networks for Causal Inference

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Understanding what quantum layers in hybrid neural networks actually do to data is still a largely open question. By performing Principal Component Analysis (PCA)[1] analysis at multiple stages within our hybrid model, we investigate the transformation of feature space through classical, quantum, and post-quantum layers. This not only clarifies where learning happens—but also reveals how poorly chosen feature mappings can collapse performance entirely.

Figure 1. PCA Analysis

This work addresses the problem of causality detection using hybrid quantum-classical neural networks. The aim is to design and analyze an architecture that combines classical convolutional processing with quantum feature mapping and a quantum neural layer. A particular focus is placed on the impact of the selected quantum feature mappings, which play a critical role in the success or failure of the training process. The proposed solution employs a hybrid architecture where a convolutional layer extracts features from input data, followed by a quantum feature mapping into Hilbert space and a parameterized quantum circuit acting as a quantum layer. Results demonstrate that a well-chosen feature mappping significantly enhances class separability and stabilizes the training process. The included PCA visualizations show how the data evolves through the network, culminating in clear clustering of classes after the quantum layer, as illustrated in the provided Figure 1. The main contribution of this work is a systematic evaluation of quantum feature mapping in hybrid models and a visualization of how quantum layers transform the data. These insights provide more transparent quantum machine learning models and contribute to building more effective networks for causality detection tasks.

Acknowledgment

This work was supported by the Ministry of Education, Youth and Sports of the Czech Republic through the e-INFRA CZ (ID:90254). We gratefully acknowledge the funding support by program "Excellence initiative—research university" for the AGH University in Krakow as well as the ARTIQ project: UMO-2021/01/2/ST6/00004 and ARTIQ/0004/2021. Italian Government (Ministero dell'Università e della Ricerca, PRIN 2022 PNRR) -- cod.P2022SELA7: ''RECHARGE: monitoRing, tEsting, and CHaracterization of performAnce Regressions`` -- Decreto Direttoriale n. 1205 del 28/7/2023.

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SpinGlassPEPS: Tensor-network package for Ising-like optimization on quasi-two-dimensional graphs

Tomasz Śmierzchalski[1], Anna M. Dziubyna[2,3], Konrad Jałowiecki[1], Zakaria Mzaouali[1], Lukasz Pawela[1], Bartłomiej Gardas[1] and Marek M. Rams[2]

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Finding the ground state of the Ising model is a well-known NP-hard problem. It is connected to Quadratic Unconstrained Binary Optimization (QUBO), a mathematical framework that can express optimization problems relevant to various fields. There are many heuristic algorithms and hardware solutions for tackling QUBOs. In recent years, quantum annealing devices have emerged as a possible avenue for addressing this task. They encode optimization problems as physical systems, which, when evolved, settle into the ground state of the relevant Ising model.

Recent work[1] introduced a novel heuristic tensor network (TN) based algorithm to reveal the low-energy spectrum of Ising spin-glass systems with interaction graphs relevant to present-day quantum annealers. It combines a branch-and-bound search strategy with an approximate calculation of marginals via TN contractions. Here, we present **SpinGlassPEPS.jl**, a Julia package that implements this algorithm and lowers the entry barrier to use advanced tensor network methods in classical optimization. It is specifically tailored to solve Ising and QUBO problems on the topologies of present and near-term quantum annealers, such as Pegasus and Zephyr geometries. **SpinGlassPEPS.jl** functions both as a standalone Ising solver and as a source of independent tools for developing physics-inspired algorithms, offering features such as droplet discovery, Schmidt spectrum calculation, and energy level degeneracy analysis.

Acknowledgment

This project was supported by the National Science Center (NCN), Poland, under Projects: Sonata Bis 10, No. 2020/38/E/ST3/00269 (T.S., Z.M.) and 2020/38/E/ST3/00150 (A.D., M.R.) and Foundation for Polish Science (grant no POIR.04.04.00-00-14DE/ 18-00 carried out within the Team-Net program co-financed by the European Union under the European Regional Development Fund) (B.G., L.P.).

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Exploiting the dynamical properties of memristors for efficient information processing

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Memristive devices are commonly benchmarked by the multi-level programmability of their resistance states. Neural networks utilizing memristor crossbar arrays as synaptic layers largely rely on this feature. However, these "static" applications leave the rich dynamical properties of memristors largely unexploited. These dynamic features include not only the availability of ultra-short switching times of 10ps,[1,2] but also the exponential voltage dependence of the resistive switching speed[3] and the tunability of the dynamic fluctuations by voltage manipulation.[4] In my talk, I will review how these can be used for efficient information processing, such as (i) solving complex computational problems with memristive Hopfield neural networks,[5] or (ii) performing time series analysis and prediction with dynamical memristor circuits.[6]

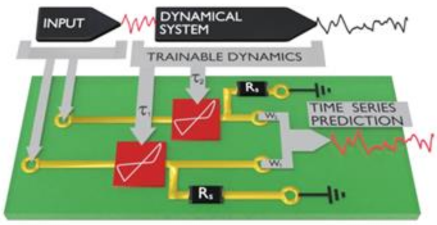

Figure 1. Time-series prediction with a simple dynamical memristor circuit.[6]

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Materials and Optoelectronic Devices for Neuromorphic Computing

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Neuromorphic engineering is poised to revolutionise current computing as it holds promise for ultra-low power operation. Drawing inspiration from the brain, its dense network of interconnected neurons and the way of transmitting and processing information via neuronal spiking events at the biological synapses, several new nanodevice paradigms have emerged for developing artificial intelligence (AI) hardware and cognitive computing systems. Among these nanodevices, memristive devices have gained a lot of attention due to their advantages, such as low power consumption, high integration density and the capability to replicate synaptic plasticity, which align with the requirements of neuromorphic computing.
In this work, I will present the work performed in my group (www.flexiblenanoelectronics.com) with two nanomaterial classes, namely zero-dimensional (0D) Bismuth halide perovskites[1] and two-dimensional (2D) transition metal dichalcogenide (TMD) materials,[2] to facilitate the development of efficient optoelectronic neuromorphic hardware. We first tune the cation size in non-toxic solution-processed Bi-based perovskites to emulate synaptic functionalities and demonstrate application in reservoir computing. We further compare different device structures able to accommodate such low dimensional nanomaterials, namely a coplanar nanogap separated electrodes[3] vs the more conventional sandwich or crossbar architecture. The utilisation of MoS_2 in 2-terminal devices fabricated with nanogap electrodes showcases the potential to reduce switching voltages to a crucial minimum.
In conclusion, by combining functional nanomaterials, such as perovskites and 2D materials, with nanoscale device architectures and looking into their future incorporation into artificial neural networks, we can expect significant advancements in neuromorphic computing, bringing us closer to a future, where computational systems mimic the remarkable efficiency and adaptability of the human brain.

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Physical AI: challenges and opportunities

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Understanding balances between computing capacity and the implementation cost is perhaps one of the most complicated aspects of Unconventional Computing. This tension becomes particularly pronounced in the realm of Physical AI, where computation is embedded directly into material substrates, which blurs the line between hardware and algorithm. Unlike traditional digital systems, which benefit from abstraction layers and well-established scaling laws, physical computing platforms often confront trade-offs between efficiency, scalability, programmability, and robustness. This leads us directly to Putnam's computing rock paradox, which provocatively suggests that under certain mappings, any physical system, even a rock, could be interpreted as implementing any computation. While intended to illustrate a problem with one of the key hypotheses in the philosophy of mind, this paradox forces us to confront a foundational issue: What constitutes meaningful computation in a physical substrate? How do we distinguish between a system that merely permits computational interpretation and one that actively performs computation with purpose and utility? The presentation will conclude with an overview of some examples regarding how to find the right balance between the amount of resources needed to realize a computation, versus the amount of computation generated.

Acknowledgment

Partners of the RECORD-IT project; Dr. Vasileios Athanasiou
Funding: H2020 FET Open, RECORD-IT, project no. 664786

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Tackling Reliability and Scalability in Neuromorphic Computing via Noise-aware Learning

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Neuromorphic computing has evolved into a broad label encompassing technologies inspired not only by biological systems but increasingly by machine learning architectures. While often promoted as a potential energy-efficient alternative to conventional hardware, many of these claims remain loosely substantiated.

This talk outlines key challenges in the field, with a focus on variability and scalability. I will present concrete examples from my recent work demonstrating how noise-aware learning—particularly in systems with stochastic, device-level behaviour—can help mitigate variability and improve robustness. These results suggest that while noise poses real constraints, it might be systematically addressed through appropriate learning strategies.

Energy consumption problems of modern digital ANNs and a possible memristive SNN solution

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Despite significant advances in computing power and data availability, digital ANNs remain fundamentally constrained when compared to their biological counterparts, especially Spiking Neural Networks (SNNs). (1) I highlight the energy inefficiency: digital ANNs consume 6–8 orders of magnitude more energy than biological SNNs. This discrepancy likely stems from the underlying learning algorithms and architectural choices, which fail to capture the sparse, event-driven nature of biological computation. (2) Current ANNs require several orders of magnitude more training data than biological SNNs, further pointing to the inefficiencies of feedforward learning and the lack of contextual adaptability. (3) The wide use of feedforward architectures severely limits the capacity for self-learning and autonomous adaptation. In contrast, biological SNNs heavily rely on feedback loops—recurrent motifs that enable real-time modulation and generation of information in situ. (4) The Perceptron model, while computationally efficient, lacks the neuromodulation. This precludes any realistic simulation of emotional or motivational states mediated by neurotransmitters such as serotonin, dopamine, and noradrenaline—key elements in biological learning. (5) A common workaround in modern ANNs is to freeze network weights after offline training, which inhibits continuous online learning—a hallmark of living neural systems.
Later, I will explore how memristive SNNs offer promising solutions to these challenges. Memristive devices, which change state only during synaptic updates, enable highly energy-efficient computation. Feedback-rich SNNs can dynamically generate and integrate information in space and time, closely mimicking the brain's information-processing strategies. Moreover, mechanisms such as bidirectional replay of waking experience—unique to biological SNNs—support memory consolidation and enable efficient one-shot learning and continual adaptation[1].
Later, I will demonstrate the use cases of the memristive SNNs: (1) the digital implementation of the neuromodulatory pathways of a rat [2]; (2) spinal cord trauma with the complete model of the spinal cord constructed as both a digital neurosimulation and a memristive spiking device[3].

Acknowledgment
This study was partially funded by the Fairground project: Artificial and Bio-Inspired Networked Intelligence for Constrained Autonomous Devices Fairground Bando A Cascata A Valere Sul Piano Nazionale Ripresa E Resilienza (PNRR) Missione 4, Istruzione E Ricerca-Componente 2, Dalla Ricerca Allimpresa-Linea Di Inve-Stimento 1.3, Finanziato Dallunione Europea Nextgenerationeu, Progetto Future Artificial Intelligence Fair PE0000013 CUP (Master): J53C22003010006 CUP: J43C24000230007. The author(s) acknowledge(s) the support of the APC central fund of the University of Messina.

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Applying neurodynamic behavior of Mott memristors for auditory sensing

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Neurodynamic behavior of artificial neuron circuits made of Mott memristors[1] provide versatile opportunities to utilize them for artificial sensing.[2] In these realizations, usually a sensor is connected to an artificial neuron or oscillator circuit to generate a spiking output encoding the stimulus, which is later carried to a spiking neural network for further processing. By directly conducting such signals encoding stimuli into the nervous system, an artificial sensory input can be created. We explore possibilities to realize an auditory sensing circuit aiming future applications in cochlear implants (hearing aids), motivated by small size and energy-efficient spike generation capabilities of VO_2 oscillator circuits.
In this work, a MEMS cantilever is connected to a VO_2 nanogap Mott memristor[3] based oscillator circuit, capable of neural spike emission. The electrical signal of the cantilever serves as an input for the VO_2 oscillator circuit. The cantilever is excited with mechanical stimuli in the range of ~10 nm, which is realistic in the human ear. As a result, the oscillator emits a train of spikes with a well-defined frequency, which can be tuned to the desired frequency domain of typical spiking rates in the nervous system. Due to the internal dynamics of the oscillator part, the frequency of oscillation encodes the amplitude of the stimulus – similarly to processes of natural hearing. The proposed circuit serves as a proof-of-concept demonstration of a Mott-memristor based auditory sensing unit for future cochlear implants.

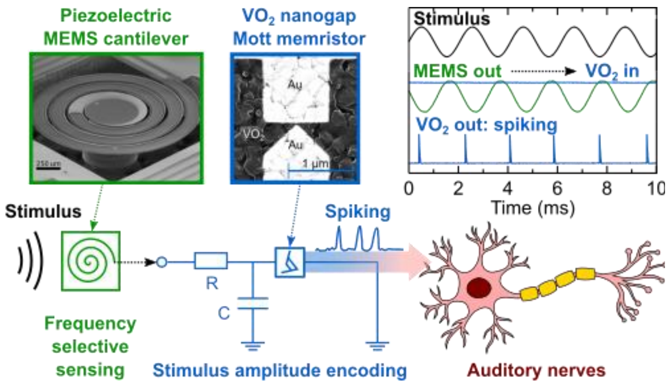

Figure 1. Concept of the auditory sensing circuit.

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Reconfigurable Magnonic-Spintronic Device Architecture Based on Domain Wall Control

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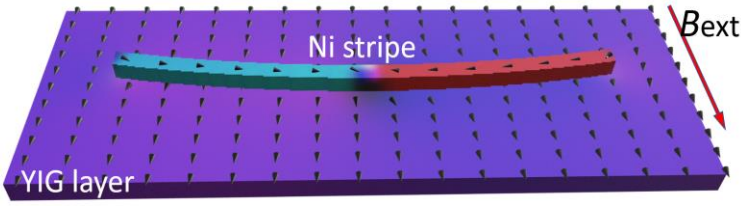

Figure 1. A YIG layer with an Ni stripe placed above it, under an external magnetic field (*B*ext).

To address the energy crisis in computation, we investigate hybrid magnonic-spintronics devices for in-memory computing. Using mumax3 simulations, we study a in-plane magnetized system composed of a soft ferromagnetic stripe (e.g., Ni or Py), capable of stabilizing domain walls (DWs) via notches or curvature, placed above a YIG film [Fig. 1]. Initially, we observe that the stray field from the DW locally modifies the YIG layer magnetization, inducing a phase shift in propagating spin waves (SWs). This phase shift can be dynamically controlled in the space by repositioning the DW using pulse-currents, enabling a reconfigurable DW position in the stripe, which overcomes limitations present in previously studied systems [1].
Another finding is based on stabilizing DWs in metastable or low-gradient energy minimum positions along the stripe through curvature or magnetization saturation gradients. We demonstrate that dynamic stray fields generated by SW propagation in the YIG layer with wavevector parallel to the stripe length and frequencies corresponded resonance in ferromagnetic stripe can displace the DW when waves pass under regions under the DW [2]. In low energy-gradient scenarios, the DW returns to its initial position post-SW excitation, functioning effectively as a flip-flop memory element.
These findings highlight the scalability and potential of hybrid magnonic-spintronics devices as robust platforms for neuromorphic computing. Future research will focus on optimizing stripe geometry, material selection, and enhancing SW-DW coupling to further improve device performance.

Acknowledgment

The research leading to these results has received funding from the Polish National Science Centre project Preludium 23 no 2024/53/N/ST3/03244 and the European Union's Horizon Europe research and innovation program under Grant Agreement No. 101070347-MANNGA.

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Thin Films, Thick Ideas: $BiVO_4$ as a Material for the Computing of Tomorrow

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In the face of the current volume of digital data and the annually increasing amount of data being generated, conventional computing is becoming an inefficient method of performing computations. The world is turning its attention in search of new ways to process information, such as quantum computing, optoelectronics, or neuromorphic solutions. Particularly interesting is the latter approach, which aims to mimic the way the human brain performs computations. For this purpose, devices capable of changing their resistance, such as memristors, are frequently used. In this work, we present a new method for obtaining bismuth vanadate ($BiVO_4$) layers, as well as a memristor fabricated based on this material.

The layers were fabricated using the spin coating method, and the devices consisted of an indium tin oxide (ITO) layer as the counter electrode, a $BiVO_4$ layer, and a thin zinc layer deposited by thermal evaporation, serving as the working electrode. The device was characterized using cyclic voltammetry and chronoamperometric experiments. The fabricated layers were analyzed in terms of band gap width, work function, and crystal structure, and their morphology was visualized using scanning electron microscopy.

The band gap width of the fabricated layer was 2.5 eV, and the work function was 5.3 eV. XRD analysis showed that the layer consists of $BiVO_4$ in the monoclinic phase. Electrochemical measurements confirmed that the device exhibits memristive behavior and switches at a potential of -5 V / 5 V. The low resistance state (LRS) and high resistance state (HRS) are stable and distinguishable over time.

Acknowledgment
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Two-dimensional MoO_3 for memristive applications – a nanoscale study

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Two-dimensional (2D) van der Waals materials, such as transition metal oxides, continue to attract attention for their unique physical and chemical properties and broad application potential. Among their emerging applications, the use of 2D materials in memory technologies such as resistive random access memory (ReRAM) and neuromorphic computing is particularly promising. Central to these technologies is the resistive switching (RS) effect — a reversible change in resistance states triggered by electrical stimulation. While RS behaviour in metal-insulator-metal (MIM) structures has been widely studied on a macroscopic scale, direct insight at the nanoscale remains limited. In this study, we focus on the local investigation of resistive switching phenomena in a layered transition-metal oxide system using atomic force microscopy (AFM). Epitaxial molybdenum trioxide thin film was grown by thermal evaporation in ultra-high vacuum conditions onto highly oriented pyrolytic graphite. Chemical characterisation performed via X-ray photoelectron spectroscopy (XPS) revealed subtle nonstoichiometry in monolayer samples, whereas thicker layers displayed a more stoichiometric composition. We show AFM-based investigation of ultrathin crystalline MoO_3 – from monolayer (0.7 nm) up to few layers. The stimulation with conductive AFM probe shows bipolar resistive switching behaviour of MoO_3, where the SET process occurs under negative bias and the RESET under positive bias. Additionally, we showed electrostimulation-induced degradation of the MoO_3 films. These findings highlight the potential of ultrathin MoO_3 layers for future nanoscale memory applications and underscore the importance of nanoscale investigation in advancing miniaturized electronic devices.

Acknowledgment

This work was supported by the National Science Centre, Poland, under the Grant 2020/38/E/ST3/00293.

Neural Information Processing by a Dynamical Memristor Circuit

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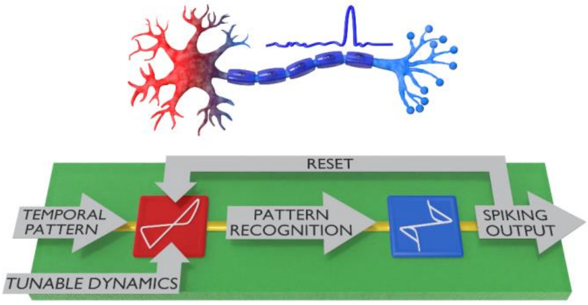

Figure 1. Schematics of the neuron detector/transceiver circuit. The module highlighted in red/ blue part is responsible for the detector / spiking output functionalities. The coupling between the two circuit parts and the feedback of the output to the input are symbolized by grey arrows.

Analog tunable memristors are widely utilized as artificial synapses in various neural network applications. However, exploiting the dynamical aspects of their conductance change to implement active neurons is still in its infancy, awaiting the realization of efficient neural signal recognition functionalities. Here we experimentally demonstrate an artificial neural information processing unit that can detect a temporal pattern in a very noisy environment, fire an output spike upon successful detection and reset itself in a fully unsupervised, autonomous manner[1]. This circuit relies on the dynamical operation of only two memristive blocks: a non-volatile Ta_2O_5 device and a volatile VO_2 unit as shown in Figure 1. A fading functionality with exponentially tunable memory time constant enables adaptive operation dynamics, which can be tailored for the targeted temporal pattern recognition task. In the trained circuit false input patterns only induce short-term variations. In contrast, the desired signal activates long-term memory operation of the non-volatile component, which triggers a firing output of the volatile block. Finally we demonstrate the generalization of this scheme to broader range of temporal signal detection tasks with a special focus on biological signals.

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Demonstration of Compact Reconfigurable SAT Problem Mapping Circuit for an Analog Electronic Amoeba

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Solving combinatorial optimization problems is involved in diverse practical applications in society, such as logistics, semiconductor chip design, and scheduling. In many cases the number of solution candidates increases exponentially with the problem scale, making it intractable for the conventional computer to find a solution within a realistic time frame. Ising machines developed as a dedicated hardware for the combinatorial optimization problem have difficulties in problem mapping, which consumes a lot of computation cost. As an alternative approach, we have developed a unique electronic computating system, called "analog electronic amoeba[1]" (Fig. 1). This system is inspired by slime mold, which has an efficient foraging ability; natural analogy for optimization process. The electronic amoeba electronically mimics the dynamic behavior of the slime mold and it is expected to achieve highly efficient solution searching.[2] An important issue is the demonstration of the performance, which needs to examine a set of large-scale problems. In this paper, we designed and demonstrated a scalable and reconfigurable problem-mapping circuit for the analog electronic amoeba. The problem-mapping circuit is called as bounceback circuit. We designed a compact reconfigurable bounceback circuit for the satisfiability problem (SAT) using two crossbars. One of them consisted of an externally controlled switch at each cross point and the instance to be solved was mapped by connecting appropriate points using the switches. In preliminary investigation using a circuit simulator, we found that the system integrating this circuit could achieve rapid solution search for 3-SAT instances with 8 variables and 60 clauses as shown in Fig. 2. It was also found that the computing ability depended on the circuit parameters. Careful control of the signal voltage range and the threshold of the nonlinear components was necessary for solution search.

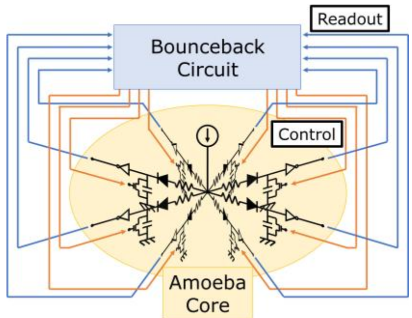

Figure 1. Schematic diagram of Analog Electronic Amoeba.

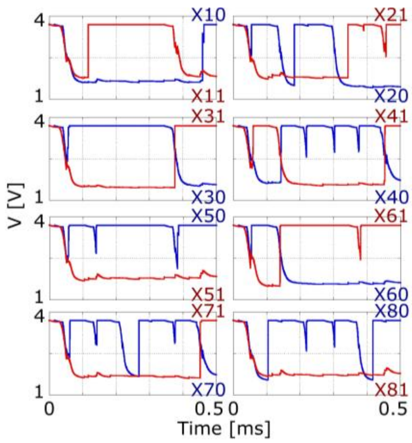

Figure 2. Transitions of state variables in solution search for a 3-SAT instance with 8 variables and 60 clauses.

Acknowledgment

This work was supported in part by JSPS KAKENHI Grant Number 23K20956, JSPS Core-to-Core Program "Material Intelligence", and by Grants for Revitalization of Regional Universities and Industries in Hokkaido.

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From Chemical Waves to Fungal Networks

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Unconventional Computing Lab, UWE, Bristol, UK

Advances in unconventional computing explore the possibility of performing computation using substrates fundamentally different from traditional silicon-based devices. In this talk, we present recent progress in harnessing chemical, biological, and soft-matter systems — specifically Belousov-Zhabotinsky (BZ) reactions, fungal networks, colloidal assemblies, and proteinoid microspheres — for novel computing architectures. Each system offers unique mechanisms of information processing: BZ reactions manifest self-organized chemical wave dynamics ideal for logic gates, pathfinding, and memory formation; fungal networks exhibit electrical spiking and adaptive routing behaviours, functioning as biological analogues of neural networks; colloidal systems demonstrate emergent organization and phase transitions that can be exploited for information storage and collective decision-making; and proteinoids, simple protocell models, can perform biochemical sensing and primitive logical operations based on their bioelectrical activity. We will discuss how computation emerges from localized interactions, chemical kinetics, and distributed architectures across these diverse substrates. Methodologies include the use of electrical and optical signal monitoring, machine learning for pattern recognition in complex dynamics, and hybrid bioelectronic interfaces to enhance controllability. Emphasis will be placed on how these systems respond to external stimuli, self-organize, and exhibit computation-like behaviours, such as classification, optimization, and memory storage, without central control. Moreover, we will highlight the challenges and opportunities in scaling up these systems, improving reliability, and integrating them into real-world applications, from environmental sensing to adaptive robotics. By moving computation into realms of soft, living, and semi-living matter, we envision sustainable, adaptive, and resilient computational systems that operate fundamentally differently from today's digital computers. Unconventional computing with BZ reactions, fungi, colloids, and proteinoids represents a step towards developing computing technologies that are not merely inspired by nature — but built directly from it.

Photochromic systems and oscillatory chemical reactions for the development of Chemical Artificial Intelligence

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The global challenges of the XXI century spur us to deal with Complex Systems and face Epistemological Complexity.[1,2] A promising strategy is the interdisciplinary research line of Natural Computing:[3] natural phenomena become a source of inspiration for formulating new algorithms, proposing new materials and architectures to compute, and new methods and models to understand the behavior of Complex Systems. The innovative Chemical Artificial Intelligence (CAI) sprouts from Natural Computing: it devises chemical systems in "wetware" (i.e., in liquid solutions) to mimic biological intelligence competencies.[4,5]
UV–visible radiation is valuable for maintaining the chemical systems out of thermodynamic equilibrium, prompting them to respond to optical and other physicochemical signals and probing their evolution. This contribution will show the roles that photochromic systems and oscillatory chemical reactions can play in the development of CAI.[6]
CAI is inspiring the design of adaptive, active, and autonomous chemical systems, which will help humanity to colonize the molecular world against diseases, pollution, and poverty. The development of CAI will probably have an alluring side effect: it will give clues for understanding the enigmatic event of the appearance of life on Earth.

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Ferrocene-based Molecular Logic Gates based on Photoinduced Electron Transfer

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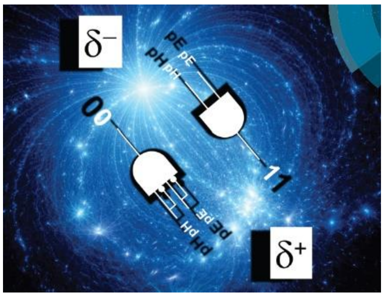
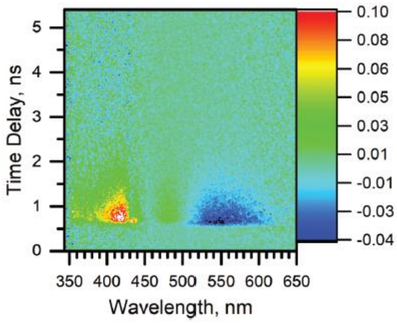
Molecular logic-based computation continues to attract considerable attention as the field contemplates societal applications.[1,2] Since the inception of the first AND logic gate for two cations, photoinduced electron transfer (PET) remains a steadfast design concept. Ferrocene is an icon organometallic compound owing to its stability, ease of functionalization and reversible redox character, which makes it a versatile building block in functional systems.[3] Our interest has been in developing ferrocene-based molecular logic gates based on PET.[4] These logic gates are typically designed in a modular format with an electron-donor (ferrocene), a fluorophore (i.e. 4-amino-1,8-naphthalimide) and a proton receptor (tertiary amine) with a fluorescence readout.[5] We are pursuing various applications of these inventions such as smart coatings for the early detection of corrosion[6] and lab-on-a-molecule systems for detecting a congregation of biologically relevant analytes.[7]





Acknowledgment

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Bridging photolithography and DNA origami for nanofabrication of molecular computers

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Molecular cellular automata, memristors, and photonic devices [1] represent the ultimate frontier in miniaturization, promising unprecedented computing speed, energy efficiency, and even the potential for implementing quantum algorithms. However, the reliable assembly of molecular components into complex, functional circuits — let alone scalable mass production — has remained an unsolved challenge for more than half a century [2].

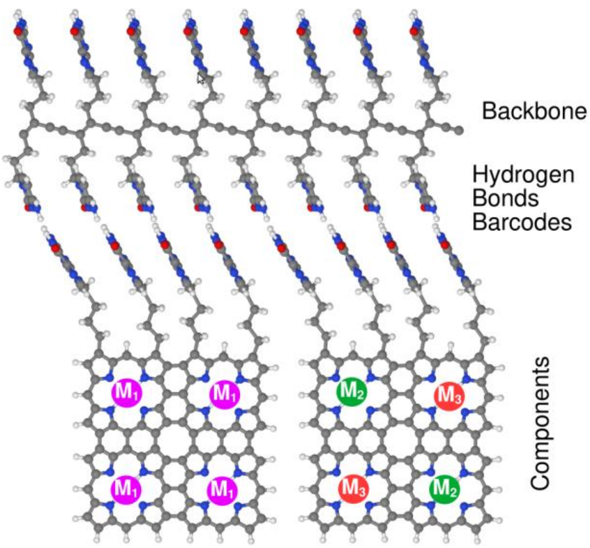

Fig 1: Schematics of MQCA assembled using photosensitive template

In this work, we address this problem through the computational design of novel polymer templates that combine bottom-up self-assembly, inspired by DNA origami, with a photo-polymerizable backbone compatible with photolithography. Unlike DNA, our synthetic polymers are engineered to operate on the surfaces of ionic crystals in anhydrous environments — conditions more suitable for integration with microelectronics and lithographic techniques.

The templates are designed to drive the non-covalent assembly of functional molecular components to precisely defined positions, programmed via unique combinations of complementary hydrogen-bonding groups. Meanwhile, the mesoscopic patterning of the polymer backbone can be controlled using a lithographic mask. As such, these nanofabrication methods promise to bridge the scale gap—from the atomic precision placement of individual molecules to the construction of complex chips composed of billions of molecular components.

In our initial publication [3], we present functional blocks of the templates, a detailed scheme of the nanofabrication process, and a computational screening of optimal complementary hydrogen-bonding

Bridging Organic - Inorganic Complexity through DFT Approaches

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Designing functional hybrid organic–inorganic materials through computational methods simplifies and accelerates the complex, time-consuming, and costly process of discovering new applicable composites.

This work demonstrates how the application of Density Functional Theory (DFT), combined with experimental techniques such as FTIR, XRD, SEM, and EIS, enables the investigation of the structural and electronic behavior of hybrid systems. Four case studies illustrate predictive insights and a deeper understanding of how atomic-scale modifications influence macroscopic properties. **The first** focuses on the problem of oxidation of metallic iron in polymer composites used, for example, in printed electronics. The combination of DFT and instrumental analyses allowed us to verify and confirm the inhibition of iron oxidation in PVDF/PMMA composites using nanometric ceramic additives [1]. **The second** example explores the promising compositions of polyvinylidene halides (PVDX) for use as solid polymer electrolytes in energy storage systems. The DFT study focused on the reactivity and ionic conductivity of PVDX/$LiClO_4$ composites and on identifying structural and electronic differences between the α and β crystalline forms of PVDX [2]. In **the third** case, the controlled oxygen implantation of 2D MoS_2 was investigated. Using DFT calculations combined with SIMS and Raman spectroscopy confirmed the formation of a stable MoS_2/MoO_3 heterostructure with distinct conductive–insulating properties [3]. Finally, **the fourth** case describe the DFT analysis of terpyridine-based organometallic wires complexed with transition metals revealed delocalized charge transport and structure–property correlations at the molecular scale [4]. These examples demonstrate how the combined theoretical–experimental framework enables the design and characterization of advanced organic–inorganic systems with tailored properties for electronic and energy applications.

Taken together, the presented work demonstrates how unconventional DFT-based modeling, can accelerate the discovery and design of hybrid organic–inorganic materials by predicting structure–function relationships critical to future applications.

Acknowledgment

Thank the Interdisciplinary Centre for Mathematical and Computational Modelling, University of Warsaw. Also thank UNINETT Sigma2 - the National Infrastructure for High Performance Computing and Data Storage for providing computational resources, and the Center of Excellence Hylleraas Center for Quantum Molecular Sciences in Norway.

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Bandgap engineering on the Cyanothiazole complexes

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Bandgap engineering enables the tailoring of the electronic properties by altering molecular geometry or the coordination environment. Band gap engineering on the Cyanothiazoles complexes enables the precise tuning of their electronic properties for optoelectronic and neuromorphic computing applications. Cyanothiazole, a small heterocyclic molecule featuring a thiazole ring and a cyano group, exhibit tunable HOMO and LUMO energy levels through the structural modification and coordination approches. By varying the positional isomerism of the cyano group, introducing electron-donating or electron-withdrawing substituents, and forming complexes with transition metals such as copper(I), the electronic delocalization and bandgap can be precisely modulated. (*1*)

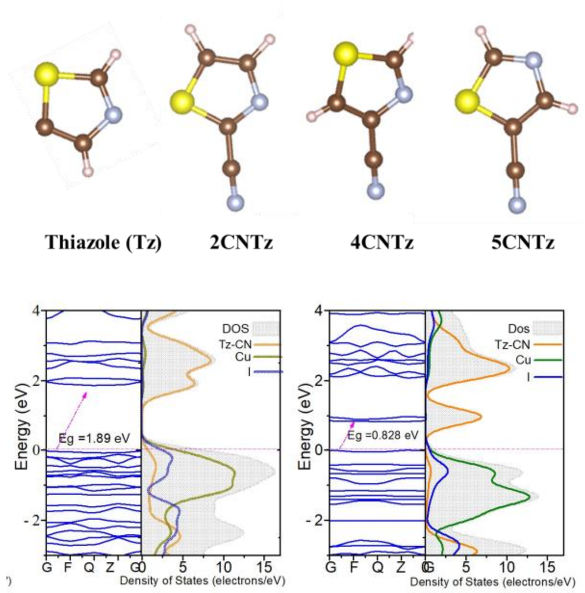

Figure 1. Thiazole (tz), cyanothiazoles (CNtz) molecule, and its band structures

As shown in Figure 1, the Thiazole molecules with three isomeric cyanothiazole-copper(I) iodide complexes demonstrate p-type, indirect bandgap semiconductor behavior, with valence bands primarily composed of hybridized 3d-copper and 5p-iodine orbitals and conduction bands dominated by unoccupied π* orbitals of the ligands. Despite their near-identical molecular geometries, these complexes exhibit distinct bandgap energies, underscoring the critical influence of ligand isomerism and anchoring group positions on electronic structure. Intermolecular interactions, including π-π stacking, hydrogen bonding, and halogen-chalcogen (I-S) interactions, further stabilize the complexes and fine-tune their optoelectronic properties by enhancing charge transfer. (*2*)

Computational calculations and spectroscopic investigations (e.g., UV-Vis, XRD) reveal that these molecular interactions enable bandgap tunability is suitable for applications such as light-emitting diodes, photovoltaics, and memory applications. The pursuit of these novel complexes is driven by the need for materials with customizable conductivity, which are essential for next-generation electronics. These findings highlight the potential of cyanothiazole complexes to bridge the gap between molecular design and functional device performance, offering a pathway to optoelectronics and molecular computing.

Acknowledgment

The authors gratefully acknowledge the Polish high-performance computing infrastructure, PLGrid

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Amoeba-inspired computing on analog electronic circuit

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A single-celled amoeboid organism is known to maximize nutrient acquisition efficiently by deforming its body, which have made it possible to survive in the harsh natural environment over a billion years. This fact suggests that the organism has a sophisticated computing ability, although it does not have a brain. Recently the high computing ability of the amoeboid organism has been demonstrated by means of the amoeba-based computer, in which the amoeboid organism searches for a solution of the combinatorial optimization problem[1].

We consider that the intelligence of the amoeboid organism arises from the body deformation dynamics. Based on this idea, we have attempted to reproduce the computing ability of the amoeboid organism in an artificial manner by electronically mimicking the amoeba deformation dynamics. Figure 1 shows a schematic view of the amoeba-inspired analog electronic computing system, called "electronic amoeba"[2]. The system consists of an amoeba core and a bounceback circuit. The amoeba core is simply designed by the commercially available electronic devices including diodes, resistors, capacitors, and transistors. Current in the circuit having star-topology network represents the dynamics of the pseudopod of the amoeboid organism. The mathematical problem that we want to solve is mapped on the bounceback circuit and it is connected with the amoeba core.

We have investigated the computing operation of the electronic amoeba using the fabricated electronic circuit on boards or electronic circuit simulator. We found that the analog electronic amoeba could find a reliable and swift solution to the intractable combinatorial optimization problems including, maximum cut problem, satisfiability problem (SAT), and traveling salesman problem (TSP)[3]. We also found that the characteristics of solution search, such as quality of the solutions and problem size dependence of exploration time, are quite similar between the amoeboid organism and the electronic amoeba. This similarity strongly suggests the validity of our hypothesis that the intelligence of the amoeboid organism arises from its deformation dynamics.

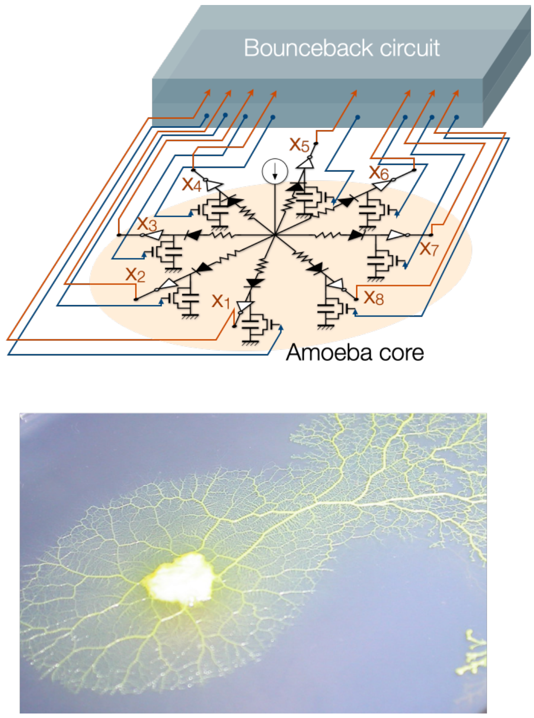

Figure 1 Analog electronic amoeba and amoeboid organism.

Acknowledgment

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Reservoir computing with nanomagnets and magnetic nanowire

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The rapid integration of artificial intelligence (AI) into modern society has highlighted the need to reduce the computational costs associated with AI systems. One promising approach to reduce the costs is physical reservoir computing (PRC), which uses unconventional physical systems—rather than traditional digital architectures—to perform complex computations. PRC maps computational calculation onto physical dynamics, enabling reduced power consumption and bypassing the von Neumann bottleneck by utilizing intrinsic memory effects. In this study, we focus on magnetic materials as physical reservoirs due to their non-volatile memory properties, as seen in technologies like magnetic recording media and magneto-resistive random-access memory. Magnetic materials are also used as computing elements. In recent years, in addition to nano-magnetic logic gates and domain wall logic gates, various types of reservoir computing have also been proposed.

We previously proposed a PRC system based on nanomagnets[1-3] and magnetic nanowires[4]. Recently, we have also performed prototype experiments of magnetic reservoir. Figure 1 shows an optical microscope image of the fabricated reservoir, which consists of λ-shaped nanowires made from MgO (3 nm)/Ni-Fe (20 nm)/Ta (5 nm)/SiO_2/Si substrate. The magnetic state of the nanowires, observed using a magneto-optical Kerr effect microscope, serves as the reservoir's dynamic node states. Binary input signals were written via current pulses applied to the electrodes for magnetic wall injection. Node state was updated by rotating elliptical magnetic fields. Evaluation using Short-Term Memory and Parity Check tasks confirmed the device's ability to store information and perform nonlinear computations. We expect that magnetic reservoirs will contribute to reducing the power consumption of AI in the near future.

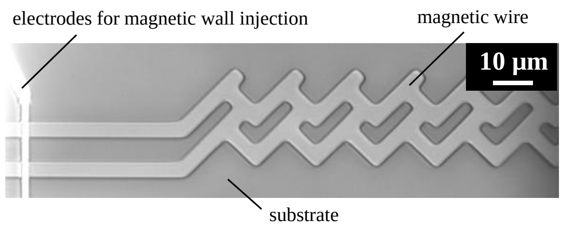

Fig. 1 Optical microscope image of magnetic wire reservoir.

This research was partly supported by received partial support from JSPS KAKENHI Grant No. 20H05655, JAPAN, JST CREST Grant No. JPMJCR20C6, JAPAN and JST CREST Grant No. JPMJCR2435.

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Reservoir computing with photon avalanching luminescencent inorganic materials

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Data processing and storage in electronic devices are typically performed as a sequence of elementary binary operations. Alternative approaches, such as neuromorphic or reservoir computing, are rapidly gaining interest where data processing is relatively slow, but can be performed in a more comprehensive way or massively in parallel, like in neuronal circuits. Here, time-domain all-optical information processing capabilities of photon-avalanching (PA) nanoparticles at room temperature are discovered. Demonstrated functionality resembles properties found in neuronal synapses, such as: paired-pulse facilitation and short-term internal memory, in situ plasticity, multiple inputs processing, and all-or-nothing threshold response. The PA-memory-like behavior shows capability of machine-learning-algorithm-free feature extraction and further recognition of 2D patterns with simple 2 input artificial neural network. Additionally, high nonlinearity of luminescence intensity in response to photoexcitation mimics and enhances spike-timing-dependent plasticity that is coherent in nature with the way a sound source is localized in animal neuronal circuits. Not only are yet unexplored fundamental properties of photon-avalanche luminescence kinetics studied, but this approach, combined with recent achievements in photonics, light confinement and guiding, promises all-optical data processing, control, adaptive responsivity, and storage on photonic chips.

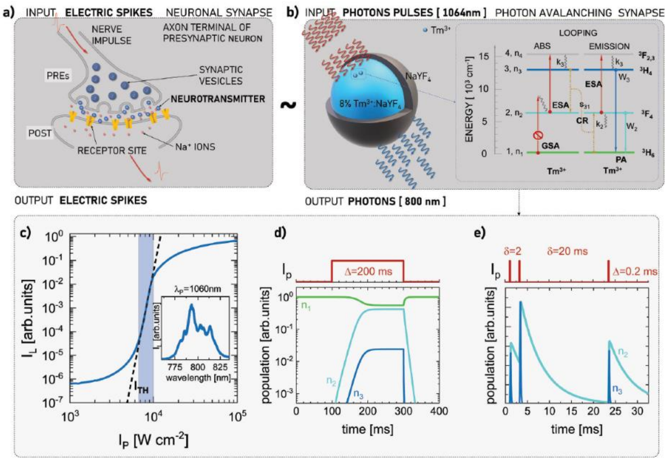

Figure 1. Artificial photon-avalanche synapse – fundamental properties

Acknowledgment

National Science Center (NCN) projects: 2018/31/B/ST5/01827 (A.B., Z.K.), 2021/43/B/ST5/01244 (A.B., M.M., M.M.), and 2018/31/G/ST3/03596 (S.M.).

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Analysis of Surface EMG Signals Based on Reservoir Computing Framework for Inferring Intended Motion

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Development of an easy-to-use myoelectric prosthetic hand is very important for upper-limb amputees. It needs an accurate analysis of the complicated electromyography (EMG) signals to infer the intended motion, thus the machine learning technique has been often used recently [1]. Considering the practical use, there are many constraints including real time analysis, low power consumption, small size, light weight, and low cost. The purpose of this paper is to investigate a novel simple and compact EMG analysis technique considering the similarity between reservoir computing (RC) and the human motor control system.

Our EMG analysis is based on the reservoir computing, but it does not use an artificial neural network for the reservoir layer [2]. We consider that the complicated EMG signal is obtained by mapping the intended motion into the high-dimensional spatiotemporal space through a nonlinear human motor nerve circuit. That is, the human motor control system can be regarded as a physical reservoir. Then, the intended motion would be represented by a linear combination of EMG signals.

The set up for concept demonstration is shown in Fig. 1. Surface EMG signals were taken on eight forearm positions together with 3-axis accelerations on the hand as performed motion data. Then, we trained the weights in the linear combination of the EMG signals to reproduce the measured accelerations. The obtained weights were implemented into a microcontroller that computed the weighted sum of the taken EMG inputs in real time and controlled the robot hand. We trained five hand movements including pronation, dorsiflexion, palmar flexion, grasping, and supination.

The system successfully reproduced pronation, dorsiflexion, and palmar flexion. However, it could not respond to the grasping and supination motions. This was simply because the EMG signal from the muscle deep inside the forearm was relatively weak on the arm surface. This problem could be solved by relatively enhancing the weak signal by a nonlinear transformation as shown in Fig. 2.

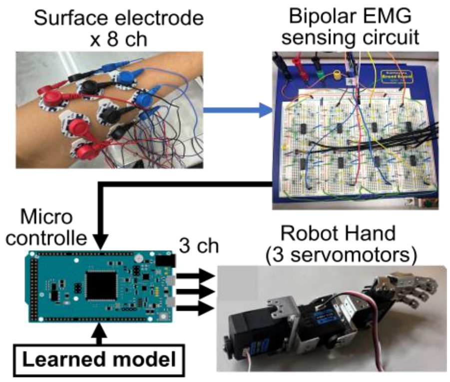

Figure 1. Experimental setup.

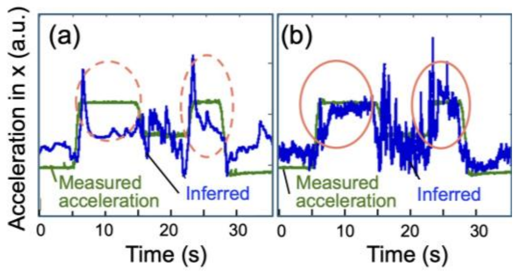

Figure 2. Results of motion inference from EMG signals: (a) without and (b) with logarithmic transformation.

Acknowledgment

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Bismuth(III)-Based Memristive Materials for Neuromorphic Computing

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As the demand for energy-efficient, brain-inspired computing surges, memristive devices have emerged as a key enabler for neuromorphic and unconventional computing paradigms. In this work, we explore bismuth(III)-based hybrid organic-inorganic materials as promising candidates for next-generation artificial synapses.[1,2] Thin-film memristor devices were fabricated using bismuth salts on ITO/glass substrates, with copper top electrodes, and their resistive switching behavior was systematically studied. Special emphasis was placed on the role of electron-rich and electron-deficient functional groups in the organic cations, influencing the devices' ON/OFF ratios, retention, and synaptic plasticity (STDP, LTP, LTD). These materials also exhibited fading memory and non-linear response dynamics, making them suitable for physical reservoir computing. To evaluate computational performance, a 16-electrode device architecture was implemented and benchmarked on tasks such as NARMA-2, waveform generation, and memory capacity. The system demonstrated strong potential in AI-relevant tasks, including MNIST digit classification and speaker-independent voice recognition. These findings position bismuth(III)-based memristors as versatile and energy-efficient candidates for hybrid neuromorphic-reservoir computing systems.

Acknowledgment
These studies were financially supported by the “Excellence initiative–research university” program for the AGH.

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Neuromorphic Physical computation using molecular networks

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In recent decades, studies on molecular electronics have made significant advances and single molecular transistors have been demonstrated. Such investigations, however, have not directly led to actual molecular-scale electronic devices, due to the lack of effective technologies for wiring between molecules. Beyond single molecular transistors, the exploration of device architecture is a central issue in molecular-scale electronics. One of the attractive directions is the realization of neural networks that utilize self-assembled molecular systems.

We focus self-doped water-soluble polyaniline sulfonate (SPAN) exhibiting high conductivity and nanoscale network structure. In our previous work, we found that SPAN ultrathin films show ohmic conduction from 10 K to room temperature. However, SPAN indicates nonlinear I-V characteristics in nanoscale and humid condition at room temperature. These nonlinearities in SPAN network are useful for a physical reservoir computing (RC). The demonstration of RC by spoken-digit classification realized with 70% accuracy.[1]

Polyoxometalates (POMs) are generic designation for condensed transition metal oxyanions used for catalysis, electrode and other applications related with electron transfer. Recently, POMs attracted much attention for the molecular devices due to their multiple redox states including pentavalent and hexavalent Mo atoms. The I-V characteristics show strong hysteresis with long time constant suggesting charging effect of mixed-valence system. These phenomena provide the ability of 4-bit classification (Figure. 1) and realize MNIST task with 90 % accuracy.

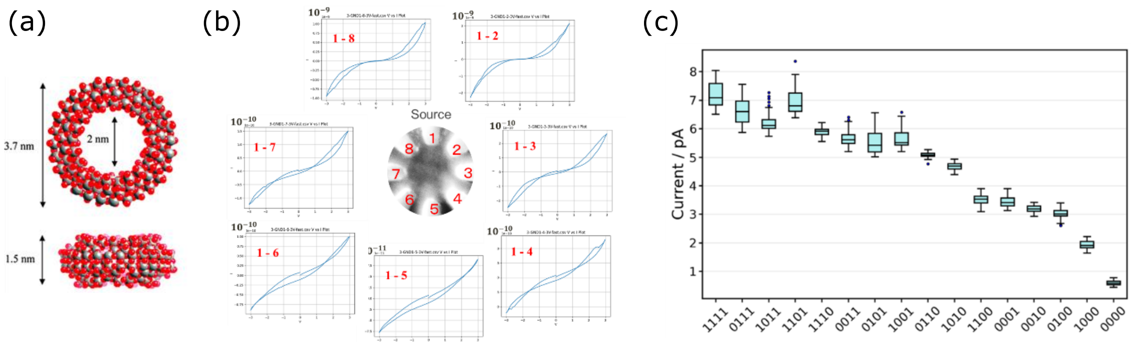

Figure. 1. (a) Molecular structure of Mo154-ring. (b) I-V characteristics of POM-nanogap junction, (c) 4-bit classification.

Acknowledgment

This work was supported by a CREST grant (No. JPMJCR21B5) from the Japan Science and Technology Agency (JST) and Core-to-Core program from Japan Society for the Promotion of Science (JSPS).

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Developing Copper Vanadate for applications in neuromorphic computing

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Photoelectrochemical (PEC) studies on copper vanadate, a semiconductor material with unique optoelectronic properties [1, 2] is recently being explored for their potential applications in neuromorphic computing and synaptic functionalities for artificial neural networks. This study presents the synthesis, structural characterization (Fourier Transform Infrared Spectroscopy, Diffused reflectance spectroscopy, Scanning electron microscopy) and photoelectrochemical characterization (Kelvin Probe, Chronoamperometry with light pulses) of different ratios of copper vanadate thin films. Optical and electrochemical analyses revealed a band gap about 2.3 eV, facilitating visible-light absorption. The best-performing films showed a photocurrent density of up to 4 μA cm^{-2} under monochromatic light beam. The material demonstrates key synaptic behaviors such as paired pulses depression (PPD), spike-timing dependent plasticity (STDP), excitatory post-synaptic current (EPSC), driven by both electrical and optical stimuli. We have proven that our thin layers exhibit a photocurrent response over a wide potential range (900mV to -500 mV) and for various wavelengths of incident light (300nm to 600 nm) with PEPS (Photoelectrochemical Photocurrent Switching) effect. PPD measurements were performed at a potential of 500mV with 5 pulses as shown in the figure. The sample was illuminated with light pulses of 460nm wavelength, 200ms pulse width and 400ms pulse period and the resultant graph indicates gradual decrease in the synapses (PPD). Our findings suggest that copper vanadate offers a robust platform for the development of next-generation, energy-efficient neuromorphic devices, capable of processing and storing information like our brain.

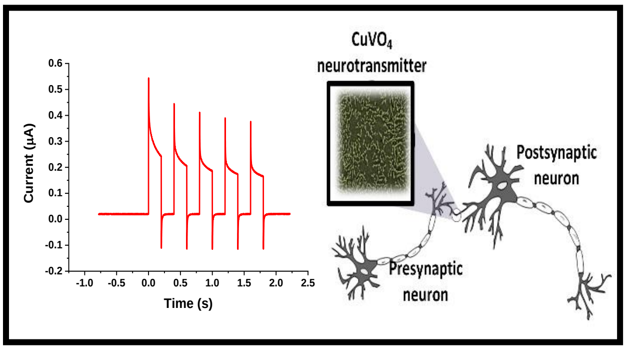

Figure 1. The decrease in synapses of the 5 pulses in PPD measurement.

Acknowledgment

This research are supported by National Science Centre (Poland) with OPUS grant no. 2022/47/B/ST4/01420

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Superconducting Diode Effect in Hybrid In/Bi_2Te_3-flake Structures

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The superconducting diode effect (SDE), characterized by a nonreciprocal supercurrent that preferentially flows in one direction without dissipation, has emerged as a key phenomenon in the field of superconducting electronics. Its potential applications range from next-generation low-power computing elements, spintronic devices, and quantum technologies. Achieving a robust and tuneable SDE in hybrid systems is particularly promising for realizing superconducting analogues of conventional semiconductor diodes, but with significantly enhanced performance due to zero resistance. A comprehensive understanding of the underlying mechanisms enabling the SDE, especially in systems exhibiting strong spin-orbit coupling and topological properties, is essential for advancing this field.

In this work, we present experimental data suggesting that the superconducting diode effect might be observable in hybrid heterostructures comprising quasi-two-dimensional flakes of the topological insulator Bi_2Te_3 coupled to an indium superconductor. The Bi_2Te_3 flakes were prepared via mechanical exfoliation using the adhesive tape method and subsequently patterned into Hall bar geometries through electron beam lithography followed by argon plasma etching. A high-quality indium layer was then deposited onto the Bi_2Te_3 flakes using molecular beam epitaxy (MBE), ensuring intimate contact and a clean interface. Covering the topological insulator with a superconductor aimed to induce superconductivity in the Bi_2Te_3 flakes via the proximity effect. This fabrication process yielded well-defined topological insulator/superconductor/topological insulator (TI/S/TI) junctions with clear transport channels.

We carried out detailed transport measurements to investigate the I–V characteristics of the devices as function of perpendicular magnetic field. The measurements reveal a pronounced asymmetry in the critical current when reversing the direction of the applied magnetic field, suggesting the presence of the SDE.

The observed SDE in our system is attributed to the interplay between the strong spin-momentum locking of the topological surface states in Bi_2Te_3 and the proximity-induced superconductivity from the In layer. Breaking of inversion and time-reversal symmetries (by topology and by magnetic field, respectively) at the interface, combined with the unique electronic structure of the topological insulator, plays a crucial role in enabling the diode behaviour.

Acknowledgment

Project supported by the program "Excellence initiative research university" for the AGH University of Krakow.

Magnetic tunnel junction with variable thermal stability for storage and P-bit applications

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Magnetic tunnel junction (MTJ) which consist of two ferromagnets separated by a thin tunnel barrier is currently used in storage and sensing applications. Contemporary MTJs take advantage of perpendicular magnetic anisotropy of composite FeCoB-based free layer (FL) which is placed between two MgO thin layers, while reference layer (RL) is pinned to the synthetic antiferromagnet (SAF). We present MTJ structure (Fig.1) based fully on abundant materials, where SAF is based on Ni/Co superlattice. The variable thickness of FL leads to different magnetic anisotropy energy, which affects the thermal stability. We used e-beam lithography and ion-beam etching to fabricate MTJ pillars ranging down to 80 nm. For the FL thickness of t_{FL} = 1.3 nm the thermal stability of D = 50 was determined based on the current-induced switching probability diagram – (Fig. 1), which drops with increasing t_{FL}. The reduced D of around 15 can cause random switching of MTJ state, which can serve as a probabilistic-bit (p-bit) [1]. P-bits created from MTJs open new path of exploration of the probabilistic algorithm such as Mote-Carlo method and quantum-like computing [2]. The most important asset of these approaches is a fact that p-Bit random generator utilizes only one MTJ and a single CMOS transistor to realize a generator [1], which enables downscaling of future unconventional computing platforms.

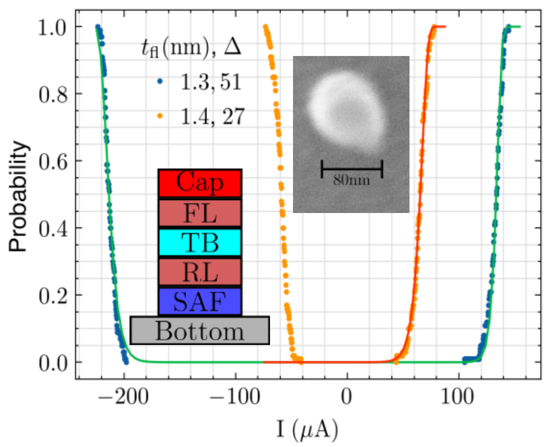

Figure 1. Thermal stability of the fabricated MTJ with different free layer thickness determined using current-induced switching probability. Inset show MTJ structure and micrograph.

Acknowledgment

Project supported by the Excellence initiative-research university programme of the AGH University of Krakow, National Science Centre, Poland grant no. 2021/40/Q/ST5/00209

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Enhancement and anisotropy of electron Landé factor due to spin-orbit interaction in InSb nanowires

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Landé factor could be seen as a proportionality constant between applied magnetic field and the effective splitting of energy levels in the system. It is widely known that in some bulk materials effective Landé factor's (g^*) magnitude could be much higher than atomic $g_0 \approx -2$. Such an enhancement is very desirable in numerous applications, e.g. spintronics or quantum computing. One could at first think that shrinking the size of the system to the nanoscale, closer to the atoms' size, would lead to decrease of g^*, therefore it came out as a huge surprise that semiconductor nanowires may exhibit values of g^* larger than the bulk values.

Using the $\mathbf{8 \times 8}\, \boldsymbol{k \cdot p}$ model and envelope function approximation, we derive a conduction band Hamiltonian[1], where g^* is explicitly related to the spin-orbit coupling constants α_R. Our model includes orbital effects from the Rashba spin-orbit term, leading to a significant enhancement of the effective Landé factor, which is naturally anisotropic. For nanowires based on the low-gap, high spin-orbit coupled material InSb, we investigate the anisotropy of the effective Landé factor with respect to the magnetic field direction, exposing a twofold symmetry for the bottom gate architecture. The anisotropy results from the competition between the localization of the envelope function and the spin polarization of the electronic state, both determined by the magnetic field direction.

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Spontaneous electrical activity in peptide-based aggregates

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Peptide coacervates can be described as the simplest self-organizing system, representing minimal models of protocellular structures and a dynamic, membraneless compartments capable of concentrating molecules and supporting primitive functions.
In 1980's S.W.Fox discovered that synthetic minimal peptides - referred as proteinoids[1] - spontaneously assemble into microspherical structures capable of generating spontaneous electrical spikes[2], supporting the notion that simple peptide polymers possess primitive electrochemical activity. Peptide-based coacervates exhibit tunable responsiveness to environmental cues such as pH, salt concentration, and ionic strength.
Herein, we report the synthesis and investigation of spontaneous electrical properties of peptide aggregates and their response under applied electrical stimuli. The materials were prepared by thermal copolymerization using various amino acids and different combination thereof. The effect of the solvent was examined to find optimal conditions for material fabrication. The resulting structures were dehydrated, resulting in powdered material, which were then subjected to morphological, compositional, and electrical characterizations. We found that aggregates of minimal peptides can generate oscillatory electrical signals that are responsive to external stimuli. A dedicated setup enabled the simultaneous analysis of aggregation and electrical spiking through dynamic light scattering (DLS) and electrical measurements. The peptides aggregates have been assembled into an agarose-gel electrolyte and used as an active component in an organic electrochemical transistor (OECT) architecture. These findings suggest their potential application in electro-responsive, coacervate-like systems to develop unconventional computing platforms.

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Limitations of tensor network approaches for optimization and sampling: A comparison against quantum and classical Ising machines

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Optimization problems pose challenges across various fields. In recent years, quantum annealers have emerged as a promising platform for tackling such challenges. To provide a new perspective, we develop a heuristic tensor-network-based algorithm to reveal the low-energy spectrum of Ising spin-glass systems with interaction graphs relevant to present-day quantum annealers. Our deterministic approach combines a branch-and-bound search strategy with an approximate calculation of marginals via tensor-network contractions. Its application to quasi-two-dimensional lattices with large unit cells of up to 24 spins, realized in current quantum annealing processors, requires a dedicated approach that utilizes sparse structures in the tensor network representation and GPU hardware acceleration. We benchmark our approach on random problems defined on Pegasus and Zephyr graphs with up to a few thousand spins, comparing it against the D-Wave Advantage quantum annealer and Simulated Bifurcation algorithm, with the latter representing an emerging class of classical Ising solvers. Apart from the quality of the best solutions, we compare the diversity of low-energy states sampled by all the solvers. For the biggest considered i.i.d. problems with over 5000 spins, the state-of-the-art tensor network approaches lead to solutions that are 0.1% to 1% worse than the best solutions obtained by Ising machines while being two orders of magnitude slower. We attribute those results to approximate contraction failures. While all three methods can output diverse low-energy solutions, e.g., differing by at least a quarter of spins with energy error below 1%, our deterministic branch-and-bound approach finds sets of a few such states at most. On the other hand, both Ising machines prove capable of sampling sets of thousands of such solutions.

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Development of MOKE Microscope system for magnetic computing

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Magnetic thin films have significant potential for use in unconventional computing. A variety of information processing devices utilizing magnetic materials have been proposed and developed. While magneto resistive random access memory (MRAM) is already in practical use as an energy-efficient recording element, various concepts of logic elements—including magnetic quantum-dot cellular automata, domain wall logic and straintronics devices—have been reported. Recently, the concept of magnetic reservoir computing has been introduced[1]. These unconventional computing devices based on magnetic materials offer key advantages such as non-volatility, computational capability, and low power consumption. In magnetic reservoir systems, external signals—such as magnetic fields and mechanical strain—can be utilized for writing data and updating node states. Therefore, the development of measurement systems capable of applying both magnetic fields and strain to a sample, while simultaneously measuring its magnetization, is essential to advance research in magnetic reservoir computing.

In this study, we have developed a MOKE (magneto-optical Kerr effect) microscope that enables the application of both mechanical strain and magnetic fields to a sample. Fig. 1(a) shows a photograph of the tensile machine that can be installed in the MOKE microscope. The system allows for biaxial stretching of the sample and includes space for positioning an electromagnet yoke close to the sample. Fig. 1(b) shows a photograph of the developed MOKE microscope. The system is equipped with two cameras, which are used to calculate the polarization rotation angle of the reflected light[2]. Using this setup, we have confirmed that it is possible to measure the magnetization states of samples while applying mechanical strain and magnetic field. With this microscope, we plan to demonstrate the operation of unconventional computing devices based on magnetic materials in a near future.

This research was partly supported by received partial support from JSPS KAKENHI Grant No. 20H05655, JAPAN, and JST CREST Grant No. JPMJCR20C6, JAPAN.

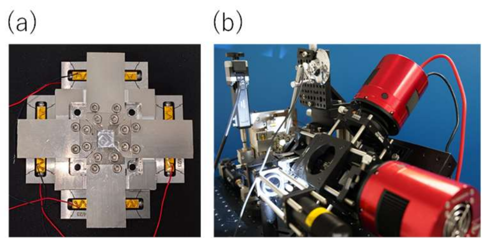

Figure 1. Photograph of (a) strain -application system and (b) MOKE microscope without stray light shields.

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Influence of Ferromagnetic IEC on CIMS and DMI in Co/Pt/Co Multilayer System

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Spin-orbit torque induced current magnetization switching (SOT-CIMS) offers an energy-efficient pathway for manipulating magnetization in ferromagnetic layers, presenting significant potential beyond conventional storage, particularly for Unconventional Computing paradigms like neuromorphic systems. We investigate the interplay between interlayer exchange coupling (IEC), Dzyaloshinskii-Moriya interaction (DMI), and multilevel magnetization switching in Ti(2)/Co(1)/Pt(0-4)/Co(1)/MgO(2)/Ti(2) (thicknesses in nanometers) heterostructures patterned into Hall-bar devices [1]. Varying the Pt spacer thickness effectively tunes the ferromagnetic IEC and influences magnetic anisotropy, leading to magnetization reorientation. Crucially, experimental findings demonstrate the achievement of four distinct, stable resistance states controllable via external magnetic fields and SOT spin currents (Fig.1) [2]. This multilevel switching capability, arising from the interplay between asymmetric Pt/Co and Co/Pt interfaces, tunable IEC, and DMI, makes these structures highly attractive for implementing multi-state memory elements or artificial synapses and neurons in bioinspired computational architectures. Brillouin Light Scattering (BLS) allowed quantification of the effective DMI, while polar-magnetooptical Kerr microscopy provided insights into the domain structures underpinning the multistate behavior. Numerical simulations, including macrospin and domain wall models, corroborate the experimental observations of multilevel switching and elucidate the underlying mechanisms driven by interface asymmetry and IEC. Understanding and engineering the relationship between IEC and DMI is key to advancing these materials for future unconventional computing applications.

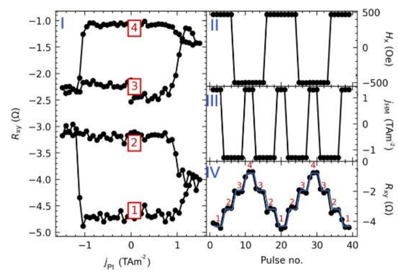

Figure 1. Four stable resistance (R_{xy}) states at t_{Pt} = 1.55 nm (I), obtained with the external magnetic field (II) and current pulses (III). Rxy levels in (IV) correspond to the Rxy levels of CIMS loops in (I).

Acknowledgment

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Experimental setup for FMR detection in thin multilayers

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Spintronic elements can serve as a building block for neuromorphic hardware by enabling energy-efficient, brain-inspired computing architectures[1]. Magnetic tunnel junctions (MTJs), the core components of magnetoresistive RAM (MRAM), rely critically on parameters such as the tunneling magnetoresistance (TMR) ratio and dynamic magnetic properties—including Gilbert damping and magnetic anisotropy. These properties are essential for high-speed switching and stability, yet their characterization in ultrathin films remains experimentally challenging. Here, we present an experimental setup for ferromagnetic resonance (FMR) spectroscopy to investigate a complex MTJ structure with four ferromagnetic layers: a two-sublayer synthetic antiferromagnet (SAF), a sub-1 nm reference layer (RL), and a free layer (FL). The SAF is based on Ni/Co superlattice and entire MTJ consist of abundant materials[2]. Magnetometry measurement (Fig.1(a)) indicate independent switching of the FL, while SAF and RL are strongly coupled. In contrast, FMR analysis of each MTJ sub-layer, enables independent determination of magnetic anisotropy and damping parameters.

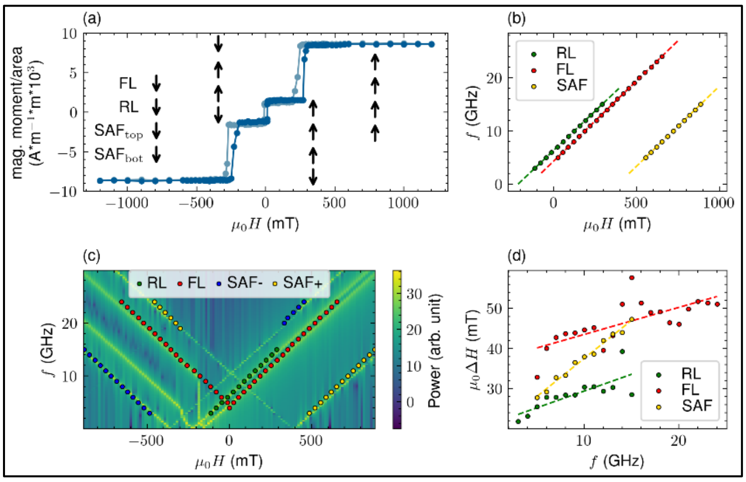

Figure 1. Wafer-level characterization of the MTJ stack. Magnetic moment per unit area vs. perpendicular magnetic field (a). Arrows indicate magnetic configuration of MTJ in the given field. f vs. H for FL, RL and SAF enabled calculation of the magnetic anisotropy (b). Modeling of full FMR map is presented in (c). Magnetization damping for each magnetic layer was calculated based on linewidth (ΔH) vs. f dependence (d).

Acknowledgment

Project supported by the National Science Centre, Poland grant no. 2021/40/Q/ST5/00209, Excellence initiative-research university programme of the AGH University of Krakow and Funded by the European Union under NICKEFFECT project, GA number 101058076

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Finite-momentum pairing in altermagnetic superconductors – step toward more efficient superconducting diodes

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Superconducting diode effect (SDE) [1], with many potential applications in electronics and spintronics was first observed in superlattice build of tantalum, niobium and vanadium layers. Breaking of time-reversal and inversion symmetry which leads to SDE appearance (nonreciprocal critical current), was achieved by application of inplane magnetic field. Theoretical description of this phenomena requires introducing finite-momentum Cooper pairing, i.e. formation of Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) phase [2,3]. Recently, discovery of new class of magnetic materials, so-called altermagnets, provides possibilities to achieve superconducting diodes with higher efficiency [4,5]. As we show by combining unconventional superconductivity with altermagnetism one can induce a non-zero momentum Cooper pairs without the presence of any external fields. In our study we focus on quasi two-dimentional systems and provide a comprehensive analysis of the spontaneous FFLO phase formation in the case of various superconducting and altermagnetic symmetries and electron concentration regimes. According to our analysis, the subtle interplay between two order parameters determines the structure of the Cooper pair momenta appearing in the FFLO state.

Acknowledgment

Research partly supported by program "Excellence initiative – research university" for the AGH University of Krakow. We gratefully acknowledge Polish high-performance computing infrastructure PLGrid (HPC Center: ACK Cyfronet AGH) for providing computer facilities and support within computational grant no. PLG/2024/017887

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Ferrocene-Based Polymer Brushes: A Versatile Platform for Engineering Soft Memristive Devices

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The increasing demands of contemporary computing necessitate the exploration of alternatives to conventional silicon-based electronics, with molecular electronics emerging as a promising field. Memristors, crucial components in this domain, offer non-volatile memory and synaptic emulation capabilities. Functionalized poly(glycidyl methacrylate) brushes, synthesized via controlled surface-initiated polymerization, present a versatile platform for advanced memristive systems. This study reports the synthesis of polymer brush systems on a conductive substrate using SI-ATRP reaction. Brushes were subsequently functionalized with bare ferrocene, fluorobenzylamine and hexylamine molecules. The resulting systems were characterized using XPS, AFM, and electrical measurements. The primary outcome is the fabrication of functionalized polymer brush systems exhibiting memristive behavior with semiconductor-like hysteresis loops. The observed hysteresis suggests a switching mechanism based on electric field-driven charge transport. Ferrocene, known for its redox activity, likely facilitates charge transfer and storage. Fluorobenzylamine and hexylamine may influence dielectric properties and chain packing. XPS confirmed elemental composition, and AFM revealed homogenity of the films. These novel functionalized polymer brush systems, demonstrating semiconductor-like hysteresis, hold significant potential for unconventional computing. Their unique electrical characteristics and tunability make them promising for neuromorphic computing, in-memory processing, and flexible electronics. Future research will focus on optimizing functionalization and elucidating switching mechanisms.

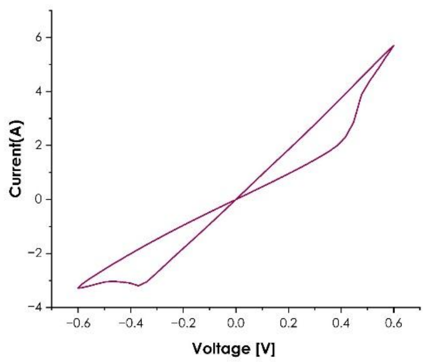

Figure 1. An I-V curve with semi- conductor-like hysteresis and a schematic of the functionalized polymer brush structure.

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Optoelectronic and Computing Systems: Thiazolothiazoles and cyanothiazole copper(I) complexes

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Memristive systems are at the forefront of analog in-memory computing, offering architectures that minimize data movement and significantly enhance energy efficiency. Their capability to emulate biological synaptic plasticity makes them particularly well-suited for neuromorphic computing in true artificial networks. A critical advantage lies in the diversity of memristive materials—enabling tunable properties for targeted applications, from low-power memory devices to high-speed computation. However, practical implementation still faces hurdles related to material stability, fabrication reproducibility, and device scalability. This study investigates a class of thiazolothiazole (TzTz) derivatives, planar π-conjugated heterocycles, synthesized with a variety of functional groups[1]. Additionally, cyanothiazole-based complexes coordinated with copper(I) iodide were examined (CNtz)[2]. All materials were extensively characterized using multiple spectroscopies techniques including FTIR, absorption and emission UV-Vis or synchrotron-based XANES, supported by DFT modeling. The first group of compounds displayed distinctive intermolecular interactions, which significantly influenced their optical and electronic properties. Several derivatives demonstrated desirable features including large Stokes shifts, and reliable resistive switching, underlining their suitability for memristive and optoelectronic applications. For the second group, although some limitations in plasticity modulation remain, the results lay a solid foundation for further material optimization. Together, these findings illustrate the promise of heterocyclic compounds in advancing neuromorphic systems, with strong potential for integration into adaptive AI hardware.

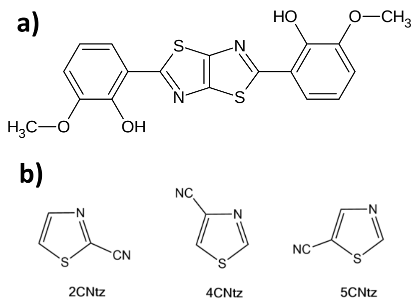

Figure 1. Exemplary a) TzTz and b) CNtz derivatives

Acknowledgment

The authors acknowledge the financial support from the Polish National Science Center within the OPUS programme (grant agreement No. 2022/47/B/ST4/00728). This research was partly supported by the program "Excellence initiative–research university" for the AGH University of Science and Technology and the Gdansk University of Technology.

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Visualization of conduction pathways in molecular network device

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The construction of neural network devices using molecules has been proposed, where molecules from the nodes and connections of the network. In such systems, electrical conduction in heterogeneous molecular networks composed of a small number of molecules is expected to occur via a hopping mechanism between localized states. The concerted propagation of electrons is anticipated to function as a physical computational process. However, understanding the phenomena inside these devices requires a molecular-level approach to clarify where and how the nonlinear electrical properties arise. Due to limited measurement techniques, the internal functionality of such devices remains largely a black box. Electrostatic force microscopy (EFM) is a technique for direct observation of molecular network systems. There have been cases where EFM has been used to identify the position of molecular orbitals by injecting electrons into molecules[1], as well as time-resolved measurements of charge distribution in conducting polymers[2]. In this study, we designed an experimental setup to visualize conduction pathways within molecular networks using EFM.

A solution (1.0 x 10^{-4} M) of {$Mo_{154/152}$}-ring (POM) with non-linear properties was dropped onto a nanogap electrode fabricated using EB lithography to form a molecular network, while electron injection into the POM by applying a pulsed voltage to the AFM tip in a one input - one output configuration, the current values were measured. Furthermore, a setup was assembled to map and visualise the current values.

To further investigate the conduction properties, a DC bias of +2 V was applied to the electrode while a pulse voltage of +6 V was applied to the AFM tip (Figure 1). The resulting measures revealed a decrease in current (Figure 2). This result suggests that electron injections from the tip altered the electronic state of the POM, thereby influencing the conduction pathway. To visualize these effects, a setup was developed to map current values at each point of electron injection from the AFM tip. The mapping obtained will be presented on the day of the presentation.

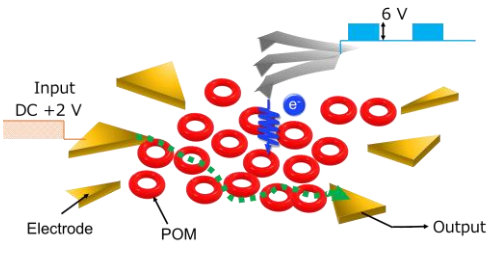

Figure 1. Schematic illustration of Change in current value(black line) when +2 V DC is applied to the electrode while a +6 V pulse voltage(red line) is applied to the AFM tip.

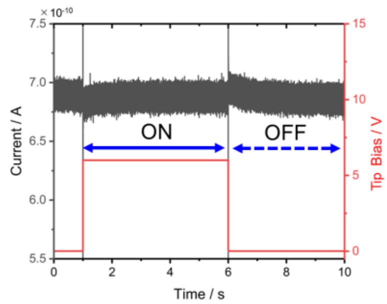

Figure 2. Change in current value(black line) when +2 V DC is applied to the electrode while a +6 V pulse voltage(red line) is applied to the AFM tip.

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Vanadium-based materials as promising candidates for neuromorphic vision

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The human nervous system is a remarkable biological system that has evolved over millions of years to enable humans to sense, process, and respond to information in a highly efficient and intelligent way. The human brain receives the most information through vision, and the human eye plays a key role in visual perception, serving as a sensory organ for imaging. Many scientists are trying to recreate an artificial system that will process and remember information. Artificial visual systems have made significant progress in implementing a wide range of optically triggered neuromorphic functions, including, but not limited to, short-term memory (STP), long- term memory (LTP), and spike-dependent plasticity. These functions have the potential to mimic various aspects of cognitive perception of images, such as pattern and image recognition, and image processing using neuromorphic computers.

In our lab, we are trying to build systems based on bismuth vanadium and its analogues (Cu, Eu, La) that will be capable of pattern recognition. The obtained thin film materials show high sensitivity to light in the visible range and can be controlled by both the wavelength of light, its intensity and the electrode polarization. All materials are stable, show the PEPS effect and the synaptic effect and can be used for pattern recognition.

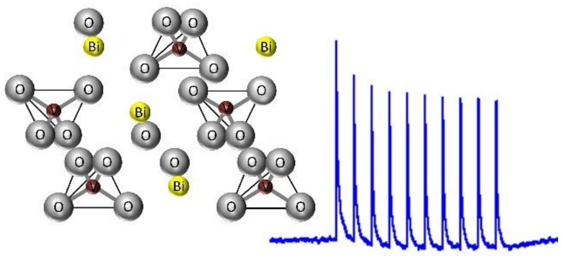

Fig. 1. BiVO4 structure and its synaptic signal.

Acknowledgment

This research are supported by National Science Centre (Poland) with OPUS grant no. 2022/47/B/ST4/01420

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Quantum Annealers as a tool for unsupervised models training

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Quantum Machine Learning (QML) is a relatively novel research domain that is a natural intersection of Machine Learning (ML) and Quantum Computing (QC). It might have multiple meanings, depending on the context, as the "quantum part" of the machine learning task may arise in different shapes or forms. The data can be quantum, the model (or it's part) can be quantum, even the training algorithm can be quantum --- all those cases describe the challenges of QML[1]. In this work we explore the latter, where we use Quantum Annealers (QA) as a Restricted Boltzmann Machine (RBM) training tool for hyperspectral images segmentation (unsupervised ML task).

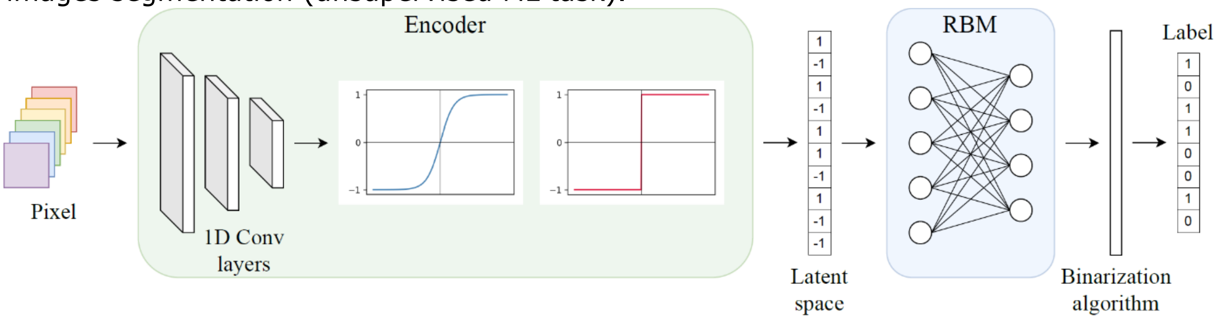

Figure 1. The model we used in our research. As the input, we used single hyperspectral pixels (120 bands). We pass it to the encoder part of a LBAE, represent the pixel in a latent space. We require that the values in the latent space are binary, so that they can be used as the RBM input. We then use RBMs to assign a label to each pixel. Since the number of RBM labels was usually greater than the number of classes in the dataset, we used agglomerative hierarchical clustering to reduce the number of final classes.

In our research we used the HyperBlood dataset[2]. We wanted to investigate if our model, presented on Figure 1, behaves differently if we use quantum algorithm for RBM training. We compared standard RMB training algorithms with the one used in QBM4EO[3]. Our results show that QA performs better than or on par with standard RMB training algorithms.

Acknowledgment

We gratefully acknowledge the funding support by program "Excellence initiative—research university" for the AGH University in Krakow as well as the ARTIQ project: UMO-2021/01/2/ST6/00004 and ARTIQ/0004/2021." The authors would like to thank Etos sp. z o.o. and the QBM4EO team for providing the QBM4EO code.

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Synchrotron studies of memristive materials and devices

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X-ray absorption spectroscopy (XAS) is a synchrotron-based technique that probes a specific element's oxidation state and local atomic environment. Operando XAS can be performed on a working memristor, where spectra are recorded simultaneously with the application of voltage to the device terminals. This enables real-time monitoring of oxidation states, electronic structure, and local structural changes providing crucial insights into resistive switching mechanisms and material dynamics.

Figure 1a illustrates the planar architecture of the studied thin-film devices, while Figure 1b presents an actual photograph of a working memristor prepared for an operando XAS experiment conducted at the ASTRA beamline of Polish National Synchrotron Radiation Facility, SOLARIS. In this study, we focus on memristors based on two distinct compounds. The first is nickel(II) tetraaza[14]annulene [Ni(Me_4dtaa)] complex, where a π-conjugated macrocyclic ligand exhibits a strong affinity for the metal forming a highly stable, porphyrin-like complex. Figure 1c shows that the Ni K-edge spectra for [Ni(Me_4dtaa)]-based memristor remain unchanged across various electrode potentials ranging from -10 V to 10 V.[1] The nickel centers do not take part in the redox processes in this system, while both oxidation and reduction of the complex occur on the organic part of the molecule. Therefore, we postulated a unique case of filamentary-type switching involving redox reactions of stationary molecules within a molecular solid.

The second studied memristive system is triphenylsulfonium tetrachlorocuprate(II) [$(TPS)_2CuCl_4$]. TPS^+ cations interact with $CuCl_4^{2-}$ anions, creating an ionic structure reminiscent of an ionic liquid. Figure 1d reveals noticeable changes in the Cu K-edge spectra for [$(TPS)_2CuCl_4$]-based memristor at potentials exceeding ±2V. They indicate a change in the oxidation state from Cu(II) to Cu(I), which may be responsible for the memristive switching observed by this device.

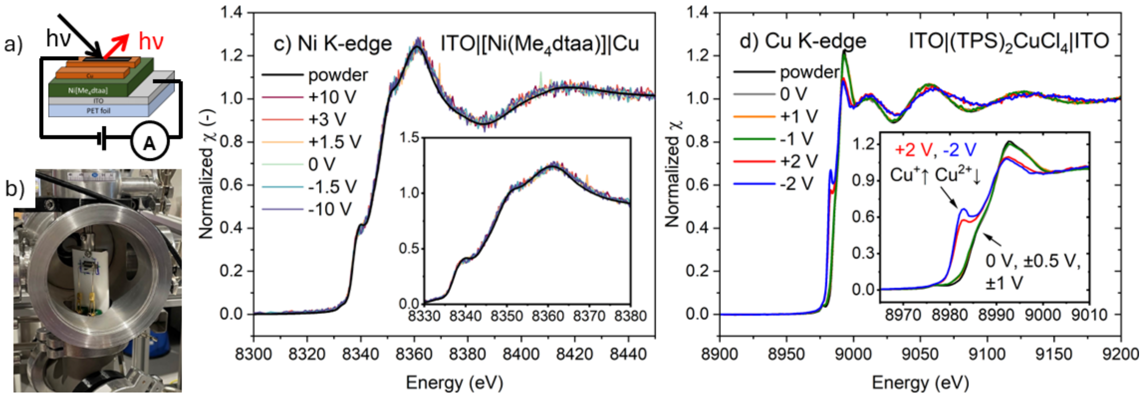

Figure 1: a) Scheme and b) photograph of the memristor device connection in the operando XAS experiment are shown with the resulting spectra recorded for c) [Ni(Me_4dtaa)] and d) [$(TPS)_2CuCl_4$].

Acknowledgment

These studies were financially supported by the Polish NCN within the OPUS program (No. UMO-2020/37/B/ST5/00663) and by the "Excellence initiative–research university" program for the AGH.

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Photoluminescence of thiazolothiazoles and their metal complexes

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Thiazolothiazoles are bicyclic aromatic compounds with four heteroatoms. Despite high stability, relatively simple synthesis and interesting photophysical and electrochemical properties, they have not attracted much attention. Due to planarity of the central ring system, they undergo efficient stacking in the solid state, which may lead, after appropriate doping, to high conductivity of these materials. Along with possible diversity of substitutions, thiazolothiazoles are an ideal playground for photophysics and molecular electronics. In this contribution we present synthetic pathways to new thiazolothiazole derivatives and their spectra properties. DFT calculations indicate that the lowest excited state has a π-π* character and, quite surprisingly, its energy does not significantly depend on peripheral substitution. On the other hand, various peripheral donor atoms may form binding sites (both chelating and monodentate) for metal ions, especially zinc(II), copper(II) and silver(I). The photoluminescence of metallated thiazolothiazoles significantly changes with the nature of metal ion and the binding mode: monodentate complexes are usually luminescent (however the photoluminescence quantum yields are decreased), but chelating ones show an efficient quenching.
Moreover, stacking interactions between individual thiazolothiazole units may lead to excimeric emission in polymer matrices. Furthermore, these materials are promising candidates for optoelectronic applications, especially memristive elements based on formation of metallic filaments in organic matrices.
This contribution presents experimental studies of thiazolothiazole derivatives with multiply substituted aromatic peripheral groups as well as DFT-based interpretation of experimental data.

Acknowledgment
These studies were financially supported by the "Excellence initiative–research university" program for the AGH.

Macromolecular approach to the topic of memristor systems

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The development of memristor systems as essential components for neuromorphic computing has been largely dominated by inorganic materials and metal oxide interfaces. However, a macromolecular approach—leveraging the tunable architecture, functional diversity, and self-assembly properties of synthetic polymers — offers a novel pathway to enhance performance and functionality in these systems. Here we explore the design and integration of macromolecules, including conductive polymers, polyelectrolytes and redox-switching systems, into memristor architectures. Emphasis is placed on molecular-level tailoring of switching thresholds and stability through precise control of macromolecular chain conformation and redox activity. Using bottom-up fabrication techniques, we demonstrate soft-matter memristors with tunable hysteresis and electrical properties. These promising findings suggest that macromolecular systems can not only replicate but also one-day surpass traditional inorganic memristors in adaptability and scalability.

Acknowledgment
This study was funded by National Science Centre (Poland) [Sonata Bis Grant no. 2021/42/E/ST4/00290].

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Tuning of memristive behavior of doped (3-trimethylsilyl-2-propynyl methacrylate) monolayers

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One suggestion for overcoming the problems associated with the von Neumann bottleneck and the limitations of Moore's Law, which hinder the development of AI-based technologies, is the development of new non-volatile computing systems based on memristors. Besides the most numerous inorganic materials, small organic molecules, biomolecules, and polymers are also applied as memory switching devices. The latter group includes polyacetylene-based architecture with a conjugated polymer chain. Due to such a molecular structure, polymers usually exhibit the acceptor-donor or reversible redox mechanism in memristive switching. Additionally, the conductive properties of polyacetylene can be changed by the introduction of positive charge carriers into its structure, thanks to the oxidation by halogens or Lewis acids.

This research aimed to synthesise the polyacetylene-based polymer brushes using photo-inferter-mediated radical polymerisation and 3-trimethylsilyl-2-propynylmethacrylate (TPM) as a monomer. A semiconductive layer composed of perpendicularly grafted polymeric chains was formed on the surface of ITO as a bottom electrode. Subsequently, the obtained layer was doped with $FeCl_3$ and $CuCl_2$ by immersing the diluted solution of this salt in nitromethane for 10 and 60 minutes. To reveal the changes in the structure of the materials during the doping, the FTIR, AFM, and XPS investigations have been conducted. Additional DFT modelling allows for determining the structure of dopant ions as $[FeCl_4]^-$ $[CuCl_2]^-$. Finally, cyclic voltammetry measurement revealed the smallest hysteresis loop on the I-V curve for native poly(TPM) brushes, and further beneficial influence of short-time doping.

Acknowledgment

This research is supported by the program „Excellence Initiative – research university" for the AGH University of Science and Technology. The authors would also like to thank also National Research Centre (Poland) for the financial support – grant 2021/42/E/ST4/00290.

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Reinforcement learning applications for macrospin modelling

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Recent advancements in reinforcement learning (RL) brought many interesting applications such as improving current-induced switching in MRAM cells [1] or guiding the design of spin orbit torque (SOT) and spin transfer torque (STT) based random number generators [2]. We propose two applications of RL for spintronic devices: a tuneable oscillator and an impulse-shaping controller for voltage-controlled magnetic anisotropy VCMA-assisted current switching.

For a spintronic oscillator, we focus on converging auto-oscillation to the user-specified frequency in the least number of steps. The RL agent controls the input feed current, the position and magnitude of the applied magnetic field. The reward is composed of a frequency alignment reward, Q-factor reward, punishment for large action derivative, and success reward upon achieving the target frequency, respectively:

$$\mathcal{R} = \alpha_1|f^* - f| + \alpha_2 Q - \alpha_3 a_t^2 + \alpha_4 I(|f^* - f| < \varepsilon)$$

α_i are the rewards weights, I is the indicator function of successful synchronisation (within a small margin ε). See Fig. 1 for a sample synchronisation trajectory.

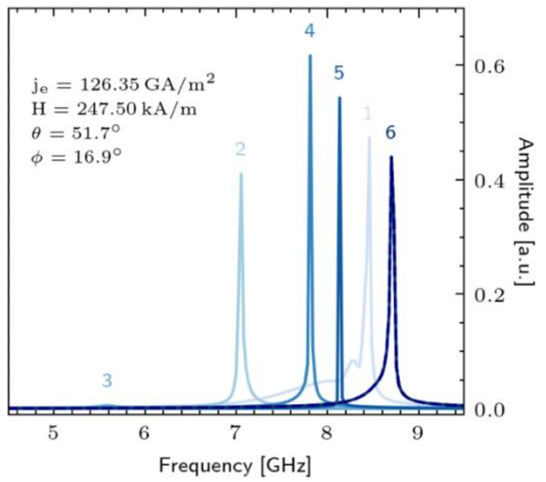

Fig.1 A sample synchronization trajectory for a Q-factor maximizing agent. Consecutive steps taken by the agent are numbered, and the final synchronization parameters are given in top left corner.

For impulse-shaping, we focus on the energy-efficient magnetization switching using SOT with the assistance of VCMA [3]. The controller adjusts the input current and voltage to regulate the perpendicular anisotropy of the device. The reward function promotes low energy use and targets small alignment error:

$$\mathcal{R} = \alpha_{\text{energy}}\left(|j|^2 + \frac{|V|^2}{R^2}\right) + \alpha_{\text{alignment}}|m_z^* - m_z|^2$$

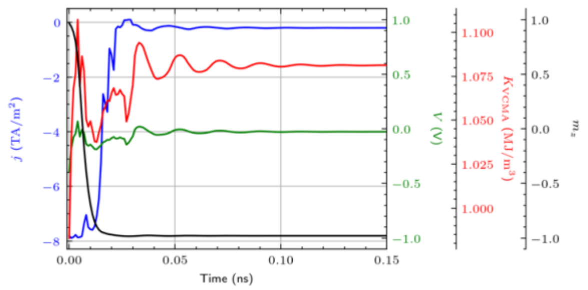

Fig.2 A sample time series of the magnetization z-component, voltage, magnetic anisotropy and current density. The current and VCMA voltage are controlled by the RL agent.

where j is the current density, V is the voltage density, R is the resistance of the MTJ, m_z^* is the target position of the magnetization (-1 or 1) and m_z is the measured position of the magnetization. α_{energy} and $\alpha_{\text{alignment}}$ are weighting factors for the individual rewards. Fig 2. shows a sample impulse shaping trajectory for a successful switching.

Acknowledgments

The research project is partially supported by the *Excellence initiative – research university* program of the AGH University of Krakow.

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