Beyond AI Project
“Next-generation AI Devices Learned from Biological Fluctuations for Realizing Ultra-low Electric Power Consumption”

Project Leader
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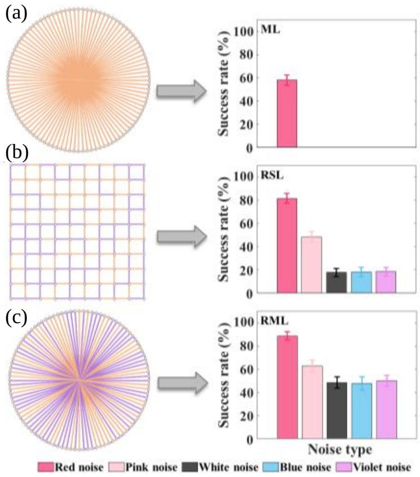
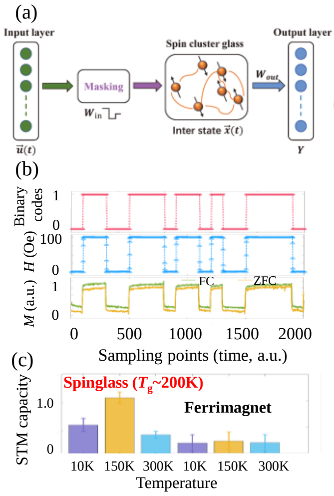
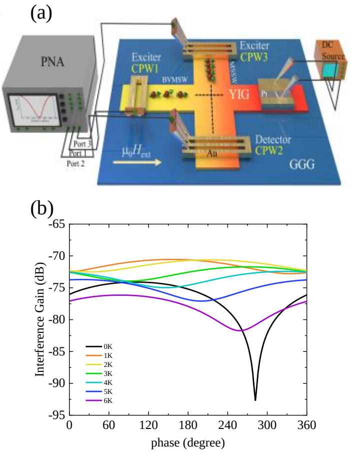
In order to develop devices that utilize fluctuations (noise/heat) in the environment, we are conducting research in various areas on theoretical calculations, material science, and device design. Solving NP-hard combinatorial optimization problems (COPs) such as the traveling salesman problem and the knapsack problem is expected to applied in a wide area not only communication services but also logistics, financial services, manufacturing processes, etc. An Ising machine is a computer specialized to solve the COPs, where the problems are converted into the interactions between spins and the solutions are obtained by searching for the ground state (minimum energy). In order to reach the true solution for the Ising machine, noise is used to escape from local energy minimum. Gaussian white noise is generally used to imitate random processes in nature, but colored noise (power spectral density: $PS=f^{\beta}$) exists in actual circuits and environments. We input various types of colored noise into the Ising machine and find the best noise promoting the development of the Ising Hamiltonian toward an optimal solution (Fig.1). Because the injection of red noise ($\beta = -2$) can effectively suppress random errors switching spin states and induce stochastic resonance, the optimal solution was efficiently found even under conditions with large noise. This research proposes improving the performance of Ising machines by effectively utilizing noise, which has traditionally been considered as an unwanted nuisance. It is expected to be applied for ultra-low energy consumption computers supported by the environment. Furthermore, we have proposed system models that efficiently utilizes noise such as multi-stable and over-damped systems, which improve the correct answer rate for hand-written digit patterns related to image recognition and associative memory, and reduce cost toward short time calculation and low power consumption.

Regarding materials, we have studied on spin glasses, which have many metastable states in free energy and spin fluctuations. Due to the magnetic interaction with randomness and frustration, spin glasses show a spin freezing state at low temperatures and exhibit a characteristic aging memory effect recording magnetic history. Reservoir computing (RC) is one of the machine learning frameworks suitable for time-series data processing represented by pattern recognition and enables high-speed learning. The learning ability depends on the nonlinearity and short-term memory (STM) capacity of the system. In terms of physical implementation, spintronic RCs has attracted attention because of the nonvolatile memory, small size, and low power consumption. Spin glasses are expected to exhibit excellent brain-type functionalities (short-term memory capacity) due to the slow magnetic dynamics, thus we quantitatively evaluated the STM capacity of spin glasses based on prevalent benchmarks. The results revealed that Co,Si-substituted $Lu_3Fe_5O_{12}$ thin films exhibiting spin glass behavior show superior STM capacity compared to unsubstituted ferrimagnetic thin films (Fig.2). STM performance has been improved reflecting the time constant of magnetic relaxation reaching maximum near the spin freezing temperature, thus spin glass can be considered as possible candidates for RC with better performance. We also reported on the development of ultra-low power consumption devices using spin waves as an information media without heat loss. We demonstrated a reconfigurable logic gates, which is constructed by the garnet-type ferrimagnetic iron oxide $Y_3Fe_5O_{12}$ with highly efficient spin wave propagation, using spin wave interference between magnetostatic surface waves







and backward volume waves in addition to local external field control (Fig.3). We also demonstrated that, unlike conventional garnet-type oxides, spinel-type oxides, which have a relatively simple crystal structure and can be used for heterodevice applications, can propagate spin waves with high efficiency.

Selected Publications:

1. Z. Liao, K. Ma, Md S. Sarker, S. Tang, H. Yamahara, M. Seki, and H. Tabata, “Quantum Analog Annealing of Gain-Dissipative Ising Machine Driven by Colored Gaussian Noise”, Adv. Theory Simul. 2100497 (2021).
2. Z. Shia, Z. Liao, H. Tabata, “Boosting learning ability of overdamped bistable stochastic resonance system based physical reservoir computing model by time-delayed feedback”, Chaos Solitons Fractals, 161, 112314 (2022).
3. Z. Liao, H. Yamahara, K. Terao, K. Ma, M. Seki, H. Tabata, “Short-term memory capacity analysis of $Lu_3Fe_4Co_{0.5}Si_{0.5}O_{12}$-based spin cluster glass towards reservoir computing”, Sci. Rep. 13, 5260 (2023).
4. Md S. Sarker, H. Yamahara, L. Yao, S. Tang, Z. Liao, M. Seki, H. Tabata, “Sensitivity enhancement in magnetic sensor using CoFeB/$Y_3Fe_5O_{12}$ resonator”, Sci. Rep. 12, 11105 (2023).
5. Md S. Sarker, L. Yao, H. Yamahara, K. Ma, Z. Liao, K. Terao, S. Tang, S. G. Ramaraj, M. Seki, H. Tabata, “Reconfigurable magnon interference by on-chip dynamic wavelength conversion”, Sci. Rep. 13, 4872 (2023).
6. S. Tang, MD S. Sarker, K. Ma, H. Yamahara, H. Tabata, M. Seki, “Efficient spin-wave transmission in epitaxial thin films of defect spinel γ-$Fe_{2-x}Al_xO_3$”, Appl. Phys. Lett. 119, 082402 (2021).

Spin-waves, the collective excitations of electron spins propagating through low-damping magnetic materials, are considered to be a promising avenue for transmitting information without generating heat. This property makes them an ideal foundation for the development of a next-generation computing with ultra-low power consumption. In the previous researches, to detect~~ed~~ the interference gain of the spin-wave device, which required two signals in different phases to be provided to the two ports respectively, an external vector network analyzer (VNA) system is usually used. The use of such a system is both costly and bulky, making it impractical for portable integration. The primary goal of our research is to realize a highly power-efficient integrated device based on spin fluctuation. To achieve this goal we are developing a high-sensitivity interface circuit for weak signal detection from spin-glass devices. Figure 1 illustrates a block diagram of the spin-wave detection circuit system, which is composed of a phase-locked loop as a sinewave signal generator, a phase interpolator to tune the relative phase of the two stimulus signal to the spin-wave device, a low-noise amplifier to amplify the weak signal from the device, mixers to down-convert the signal frequency, and baseband amplifiers and filters to acquire the signal to be processed by a subsequent digital processor. We have developed these building blocks to compose the system and fabricated a chip for verification as shown in Fig. 2. Among them, a chip photo of the low-noise inductorless PLL with a cascaded architecture is shown in Fig. 3. This PLL features extremely low jitter and spur without using an on-chip inductor, which is sensitive to the external magnetic field. In addition, we have applied stochastic resonance, where the noise helps to improve the signal-to-noise ratio of nonlinear systems, to enhance the performance of the analog-to-digital converters. The analysis proves the meaningful performance improvement with proper intensity of noise as shown in Fig. 4.

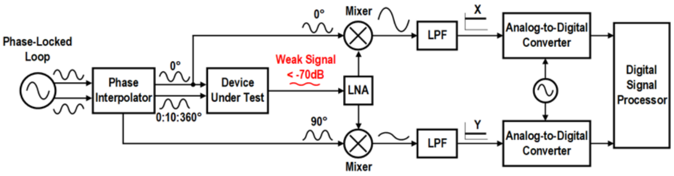


Fig. 1. Block diagram of spin-wave detection circuit

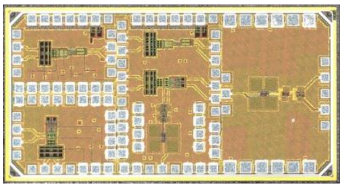
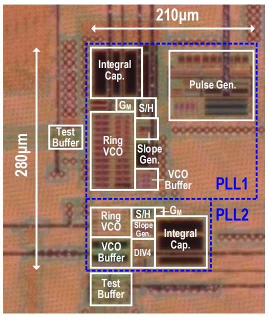


Fig. 2. Chip photo of the system



Power Consumption		
PLL1 (59%)	1.25GHz Ring VCO	46.7%
	Pulse Gen.	4.4%
	VCO Buf. + Slope Gen. + S/H	7.6%
	G_M	0.4%
PLL2 (41%)	10GHz Ring VCO	23.8%
	DIV4 + Slope Gen. + S/H	9.9%
	VCO Buffer	7.0%
	G_M	0.4%
Total Power: 30.82mW		

Fig. 3. Chip photo of inductorless PLL

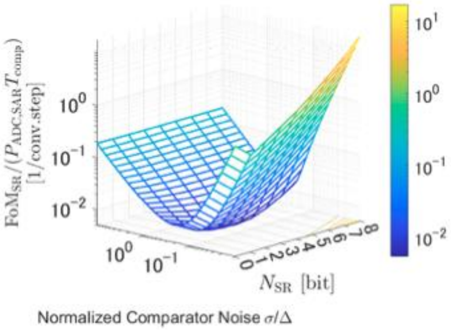


Fig. 4. ADC Performance enhancement

Selected Publications:

1. R. Shibata, Y. Hotta, H. Tabata and T. Iizuka, "Analysis of SAR ADC Performance Enhancement utilizing Stochastic Resonance," IEEE Trans. on Circ. and Syst.-II: Express Briefs, 2023.
2. Y. Zhu, Z. Yang, Z. Cheng, Md S. Sarker, H. Yamahara, M. Seki, H. Tabata and T. Iizuka, "A 1-5GHz Inverter-Based Phase Interpolator With All Digital Control for Spin-Wave Detection Circuit," IEEE ICICDT, Sep. 2023.
3. Z. Cheng, Z. Yang, Y. Zhu, Md S. Sarker, H. Yamahara, M. Seki, H. Tabata and T. Iizuka, "Design of 1-5 GHz Two-Stage Noise-Canceling Low-Noise Amplifier With Gm-Boosting Technique for Spin Wave Detection Circuit," IEEE ICICDT, Sep. 2023.
4. Z. Yang, Z. Xu, M. Osada and T. Iizuka, "A 10-GHz Inductorless Cascaded PLL with Zero-ISF Subsampling Phase Detector Achieving −63-dBc Reference Spur, 175-fs RMS Jitter and −240-dB FOMjitter," IEEE Symp. VLSI Technology and Circuits, Jun. 2022.

Design-driven exploration of spin glass materials with high spin-freezing temperatures requires (i) description of electronic structure in strongly correlated electron systems, (ii) treatment of disorder systems, and (iii) combination of first-principle calculations and statistical mechanics models. We have developed a fundamental simulation method and software to satisfy the above requirements. The software is based on the KKR Green's function method, and by using the self-interaction correction method, it is possible to describe the electronic structure of strongly correlated materials, which has been considered difficult, without any empirical parameters. The spin glass phenomenon is caused by the atomic randomness and magnetic frustration. The atomic randomness can be treated by the coherent potential approximation, and the magnetic frustration can be quantitatively evaluated by calculating magnetic interactions and effective pair interactions between the magnetic atoms. Finally, combining the above results with the replica exchange Monte Carlo method, we can estimate the spin-freezing temperature of the spin glass materials with high accuracy. Figure 1 shows a schematic of the software we have developed. Figure 2 indicates the spin-freezing temperatures of CuMn alloys calculated by our software, where the experimental results are well-reproduced and the validity of our method is proven. Figure 3 shows the chemical trend of the spin-freezing temperature for magnetite-based spin glass materials. From these results, we succeeded in obtaining a guideline for achieving high spin-freezing temperatures. Experiments are currently conducted according to this guideline. We are also planning to perform an exhaustive search by combining this software with a supercomputer.

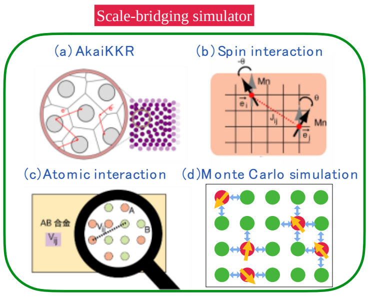


Fig.1 Scale-bridging simulator. (a) AkaiKKR code, (b) magnetic exchange interaction, (c) effective pair interaction, and (d) Monte Carlo method.

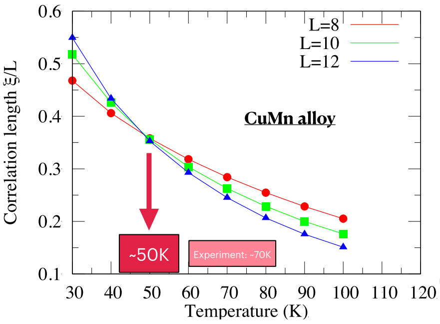


Fig.2 Spin freezing temperature of Mn 17 doped FCC-Cu.

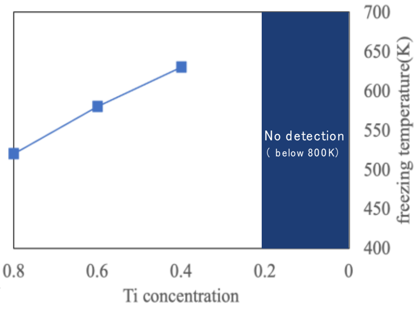


Fig.3 Chemical trend for the spin freezing temperature of Ti doped magnetite Fe_3O_4.

Selected publications:

1. T. Fukushima, H. Akai, T. Chikyow, and H. Kino, "Automatic exhaustive calculations of large material space by Korringa-Kohn-Rostoker coherent potential approximation method — Applied to equiatomic quaternary high entropy alloys", Physical Review Materials 6 023802/1-19 (2022).
2. T. Fukushima, H. Akai, T. Chikyo, and H. Kino, "Automatic Generation of Material Property Data by Supercomputer "Fugaku" - Toward Realization of Big Data in Magnetic Materials, February 16th, 2022