【Grant-in-Aid for Scientific Research (S)】

Quantum Annealing to Solve Complex Optimization Problems Using Negative Inductance and Thermal Fluctuations

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Purpose and Background of the Research

●Outline of the Research

In nature, a change of phase from ‘disordered’ to ‘ordered’ is often observed. For example, ferromagnetic materials exhibit paramagnetic properties at temperatures above the Curie point (T_C). On the other hand, when the temperature is lowered below T_C under local magnetic field, magnetic domains are formed in a corresponding manner. This process can be viewed as a ‘calculation’ if this field is regarded as the problem (input) and the corresponding domain distribution as the solution (output).

The physical picture can be traced back to the problem of using fluctuations to search for the most stable point or an equally stable point of the potential determined by the input. The method using quantum fluctuation is called quantum annealing (QA), which uses the tunneling to pass through the barriers and eventually reach the most stable point. In simulated annealing (SA), thermal fluctuation assists in jumping over barriers. In this research, when faced with a situation where the solution cannot be reached due to a 1st-order quantum phase transition, etc., the situation is identified during the calculation and QA is performed using controlled thermal fluctuation.

The specific circuit will be realized by a superconductor circuit. In particular, the use of a π junction enables not only the efficient formation of qubits, but also strength-controlled coupling between qubits due to its negative inductance effect. The effects of incorporating thermal fluctuations into quantum fluctuations and introducing new devices will be implemented at the basic science to prototype system level.

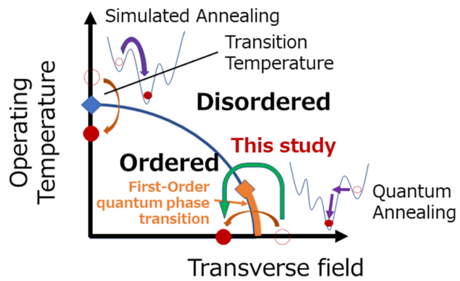

Figure 1. An image of quantum annealing studied in this study, where controlled thermal fluctuation is utilized.

●Related Previous Achievement

In contrast to a conventional Josephson junction, a π junction behaves as a negative inductance. In the specially promoted research, we found that the effect of negative inductance becomes apparent when the inductance is connected in parallel with a π junction. In this research, this phenomenon is used to improve the functionality of the coupling circuits.

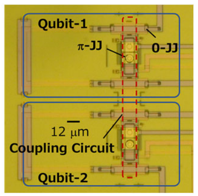

Figure 2. π-junction-based coupling circuit.

●Background of Idea

Team member Tanaka et al. showed by quantum Monte Carlo simulations that QA produces poorer solution quality (higher energy) than SA for some problems. On the other hand, they also found that simultaneous annealing, in which QA and SA are performed at the same time, provides the highest solution quality for the same problems. Based on this idea, our approach is to add thermal fluctuations to QA as needed.

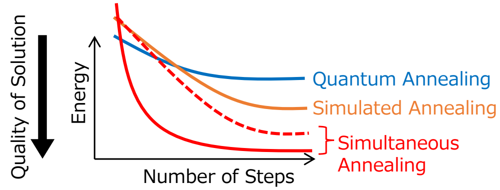

Figure 3. Advantage of Temperature-Quantum Simultaneous Annealing

Expected Research Achievements

We are challenging quantum annealing assisted by thermal fluctuation (hereafter TF-assisted QA) in both theory and experiment, including computer architecture, and obtaining academic knowledge. We also construct a chip-level prototype and show that it can achieve higher-quality solutions faster than conventional systems. Through these efforts, we explore the possibility of expanding the range of applications of TF-assisted QA as shown in Figure 4.

Specifically, we are doing research as follows,

- Build a model of TF-assisted QA. Based on that, we study on the method of avoiding 1st-order quantum phase transition, quality of solution, and its speed-up by simulation.
- Make qubits and several functional couplings using π-junction-based superconductor circuits. Combining these circuits, we fabricate QA with individual control circuits for each qubit, including operating temperature control, on a single chip. We evaluate the superiority of TF-assisted QA and the effect of thermal control. The results will be fed back to the simulation to increase the validity of the model.
- Build a system to monitor the solution on the way to the optimal one and remap the problem into a small graph. Improvement of solution quality and speed-up by re-mapping are studied, and the effectiveness of re-mapping is evaluated.

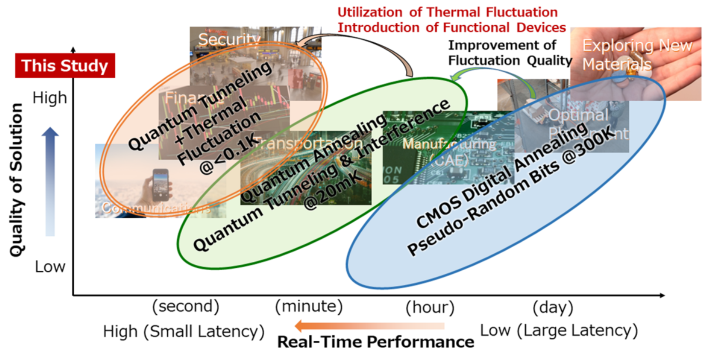

Figure 4. An advantage of TF-assisted QA

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