Power Reduction of Josephson Random Access Memory Using Stochastic Resonance

Ryosuke Kihara, Yuki Yamanashi, *Member, IEEE,* and Nobuyuki Yoshikawa, *Member, IEEE*

***Abstract*— A superconducting quantum interference device (SQUID) is used as a memory cell in a superconducting Josephson random access memory (RAM) system. In the Josephson RAM, power is mainly consumed by driver circuits, which drive word and bit lines to select the target memory cell. We investigated power reduction of read/write operation of the SQUID memory cell by using a stochastic resonance phenomenon. By using a noise-assisted state transition of the SQUID, the driving current required for read/write operation of the memory cell can be reduced. We investigated optimum bias and noise conditions where stochastic resonance efficiently occurs on the basis of analog circuit simulation that takes influences of thermal noises into account. According to the simulation results, the power dissipation required for read/write operation can be reduced by approximately 20% under the optimum bias and noise conditions when the error rate of read/write operation is 10^{-10}. We designed a 1-bit rf-SQUID memory cell using the AIST 2.5 kA/cm^2 Nb standard process 2, and tested the cell by applying a white noise from the room-temperature instrument. The probability that a datum is written to the memory cell and read-out correctly was measured under various bias and noise conditions. We have experimentally observed stochastic resonance and obtained the error rate of 10^{-5} when the power dissipation of read/write operation is reduced to 80% compared to the conventional Josephson RAM.**

***Index Terms*— Josephson RAM, memory, stochastic resonance, rf-SQUID, SFQ circuit**

I. Introduction

The performance of the computation system has been improved for several decades. At the present time, the performance of the supercomputer reaches 93.0 PFLOPS [1]. However, power consumption of such high-performance computer is more than 10 MW. Power consumption of the next-generation supercomputer that has the performance of 1 Exa-FLOPS system is estimated to reach several hundred MW. It is not practical to build such a large power system.

Energy efficiency of the superconducting circuits is more than three orders of magnitude higher than that of the semiconductor integrated circuit [2, 3]. High energy efficiency of the superconducting circuits have been demonstrated [4–8]. In the superconducting computation system, memory access is thought to be the main origin of power consumption because of driving of word and bit lines for the random access memory (RAM) [9–12]. To reduce total power consumption of the computation systems based on the superconducting circuit, reduction in power consumption of memory access is efficient. Recently, RAM cells based on novel materials have been proposed and implemented for superconducting computation systems [13–16]. Power reduction of memory access benefits not only conventional Josephson RAM but also these novel RAMs.

In this study, we investigated power reduction in the superconducting RAM by introducing stochastic resonance [17]. By using stochastic resonance, signal to noise ratio of the sensing circuit can be improved [17]. It is known that stochastic resonance occurs in a superconducting circuit [18]. We investigated use of stochastic resonance to reduce the driving current for datum read/write operation for the superconducting RAM. We derived the appropriate noise condition to efficiently obtain stochastic resonance in the memory cell of the superconducting RAM. We implemented and tested the memory cell by applying white noise from a room-temperature instrument.

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II. State Transition of SQUID by Stochastic Resonance

Fig. 1 shows an equivalent circuit of an rf-SQUID comprising of one Josephson junction. The rf-SQUID is bistable device and thus can be used as a memory cell for the superconducting RAM [9, 10]. Potential energy of the rf-SQUID is represented by

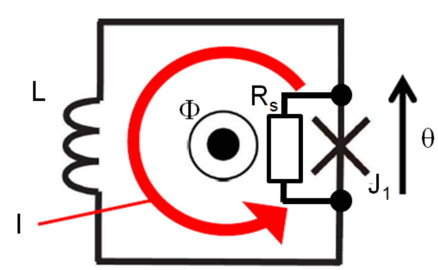

Fig.1. Equivalent circuit of an rf-SQUID. L is inductance consisting rf-SQUID loop. J_1 is Josephson junction. Φ is internal magnetic flux in rf-SQUID, I is the circular current. R_S is shunt resistance of Josephson junction J_1. θ is the phase difference of the macroscopic wave function across the Josephson junction J_1.

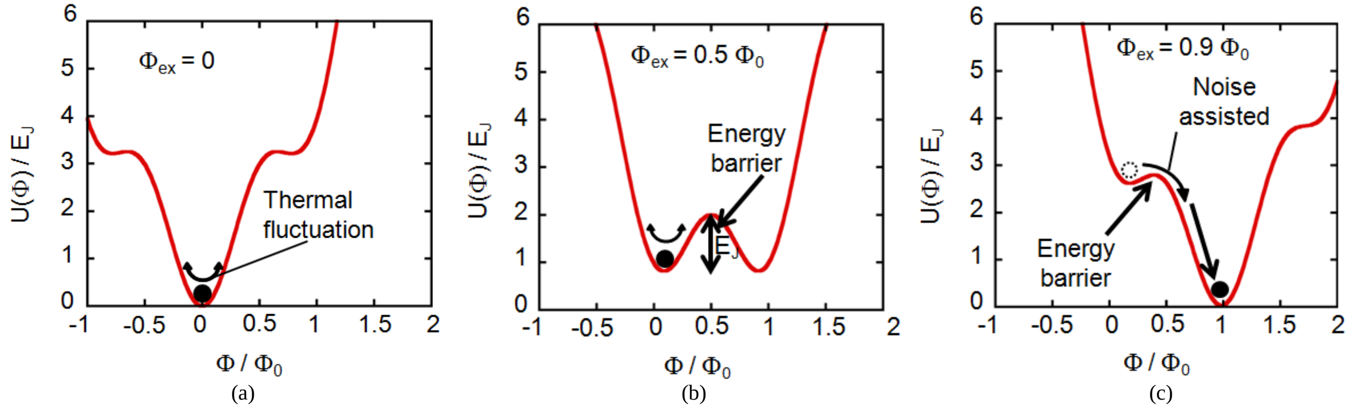

Fig. 2. Potential energy diagrams of rf-SQUID. (a) $\Phi_{ex} = 0$, (b) $\Phi_{ex} = 0.5\ \Phi_0$, (c) $\Phi_{ex} = 0.9\ \Phi_0$. Φ_{ex} is the external magnetic flux uniformly applying to whole of the rf-SQUID, $\Phi_0 = 2.07 \times 10^{-15}$ Wb is single flux quantum, E_J is Josephson energy. $L = 30.1$ pH, $J_1 = 50$ μA in Fig. 1. $E_J = 1.68 \times 10^{-20}$ J, corresponds to 1200 K thermal energy.

$$U(\Phi) = (1/2)LI^2 + E_J(1-\cos\theta) \\ = \{(\Phi-\Phi_{ex})/2L\} + E_J[1-\cos\{2\pi(\Phi-\Phi_{ex})/\Phi_0)\}] \quad ,(1)$$

where L is inductance of the rf-SQUID loop, I is the superconducting current flowing in the rf-SQUID, Φ is the internal magnetic flux, Φ_{ex} is the external magnetic flux applied to the rf-SQUID, E_J is Josephson energy when no current is flowing in the junction, θ is phase difference of the macroscopic wave function across the Josephson junction, and Φ_0 is a magnetic flux quantum in a superconductor.

Fig. 2 shows noise-assisted state transition of the rf-SQUID, which corresponds to datum write operation for the SQUID memory cell in this study. The circuit parameters were optimized to obtain the stochastic resonance characteristic. In the initial state, where no magnetic flux is applied to the SQUID, energy potential of the SQUID has one minimum and thus the state is stable (Fig. 2(a)). When the external magnetic flux is applied, two potential minima appear according to eq. (1) as shown in Fig. 2(b). These two potential minima correspond to ‘0’and ‘1’ sates in the memory cell, respectively. Because these minima are isolated by a potential barrier, state transition does not occur. Fig. 2(c) shows potential energy of the SQUID when the magnetic flux of $0.9\Phi_0$ is applied. In this case, potential barrier that isolates two stable states is low and the state can transit from the ‘0’ state to the ‘1’ state if appropriate noises exist. In this noise-assisted transition, the required magnetic flux is less than Φ_0, whereas magnetic flux of more than Φ_0 is required to induce state transition from ‘0’ to ‘1’ states in the conventional SQUID memory.

We simulated read/write operation of the rf-SQUID memory cell taking thermal noises into account using the circuit simulator, JSIM_N [19]. In simulation, datum ‘1’ is written to the SQUID by inputting square wave shaped magnetic flux with the amplitude of Φ_{amp} and the datum is read-out 10000 times at the frequency of 1 GHz assuming existence of a thermal noise that has the bandwidth of 10 THz. We defined the probability that the datum is written to the memory cell and the datum is read-out correctly as a success rate. We calculated the success rate of the SQUID memory read/write operation under various noise and magnetic flux conditions by changing temperature T and Φ_{amp}. Fig. 3 shows calculated dependences of success rates on noise energy. When the noise is too small, the success rate is low because the noise assisted transition does not occur. The highest success rate is obtained under the optimum noise condition. On the other hand, the success rate is deteriorate with increase in noise energy because state returning from ‘1’ to the ‘0’ and the input of two flux quanta occurs by large noise energy. This is the typical characteristic of stochastic resonance [17].

The simulation result shows the success rate of 1.000 is obtained under the appropriate noise condition where the ratio of noise energy and Josephson energy (k_BT/E_J) is 0.16–1.08. when Φ_{amp} is $0.45\Phi_0$, power consumption for read/write operation of the SQUID memory cell can be reduced by approximately 20% because required Φ_{amp} for write/read

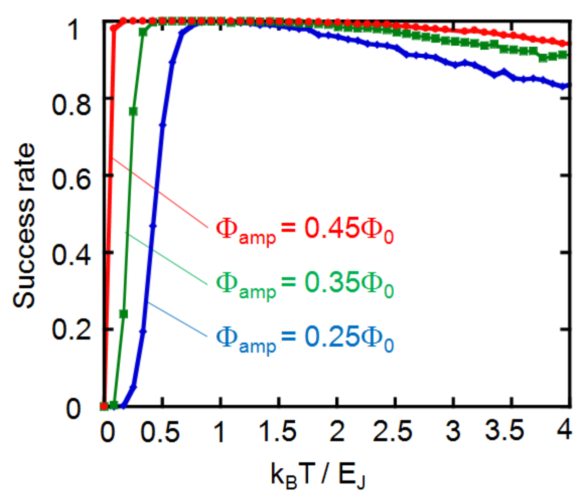

Fig. 3. Simulated dependences of the success rate of the read/write operation of the rf-SQUID memory cell on the noise energy when Φ_{amp} is $0.25\Phi_0$, $0.35\Phi_0$ and $0.45\Phi_0$. The horizontal axis is normalized by Josephson energy E_J. k_B is the Boltzmann constant.

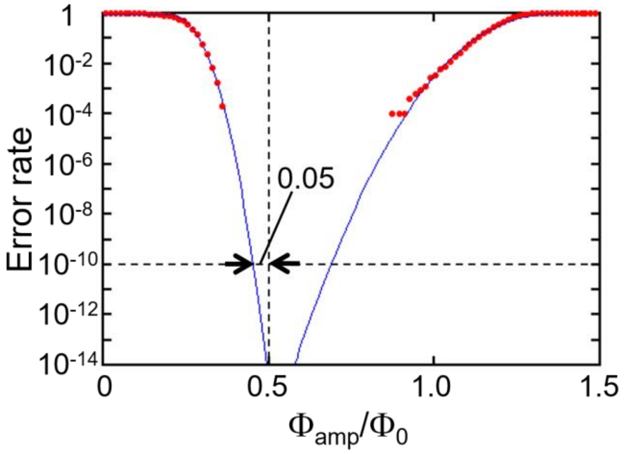

Fig. 4. Simulated dependences of the error rate of the read/write operation of the rf-SQUID memory cell on the input magnetic flux amplitude Φ_{amp} when k_BT/E_J is 0.42. The horizontal axis is normalized by single flux Φ_0. k_B is the Boltzmann constant. Solid curves are fitting characteristics based on the error function.

operation without applying noise is $0.5\Phi_0$ and the power dissipation is proportional to the square of the input magnetic flux amplitude Φ_{amp} $((0.45\Phi_0/0.5\Phi_0)^2 = 0.81)$. Though the power consumption from noise is not taken into account in this estimation, noise input from room-temperature instruments is not necessary by using internal noises such as thermal noises.

Fig. 4 shows simulated dependences of the error rate of write/read operation on the input magnetic flux amplitude Φ_{amp} when k_BT/E_J was the optimum value of 0.42. The error rate characteristic (*ER*) can be fitted by using the error function represented by

$$ER(\Phi_{amp}) = (1/2)[1 + erf\{(\Phi_{amp} - \Phi_m)/\Phi_s\}], \quad (2)$$

where Φ_m is the magnetic flux value of Φ_{amp} when the error rate is 0.5, Φ_s is the equivalent flux noise induced by thermal fluctuation, and k_B is the Boltzmann constant. When Φ_{amp} of 0.45 is used, the error rate of approximately 10^{-10} is obtained. Use of stochastic resonance for superconducting circuit operation could contribute to not only reduction in power of the superconducting RAM systems but also stabilization of the low-power SFQ circuits with low critical current Josephson junctions [20].

III. Experimental

We designed the 1-bit rf-SQUID memory cell using the AIST 2.5 kA/cm^2 Nb standard process 2 [21], and tested the SQUID memory cell by applying noise from a room-temperature instrument. The InductEX [22] was used for extraction of self- and mutual inductance of the designed circuit. Fig. 5 shows an equivalent circuit schematic of the implemented rf-SQUID memory cell and the test setup. A properly biased dc-SQUID is used to detect the state transition of the memory cell. The differential amplifier amplifies the output voltage from the dc-SQUID. The external magnetic flux

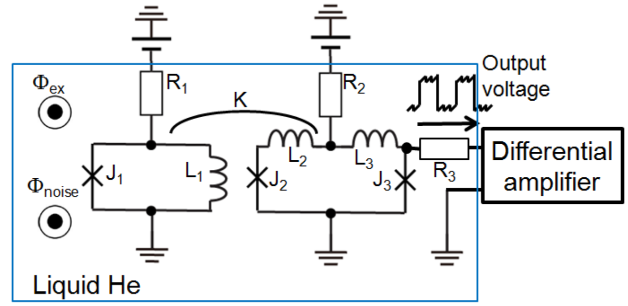

Fig. 5. Circuit schematic of the measured rf-SQUID memory cell. The dc-SQUID detects datum write/read. The external magnetic flux Φ_{ex} and the noise magnetic flux Φ_{noise} are applied to the rf-SQUID from a room-temperature instrument. J_1 = 50 µA, J_2 = J_3 =100 µA, L_1 = 30.3 pH, L_2 = L_3 = 3.5 pH, R_1 = R_2 = 500 Ω, R_3 = 7.5 Ω, k = 0.3 is magnetic coupling coefficient between L_1 and L_2, L_3.

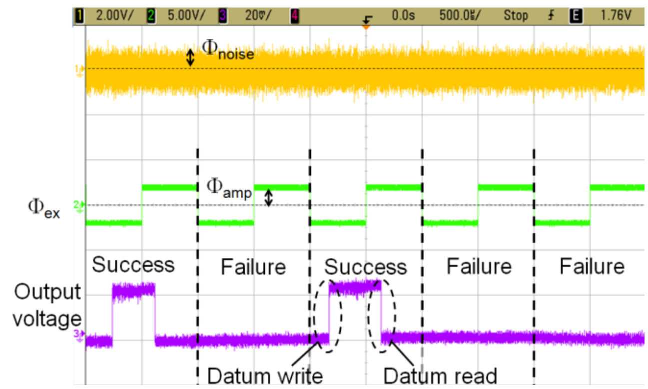

Fig. 6. Measured waveform of write/read operation of the rf-SQUID memory cell. The dc-SQUID is properly biased to detect datum write/read. Φ_{ex} is the inverse of the current supplied to the memory cell. Φ_{amp}/Φ_0 was 0.25 in this measurement. Because the noise condition was not optimum, long delay of datum wite was observed.

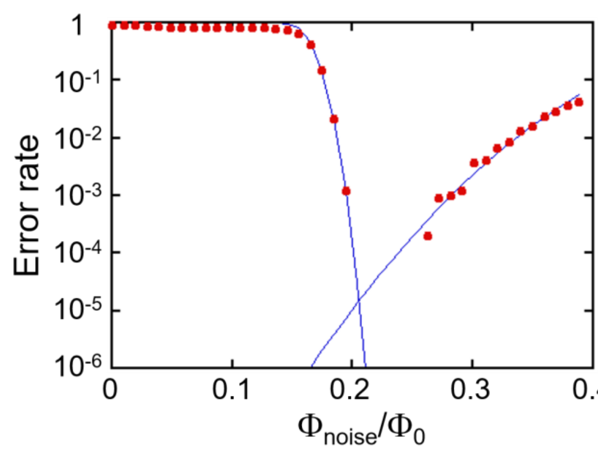

Fig. 7. Dependence of the measured error rate of the read/write operation of the 1-bit rf-SQUID memory cell on the amplitude of the standard deviation of magnetic flux noise Φ_{noise}. Dots are measurement results. Solid curves are fitting characteristics.

Φ_{ex} and the magnetic flux noise Φ_{noise} were applied by arbitrary wave generators. The applied noise was white noise with the bandwidth of 20 MHz. Fig. 6 shows the measured waveform. We repeated 10000 read/write operations at the frequency of 1 kHz. By monitoring the output voltage from the dc-SQUID, the error rate was experimentally evaluated using an automated measurement system based on a LabVIEW program.

Fig. 7 shows the dependence of the measured error rate on the standard deviation of the applied magnetic flux noise Φ_{noise} when $\Phi_{amp} = 0.45\Phi_0$. We obtained the characteristic similar to the simulated one. The experimentally obtained lowest error rate was approximately 10^{-5}. In this case, power consumption of write/read operation was reduced by approximately 20%. Discrepancy of the lowest error rate between simulated and measured results is thought to be caused by difference of the operations frequency and the noise bandwidth between simulation and experiment. The ratio between the noise bandwidth and input frequency was 20000 in the measurement, whereas the ratio is 10000 in circuit simulation. High noise power might deteriorate the measured error rate.

IV. Conclusion

We investigated reduction in power consumption of read/write operation of the rf-SQUID memory cell using stochastic resonance. Simulation results show that stable read/write operation can be expected with reduced power consumption by using noise-assisted state transition. We designed and tested the rf-SQUID memory cell, and experimentally observed clear stochastic resonance. By introducing stochastic resonance, total power consumption of the superconducting RAM can be reduced by approximately 20 % compared to that of the conventional superconducting Josephson RAM.

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