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New Approach to Hardware Implementation of Neural Circuits Using Superconductive Devices

Yoshinao MIZUGAKI, Koji NAKAJIMA, Yasuji SAWADA, and Tsutomu YAMASHITA

Research Institute of Electrical Communication, Tohoku University
2-1-1 Katahira, Aoba-ku, Sendai, 980-77 JAPAN

We report the implementation of neural circuits using superconductive devices. Superconductive devices have large potential for the integration of artificial neural networks, because of their ultra-high speed operation with very low power dissipation. The neural circuits, a neuron and a synapse, have been designed and fabricated in a Nb/AlO$_x$/Nb Josephson junction technology. A 3-bit neural-based A/D converter, which contains three neurons and three synapses, has been successfully operated in liquid helium.

1 INTRODUCTION

Recently, artificial neural networks (ANNs) are receiving extensive attention as a new approach to intelligent information processing. Some groups have reported the implementation of ANNs using silicon IC.[1] However, power dissipation will be a serious problem with increasing the scale of ANNs which require a huge number of devices and interconnections.

Superconducting Josephson devices are attractive for not only post-Si digital computer but also integration of ANNs, because of their three striking features [2]:

- extremely fast switching time (< 10ps).
- extremely low power dissipation ($< 10\mu$W/gate).
- low noise operation at very low temperatures (~ 4K).

In this paper, we present our superconducting neural circuits. The circuits have been fabricated in a Nb/AlO$_x$/Nb technology, and operated successfully at liquid helium temperature.

2 DESIGN AND FABRICATION

The Josephson IC have been designed with 5μm design rule. They are composed of a Nb ground plane, Nb/AlO$_x$/Nb junctions with the Josephson critical current density J_c=1~2kA/cm^2, Au-In resistors of 0.6~1.1$\Omega/\Box$, and Pb-In wiring. Each layer is isolated by SiO or Nb$_2$O$_5$.

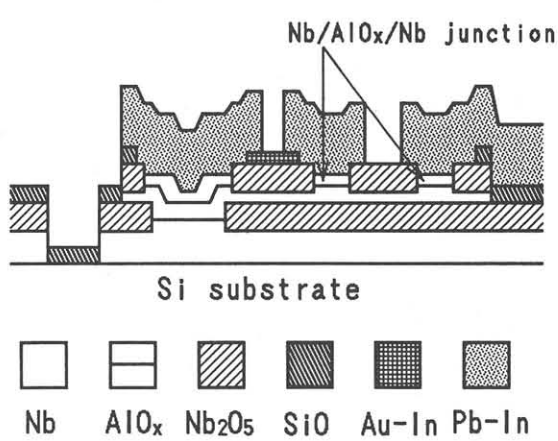


Figure 1: Cross sectional view of the Josephson IC.

Figure 1 shows the cross sectional view of the Josephson IC. Details of the fabrication process were reported in our previous paper.[3]

3 NEURON USING JOSEPHSON TRANSMISSION LINES

A fluxon pulse on a Josephson transmission line (JTL) has a soliton characteristic, and hence, it can be used as a neural impulse in superconducting ANNs. Figure 2 (a) and (b) show a photomicrograph of a 2-bit neural-based A/D converter and

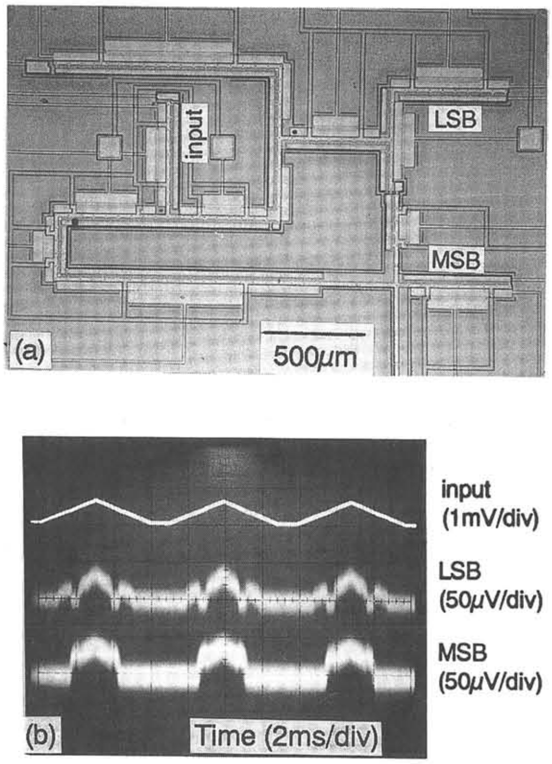


Figure 2: First superconducting implementation of ANNs (2-bit neural-based A/D converter). (a) Photomicrograph. (b) Experimental operation.

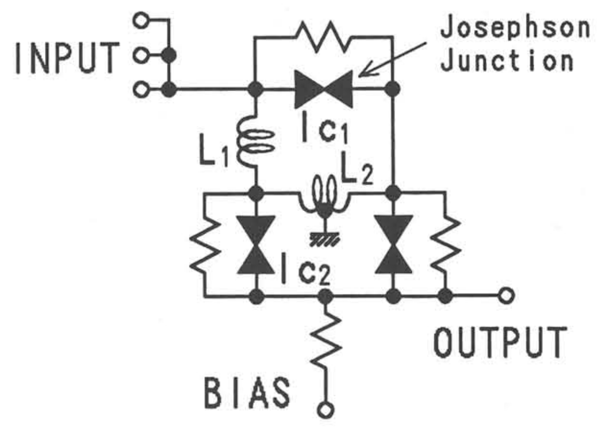


Figure 3: Equivalent circuit of a neuron using coupled SQUID.

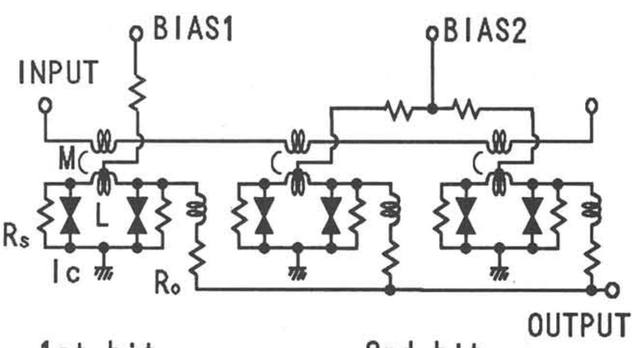


Figure 4: Equivalent circuit of a 2-bit synapse using double-junction SQUIDs.

its experimental operation, respectively.[4, 5] A neuron is composed of two JTLs and a resistor which connects them. The conductance value of the resistor represents the synaptic strength. This is the first verification of the real possibility of superconducting integration of ANNs.

4 NEURAL CIRCUITS USING SQUIDS

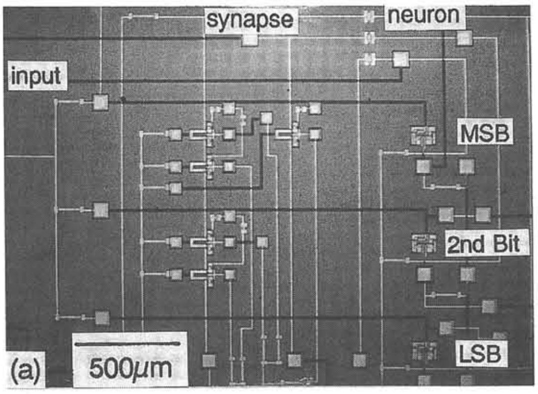
4.1 Neuron

To improve the sigmoid characteristics and input-output isolation, we employ the coupled SQUID (superconducting quantum interference device) for a neuron.[6] Figure 3 shows the equivalent circuit. The coupled SQUID is a combination of a single-junction SQUID and a double-junction SQUID. The quantum state of the single-junction SQUID represents a neuron state, which is read out by the biased double-junction SQUID. The designed circuit parameters for Ic_1, Ic_2, L_1, L_2 are 0.25mA, 1.0mA, 0.83pH, 0.82pH, respectively. The double-junction SQUID is shunted by two resistors of 0.24Ω and operated in non-latching mode.

As shown in Fig. 3, the neuron is an analog-type and composed of only three shunted junctions and two inductors. Its power dissipation without biasing is estimated as small as 0.26μW at "1" state. The area occupancy of a fabricated neuron is $130\times110\mu m^2$. Assuming J_c=10kA/cm^2 and 1μm design rule, it would be reduced as much as a factor of 1/50 without increasing its dissipation.

4.2 Synapse

Figure 4 shows the equivalent circuit of a 2-bit "active" synapse.[7] The 1st and the 2nd bit have one and two double-junction SQUIDs, respectively. They are shunted by resistors of R_s and operated in non-latching mode. The ratio of the output current from the 1st and the 2nd bit become 1 : 2, and hence, we can change the synapse output currents digitally by switching BIAS1 and BIAS2. The designed circuit parameters for Ic, L, M, R_s, and R_o are 0.25mA, 4.0pH, 3.2pH, 0.94Ω, and 0.94Ω, respectively.



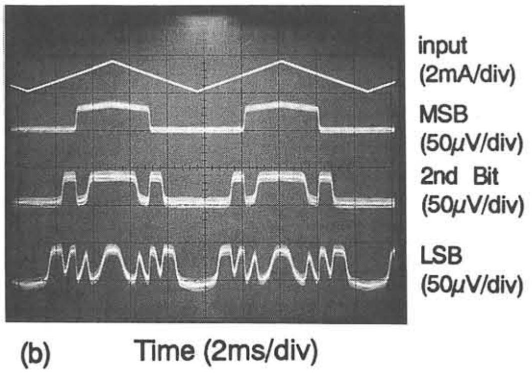


Figure 5: 3-bit neural-based A/D converter. (a) Photomicrograph of the fabricated circuit. (b) Experimental result of A/D conversion.

Though the synapse changes its output current digitally, it is also an analog-type. The power dissipation of the 2-bit synapse without biasing is estimated as small as 0.19μW at (1,1) state. The area occupancy of a fabricated double-junction SQUID is $120 \times 75\mu\mathrm{m}^2$. It would be also reduced as much as 1/50 using J_c=10kA/cm^2 and 1μm design rule.

4.3 3-bit neural-based A/D converter

To demonstrate the ability of the superconducting neuron and synapse experimentally, we have fabricated a 3-bit neural-based A/D converter.[7]

Figure 5 (a) shows the photomicrograph of the fabricated circuit. The network contains three neurons and three synapses.

Figure 5 (b) shows the experimental result of the operation. This A/D converter demonstrates a correct operation with 100kHz input signal, which means that the LSB is operated at 1.5MHz. This is the highest frequency limited by our high-gain measurement equipments. It is confirmed by simulation that this network responds to analog input over 100MHz.

5 SUMMARY

We report the implementation of neural circuits using superconductive devices. Superconductive devices have large potential for the integration of artificial neural networks, because of their ultra-high speed operation with very low power dissipation. A neuron and a synapse using superconducting devices have been designed. To demonstrate the ability of these neural circuits, a 3-bit neural-based A/D converter, which contains three neurons and three synapses, has been fabricated in a Nb/AlO$_x$/Nb Josephson junction technology, and successfully operated in liquid helium.

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