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SUPERCONDUCTING IMPLEMENTATION OF NEURAL NETWORKS USING FLUXON PULSES

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Abstract--We fabricated neural-based superconducting integrated-circuits by using Nb/AlO$_x$/Nb Josephson junctions, and demonstrated the operation of 2-bit neural-based A/D converter which is one of the circuits solving optimization problems. We used fluxon pulses as neural impulses and a Josephson junction as a threshold element. The conductance values of resistors by which Josephson transmission lines are connected represent fixed synaptic strengths. The preliminary experimental result suggests that variable critical currents of dc-SQUID may provide synapses with variable strength.

I. INTRODUCTION

Recently, there has been increasing interest in the application of artificial neural networks for parallel and intelligent information processing. In comparison with ordinary computing devices, models of neural networks are simple; they consist of neuron devices which are connected to one another via synapse elements. In a network of n neurons, the activity of the i-th neuron is described as

$$X_i = f(v_i), \quad \tau\, dv_i / dt = \sum_{j}^{n} T_{ij} X_j + h_i - v_i \qquad (1)$$

where τ, X_i, v_i, h_i, and T_{ij} are a time constant, the output, the potential level, the threshold value, and the synaptic strength of the i-th neuron bringing input from the j-th one, respectively. $f(v_i)$ is a sigmoid-shape function. Synaptic strengths are programmed (or taught) externally or internally to vary the function of the network. For example, they can rapidly compute good solutions to difficult optimization problems of np-complete class.[1] Several groups have reported the implementation of neural networks using semiconductor integrated circuits.[2] However, power dissipation will be a serious problem when large scale networks are tried to be built, because neural networks require a huge number of interconnection.

In this paper, we report superconducting implementation of neural networks. Superconducting Josephson circuits have ultra-high speed operation with very low power dissipation, and hence, they are more suitable for large scale neural networks than semiconductor integrated-circuits. We use fluxon pulses on a JTL (Josephson Transmission Line) as neural impulses. We fabricated a neuron with constant or variable synaptic strengths and a 2-bit neural-based A/D converter by using Nb/AlO$_x$/Nb junctions, and their operations were verified with numerical simulations. An A/D converter is one of the circuits solving optimization problems, and good for demonstrating the operation of neural networks. Because our circuits are based of Phase-mode Logic[3] and do not use gap voltage, they have a potential to be fabricated with non-hysteretic Josephson junctions of the high-Tc superconductors.

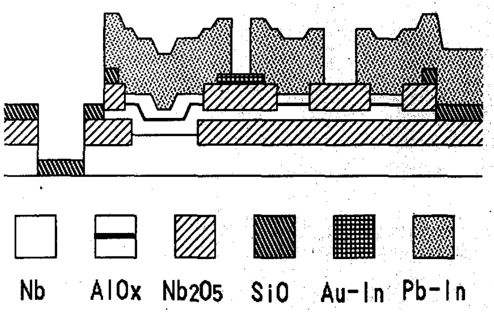

Fig.1 Cross section view of Nb/AlO$_x$/Nb IC.

II. FABRICATION OF Nb/AlO$_x$/Nb CIRCUITS

The Josephson circuits on the 2-in. Si substrate are composed of a Nb ground plane, Nb/AlO$_x$/Nb junctions, Au-In resistors, and Pb-In wiring. Each layer is isolated by SiO or Nb_2O_5. Sputtered Nb layers were patterned by anodization and wet etching. Anodization was done in an electrolyte of ethylene glycol, ammonium pentaborate, and H_2O; wet etching in an etchant of HF, HNO_3, and H_2O. Nb_2O_5 was also used as a etching stopper.[4] Nb/AlO$_x$/Nb junctions were defined by use of the SNAP (Selective Niobium Anodization Process) technology.[5] Fig.1 shows the cross section view of the circuit. The wafer was sectioned to thirty-six 5mmX5mm chips.

The JTLs are discrete type with overlap structure and are composed of 18 junctions of 5μmX5μm with shunt resistance, 0.66Ω or 0.33Ω. The critical current of each junction is designed to be 0.5mA. The spacing between junctions is 60μm, and the calculated penetration depth λ_J is 84.6μm.

III. NEURON WITH CONSTANT SYNAPTIC STRENGTH

A basic superconducting circuit for a neuron, a threshold element, with constant synaptic strength is shown in Fig.2. It is composed of two JTLs and a resistor which connects them. The spatial summation of pulses (fan-in) is accomplished to connect plural input JTLs to the neuron junction which is the first junction of the output JTL, as shown in Fig.3. Fluxon pulses on JTLs work as neural

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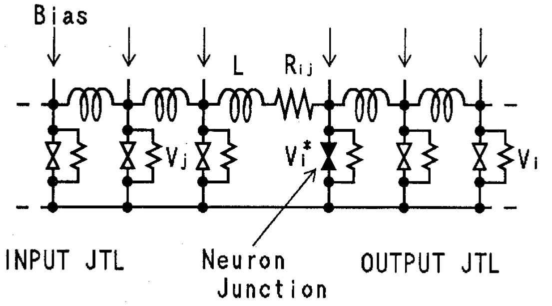

Fig.2 Equivalent circuit of a neuron with a constant synaptic strength.

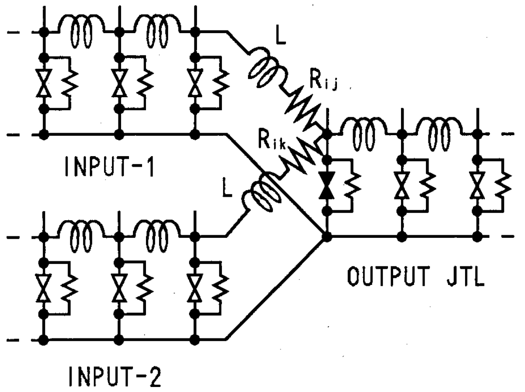

Fig.3 Spatial summation (fan-in) on a neuron circuit.

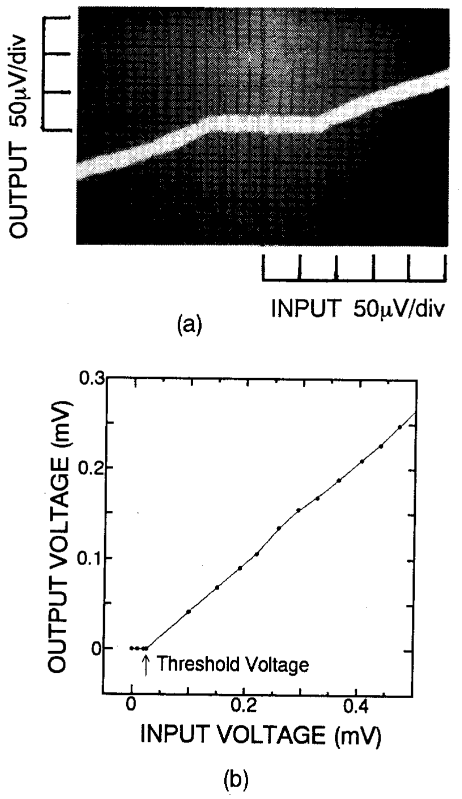

Fig.4 Input-output characteristics of a neuron in Fig.2. (a) Experimental and (b) Numerical simulation results. The inductance and the resistance inserted to the JTL are 4.1pH and 0.023Ω, respectively.

impulses with soliton characteristics in this circuit. When a fluxon propagating on the input JTL reaches at the LR_{ij} loop, it is trapped there because of the loss of the resistor and the threshold characteristics of the neuron junction. The circulating current to hold the fluxon, which corresponds to neural potential level, decreases with the time constant L/R_{ij}. When the temporal and spatial summation of the current flowing into the neuron junction exceeds the critical current, one fluxon come out to the output JTL. The fan-out is accomplished by the phase-conserving branch.[3] The frequency of fluxon pulses on the JTLs is measured as the voltage across the junctions due to the ac Josephson effect. If the time constants of all inputs are same, the current flowing through the i-th neuron junction is described as

$$\tau\, du_i/dt = \sum_{j}^{n} (1/R_{ij})V_j - \sum_{j}^{n} (1/R_{ij})V_i^* + I_i - u_i \qquad (2)$$

where τ, V_i, V_i^*, u_i, I_i, R_{ij} are the time constant ($=L/R_{ij}$), the output voltage, the voltage of the neuron junction, the summation of the loop current, the external bias current for the i-th neuron junction, and the resistor value which connects the j-th output to the i-th input, as shown in Fig.2, respectively. Eq.(2) has the same form as Eq.(1) except the second term in the right-hand side. The existence of the second term means that this neuron circuit cannot avoid to have self-connection because of the incomplete input-output separation.

Fig.4(a) shows the experimental result for the relation between input and output voltage of the 1-input neuron circuit where L=4.1pH and R_{ij}=0.023Ω, and Fig.4(b) the numerical simulations. No output voltage is observed until the input voltage is over the threshold value V_T.

Fig.5 shows the resistor value dependence of V_T. From Fig.5, V_T might be written as

$$V_T = \Phi/\tau = L \times Ic^{o} / (L/R_{ij}) = Ic^{o} \times R_{ij} \qquad (3)$$

where Φ is flux in the LR_{ij} loop and Ic^{o} corresponds to the sum of the critical current of the output JTL with a length of about λ_J. The slope of the output characteristics over the threshold amounts to $r/(R_{ij}+r)$, where r is the resistance of the output JTL over its critical current.

Spatial summation of fluxons in the 2-inputs neuron circuit was experimentally verified with numerical simulations. As shown in Fig.6, the threshold voltage from one input decreased with increasing another input.

One can break the linear relation between V_i and V_i^*,

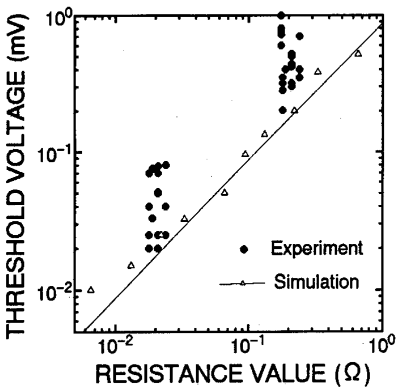

Fig.5 Resistor value dependence of the threshold voltage of a neuron with constant synaptic strength.

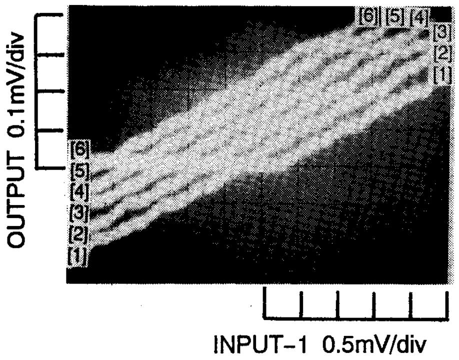

Fig.6 Experimental Input-output characteristics of a 2-input neuron circuit. The inserted L and R are 4.1pH and 0.23Ω in both input JTLs, respectively.
Input-2 is [1]0.0mV, [2]+0.5mV, [3]+1.0mV, [4]+1.5mV, [5]+2.0mV, [6]+2.5mV.

and make saturation characteristics at high V_i by inserting a junction ("Saturation junction") into the part of inductance of the output JTL. Because the "Saturation junction" switches to voltage state with increasing V_i^*. We verified the saturation characteristics by the numerical simulation.

The experimental and simulated input-output characteristics included some undulation, which is not investigated in details. This undulation also appears as the discontinuity on the bias current dependence of the threshold voltage.

IV. NEURON WITH VARIABLE SYNAPTIC STRENGTH

A neuron with variable synapse is accomplished to connect dc-SQUID parallel to the neuron junction as shown in Fig.7(a). The control current changes the critical current of the dc-SQUID. Then the critical current I_{c0} and the threshold voltage V_T suffer change. Fig.7(b) shows the periodic modulation of the threshold voltage at the neuron circuit with variable synapse. The attached dc-SQUID is composed of two 10μmX10μm junctions and 0.38pH loop inductance. The threshold voltage was reduced to 50% of the maximum.

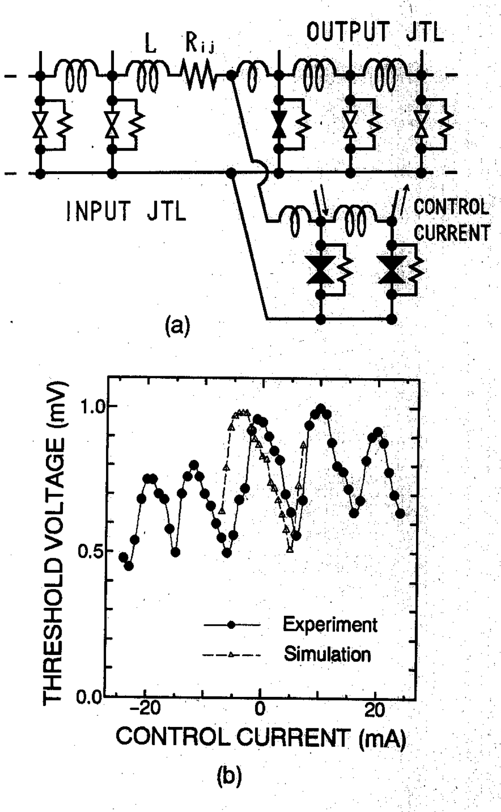

Fig.7 Neuron with a variable synaptic strength.
(a) Equivalent circuit., (b) Experimental and simulated results of the periodic modulation of the threshold voltages

This result suggests that variable critical current of dc-SQUID may provide a synapse with variable strength. It would be possible to control the critical current of dc-SQUID by fluxons in the rf-SQUID loop which is magnetically coupled to the dc-SQUID. The number of fluxons in the rf-SQUID might be changed external or internal learning system. The rf-SQUID would be used as the memory for a variable synapse.

V. 2-BIT A/D CONVERTER

We designed a 2-bit A/D converter of a correct reaction neural network (CRANN) [6] which is the modification of Hopfield-type [7] and excludes the local minima. The A/D converter is, as shown in Fig.8(a), composed of three resistors, an input JTL, two output JTLs including two neuron junctions, and the fourth JTL which makes a synaptic connection between the two neuron junctions. In order to make a inhibitory connection, the fourth JTL is twisted. The

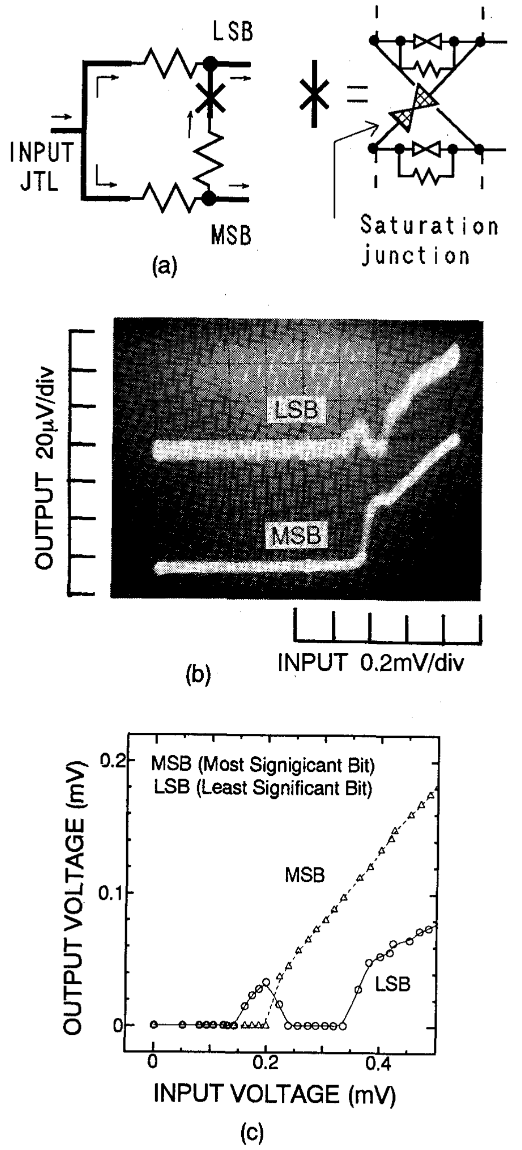

Fig.8 2-bit neural-based A/D converter.
(a) Schematic configuration., (b) Experimental results., (c) Numerical simulations.

twist is accomplished by inserting a 40μmX35μm "Saturation junction". The JTLs are biased to obtain proper thresholds. Fluxon pulses from the input diverge at the phase conserving branch[3] and propagate to each neuron junction through each resistor. When the frequency of input fluxons is low, no fluxon appears on each output JTL. This is "00" state. If the input voltage exceeds the threshold V_{TL} of the LSB (least significant bit) neuron, the LSB neuron switches to voltage state and "01" state is achieved. When the input exceeds the threshold V_{TM} of the MSB (most significant bit) neuron, where $V_{TM}>V_{TL}$, the MSB output suppresses the LSB activity; that is "10" state. The increase of the suppressive signal let the "Saturation junction" transit to voltage state. It suppresses the increasing rate of the suppressive signal and then "11" state appears. Fig.8(b) shows the experimental results for the operation of the 2-bit A/D converter and Fig.8(c) numerical simulations. The two figures agree excellently to each other. The "soft" digital output would be improved to be a "hard" output by inserting "Saturation Junctions" into the output JTLs.

The power dissipation for a junction in the present experiment was estimated to be as low as 11nW and would be made less than 100nW including biasing circuit for a junction.[3]

VI. CONCLUSION

In summary, we propose superconducting neural circuits using fluxon pulses and implement them to Nb/$\mathrm{AlO_x}$/Nb integrated-circuits. Superconducting Josephson circuits are suitable for large scale neural networks because of its excellent characteristics, ultra-high speed switching and very low power dissipation. A neuron with constant synaptic strength is composed of JTLs connected by resistors. The inverse of the resistor value represents synaptic strength. The modulation of the threshold voltage by control current suggests that variable critical currents of dc-SQUID may provide synapses with variable strength. We demonstrate the operation of 2-bit neural-based A/D converter. This is the first experimental measurement of superconducting neural IC up to the authors' best knowledge.

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