Superconducting implementation of neural networks using fluxon pulses

Mizugaki Y., Nakajima H., Sawada Y., Yamashita T.

IEEE Transactions on Applied Superconductivity

volume 3

number 1

page range 2765-2768

year 1993-03

URL http://hdl.handle.net/10097/48262
doi: 10.1109/77.233508
SUPERCONDUCTING IMPLEMENTATION OF NEURAL NETWORKS USING FLUXON PULSES

Y. Mizugaki, K. Nakajima, Y. Sawada, and T. Yamashita
Research Institute of Electrical Communication, Tohoku University
2-1-1 Katahira, Sendai, 980, JAPAN

Abstract—We fabricated neural-based superconducting integrated-circuits by using Nb/AlOx/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

\[
X_i = f(v_i), \quad \tau \frac{dv_i}{dt} = \sum_j T_{ij} X_j + h_i - v_i \tag{1}
\]

where \( \tau, X_i, v_i, h_i, \) 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. \( f(v) \) 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/AlOx/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.

II. FABRICATION OF Nb/AlOx/Nb CIRCUITS

The Josephson circuits on the 2-in. Si substrate are composed of a Nb ground plane, Nb/AlOx/Nb junctions, Au-In resistors, and Pb-In wiring. Each layer is isolated by SiO or Nb O . 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 \( H_2O \). \( NbO_2 \) was also used as an etching stopper.[4] Nb/AlOx/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 5mm×5mm chips.

The JTLs are discrete type with overlap structure and are composed of 18 junctions of 5μm×5μm with shunt resistance, 0.65Ω 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 \( \lambda \) 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.
impulses with soliton characteristics in this circuit. When a soliton propagating on the input JTL reaches at the LR 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 soliton, which corresponds to neural potential level, decreases with the time constant $L/R$. When the temporal and spatial summation of the current flowing into the neuron junction exceeds the critical current, one soliton come out to the output JTL. The fan-out is accomplished by the phase-conserving branch. The frequency of soliton 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

$$\tau \frac{du_i}{dt} = \sum_{j \neq i} \left( \frac{1}{R_{ij}} \right) V_j - \left( \frac{1}{R_{ij}} \right) V_i^* + I_i - u_i \quad (2)$$

where $\tau$, $V_j$, $V_i^*$, $u_i$, $I_i$, $R_{ij}$ are the time constant ($=L/R$), 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, 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 $L=4.1\mu H$ and $R_{ij}=0.023\Omega$, 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

$$V_T = \frac{\Phi}{r} = L \times Ico / (L/R) = Ico \times R_{ij} \quad (3)$$

where $\Phi$ is flux in the LR loop and $Ico$ corresponds to the sum of the critical current of the output JTL with a length of about $\lambda$. 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 solitons 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 $V_i^*$, and...
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.

Fig. 7  Neuron with a variable synaptic strength.

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_c 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 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 an inhibitory connection, the fourth JTL is twisted. The
twist is accomplished by inserting a 40μm×35μm "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 1nW 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/AlOx/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.

REFERENCES