Design and Component Test of a Tiny Processor Based on the SFQ Technology

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Abstract—An eight-bit SFQ processor has been designed and some key components have been tested to confirm feasibility of the large-scale SFQ digital circuit. The designed processor is composed of a one-bit ALU, two eight-bit registers with local clock generators, an instruction register, a five-bit program counter, a state controller, and a 32-byte register file. A bit-serial architecture and a distributed local clock architecture, where each register has its own local clock generator, have been employed in order to increase the local clock frequency. The target clock frequency is 16 GHz and 10 GHz for the NEC 2.5 kA/cm² and Hypres 1 kA/cm² Nb processes. On the circuit design level, we have used a data-driven self-timed architecture and a binary decision diagram, which reduce the timing design difficulty in high frequency operation. The processor, which contains 7,300 Josephson junctions, has been designed by using a cell-based design methodology with the assistance of a top-down CAD environment. We have successfully tested some important circuit blocks, including a one-bit ALU, eight-bit registers, and a demultiplexer for register files.

Index Terms—Binary decision diagram, bit-serial architecture, RSFQ, SFQ processor.

I. INTRODUCTION

THE most attractive and challenging application of the SFQ digital systems [1] is a high-end computing or server application [2]–[5], where both strong points of the SFQ circuits, high speed and low power, are fully utilized. We have been developing tiny SFQ processors to show the feasibility of large-scale SFQ circuits. We call this project Tiny Processor Project in Yokohama (TIPPY). The aim of the project is to realize the simplest SFQ processor having complete functionality as a general purpose computing system. For practical demonstration of the processor operation, we are planning to implement all circuit components on a single chip of a 5 mm die size. Throughout the project, we also expect to encounter unforeseen problems when designing the large-scale circuits, and to find appropriate architectures for the SFQ digital system. Design methodologies and CAD tools are also being developed to design the large-scale system.

The first version of our SFQ processor, TIPPY1, is an 8-bit processor containing an 8-bit ALU and an accumulator (ACC). It is composed of 7,800 Josephson junctions (JJ) and occupies the area 10,500 $\mu\text{m} \times 7,500 \mu\text{m}$ [6]. Its clock frequency is very slow (670 MHz) for a 1kA/cm² Nb process, because the ALU is

Fig. 1. A block diagram of the 8-bit SFQ microprocessor, TIPPY3.

composed of a simple ripple carry adder that limits the critical speed of the processor. However, it also turned out that a CMOS processor having the same architecture is ten times slower than TIPPY1 assuming a 0.6 μm CMOS process.

The second version of our SFQ processor, TIPPY2, employed a bit-serial architecture to increase the local clock frequency and decrease the circuit size [7]. As a result, it operates at 6.25 GHz, contains 5,118 JJ and occupies the area 7,300 $\mu\text{m} \times 7,000 \mu\text{m}$, for the 1kA/cm² Nb process.

The third version, TIPPY3, has been designed for the purpose of real implementation and demonstration of the SFQ processor by modifying the design of TIPPY2. Their main difference is that the ACC in TIPPY2 is replaced with two registers in TIPPY3, which are placed adjacent to the ALU to maintain precise timing of the ALU operation at high speed. In the TIPPY3 design, a floor plan is carefully considered to decrease the routing path length between circuit blocks. As a result, all passive transmission lines in TIPPY2 are removed in TIPPY3.

In this paper we will describe the design details of TIPPY3 and show their functional simulation results using a logic simulator. Component test results of some main circuit blocks will also be shown.

II. MICROPROCESSOR ARCHITECTURE

A block diagram of the 8-bit SFQ processor, TIPPY3, is shown in Fig. 1. The processor is composed of a one-bit

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Fig. 2. Instruction format of TIPPY3.

TABLE I
INSTRUCTION SET OF TIPPY3

Instruction Example	Instruction Name	Meaning
HLT	Halt	Stop
ADD	Add	$REG0 + REG1 \rightarrow REG0$
LD R1	Load	$Mem[R1] \rightarrow REG1$
ST R2	Store	$REG0 \rightarrow Mem[R2]$
SKZ	Skip if Zero	$If(REG0=0)PC+1 \rightarrow PC$
JMP R3	Jump	$R3 \rightarrow PC$
MOVE	Move	$REG1 \rightarrow REG0$

ALU, two eight-bit registers (REG0 and REG1), an instruction register (IR), a five-bit program counter (PC), a data selector (DS), a state controller, and a 32-byte register file (RAM). Its basic structure is similar to TIPPY2 except that TIPPY3 has two registers adjacent to the ALU. This revision guarantees the precise timing of the ALU operation at high clock frequency. The data bus width is 1-bit, therefore all data in the data path are processed serially. This bit-serial architecture increases the local clock frequency up to the limit of the SFQ circuit. Though the system cycle frequency is reduced in the bit-serial architecture, it decreases the system size. Therefore we can say that the advantage of the speed of the SFQ circuits is utilized to reduce the system complexity [5].

Fig. 2 shows the instruction format of TIPPY3. The 8-bit instruction is composed of a 3-bit opcode and a 5-bit operand. The 3-bit opcode determines the processor operations, which consists of seven instructions as listed in Table I. In TIPPY3 a MOVE operation is added to move the data from the REG1 to the REG0. The 5-bit operand directly specifies the data address of the 32-byte RAM. It should be noted here that though TIPPY3 has only seven instructions, it includes a basic function for the conditional branch operation, which is necessary for general purpose computing.

The internal state of TIPPY3 has eight phases: The first four phases are used for the instruction fetch, and the second four phases are the instruction decode, the ALU setup, the execute and the store-result phases. In the instruction fetch phase, the data on the RAM specified by the PC are sent to the IR. In the instruction decode phase, the 3-bit opcode in the IR is sent to the controller. In the ALU setup phase, the ALU function is setup by the controller according to the instruction. After the execute phase, where the ALU operations are executed, the data in REG0 is moved to the RAM in the store-result phase. No pipelining technique is used for the simplicity of the system.

Fig. 3. (a) A binary decision diagram. The diagram shows the logical function $x_1x_2 + \overline{x_3}$. (b) Symbols and (c) photographs of the basic cells in the BDD SFQ standard cell library.

III. DESIGN METHODOLOGY

We have used several design methodologies and techniques when designing the SFQ processor as described in the following subsections.

A. Data-Driven Self-Timed Architecture

In the data-driven self-timed (DDST) architecture [8], the data communications between circuit blocks are carried out by using dual-rail lines, by which we can eliminate the globally synchronous clock that is necessary in the conventional SFQ circuits.

B. Binary Decision Diagram

We have used the binary decision diagram (BDD) for logic synthesis and circuit implementation [9]. Fig. 3(a) shows the BDD representing the logical function $f = x_1x_2 + \overline{x_3}$. The BDD is composed of binary switches having one input (root) and two outputs (branch0 and branch1), where an SFQ pulse entering the root is switched into one of two branches according to its internal state. Because the binary switch is implemented by using the D2 flip-flop having dual-rail inputs, the BDD SFQ circuit is one of the DDST logic circuits. The advantage of the BDD SFQ circuit is the simplicity in the timing design and the short delay due to its asynchronous nature. Note that the logic synthesis methodology by using the BDD is well established [9].

Fig. 4. Conceptual diagram of distributed local clock (DLC) architecture.

C. Distributed Local Clock Architecture

Because we employ the bit-serial architecture for the data path, the data communication between circuit blocks is carried out serially at very high clock frequency, above 10 GHz. It seems very difficult to distribute clock signals to each circuit block by using a single clock generator. In the distributed local clock (DLC) architecture, each register has its own local clock generator and generates high-speed bit-serial data by itself as illustrated in Fig. 4. The controller only provides an SFQ trigger pulse to activate the read-out operation of the register block.

D. Cell-Based Design Methodology

We have used cell-based design methodology to simplify the layout design [10]. In our cell-based design approach, the circuit is designed by simply placing the tile-shaped basic cells. Fig. 3(b) and 3c shows a symbol view and a photograph of the basic cells in our BDD SFQ cell library. In the figure, the Bina works as a binary switch of the BDD, where input node s_0, s_1 are used to set the internal state. The r, b_0 , and b_1 correspond to root, branch0 and branch1, respectively. We have implemented the BDD SFQ cell library [11] by using the Hypres 1 kA/cm² Nb standard process. We have also added our BDD cells to the CONNECT cell library for the NEC 2.5 kA/cm² Nb standard process [12].

E. Logic Level Simulation

We have developed a logic simulation environment based on a Verilog HDL, by which we can check the functionality and timing violation of the circuits by changing the bias voltage [13]. We can also execute small benchmark test programs by using our logic simulator.

IV. CIRCUIT DESIGN DETAILS

A. 8-Bit Bit-Serial Register

As stated above, we use the DLC architecture for the register design. Fig. 5 shows a circuit schematic of the 8-bit bit-serial register, which is composed of an 8-bit ladder type clock generator and an 8-bit DDST shift register. In the write operation of the register, the data stored in the register is rewritten every time the data is input, and during this time no datum is output. In the read operation, when a trigger pulse, (the REG_trg), is applied, the clock generator generates 8 pulses, then the data stored in the register is pushed out. The register design is modified from the previous version so that the propagation delay, the time it takes for the output to appear after the incidence of the trigger pulse,

Fig. 5. A circuit schematic of the 8-bit bit-serial register.

Fig. 6. A circuit schematic of the 1-bit ALU.

is reduced. Circuit simulations by JSIM show that the propagation delay is 144 ps and the DC bias margin is $-26\% \sim +30\%$ at 10 GHz assuming the NEC process.

B. ALU

Fig. 6 shows a circuit schematic of the 1-bit ALU, which is composed of a bit-serial full adder, an OR gate to perform the zero check operation, and a multiplexer. The ALU executes four operations: add, zero check, REG0 through and REG1 through. These functionalities are selected by the multiplexer. Logic simulations of the ALU indicate that its DC bias margin is $-30\% \sim +30\%$ at 10 GHz. Its total junction number is 1710 JJ and the area is $1400 \mu\text{m} \times 1840 \mu\text{m}$.

C. Controller

Fig. 7(a) shows a BDD representation of the controller. The controller has seven dual-rail inputs and 11 single-rail outputs. In the figure, the nodes denoted as “1”, “2” and “3” correspond to the state of the opcode, and the nodes “clk”, “clk2” and “fetch” are the state of the system clocks that determine the internal phase of the processor. The boxes denoted by “PC_trg” mean the output of the PC_trg pulse, for example. It can be seen from the figure that the BDD is useful in representing and implementing the state machine such as state controller of the microprocessor. Fig. 7(b) shows a schematic of the controller. It is found from the logic simulations that its DC bias margin is $-30\% \sim +30\%$. Its junction count is 1936 JJ and the area is $1560 \mu\text{m} \times 1440 \mu\text{m}$.

Fig. 7. (a) The BDD graph and (b) a circuit schematic of the controller.

D. Microprocessor

We have designed all other components and integrated them on a single chip except the RAM. Simulated DC bias margins and JJ counts of the components are listed in Table II. Fig. 8 shows a chip layout of TIPPY3, which is implemented by using the NEC process. Chip size is 5 mm $\times$ 5 mm and the total JJ number is about 7,300. The bias current necessary for the circuit

TABLE II
SIMULATED AND TESTED DC BIAS MARGIN OF THE
MICROPROCESSOR COMPONENT

Circuit Component	JJ count	DC bias margin		Process
		Simulated @10GHz	Tested @1KHz	
ALU	730	-32%~+32%	$\pm 3.3\%$	Hypres
Register (REG)	560	-32%~+36%	$\pm 6.9\%$ (@10GHz)	Hypres
Data selector (DS)	950	-26%~+30%	---	NEC
Instruction Register (IR)	80	-30%~+30%	$\pm 21.1\%$	NEC
Program Counter (PC)	1090	-28%~+30%	---	NEC
Decoder for RAM	620	-30%~+30%	$\pm 11.5\%$	NEC

Fig. 8. A chip layout of the 8-bit SFQ microprocessor, TIPPY3, implemented by using the NEC Nb 2.5kA/cm² standard process. Chip size is 5 mm $\times$ 5 mm.

is 940 mA in total, therefore total power is 2.35 mW. No passive microstrip line is used in contrast to the previous version.

Fig. 9 shows the logic simulation results of TIPPY3. The figure demonstrates the ADD operation. It is found from the logic simulation that TIPPY3 operates correctly at a local clock frequency of 10 GHz and at a system cycle frequency of 1.2 GHz. Fig. 10 shows the test program and its execution results by the logic simulator. We can verify that all the operations are executed correctly from the result.

V. COMPONENT TEST RESULTS

We have implemented some circuit components using the Hypres and NEC Nb standard process and tested them at low

Fig. 9. Logic simulation results of TIPPY3. The figure shows a sequence of the ADD operation. The local clock frequency is 10 GHz.

//opcode operand	//addr assembly code
@00 111_11011	//00 BEGIN: LD DATA_2
011_00000	//01 MOVE
111_11101	//02 LD DATA_4
101_00000	//03 ADD
100_00000	//04 SKP
000_00000	//05 HLT
111_11010	//06 LD DATA_1
011_00000	//07 MOVE
111_11100	//08 LD DATA_3
101_00000	//09 ADD
100_00000	//0a SKP
001_01101	//0b JMP 0d
000_00000	//0c HLT
110_11110	//0d STO TEMP
000_00000	//0e HLT :END
011_00000	//0f JMP BEGIN
@1A 00000001	//1a DATA_1
11111111	//1b DATA_2
00000010	//1c DATA_3
00000001	//1d DATA_4
00000000	//1e TEMP

(a)

TIME	PC	INSTR	DATA	IR_reg	REG0	REG1	MEM_addr
2603	00		00000000	00000000	00000000	00000000	00
13011	01	LD	00000000	11111011	00000000	11111111	01
23419	02	MV	11111111	01100000	11111111	00000000	02
33827	03	LD	00000000	11111101	11111111	00000001	03
44235	04	ADD	00000000	10100000	00000000	00000000	04
54643	06	SKZ	00000000	10000000	00000000	00000000	06
65051	07	LD	00000000	11111010	00000000	00000001	07
75459	08	MV	00000001	01100000	00000001	00000000	08
85867	09	LD	00000000	11111100	00000001	00000010	09
96275	0a	ADD	00000011	10100000	00000011	00000000	0a
106683	0b	SKZ	00000000	10000000	00000000	00000000	0b
117091	0d	JMP	00000000	00101101	00000000	00000000	0d
127499	0e	STO	00000000	11011110	00000000	00000000	0e

(b)

Fig. 10. (a) A test program and data in the memory. (b) A functional simulation result using the test program. The program tests all operation of the TIPPY3. In the test program, if all operations are executed correctly, the PC and memory address finish at the address "0e".

speed. Tested DC bias margins of the components are listed in Table II. It should be noted that the register has also been tested at 10 GHz using an on-chip high-speed test system [14]. It is found from the table that the tested DC bias margins of large cir-

cuits are rather small in contrast to the simulation results. This is probably due to the large bias current flowing along bias lines and ground planes, which induces a magnetic field.

VI. CONCLUSIONS

We have designed the third version of the tiny SFQ processor, TIPPY3, by using several design approaches such as the DDST, the BDD, the bit-serial architecture, the DLC architecture, and the cell-based design methodology. TIPPY3 contains 7,300 JJ and has been implemented on a single chip of 5 mm die size. Logic simulations shows that it operates at a local clock frequency of 10 GHz using the NEC 2.5 kA/cm² standard process. Some key components, including the ALU, the register, the data selector and demultiplexer are tested and their correct operation is confirmed.

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