Tu-KEY-01

Impact of Recent Advancement in Cryogenic Circuit Technology

Akira Fujimaki and Masamitsu Tanaka
Nagoya University

Acknowledgment
This work was supported by JST ALCA and JSPS KAKENHI (Grant Numbers 16H02340, 26220904, and 16H02796), JST-ALCA and the VLSI Design and Education Center of the University of Tokyo, in collaboration with Cadence Design Systems, Inc. The circuits were fabricated in CRAVITY of AIST.
What we have introduced to superconductor circuits within the past decade?

- Locally generated heat is introduced, opening ‘Superconductor phononics’, ‘Superconductor phonon engineering’?
- Ferromagnetic materials are introduced, opening ‘Superconductor spintronics’, or ‘Superconducting phase engineering’.
- Only currents are used for controlling circuits.

Increased degree of freedom
Outline

- Introduction
- More SFQ
  - More powerful computing
  - More energy-efficient computing
- Superconducting Phase Engineering
- Superconductor Phonon Engineering
- Summary
Special Features of SFQ Circuits

- Signal propagation at the speed of light with small distortion in interconnects based on waveguides.
- No recharge process both in logic operation and interconnects.
- Scaling law

High-speed & low power
Suitable to LSIs
Appealing Feature of SFQ Circuits

Limit due to heat generation in CMOS
Limit due to interconnect delay

Target of SFQ Circuits

Limit due to heat generation in compound semiconductor

Clock Frequency (GHz)

Integration Density (Trs/cm$^2$, JJs/cm$^2$)

Si MOSFET
GaAs MESFET
Si Bip
GaAs HEMT
SiGe HBT
InP HEMT
History of RSFQ Microprocessors

CORE1α (2003)
- 4999 JJs
- 15 GHz
- 167 M Instructions/s
- 1.6 mW

CORE1β (2006)
- 10955 JJs
- 25 GHz
- 1400 Million Operations/s
- 3.3 mW

What’s next?
- More Powerful
- More Energy-Efficient
- More Flexible

The base of the new computational paradigms
- Adiabatic
- Reversible
- Neuromorphic
- ...

---

This keynote presentation Tu-KEY-01 was given at ISEC 2017.
More Powerful Computing Based on RSFQ

Bit-serial μP
100 GHz
μP w/o Memory

Bit-serial μP
50 GHz
Memory Embedded

CORE100 (2015)
3073 JJs
800 MIPS
1.0 mW
800 GIPS/W
New Fabrication

COREe2 (2017)
10655 JJs
500 MIPS
2.4 mW
210 GIPS/W
Programs Executed
Program Execution in $\mu$-processor COREe2

Execute a program to find a highest proper factor, which is stored in the embedded memory.

| 00: | LD 00 |
| 01: | MV    |
| 02: | DEC   |
| 03: | ST 01 |
| 04: | LD 00 |
| 05: | MV    |
| 06: | LD 01 |
| 07: | SUB   |
| 08: | SKNE  |
| 09: | HLT   |
| 0a: | SKLT  |
| 0b: | JMP 07 |
| 0c: | LD 01 |
| 0d: | JMP 01 |

Margins are independent of the total number of instructions

$X = 21$

$\text{aliquot} = 7$

160 instructions
Main Issues Left for Practical Applications

• High-frequency operation of bit-parallel processing
• Energy-efficient SFQ circuits
• Energy-efficient power supply for dc-powered SFQ circuits
• Amplifier for driving a large capacity memory
• Amplifier serving as an interface device between SFQ circuits and room temperature electronics
More Powerful Computing Based on RSFQ

Bit-serial μP
100 GHz
μP w/o Memory

Bit-serial μP
50 GHz
Memory Embedded

Bit-Parallel ALU
50 GHz
ALU

CORE100 (2015)
3073 JJs
800 MIPS
1.0 mW
800 GIPS/W
New Fabrication

COREe2 (2017)
10655 JJs
500 MIPS
2.4 mW
210 GIPS/W
Programs Executed

GLP (2017)
4868 JJs
50 GIPS
1.4 mW
36000 GIPS/W
Gate-Level Pipelining

The detail will be given by Prof. Tanaka in this morning session
Addition/subtraction in Parallel ALU

Input
- Op_xor
- Op_and
- Op_arith
- Inv_x
- Inv_y
- clk
- Carry_out

Output
- S0
- S1
- S2
- S3
- S4
- S5
- S6
- S7

Result

Input to SR_IN

High Frequency clock

2 ms/div.

Example:
- \( 1111\ 1111 - 1111\ 1111 = 1\ 0000\ 0000 \)
- \( 1010\ 1010 - 1001\ 1001 = 1\ 0001\ 0001 \)
- \( 1111\ 1111 + 1111\ 1111 = 1\ 1111\ 1110 \)
- \( 1010\ 1010 + 1001\ 1001 = 1\ 0100\ 0011 \)
Advantage of RSFQ Technology

![Graph showing performance vs. energy efficiency for various processors, including Athlon 64FX57, Pentium 4, RSFQ CORE1α, RSFQ CORE2, and Future RSFQ. The graph includes a legend for MIPS/W (Million Instructions/s) and MIPS (Million Instructions/s).]

Estimation of performances of a 32-bit single-core microprocessor based on the experiments.
Main Issues Left for Practical Applications

• High-frequency operation of bit-parallel processing  
  ✔ resolved
• Energy-efficient SFQ circuits
• Energy-efficient power supply for dc-powered SFQ circuits
• Amplifier for driving a large capacity memory
• Amplifier serving as an interface device between SFQ circuits and room temperature electronics
Issue for Energy-Efficiency

Power consumption at $R_b$ (Static power consumption)

$$P_{\text{bias}} = \frac{V_b^2}{R_b} \approx 0.7 I_c V_b$$

Example: DFF

$P_{\text{bias}} = 1.8 \mu W$

Power consumption at $R_s$ (Dynamic power consumption)

$$P_{\text{shunt}} = f I_c \Phi_0$$

Example: DFF

$P_{\text{shunt}} = 36 nW$

Typically, $I_c \Phi_0 \approx 2 \times 10^{-19} (J)$

$R_b$ is used for providing a constant current to each Josephson junction.

Necessity for eliminating static power consumption.
DC-Powered Energy-Efficient SFQ Circuits

Bias resistors are replaced with inductors and junctions.

**ERSFQ circuit (Hypres)**

![Diagram of ERSFQ circuit](image)

**Advantage**
- The base of design has been established because resources obtained from the RSFQ circuits can be used.
- PTLs can be used as interconnects.
- Possibly suitable to higher density because no mutual coupling is used.

**Disadvantage**
- Difficult to make energy-efficient voltage supply around 0.1 mV.

AC-Powered Energy-Efficient SFQ Circuits

Circuits are driven by AC currents provided via transformers.

Example

Reciprocal Quantum Logic
(Northrop Grumman)

\[ \text{ac bias} \]

\[ \phi_1 \rightarrow M_1 \xrightarrow{\phi_2} M_2 \xrightarrow{\phi_3} M_3 \]

\[ J_1 \rightarrow L_1 \xrightarrow{L_2} L_3 \]


Advantage

- Provided AC currents are used as clock signals.
- NOT logic is easy to be made.
- The above means the RQL can be made up of smaller number of junctions.

Disadvantage

- Transformers are needed for all the gates, indicating downsizing to sub-micron scale is difficult.
- High-frequency design technique is essential for operation.
AC-Powered Energy-Efficient SFQ Circuits

Circuits are driven by AC currents provided via transformers.

Example
Adiabatic Quantum Flux Parametron
(Yokohama Nat’l Univ.)

Advantage
- Very small energy consumption because of no phase jump in switching.
- All the logic operations are achieved based on a single ‘majority’ gate, leading to the robustness to the process variation.

Disadvantage
- Operating frequency is relatively low.
- Difficult to make long interconnects.
- DC offset currents are needed for operation.
Energy-Efficiency in Integrated Circuits

Energy Consumption

\[ \text{Energy Consumption} = \frac{\text{Total power} \times \text{Clk cycle}}{\text{Number of devices}} \]

STP: AIST 2.5-kA/cm\(^2\)
Nb/AlO\(_x\)/Nb Standard Integrated Circuit Process.

ADP: AIST 10-kA/cm\(^2\)
Nb/AlO\(_x\)/Nb Advanced Integrated Circuit Process
Outline

• Introduction
• More SFQ
  ▫ More powerful computing
  ▫ More energy-efficient computing
• Superconducting Phase Engineering
• Superconductor Phonon Engineering
• Summary
Superconducting Phase Engineering

Phase of a macroscopic wave-function of a superconductor or a superconducting ring is controlled with ferromagnetic materials.

Benefits of ferromagnetic materials

- Fixed flux biasing or Phase shift element (PSE)
  - AC/DC converter
  - Reduction of total bias currents
- Magnetization Reversal
  - Increased flexibility, i.e., reconfigurable circuits
- Magnetic Josephson junction
  - Energy-efficient circuits based on $\pi$-phase-shift
  - Energy-efficient memories
Main Issues Left for Practical Applications

• High-frequency operation of bit-parallel processing
  ✓ resolved

• Energy-efficient SFQ circuits
  ✓ resolved

• Energy-efficient power supply for dc-powered SFQ circuits

• Amplifier for driving a large capacity memory

• Amplifier serving as an interface device between SFQ circuits and room temperature electronics
AC/DC Converter for DC-Powered SFQ Circuits

AC/DC converter is essential for DC-powered SFQ circuits.
Superconducting Diode Based on Residual Magnetization

- A diode with $V_{th}=0$ is obtained.
- Critical currents can be controlled.

In-line-type JJ (20 μm x 1 μm)

Critical currents can be controlled.
Rectification with Superconducting Diodes

We can control DC output voltages by changing the phase of the switching. This might open superconducting power electronics.
Main Issues Left for Practical Applications

- High-frequency operation of bit-parallel processing
  ✔ resolved

- Energy-efficient SFQ circuits
  ✔ resolved

- Energy-efficient power supply for dc-powered SFQ circuits
  ✔ resolved

- Amplifier for driving a large capacity memory
- Amplifier serving as an interface device between SFQ circuits and room temperature electronics
More Flexible Computing

Screening current $I_{sc}$

Josephson junction

External Flux $\Phi/\Phi_0$

Critical current $I_c$

SQUID modulation pattern
Demonstration of Look-Up Table

- Successfully demonstrate 2-input LUTs.
- Operate up to 52 GHz.
Outline

• Introduction
• More SFQ
  □ More powerful computing
  □ More energy-efficient computing
• Superconducting Phase Engineering
• Superconductor Phonon Engineering
• Summary
Nanowire Cryotron (nTron)

- Fabricated by a single NbN layer
- Switched by thermal assisting
- High output voltage (Sub-V)
- High-impedance (kΩ range)
- ~ 100 ps, 10^{-18} J/bit

nTron Family (MIT)

Single nanowire SNSPD

NanoCryotron (nTron)

Gate isolated cryotron (hTron)

Current crowding cryotron (yTron)

Courtesy of Dr. Zhao (MIT)
Main Issues Left for Practical Applications

- High-frequency operation of bit-parallel processing
  ✓ resolved
- Energy-efficient SFQ circuits
  ✓ resolved
- Energy-efficient power supply for dc-powered SFQ circuits
  ✓ resolved
- Amplifier for driving a large capacity memory
- Amplifier serving as an interface device between SFQ circuits and room temperature electronics
nTron can serve as a voltage amplifier needed between SFQ circuits and semiconductor circuits.

NbTiN nTron + CMOS memory cell
Summary

- Classical RSFQ circuits have matured over the decades.
- Programs stored in embedded memories have been demonstrated and bit-parallel processing has been executed at 50 GHz.
- By introducing new concepts referred to as superconducting phase engineering and phonon engineering, the issues for the practical applications are resolved.
- Cryogenic digital circuit technology is really competitive in processing speed or energy-efficiency to semiconductor.
- Advancement in fabrication technology is needed.
- New technologies such as quantum information processing, deep learning should be introduced positively.
Grazie tante