THE RSFQ TECHNIQUE – AN ALTERNATIVE OF THE CONVENTIONAL SEMICONDUCTOR TECHNOLOGY

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Abstract. *Superconducting Rapid Single-Flux Quantum (RSFQ) electronics is a well-established technique for digital signal processing, which is a serious alternative to the conventional semiconductor technology. RSFQ circuits are very promising for high-speed operation with low power consumption for digital systems in the medical science, telecommunications, quantum computing, etc. The basic switching element of the RSFQ electronic is the Josephson junction, where on the boundary between two superconductors separated by very thin insulating layer flows super current, in spite of the dielectric barrier between them. In this paper some of the main features of the RSFQ technique are described as well as some of its advantages and disadvantages.*

Keywords: *Rapid Single-Flux Quantum (RSFQ), SFQ pulse, Josephson junction*

1. INTRODUCTION

One of the first attempts to create high-speed devices using superconducting electronic was launched in the mid 1970s and early 1980s from IBM Corporation starting their “Josephson Computer Technology Project” [1].

Superconductors were first proposed for digital circuit by D. Buck [2] in 1956 when he reported switching devices, which could be switched from a superconducting to a normal conducting state by application of magnetic fields. The satisfactory explanation of a superconducting theory is given by Bardeen, Cooper, and Schrieffer in 1957 in their now famous BCS theory of superconductivity [3]. This theory postulates that electrons in a superconductor are grouped in pairs, so-called Cooper pairs, when they are cooled to temperatures near absolute zero. These Cooper pairs can behave very differently from single electrons and act more like bosons, which can condense into the same energy level [4].

IBM began its Josephson junction studies following the mid-1960's demonstration by Juri Matisoo that the devices could serve in digital electronic circuits [5]. A Josephson junction begins with two strips of metallic superconductor, such as lead separated from one another by a layer of insulating material. It switches from superconductive to resistive state very fast in the order of *ps*, when the input current is applied but the transition from resistive to superconductive state is in order of *1ns*. This restricts the processor’s working frequency of about 1GHz and the project was finished in 1983.

The new approach in superconductive electronics was developed by Russian physics K. K. Likharev, O. A. Mukhanov and V. K. Semenov in 1985 [6]. The logical level are coded with presence of SFQ pulse for logical "1" and absence of such a pulse for logical "0" contrary to conventional CMOS electronics and the IBM's Josephson's computer project. Overdamped Josephson junction is used as a switching element in this technique. Rapid Single Flux Quantum Logic (RSFQ) deals with the generation and manipulation of magnetic flux quanta in the form of short voltage pulses across a Josephson weak link interrupting a superconducting loop. The fast switching time of Josephson junctions of the order of picoseconds, and the low power dissipation make them suitable for high speed data processing in wire-less technology, military applications, high speed computing and digital signal processing circuits.

2. JOSEPHSON JUNCTION

Two superconductors, S1 and S2 separated by a thin insulating layer Fig. 1 form a Josephson junction. Tunneling of super current in the form of Cooper pairs across the barrier without applying any voltage was predicted by Josephson in 1962. The magnitude of the super current is given by

$$I_s = I_c \sin(\theta_1 - \theta_2) \tag{1}$$

where I_c is the maximum value of the super current, which can flow through the junction without developing any voltage, called critical current Fig. 2. $\theta_1 - \theta_2 = \phi$ is the phase difference between the wave functions in the two superconductors.

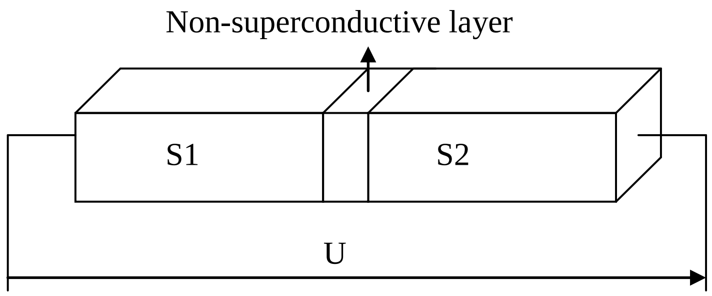

Fig. 1. Josephson junction

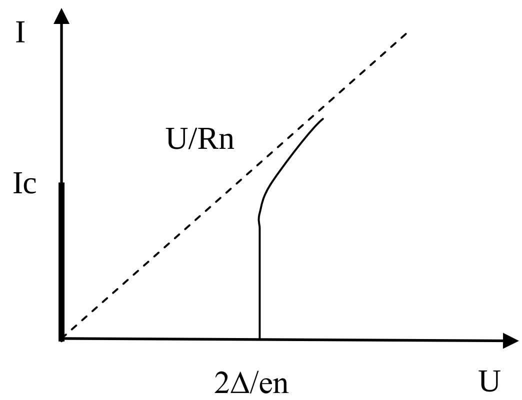

Fig. 2. Voltage-current curve for a classiacal junction

The magnitude of the critical current, which can be derived from the microscopic theory [7], is given by

$$I_c = \frac{\pi\Delta}{2eR_n} \qquad \text{for } T \ll T_c \tag{2}$$

where Δ is the superconducting energy gap and R_n is the normal state resistance. When a dc voltage is applied across the junction, the phase difference oscillates according to

$$\frac{d\ \ (t)}{dt} = \frac{4\pi e}{h}U(t) = \frac{2\pi}{\Phi_0}U(t) \tag{3}$$

A real junction Fig. 3 is considered as an ideal junction connected in parallel with a resistor, R representing the normal electron current and a capacitor C contributing the displacement current. This model describing the current flow through a practical junction is known as the Resistively and Capacitively Shunted Junction (RCSJ) model.

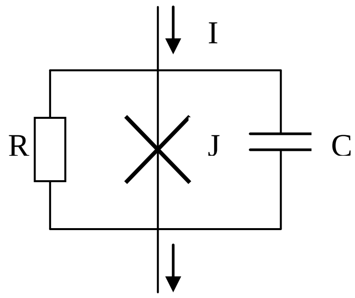

Fig. 3. Equivelent circuit of Josephson junction

From Eq. (3) Φ_0 = h/2e ≈ 2.07 mV.ps is being fundamental physical constant named the magnetic flux quantum.

A transient process during which ϕ changes with 2π is called a switching of the junction and a voltage pulses generated during such a switching can be derived by integrating:

$$\int_0^\infty U(t)d(t) = \Phi_0 \tag{4}$$

i.e. such a pulse carries exactly one magnetic flux quantum Φ_0. The typical shape of an SFQ pulse is shown on Fig. 4.

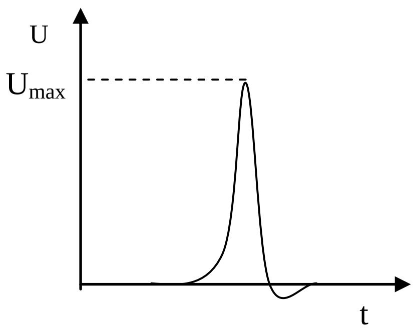

Fig. 4. Typical shape of an SFQ pulse

3. RSFQ TECHNIQUE

Superconductive Rapid Single-Flux Quantum (RSFQ) electronics [8] is characterized with some unique features:

– extreme high operation speed – the tunnelling Josephson junction with its switching time of about 1-2*ps* allows RSFQ circuit operating in sub THz frequencies;

– low power consumption – the energy dissipated during one switching of single Josephson junction with I_c=250µA is $\Delta W \approx \Phi_0 I_c \approx 5*10^{-19}$ *J/bit* it is about 5 *nW/GHz*, while the signals are communicated via superconductive transmission lines;

– a binary information is represented by naturally flux quantization pulses and they propagate through superconductive passive transmission lines with speed closely to speed of light - 150*µm/ps;*

– signals using for binary coding are with very low energy amplitude. Thus counts as an advantage for creating a quantum computer but when needed to shield against electromagnetic fields and noises it is a disadvantage;

– RSFQ circuits are self switching which makes asynchronous approach suitable for this technique.

The asynchronous circuits [9] have lower power consumption than synchronous because the switching occurs only in the part of the circuit involved in current computation [10]. There is no need of a global clock distribution signal. Thus also leads to reduced emissions of electromagnetic noise and sensitivity towards environment variations (temperature, voltage supply). However in more complex RSFQ circuit, where there are different paths through which a given signal can reach a signal competition occurs [11], [12]. The most reliable asynchronous communication is provided by Dual-Rail data coding (DR) shown schematically in Fig. 5. It is based on two signal lines where a pulse on the one represents logical “1” and the pulse on the other one represents a logical “0”. A simultaneous propagation of pulses on both one is forbidden. The Dual-Rail coding allows synchronous blocks to be easily included into the asynchronous architecture.

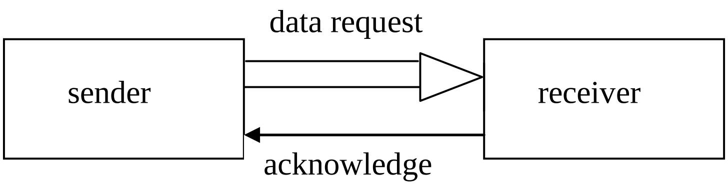

Fig. 5. Asynchronous data exchange between two circuit blocks

Currently the companies and universities involved in high-level synthesis of complex circuit have developed and tested the entire cell library of basic RSFQ cells [13-16]. The library contains schematics, layouts, transient simulation, logical model. The fabrication of Josephson tunnel junctions is based on well-developed *Nb/AlO$_x$/Nb* technology.

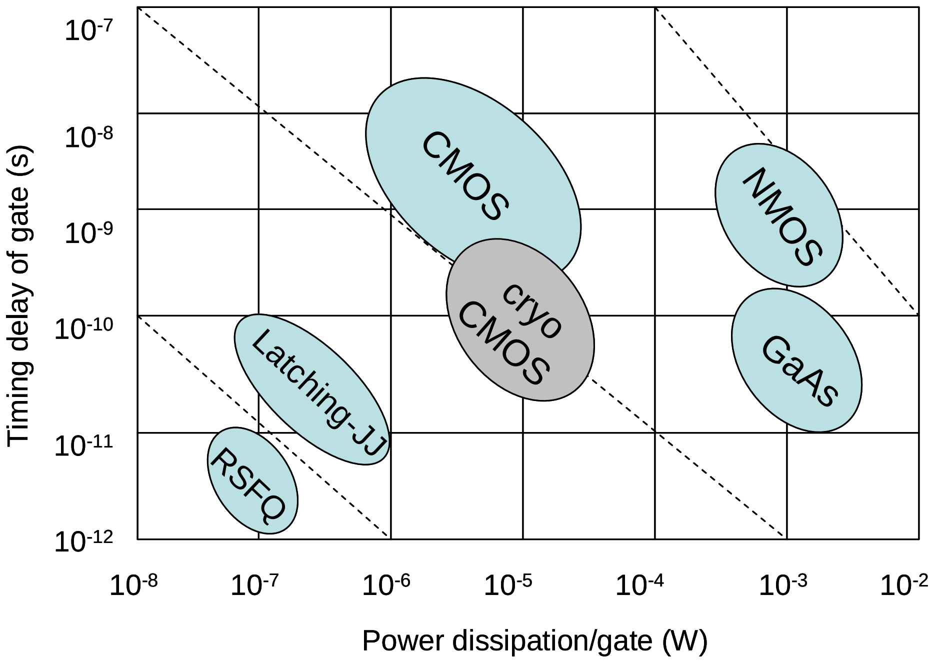

Fig. 6. Comparison between different fabrication technologies based on timing delay – power dissipation per gate.

4. CONCLUSIONS

RSFQ circuits are very promising for high-speed operation with low power consumption. Nevertheless RSFQ circuit requires cryogenic cooling (mostly with liquid helium) to temperature of about 4K, which is the main drawback of these circuits. Comparison between different technologies is given on Fig. 6.

Non-equilibrium structures and interfaces, in particular, may provide an important route to novel superconductors. The successful finding of a material superconducting near room temperature would have enormous technological impact, for example, help to solve the world's energy problems and provide for faster computers.

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