Journal of Superconductivity and Novel Magnetism
https://doi.org/10.1007/s10948-020-05680-2

LETTER

Josephson Memories

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Received: 29 August 2020 / Accepted: 7 September 2020

Abstract
A brief overview will be provided on superconducting memory elements incorporating Josephson junctions, from the tunneling cryotrons in the 1960's to contemporary RSFQ devices, with an outlook to future developments such as Josephson junction-based neuromorphic circuitry.

Keywords Josephson junctions · Superconducting memory · Superconducting electronics

This manuscript is part of a Special Issue celebrating this years' 80th birthday of Prof. Brian Josephson. I herewith like to express to him my sincere congratulations and best wishes! While we do not share personal memories, we do share our fascination for the beautiful phenomenon of superconductivity and the interest in superconductive tunneling. Researching and lecturing about Josephson junctions has always brought me great joy, for their clear-cut manifestation of profound quantum physics and for their mindboggling capabilities as central elements in highly sensitive or ultrafast electronic devices. As a tribute to Prof. Josephson I will reflect in the following on one particular device type of importance for applications in superconductive (quantum)-information technologies, namely, the Josephson memory element.

First, it may be surprising to note that already in the years prior to Josephson's discoveries [1], there was a major industrial effort going on, especially by institutions and companies in the USA, to build a superconducting computer. At some point in the late 1950s–early 1960s, superconductivity was even ahead of semiconductor technology in its level of integration, using such modern-sounding concepts as thin film-based integrated circuitry and electron beam lithography [2]. The basic element for superconducting processor and memory circuits was the "cryotron" [3]. This switching device utilized the principle that by applying a current through a control line, the superconductivity in the gate (a strip of superconducting material) could be switched on and off. Memory elements such as flip-flops were realized based on the rerouting of persistent superconducting currents along different paths using such cryotrons.

While promising, an issue with the cryotrons was their limited switching speed, of typically several (tens of) nanoseconds. For the most popular "in-line" cryotron configuration this was found to be limited by the characteristic propagation speed for the phase boundary between the superconducting and normal states in the superconductor [4]. As semiconductor technology was advancing at a rapid speed, leading to faster devices at lower costs, and had the additional advantage of being a room temperature technology, the cryotron-based computing paradigm became largely abandoned in the early 1960s.

Smaller research activities on superconducting electronics remained though at various places, including at the IBM Yorktown Heights Research Lab. Quickly following Josephson's groundbreaking theory and the experimental confirmation of the Josephson effects by Anderson and Rowell [5], interest arose in the use of Josephson junctions for electronics applications. After confirming the high switching speed of Josephson junctions [6], Matisoo proposed the "Tunneling cryotron," based on the switching of hysteretic Josephson junctions between the supercurrent and the single-particle tunneling branches [7], employing magnetic field pulses applied via a control line. This marked the start of the IBM Josephson computer program, driven by the potential of ultrafast and ultra energy-efficient information processing and storage. [8–10].

The IBM Josephson program went on all the way till 1983, at which time it could not compete anymore against the spectacular ongoing developments in semiconductor industry following Moore's law. One of the complications in the development of large-scale Josephson computing technologies at that time was the controllable fabrication of the Josephson junctions, typically being implemented in a Nb-NbOx-Pb alloy configuration [11].

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Noteworthy, the struggle to create reproducible Josephson junctions with homogeneous barrier layers was one of the motivations for the Nobel Prize winning development of the scanning tunneling microscopy by Rohrer and Binnig [12].

Right about the time when the IBM Josephson project came to an end, a breakthough development in the fabrication of highly reproducible junctions took place, with the invention of the Nb/Al/AlOx(/Al)/Nb technology by Gurvitch et al. at Bell Labs [13]. Besides the high controllability, due to the excellent wetting properties of the Al layer on the Nb bottom-electrode and the highly controlled oxidation of the Al, it also allowed the establishment of processes for very high Josephson critical current densities, even beyond the 50 kA/cm^2 range [14] as compared to about 500 A/cm^2 typically used in the NbOx-based process. These higher critical current densities facilitated the miniaturization of Josephson devices, with the current state-of-the-art exemplified by Very Large Scale Integrated Josephson junction-based Random Access Memories fabricated at MIT Lincoln Labs with functional densities of up to 1 Mbit/cm^2 [15]. While this density may still be modest as compared to CMOS, combined with the high speed of Josephson circuitry it is of interest for, e.g., ultrafast signal processing applications.

A further groundbreaking step in the development of Josephson information processing and storage technologies was the establishment of the Resistive/Rapid Single Flux Quantum (RSFQ)-technology by the group around Konstantin Likharev at Moscow State University in the course of the 1980s [16, 17]. Departing from the “latching logic” that employs switching between the superconducting and voltage states of hysteretic Josephson junctions, the RSFQ circuits use the aspect of flux quantization in superconducting loops. Single magnetic flux-quanta can enter or leave superconducting loops by means of the 2π phase slip associated with a single Josephson oscillation, induced by a current/voltage pulse. This concept allows extremely fast (few ps) and ultra low energy (10^{-18} J) switching between different discrete flux states stored in the loop. The RSFQ paradigm is the standard now for superconducting information processing devices. Examples of advanced RSFQ-processors include the “CORE e4” 8-bit serial microprocessor culminating from sustained developments by Fujimaki et al. at Nagoya University. It contains approximately 7000 Josephson junctions on an area of about 3×2 mm^2, carrying out 333 million instructions per second at an energy consumption of 2 mW [18].

The worldwide interest in superconductivity got a tremendous boost with the discovery of high-T_c superconductivity by Bednorz and Müller in 1986 [19, 20]. Various high-T_c Josephson junction concepts were developed, whereby the short coherence length and the sensitivity of the cuprate superconductors to modulations of the carrier density also allowed the use of crystalline defects such as grain boundaries to be used as Josephson junctions [21, 22], in addition to concepts using an artificial barrier layer or the intrinsic Josephson effects between the CuO$_2$ layers of the perovskites [23, 24]. While over the years various basic RSFQ-type devices have been demonstrated containing a few high-T_c Josephson junctions, it has proven very difficult to reach the level of controllability and reproducibility for large-scale integrated circuitry, in particular when going down to sub-micron dimensions.

A tantalizing aspect of high-T_c superconductivity is the d_{x2-y2} symmetry of the pair wave function [25–28]. This allows the creation of Josephson circuitry with built-in π-phase shifts, in which fractional magnetic flux quanta are spontaneously generated [29]. For superconducting memory-devices this is of particular interest, as such pi-shift devices have a degenerate ground state with up- or down-polarity of this self-induced magnetic flux. Continuing on earlier work together with Jochen Mannhart at IBM Zurich [30, 31] and the University of Augsburg [32], my group at the University of Twente together with John Kirtley and Chang Tsuei at IBM Yorktown Heights and Thomas Ortlepp and coworkers at the University of Technology of Ilmenau has explored such pi-shift Josephson memory devices in ring structures and arrays of corner junctions combining high-T_c and low-T_c superconductors (see Figs. 1 and 2). Related d-wave-based Josephson devices have been realized, e.g., in a collaboration between Chalmers University and the University of Naples [33, 34].

An alternative way to create π-shift devices is by making use of phase shifts occurring inside the Josephson junctions, as can be realized for example by incorporating ferromagnetism in the junction barrier (see [29] and references therein). This leads to a new paradigm of “Josephson spintronics,” in which by the manipulation of the magnetization in a Josephson junction barrier material, which may be a single magnetic layer of a spin-valve type stack of magnetic layers, the critical current and its sign can be altered. Recent implementations include, e.g., Banerjee et al. [36], Dayton et al. [37], Nevirkovet and Mukhanov [38], Klenov et al. [39], Tolpygo et al. [40], and Parlat et al. [41].

In the last decades, Josephson junctions have also become a popular basis for qubit-implementations, in the quest to realize quantum computers. The most advanced version to date is the 53 qubit processor demonstrated by the group around Martinis at Google and UC Santa Barbara [42]. The qubits in that system are of the “transmon” configuration, which is a Josephson junction-based device [43]. Operating in the 10-mK range, the junctions are usually based on aluminum as the superconductor. Noteworthy are also the quantum annealing approaches as pursued by D-Wave, incorporating chips containing thousands of coupled Josephson junction-based qubits [44]. A more exotic concept is represented by topological quantum computing, in which the qubits are represented by pairs of Majorana anyons [45]. For this, novel forms of Josephson junctions are being realized that can harbor such Majorana bound states, like nanowire-based Josephson junctions

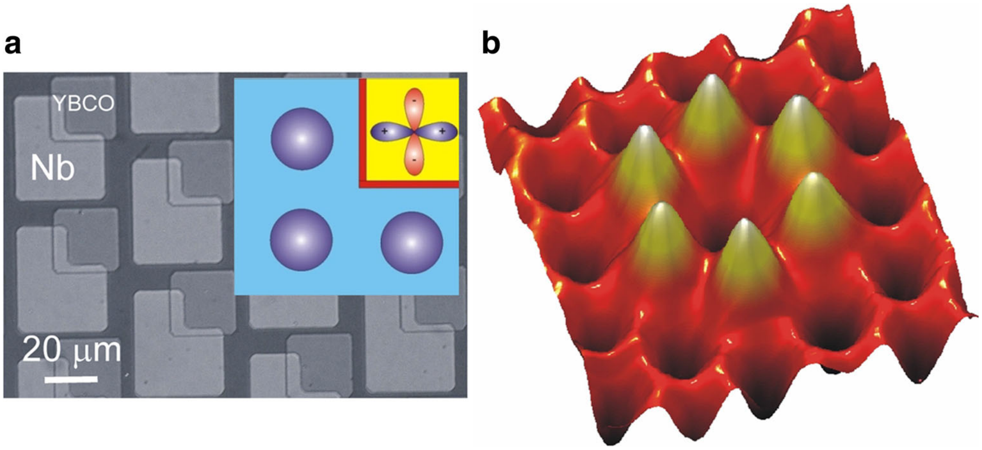

Fig. 1 **a** Thin-film $YBa_2Cu_3O_7$-Nb corner junctions and **b** imaging by Scanning SQUID Microscopy of half-integer magnetic flux quanta occurring spontaneously in these structures (from [27])

[46] or junctions incorporating topologically non-trivial barrier layers [47]. The tremendous challenge of realizing functional quantum computers is giving a great boost to the material science of Josephson junctions, with potential spin off also for more classical superconducting electronics.

Another promising paradigm for novel electronics, aiming in particular for energy-efficiency and high-speed pattern recognition, is presented by "neuromorphic computing." It uses concepts inspired by the functioning of the brains, such as neurons that can hold and process information, connected in artificial neural network configurations by synapses with adaptable strengths, allowing learning modalities. Implementing neuromorphic circuitry in superconductors is particularly attractive because of the high speed of signal transmission and switching processes, the high intrinsic energy-efficiency of superconductors, and the possibility for a large fan out of individual neurons to many others.

First designs and implementations of superconducting neurons and neuromorphic circuitry are being realized using Josephson junctions and RSFQ circuitry [48, 49]. Also, artificial superconducting synapses have been developed using, e.g., the polarization states of collections of magnetic nanoparticles inside the Josephson junction barries to set—in a guided learning process—the critical currents of the junctions [50]. A particularly interesting aspect of using Josephson junctions for neuromorphic circuitry is the potential for making spiking neural networks, in which the firing of single flux quantum pulses by Josephson junctions mimicks the firing of a voltage pulse by the neurons in the brain.

I expect the research field of superconducting (Josephson junction-based) neuromorphics to develop further in the next years, especially because of the increasing interest in energy-efficient, high-speed machine learning concepts for complex, and

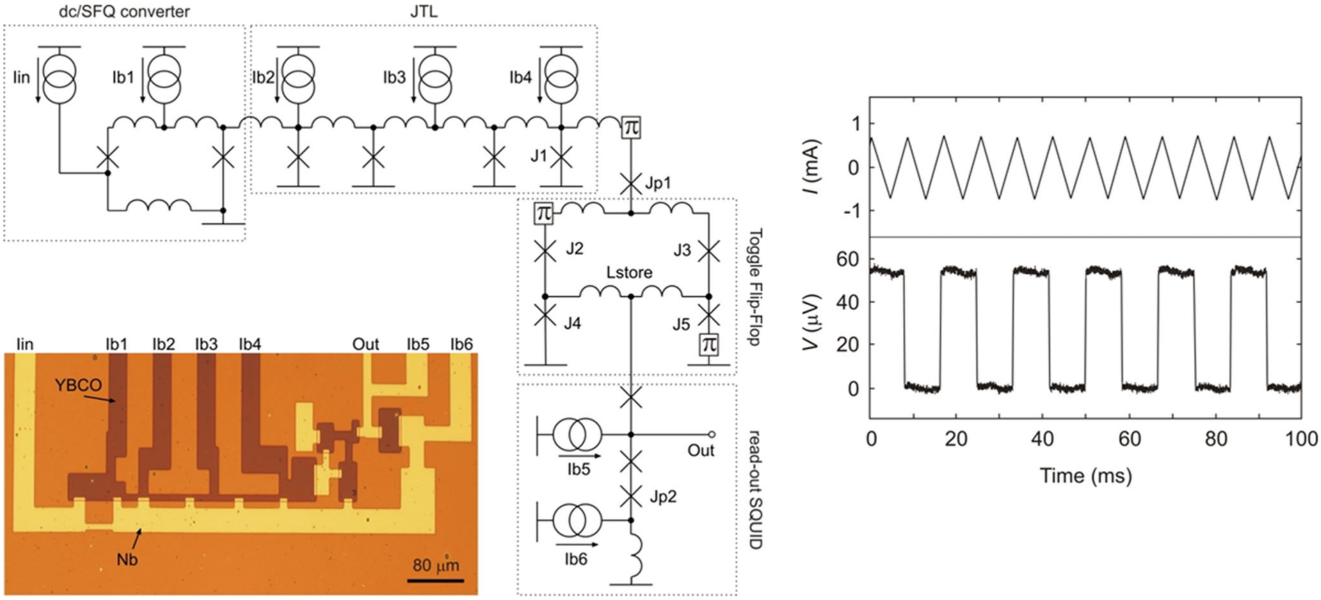

Fig. 2 Rapid Single Flux Quantum device (a toggle flip-flip) making use of spontaneous magnetization occurring in Josephson circuits connecting high-T_c and low-T_c superconductors (from Ortlepp et al. [35])

data-rich applications. In a similar manner, various further alternative computing paradigms have been proposed in recent years, in which Josephson memory devices (can) play an important role. I mention here the interesting "memcomputing" concepts by DiVentra et al. [51–53], based on self-organizing effects in networks of memory elements of which the terminals have both input and output functionalities.

In conclusion, the initial fundamental studies on superconductive tunneling in 1962 have lead to an enormous development of superconducting Josephson technologies. Here, I have only briefly sketched progresses in memory devices for information processing, but one could equally show the developments of, e.g., ultra-sensitive (SQUID) sensors and Josephson voltage standards. With the ongoing advances in (nano)-materials science and the need for new technologies to overcome major hurdles in energy-efficient and data-intensive computing, it can be expected that superconducting (quantum)-electronics will show great further development, of course with the Josephson junction as its key element.

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