APPLICATIONS OF THE MAIN DEVICES BASED ON JOSEPHSON JUNCTION: A REVIEW

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ABSTRACT

In this paper we present a review of the main applications of Josephson Junction (JJ). This device bases its properties on the Josephson Effect, based on the relationship between Tunnel Effect and Superconducting Theory. The properties of JJ allow to realize Superconducting Quantum Interference Devices (SQUIDs), used in medical field, or industrial level electronic circuits such as Superconducting Qubits. We also describe the hybrid technology named RSFQ-CMOS, which is not realized yet for general purposes because it requires cryogenic cooling system. Although, if this problem will be bypassed, the devices based on Josephson Junction will be ready to substitute the current electronic and its limitations.

KEYWORDS: *Josephson Junction, Tunnel Effect, Superconductivity, SQUIDs, RSFQ-CMOS Technology.*

I. INTRODUCTION

In 1962, Brian David Josephson discovered an important relationship between Superconducting theory and Tunnel Effect. This behaviour was named Josephson Effect [1].

Since that time, Josephson was able to control this effect and so invented a device, the Josephson Junction (JJ) that allows to increase performances respect to the current electronic devices and to realize new devices such as, for example, Superconducting Quantum Interference Devices (SQUIDs) and Rapid Single Flux Quantum (RSFQ) [2-3].

In this review we explain the fundamentals of Josephson Junction, from the phenomenon of superconductivity to the Josephson Effect. Then we examine the applications of the main devices based on JJ, such as SQUIDs, Superconducting Tunnel Junction and RSFQ, with particular reference to medical field.

The presentation is organized as follows. At first we briefly describe the effect of superconductivity and the principle of operation of Josephson junction. Then we review the main applications of devices based on JJ, together with the discuss of the current results.

II. STUDY OF JOSEPHSON JUNCTION

II-a) Superconductivity

The phenomenon of superconductivity was discovered in 1911 by Heike Kamerlingh Onnes [4-5]. He observed that mercury, if cooled to temperatures below 4.16 K, suddenly ceases to offer any resistance to the passage of electric current. Subsequently it was possible to ascertain that this phenomenon is not limited to mercury, but there is a long series of other elements or compound substances which, if cooled below a certain temperature, called **critical**, allow the transport of electric current without the slightest energy loss.

For example, aluminum has a critical temperature of 1.19 K, lead of 7.2 K, and, in the field of compound substances, it is worth mentioning niobium-titanium, due to its wide use in commercial applications, which becomes superconducting at about 9 K.

Quite interesting and curious is the fact that copper, gold and silver, i.e. those materials that at room temperature are among the best electrical conductors, at low temperatures do not become superconductors: there is no simple rule that allows us to establish a priori which materials become superconductors at sufficiently low temperatures.

The following points, based on empirical observations, are worth mentioning:

1. only metals or metal compounds become superconductors;
2. all critical temperatures are below 23 K;
3. noble metals e magnetic metals do not become superconductors.

However the absence of electrical resistance is not the only fundamental characteristic of superconductors. In fact, there is a second important property that a superconductor must manifest so that it can be considered as such: **the Meissner effect**, which consists in the property of the superconducting material to exclude from its inside any magnetic field: i.e. the superconductor behaves like an **ideal diamagnete**. Without this property a material without electrical resistance is not a superconductor, it is "simply" an ideal conductor.

Regarding superconductivity, the theoretical model, able to explain this phenomenon, was developed in 1957 by John Bardeen, Leon Cooper and Robert Schrieffer, and therefore known in the literature as **BCS model**. It is based on the consideration that at low temperature the effect of the interaction between two isolated electrons is that of joining them in a pair, called **Cooper pair**. However, due to their electric charge, electrons tend to repel each other, and therefore, in order for the resulting force between them to be attractive, the action of a second force is necessary, capable of dominating, at low temperatures, the electric repulsive force.

Once a pair of Cooper has been created, if one of the electrons of the pair hits an atom or a defect in the crystal lattice, it cannot be deviated from its trajectory in an arbitrary manner due to the presence of its companion, which reacts promptly to the bump holding him back. In other words, the electrons, which form the Cooper pair, change their direction of motion but not their energy. Thus the transfer of energy to the atoms of the crystal lattice, which in a normal metal gives rise to electrical resistance, does not occur in a superconductor.

In the final analysis, the phenomenon of superconductivity arises from a delicate and complex predominance of an attractive force, which promotes a coupling of electrons, against an electric force that causes them to repel each other.

This fragile dominance can easily be cancelled by external influences such as temperature, the intensity of the magnetic field in which the superconducting material is immersed, or the intensity of the electric current it carries.

In fact, it is immediate to sense that, as the temperature increases, the Cooper pair is constantly shaken by the thermal excitations due to the vibrating nuclei of the lattice. There is therefore a temperature value for which the thermal energy involved is sufficient to separate the electrons of a pair, thus destroying the superconducting state. This temperature is the critical temperature, which typically does not exceed 23 K (-250 ° C).

Until 1986 superconductivity was a phenomenon limited to temperatures below 23 K, and for this reason superconductors never really managed to compete with conventional conductors. In 1986 at IBM laboratories (Zurich), Alex Müller and Georg Bednorz discovered the so-called **high temperature superconductors** (the material that currently holds the record becomes superconducting already at a temperature of about 133 K).

The basic material of these new superconductors is always an insulator made up of layers of copper oxide, which, by means of chemical doping, is transformed into a metal. The structure is formed by intercalating layers of electrically conductive copper oxide with insulating layers composed of other oxides, giving rise to a strongly anisotropic structure, which differs markedly from the generally isotropic structure of conventional superconductors.

The strong anisotropy is one of the main factors that currently hinders the engineering of high temperature superconductors.

IIb) Josephson Junction

It is a junction in which the metal electrodes, generally niobium (Nb), are separated by a thin (few nm) barrier of aluminium oxide.

As we have already said, under a critical temperature Tc (for the Nb 9.2K, for the Al 1K), the superconducting materials have the following properties:

- no electrical resistance
- perfect diamagnetic behavior, that is, magnetic induction B is nothing everywhere inside the superconductor.

These properties disappear with temperatures higher than the critical temperature and in the presence of very intense external magnetic fields.

If the temperature is sufficiently high, higher than the critical temperature of the electrodes (Tc = 9.2 K in the case of niobium), the tunnel barrier will behave as a resistance, which follows the Ohm's law, because the electric charges responsible for the passage of current through the junction are the "free" electrons of the metal.

Below the critical temperature Tc, niobium becomes superconducting. In the ground state below Tc, the electrons of the superconductor bind in Cooper pairs of opposite spins and total zero moment. In this case the conduction through the tunnel barrier no longer follows the Ohm's law, because the electric charges responsible for the passage of current through the junction are no longer the "free" electrons of a metal, but the Cooper pairs.

They carry current without resistance and are described by a single wave function.

In the presence of a very thin barrier, the couples manage to pass through the tunnel effect (called, in this case, **the Josephson effect**), modifying only the phase of the wave function that describes the system. So there is a supercurrent with no voltage (V = 0 V).

The electrons in a Cooper pair are normally bound by an energy gap Δ, typically of the order of meV or meV fractions, depending on the material, and cannot contribute to conduction until a potential difference V is applied to the junction which makes them overcome the energy gap.

In this case the electrons, coming from dissociated pairs, contribute significantly to the passage of electric current giving rise to a response that substantially follows the Ohm law.

Ultimately the current-voltage characteristic is strongly non-linear and consists of two branches:

- supercurrent at zero voltage, up to a maximum value Ic
- branch with non-zero voltage, hysteretic (it runs along two different curves as the current increases and decreases).

Depending on the applications, Josephson junctions are made in various sizes, ranging from 0.3 μm to hundreds of μm per side, with a typical value of the order of 1-3 μm.

III. APPLICATIONS OF THE MAIN DEVICES BASED ON JJ

IIIa) Superconductive QUantum Interference Device and its applications

An important device based on JJ is the Superconductive QUantum Interference Device (SQUID), which is essentially a superconductive ring with one or two Josephson junctions.

There are two types of SQUIDs commonly used in applications: a DC SQUID, composed by two Josephson Junctions, ever separated by a superconductive ring, and a RF SQUID, composed by a unique Josephson Junction closed in a superconducting ring with its Self- Inductance [6].

Without examining the basic principles of the SQUID, we only examine their main applications, with particular reference to biomedical field.

SQUIDs in all their forms but especially DC versions, are important to measure a very small value of magnetic field or flux near something. This property is, for example, extremely interesting in biomedical field. This because all the human organs are crossed by central and peripheral nervous system. It implicates that there is a current passing across them. When an alternating value of current (in the time) flows through a "human organ", it produces an extremely little value of that magnetic field. Often, if there is the possibility to measure these values there will be an important possibility to predict some significant illnesses like: cancers, heart attacks, Alzheimer's or Parkinson disease, epilepsy and other pathologies connected to the normal organ evolution [7].

Arrays of SQUIDs are currently the most common magnetometer and are implemented for **Magneto Encephalo Graphy** (MEG), which is a functional neuroimaging technique for mapping brain activity by recording magnetic fields produced by electrical currents occurring naturally in the brain.

Fig. 1 shows the origin of the brain's magnetic field [7]. The electric current also produces the **Electroencephalography** (EEG) signal.

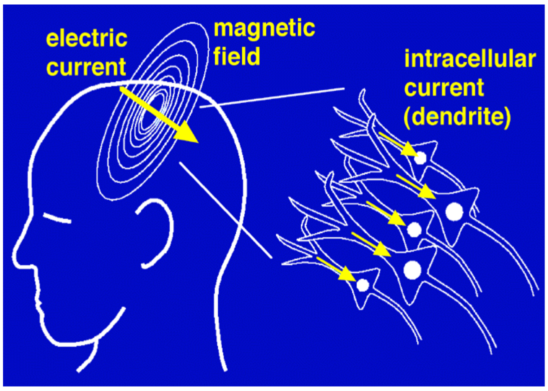

Figure 1. Origin of the brain's magnetic field [7].

Fig. 2 shows an image of a neural defect with SQUID system, which allow the diagnosis of focal epilepsy.

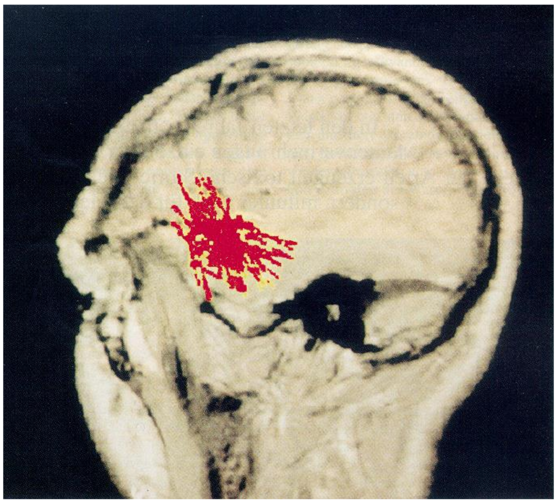

Figure 2. An image of a neural defect with SQUID system [7].

This medical system was invented in 1970 by James E. Zimmermann of Ford Motor Company, with the collaboration of researchers of MIT (Massachusetts Institute of Technology) [8].

Initially it was projected because previously copper coil systems were not really performant due to the high noise. In the first models, MEG had only one SQUID sensor and so this was not good to use in a large area like a human head. Next, was implemented a Dewar potter inside MEGs to improve the situation.

SQUIDs, and so Josephson Junctions, implemented in a MEG appear to have no problems but some studies reveal some thickness about interference with other organs activities. This because SQUIDs measure ultra-low magnetic fields of an organ and so can reach flux of other organs close to that.

An example of existing MEG is provided from the society: CTF MEG INTERNATIONAL SERVICES LP [9].

In Fig. 3 we have reported the new MEG by CTF [9], while on the right the diagram outlines the 100% Helium recovery system for the CTF MEG.

This helium recovery system operates in a closed-loop mode ensuring that no manual liquid Helium refills are required. A special non-magnetic transfer line is always in the dewar and automated transfers take place at scheduled times, ensuring that an optimal liquid helium level is maintained in the MEG.

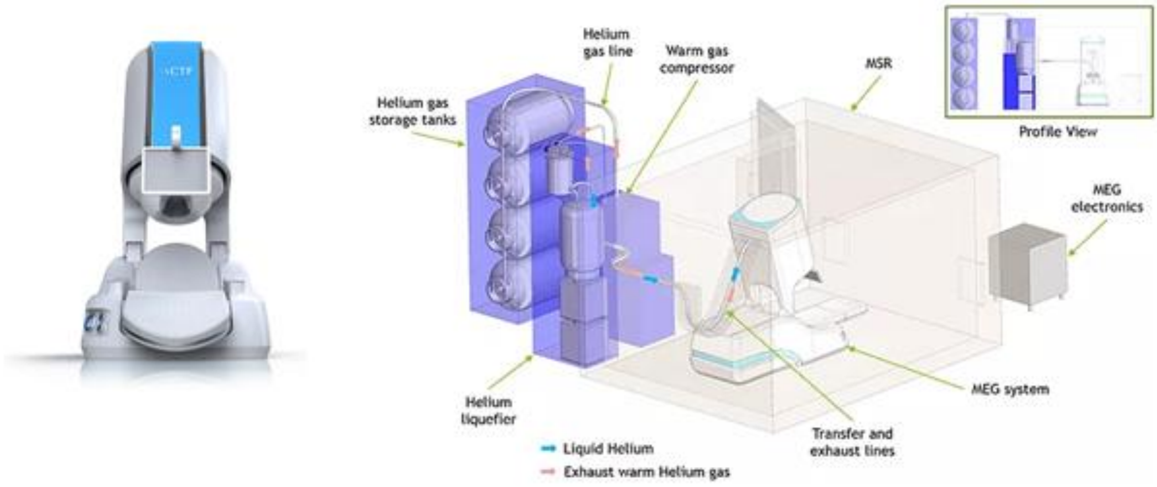

Figure 3. On the left the commercial MEG by CTF. On the right the diagram outlines the 100% Helium recovery system for the CTF MEG [9].

Another application is the **Scanning SQUID Microscope**.
It is a technique that measures weak magnetic fields by moving a SQUID across an area.
This is shown in Fig. 4.

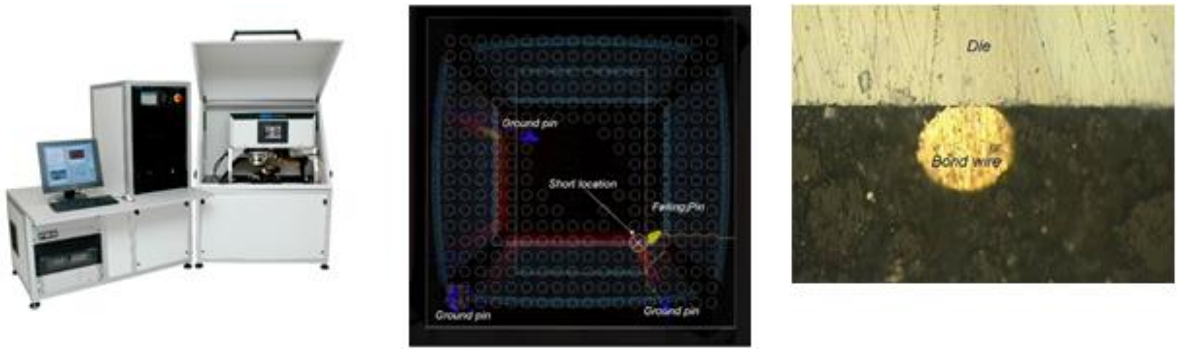

Figure 4. On the left a realized scanning SQUID microscope. In the middle overlay of current density, optical, and CAD images in triple-stacked die package with electric short failure mode. On the right, cross sectional image showing a bond wire touching the die causing signal to ground leakage [3].

IIIb) Josephson Junction named STJs or Superconducting Tunnel Junction

The superconducting tunnel junction (STJ), also known as a Superconductor-Insulator-Superconductor (SIS) tunnel junction, is an electronic device consisting of two superconductors separated by a very thin layer of insulating material. Current passes through the junction via the effect tunnel.
These devices have a wide range of applications, including high-sensitivity detectors of electromagnetic radiation, magnetometers, high speed digital circuit elements, and quantum computing circuits [3].

IIIc) Rapid single flux quantum (RSFQ)

It is a digital electronic device that uses JJs to process digital signals.
In RSFQ logic, information is stored in the form of magnetic flux quanta and transferred in the form of Single Flux Quantum (SFQ) voltage pulses.
RSFQ is one family of superconducting or SFQ logic. Josephson junctions are the active elements for RSFQ electronics, just as transistors are the active elements for semiconductor electronics.

The RSFQ technology presents the following advantages respect to CMOS technology:

- Interoperable with CMOS circuitry, microwave and infrared technology.
- Extremely fast operating frequency: from a few tens of gigahertz up to hundreds of gigahertz.
- Low power consumption: about 100,000 times lower than CMOS semiconductors circuits, without accounting for refrigeration.
- Existing chip manufacturing technology can be adapted to manufacture RSFQ circuitry.
- Good tolerance to manufacturing variations.

However RSFQ technology presents the following disadvantages:

- Requires cryogenic cooling.
- The cooling requirements can be relaxed through the use of high-temperature superconductors.
- Static power dissipation that is typically 10-100 times larger than the dynamic power required to perform logic operations was one of the drawbacks.

There are, so, a lot of applications of this device like:

- Optical and other high-speed network switching devices;
- DSP up to X-band signals and beyond;
- Ultrafast routers;
- Software-defined radio (SDR);
- High speed analog-to-digital converters;
- High performance cryogenic computers;
- Control circuitry for superconducting qubits and quantum circuits.

It has been realized at Tokyo a quantum computer that can examine data 100 million times faster than other computers.

In Fig. 5 we have reported the photo of the realized quantum computer processing unit [10]

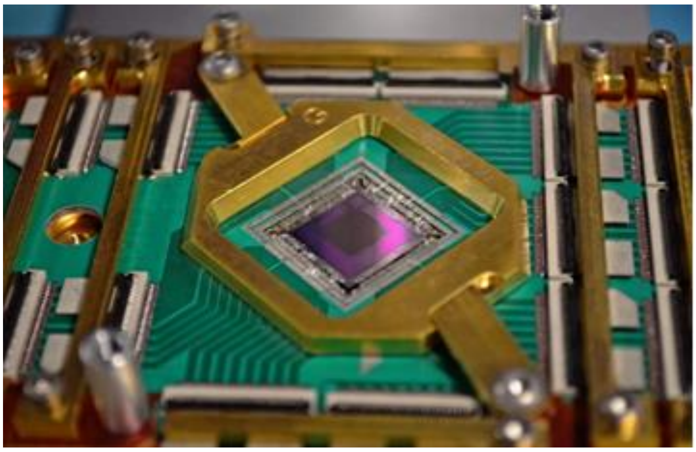

Figure 5. A quantum computer processing unit [10]

IV. CONCLUSIONS

In this paper we have reviewed the applications of the main electronic devices based on Josephson Junction such as SQUIDs, Superconducting Tunnel Junction and RSFQ devices, with particular reference to medical field. At first we explained the fundamentals of Josephson Junction, from the phenomenon of superconductivity to the Josephson Effect. Then we examined in particular the applications of the SQUIDs, STJs and the hybrid technology named RSFQ-CMOS.

For any device examined we have highlighted the state of the art, the advantages and disadvantages. Among these we emphasized that, first of all, it is the expansive and expensive cooling system that limits considerably the commercial use of these devices.

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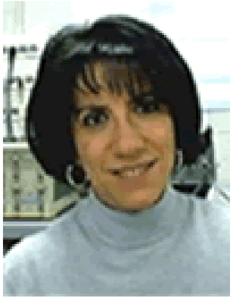

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