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Review Article

Quantum Technologies and the Engineering of Josephson Junction-Based Sensors: Disruptive Innovation as a Strategic Differential for National Security and Defense

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Abstract

The so-called area of quantum technologies is a new and disruptive technological field, essentially from physics and engineering, with the ability to affect almost all human activities. They are based on the properties of quantum mechanics like quantum tunneling, quantum entanglement, and quantum superposition. Examples of areas of application of these emerging technologies are quantum computing, quantum communications, quantum sensing, quantum cryptography, quantum internet, quantum imaging, quantum metrology, quantum biology, among others. These technologies are of the interest of both the defense and security industry, and military and governmental actors. For military applications, and after a strong advanced engineering process, these technologies introduce new capabilities, improving effectiveness and increasing precision, thus leading to the so-called quantum warfare, wherein new military strategies, doctrines, policies, and ethics should be established. In particular, these military applications of quantum technologies can be described for various warfare domains like land, air, space, electronic, cyber, and underwater warfare and also for intelligence, surveillance, target acquisition and reconnaissance. Among those applications mentioned before, quantum computing is expected to have a number of important uses such as optimization and machine learning, associated to both artificial intelligence and blockchain. Quantum computers are perhaps best known for their expected ability to carry out Shor's algorithm, which can be used to factorize large numbers and is an important process in the securing of data transmissions, essential for military applications. In this review of our own work, we show the physics and some of the applications of the Josephson junction which plays and important and essential role in the fabrication of quantum computers with superconducting qubits. Nowadays, applications of Josephson junction devices go from the most sensitive sensor to measure magnetic flux, called S.QU.I.D. (from Superconducting Quantum Interference Device) to the core of quantum computers, the quantum bits. The Josephson junction is an old quantum engine for a rising new world with incredible disruptive technological possibilities in engineering, especially in military applications where it plays a fundamental strategic differential for National Security and Defense.

Introduction

Without going into a detailed explanation of the physics involved, it is interesting to briefly discuss some of the fundamental underlying principles to understand the potential applications of the so-called Quantum Technologies in the area of Security and Defense. They explore physical phenomena on the atomic and subatomic scale.

Quantum physics (or mechanics) is the theory that successfully describes physical systems whose dimensions are close to or below the atomic scale (atoms, molecules, atomic and subatomic particles, etc.). German physicist Max Planck is considered the father of quantum mechanics. His focus was the study of electromagnetic radiation, and in his study appears one of the most important constants of modern physics, called Planck's constant (h = 6.63 x 10-34J·s). It is used to define the energy (E) and frequency (f) of a photon associated with electromagnetic radiation. This constant determines the energy of a photon using the equation E = h x f. In addition to Planck, Albert Einstein, Werner Heisenberg, Louis de Broglie, Niels Bohr, Erwin Schrödinger, Max Born, Paul Dirac, Wolfgang Pauli, among others, also contributed to the foundations of this area [1]. It can be considered the basis of all modern physics and has profound implications in many areas, from technology to cosmology, in the study of the formation of the Universe [1].

At the atomic scale, the key aspect in quantum mechanics is that the world is probabilistic as opposed to deterministic. This new scenario based on probability was the subject of a historical debate between Einstein and Bohr during the fifth Solvay Conference on Quantum Physics, in 1927. To discuss the newly formulated quantum theory, this conference brought together the 29 most famous scientist of that time where 17 of them would later become Nobel Prize winners [1,2]. During this event, Bohr defended the new theory of quantum mechanics as initially formulated by Heisenberg. On the other side of the discussion Einstein tried to maintain the deterministic paradigm of cause and effect. Was during this discussion that Einstein said the famous words that God does not play dice after which Bohr countered Einstein, stop telling God what to do. Today, the scientific community agrees that Bohr won the debate. In few words, it means that our world does not have a fixed script based on cause and effect but is in fact subject to chance. We may know everything about the universe and still not know what will happen next. This new probabilistic scenario has given the way for a better understanding of the new physical properties of quantum particles underlying quantum technologies like tunneling, superposition, and entanglement. Their better understanding has spurred the development of next- generation Quantum Technologies: quantum sensing, quantum communication, and quantum computing, among many others [1].

Quantum mechanics arose in the early twentieth century due to problems encountered in the industrial area associated with the measurement of temperature in steel furnaces. In some cases, it also succeeds in describing and explaining macroscopic phenomena such as superconductivity and superfluidity both consisting of macroscopic quantum states with carriers called bosons because they follow the Bose-Einstein statistical distribution. With the advancement of the study of phenomena at the atomic world, the failure of Newtonian physics on this scale became increasingly clear. Thus, it was necessary a profound conceptual revision resulting in the generation of new ideas that, in many cases, contradict – even today – our intuition. As it was mentioned before, phenomena such as quantum tunneling, superposition, and entanglement are part of these new concepts. Quantum mechanics is one of the most promising areas of modern physics and can lead to considerable advances in the area of information technology and quantum computing, among other areas that form the so-called Quantum Technologies and that we will describe next. In several ways, many of the modern technologies operate on a scale where quantum effects are significant. Important applications of quantum mechanics include quantum chemistry, quantum optics, quantum computing and communication, superconducting magnets, S.QU.I.D. (Superconducting Quantum Interference Device) magnetometers, light-emitting diodes, optical amplifiers, laser, transistors and semiconductors, microprocessors, imaging in medicine and research in materials such as nuclear magnetic resonance and electron (scanning, transmission and tunneling) microscopy.

The 1950 experiment conducted by Chinese American physicist Chien Shiung Wu in collaboration with his research assistant, Irving Shaknov, became known as the WS experiment [3]. It is commonly touted as being the first experiment capable of representing the aforementioned quantum entanglement phenomenon, becoming the key to the development of new technologies such as cryptography, teleportation, and quantum communication and computing. It was the beginning of the Second Quantum Revolution. The phenomenon of quantum entanglement proved to be so relevant to science. Because of that, the French physicist Alain Aspect, awarded for his experimental works associated with EPR and Bell's theorem, coined the term Second Quantum Revolution because he considered the 60s as the moment of change in physics and of great technological advance. The experimental ability of physicists to individually manipulate quantum systems, such as electrons and photons, is also part of this revolution in physics. Similar to the First Quantum Revolution, which refers to the very advent and unfolding of quantum physics in the mid-1920s, the Second Quantum Revolution also developed gradually. The material culture itself, associated with the techniques and instrumentation available at the time to obtain significant results, had its advance gradually. If we think of the Second Quantum Revolution based on experiments, where the phenomenon of entanglement was one of the main ones to be developed, it is clear that this theory would need a few generations of experiments to reach the current stage. An important factor that contributed to the consolidation of the Second Quantum Revolution was the way in which entangled photon pairs were produced, in addition to the detection techniques and experimental apparatus that was developed over the years [3].

The applications of quantum mechanics associated to both First Quantum Revolution and Second Quantum Revolution are a result of the enormous success it has had in explaining many of the open questions related to the atomic and subatomic world. Thus, as a result of this new era called the Second Quantum Revolution, the so-called quantum technologies emerged, with applications that, until recently, were unimaginable. These new technologies are clearly disruptive, and it is undeniable the fundamental, preponderant, and strategic role that they will have in the coming decades, especially in the areas of security and defense [4]. Among them we highlight (Figures 1 & 2) quantum cryptography, quantum simulation, quantum metrology, quantum sensors, quantum imaging, quantum internet, and quantum computing strongly related to what we call the quantum engine: the Josephson junction [5].

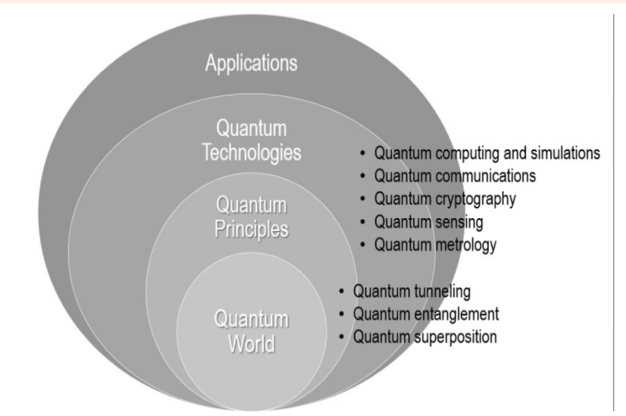

Figure 1: Second generation quantum technologies and correlated big areas [4].

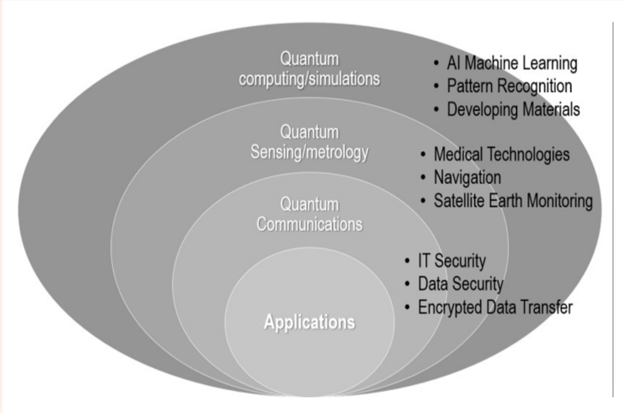

Figure 2: Second generation quantum technologies and correlated application areas [4].

In our daily life, there are a lot of electronic devices operating under the physics of quantum mechanics. It is present in light switches that would not work if electrons could not perform a quantum tunnel through the oxidation layer on the contact surfaces of the metal. It is also present in the flash memory chips found in USB drives which use quantum tunneling to erase their memory cells. Of course, quantum mechanics is also present in more sophisticated devices, as it is essential to understand and design them for many different purposes [4,5]. Since the complexity of quantum devices is increasing almost daily, researchers are currently searching for new and solid methods of direct manipulation of quantum states to support them. Example of this are the actual efforts to develop quantum cryptography. This quantum technology will allow the secure transmission of information, which is essential for military applications. Its main advantage is the detection of hackers performing passive spying while classical cryptography is not able to do that. This behavior is a direct consequence of the physical properties of the quantum bits and the observer effect. In this case, a quantum bit in a superposition state collapses when it is observed, thus becoming an autonomous state. Since the intended recipient is expecting to receive the quantum bit in an overlapping state, it will know that there was a hacker attack because the actual state of the bit is no longer in the original state [1,4,5].

The quantum computing is the most disruptive between them all and the one that has received the strongest attention around quantum technologies, with huge possibilities in the area of defense and security as we will show in next sections. Among all the possible options to obtain the central core of a quantum computer - the qubit – the most reliable with the highest TRL (Technology Readiness Level) and the highest investment are those based in the phenomena of superconductivity and the Josephson junction device (Figure 3). This qubit type is the one chosen by main players like Google and IBM (Figure 4). For example, the processor IBM Osprey has the largest qubit count of any IBM quantum processor, more than tripling the 127 qubits on the IBM Eagle processor unveiled in 2021. This processor has the potential to run complex quantum computations well beyond the computational capability of any classical computer. We will show in the next section the physical properties of the Josephson junction and the two-dimensional arrays (2D-JJA) made by using thousands of this unit [5].

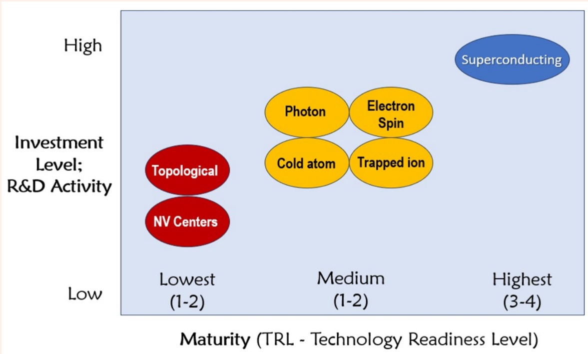

Figure 3: Technological maturity in terms of TRL (Technology Readiness Level) for different qubit platforms; adapted from [6].

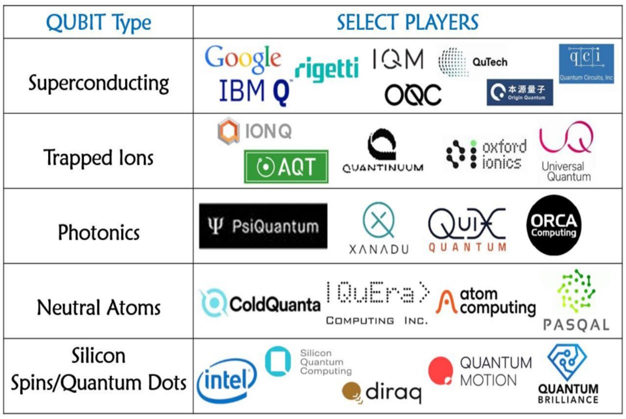

Figure 4: qubit modalities in use by some of the Quantum Computing hardware players; adapted from [7].

Josephson Junction - The Quantum Engine

Main Features

Brian Josephson was 32 years old when he did the work - published in 1962 - on quantum tunneling that won him the Nobel Prize in 1973. He discovered that a supercurrent – from superconductor carriers - could tunnel through a thin barrier, predicting, according to physicist Andrew Whitaker, that at a junction of two superconductors, a current will flow even if there is no drop in voltage; that when there is a voltage drop, the current should oscillate at a frequency related to the drop in voltage; and that there is a dependence on any magnetic field. This became known as the Josephson Effect and the junction as a Josephson junction (JJ). This is a phenomenon that occurs when two superconductors are placed in proximity, with a barrier or restriction between them (called weak links). This effect produces a supercurrent that flows continuously without any voltage applied, across the Josephson junction. The weak link can be a thin insulating barrier (known as a superconductor-insulator-superconductor junction, or S-I-S), a short section of non-superconducting metal (S- N-S), or a physical constriction that weakens the superconductivity at the point of contact (S-c-S) [8,9] as shown in figure 5. Types of Josephson junctions include

a) φ Josephson junctions (Josephson junction which has a non-zero Josephson phase φ across it in the ground state)

b) long Josephson junction (LJJ, is a Josephson junction which has one or more dimensions longer than the Josephson penetration depth, λ_j; however, this definition is not strict

c) superconducting tunnel junction (STJ it consists of two superconductors separated by a very thin layer of insulating material

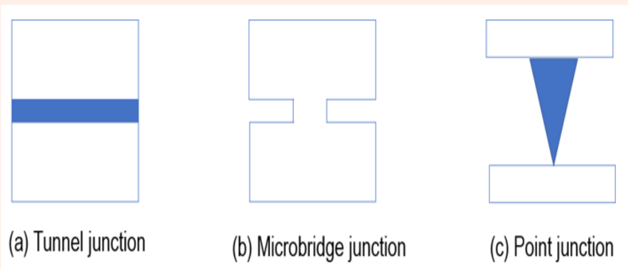

Figure 5: Types of weak links: (a) a thin insulating barrier (tunnel junction) that can be superconductor-insulator- superconductor junction (S-I-S type), or superconductor-non-superconducting metal -superconductor junction (S-N-S type); (b) microbridge and (c) a physical constriction that weakens the superconductivity at the point of contact [10].

The NIST (National Institute of Standards & Technology) standard for one volt is achieved by using an array of 20,208 Josephson junctions in series. In precision metrology, the Josephson effect provides an exactly reproducible conversion between voltage and frequency. When a high-frequency current is applied to a Josephson junction, the AC Josephson current will synchronize with the applied frequency giving rise to regions of constant voltage in the I x V curve of the device (called Shapiro steps). For voltage standards, these steps occur at the voltages n×f/KJ where n is an integer, f is the applied frequency and the Josephson constant KJ = 483597.9 GHz/V is a constant equal to 2×e/h. These steps provide an exact conversion from frequency to voltage. Because frequency can be measured with very high precision, this effect is used as the basis of the Josephson voltage standard, which implements the international definition of the conventional volt [8].

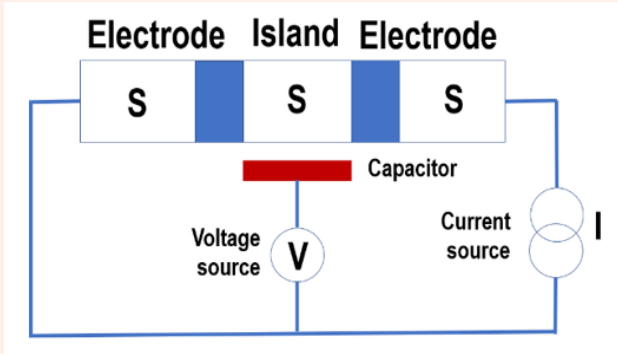

Figure 6: Sketch of a superconducting single-electron transistor (SSET); the island is connected to two superconducting electrodes by Josephson junctions biased by a current source (I) where the island can be polarized by a capacitance connected to a voltage source (V) [11].

Also, single-electron transistors are often constructed by using superconducting materials, allowing us use to be made of the Josephson effect to achieve novel effects resulting in the so-called superconducting single- electron transistor (SSET, Figure 6). The Josephson effect is also used for the most precise measurements of elementary charge in terms of the Josephson constant and von Klitzing constant which is related to the quantum Hall effect. Josephson junctions are also used in superconducting quantum computing such as flux qubits or other ways where the phase and charge act as the conjugate variables [8,9].

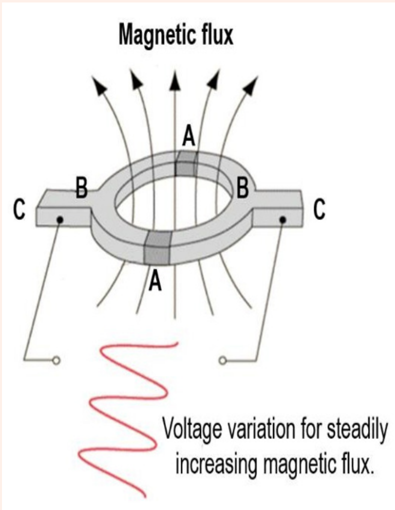

Figure 7: Sketch of a superconducting quantum interference device (S.QU.I.D.) where: A are the Josephson junctions, B is the superconducting ring, and C is the biasing current. The period of the variation of the voltage signal (in red) corresponds to an increase of one quantum of magnetic flux, ϕ_0 [12].

Superconducting quantum computing utilizes STJ-based circuits, including charge, flux, and phase qubits. Also, STJ can be used as direct detectors where the junction is biased with a dc voltage less than the gap voltage. A photon absorbed in the superconductor breaks the superconducting carriers (i.e., the Cooper pairs) and creates quasiparticles. They tunnel across the junction in the direction of the applied voltage, and the resulting tunneling current is proportional to the photon energy. Therefore, STJ can be employed as single-photon detectors for photon frequencies ranging from x-rays to infrared values [9]. The Josephson effect has found wide usage with many practical applications because it exhibits a precise relationship between different physics quantities, such as voltage and frequency, facilitating highly accurate measurements. Josephson junctions have important applications in quantum-mechanical circuits in very sensitive magnetometers like S.QU.I.D. (Superconducting Quantum Interference Device; Figure 7), superconducting qubits, and RSFQ (Rapid Single Flux Quantum) digital electronic devices that use Josephson junctions to process digital signals [8,9,13,14].

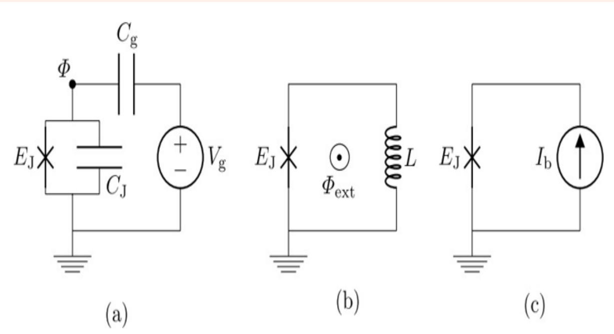

Figure 8: There are three basic designs for Josephson-junction qubits: (a) charge qubit, (b) flux qubit, and (c) phase qubit, where EJ is a Josephson junction with capacitance C_J, ϕ_{ext} is the external magnetic flux and I_b is the bias current [13,14].

In quantum computing, and more specifically in superconducting quantum computing, the qubit is a superconducting device based on a SIS Josephson junction designed to operate as a quantum bit. There are three basic designs for Josephson-junction qubits, depicted in figure 8. The three are known as a charge qubit (Figure 8(a)), a flux qubit (Figure 8(b)), and a phase qubit (Figure 8(c)), respectively. The charge qubit is a box for the charge, controlled by an external voltage Vg; the flux qubit is a loop controlled by an external magnetic flux ϕ_{ext} and the phase qubit is a Josephson junction biased by a current I_b [8,9,13,14]. Since the last decades of the twentieth century, Josephson junctions have also been used in large arrays represented by JJA. They have been used to study the physics of low-dimensional systems i.e., solid-state system in which the spatial dimension is less than three like a thin film (2D), a layer (2D), or a wire (1D). These JJA have also proven to be extremely useful model systems for studying a wide variety of other physics, including phase transitions in frustrated and random systems, dynamics in coupled nonlinear systems, and macroscopic quantum effects among others [15,16].

To understand both the physical properties and the relation with high-temperature granular superconductors is essential in the fabrication of conventional and novel Josephson junction-based devices.

Physical properties of arrays of josephson junctions

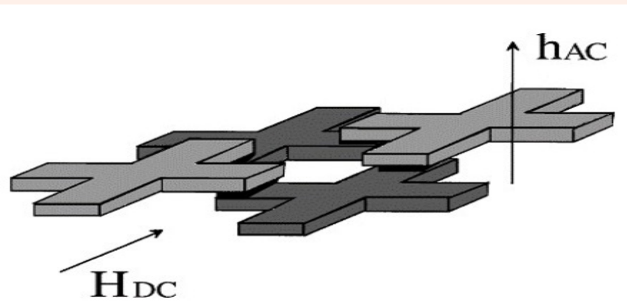

Figure 9: Sketch of a unit cell of the JJA; the crosses are niobium islands, and the junctions are in the overlap region between them. hAC is the oscillating excitation field from the primary coil and HDC is a DC magnetic field, applied in the direction parallel to the sample [17].

The Josephson junction arrays (JJA) mentioned at the end of the last section, consist of islands of superconductor, usually arranged on an ordered lattice, coupled by Josephson junctions (Figure 9) [17]. An N x N Josephson junction array is represented by N2 coupled nonlinear differential equations. According to R.S. Newrock et al. [15], the response of JJA to various driving currents often aids theoreticians in generating solutions to the equations that often suggest experiments to physicists.

Since JJA are artificial structures, they are very well characterized, leading to an interesting synergy between experiments, computer simulations, and applied mathematics and theoretical physics. The discrete nature of an array and the well-known physics of a Josephson junction allows easy computational simulations of JJA behavior, and their results can be compared to experiments or suggest the need for extra experiments. This is of considerable benefit, for example, in studying high-temperature superconductors since JJA with the disorder can be shown to be the limiting case of an extreme inhomogeneous type-II superconductor, allowing the study of such superconductors in the JJA in which the disorder is nearly exactly known. Because of that, JJA are powerful artificial structures equivalent in many aspects to granular superconducting systems. Our results for the physical properties (magnetic, thermal and transport) of JJA were obtained by studying shunted and unshunted SIS and SNS Josephson junction arrays (Figure 10) formed by 10.000 units of these structures. We have considered the geometrical parameters of those structures [18,19]. Their magnetic properties were determined by using the mutual-inductance technique (Figure 11) [20].

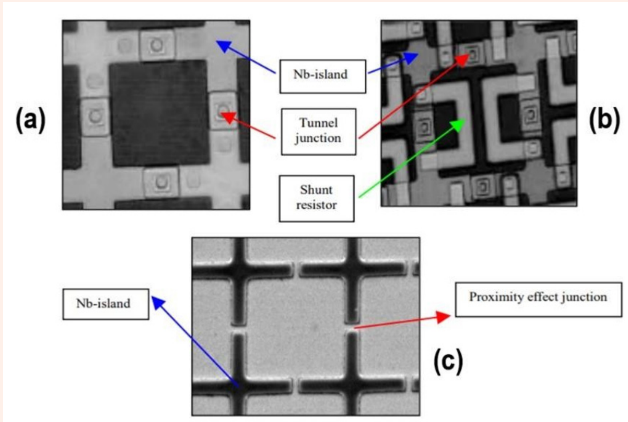

Figure 10: Geometrical characteristics of Josephson junction in JJAs: (a) SIS unshunted junction; (b) SIS shunted; (c) SNS junction. The figure also shows the Nb islands and the shunt resistor [20].

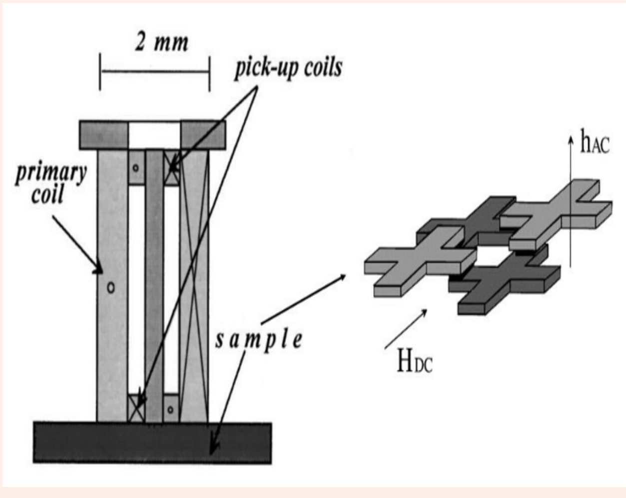

Figure 11: Sketch of the experimental setup for the mutual-inductance technique. The two pickup coils are counterwound [20]. The unit cell of the array (at the right in the figure) is the same shown in figure 9.

Arrays of josephson junction and high-temperature superconductors

Persistent shielding currents circulating on superconductors can be detected by magnetization and susceptibility measurements. dc or ac susceptibility may be measured using direct or alternating magnetic fields. These types of measurements have been widely used to accurately determine the critical temperature (TC) of conventional metallic superconductors and, in recent years, to measure the magnetic transition of high-Tc oxide superconductors. In these latter materials, detailed AC susceptibility ($\chi' + i\chi''$) measurements as a function of temperature and in a fixed AC field amplitude (H_m) typically show two drops in the real component, χ', and two corresponding peaks in the imaginary component, χ", when H_m exceeds some threshold value which depends on sample quality. This suggests a granular behavior such that superconducting regions or grains are coupled through weak links or Josephson-type junctions, reflecting low values of transport critical current densities [21]. On the other hand, AC susceptibility measurements as a function of Hm and in a fixed low temperature, typically show two plateaus and two peaks in the real and imaginary parts, respectively. The first plateau at lower Hm values is associated with the total magnetic shielding of the sample. The second plateau is associated with shielding of the grains only, allowing a magnetic field along the grain boundaries, generally a very poor superconducting material. By increasing H_m above the second plateau, exceeding the bulk lower critical field HC1, flux penetrates into the grains (Figure 12) [21,22].

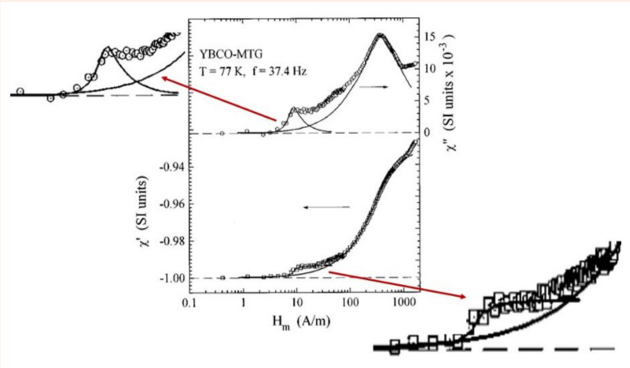

Figure 12: Data points for both components of the AC susceptibility as a function of the magnetic field amplitude for the YBCO-MTG sample in a fixed temperature. Two plateaus in χ' and the associated two maxima in χ" can be seen at H_m ~ 8.5 A/m and Hm ~ 334 A/m. Solid lines represent the exponential critical state model fit to the data [21].

Susceptibility data for polycrystalline samples are complicated to analyze quantitatively. The fraction of intergranular material, the shape, size, and demagnetization factors of the whole sample and grains, the anisotropy of current inside and between grains, the flux pinning properties of granular and intergranular materials, the volume distribution of superconducting parameters, and the coupling properties between grains, are the main factors that influence susceptibility data [21,22]. Our results for granular systems associated to Josephson junction arrays allowed to pioneer understand the problem related to the Paramagnetic Meissner Effect (PME), also called Wohlleben Effect [23-26].

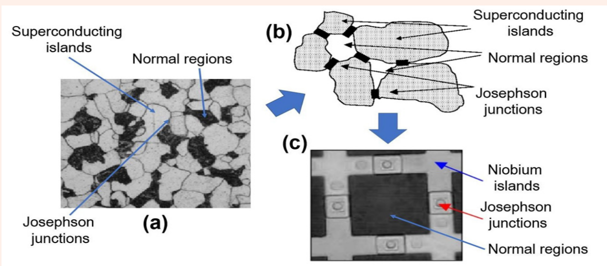

Figure 13: Sketch showing equivalent regions between a granular sample and a JJA; (a) typical micrograph of a granular superconductor; (b) A schematic view of a granular superconductor. The grey areas are the superconducting islands separated by white areas of normal material. Josephson contacts are dark rectangles in the connections between the islands; (c) The simplified topology of a regular square unit cell of a JJA [5,21,22].

Granular superconductors can be considered as a collection of superconducting grains embedded in a weakly superconducting (or even non-superconducting) matrix (Figure 13). For this reason, granularity is a term intimately related to high-temperature superconductors (HTS). The magnetic and transport properties of these materials are usually manifested by a two-component response. One of them represents the intragranular contribution, associated with the grains which exhibit ordinary superconducting properties. The other component originates from intergranular material, being thus associated with weak-link superconductivity. In this sense, intragranular properties would be inherent, while intergranular, on the contrary, would be extrinsic, generating effects dependent on the processing conditions [21,22,27,28].

Due to the smallness of the coherence length, practically any imperfection may contribute to both the weak-link properties and the flux pinning in high-temperature superconductors. Such an inevitable dualism brings about a great number of peculiarities and anomalies [29-31]. Examples of these interesting features are the Wohlleben effect (WE) on the field-cooled magnetization; the fishtail anomaly on the magnetic field dependence of the isothermal magnetization; the magnetic remanence observed in Josephson junction arrays (JJAs); and the occurrence of jumps on the magnetic response of mesoscopic samples submitted to an external magnetic field (H) [32-35].

Quantum Technologies and Security & Defense Applications

As we have mentioned before, the result of the Second Quantum Revolution are the quantum technologies emerging with undeniable, fundamental, preponderant, and strategic role especially in the areas of national security and defense [36,37]. Here we highlight Quantum Information Science; Quantum Computing (where the Josephson junction described before plays an essential and important role), Quantum Communication and Cryptography, and Quantum Sensing and Metrology [38-41].

Quantum information science

When we consider Classical Information Science (CIS), the elementary carrier of information is a conventional bit. that can take two possible values, 0 or 1. On the other side, in Quantum Information Science (QIS) the carrier of information is the quantum bit, or qubit, and its behavior is ruled by the physics of quantum mechanics. In this case the qubit can take are all possible values but following a specific (complex or not) combination (linear or not) of both states 0 or 1. This state formed for all those combination describe what is called a quantum superposition. Quantum systems have another property characterized by a strong physical correlation between qubits and it is called quantum entanglement. This physical behavior is responsible for many quantum features and is directly associate to quantum communications and some quantum sensors like the quantum radar. In the military applications associated to quantum communication it is essential to ensure that the transmitted data is safe what is based in the QIS and the no-cloning theorem. According to this, the quantum transmitted information represented by a qubit, cannot be copied. This is of with great relevance for Armed Forces. Also, QIS can also be successfully applied in both quantum sensing and quantum metrology. QIS has powerful applications like those shown in figure 14 where we can observe its four aspects and the utility in different areas related to energy research and engineering.

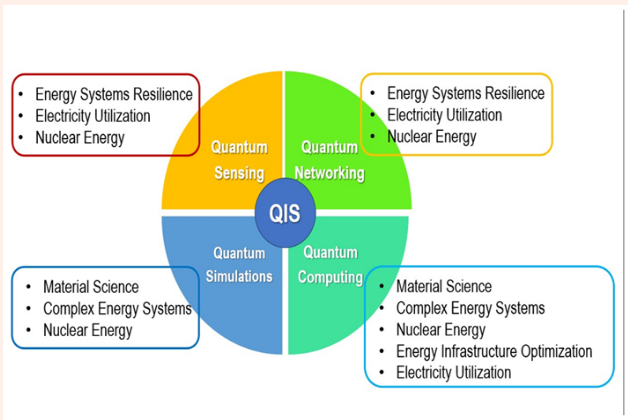

Figure 14: The four aspects of Quantum Information Sciences (QIS) and the possible applications to different areas related to energy research and engineering; adapted from [42].

Quantum computing

This quantum technology uses the QIS described before to perform computations through the use of a quantum computer. These machines will be practical and useful just for a limited type of high complexity problems. Actual applications of quantum computers basically depend on parameters like coherence, error resistance, gate fidelity and, of course, in the number of qubits and their inter-connectivity to perform the desired calculations. Physical qubits can be fabricated by different techniques and following different concepts. Among all possible options, quantum computers based on superconducting qubits and based on trapped-ion qubits are those with higher TRL values (Figure 3). Moreover, those different quantum bits are adopted for the main players in this area, like IBM and Google (Figure 4). Other technologies based in other different concepts like cold atoms, topological, electron spin, photonic or nitrogen-vacancy (NV) center-based qubits (for example, in a diamond lattice), have low TRL values and are still in a lower stage or are developed just in theory. When talking about qubits, we can have physical qubits or logical qubits. The physical qubit is related to the quantum system itself while the logical qubit is formed by many physical interconnected qubits working together to perform a computation. For each physical qubit used in that computation we find other subordinated qubits performing a range of tasks such as spotting and correcting errors as they occur. Logical qubits are perfect quantum cells, or near-perfect quantum cells, characterized by long-to-infinity coherence time, high fidelity, and higher environment resistivity. Most probably, nowadays the quantum computers manufactured by both Google and IBM have the best quantum processors, where the former has claimed to achieve quantum supremacy in 2019. Also, Google is planning to release soon a quantum processor having 10,000 qubits and by 2029 another with 1 million qubits. Also, we have differences in the concept of quantum computers having two possible options, analogue and digital quantum computers depending in both their physical principles and their limitations. The first (with machines from Google and IBM) is limited by resources and not by the noise generated, since this problem can be easily fixed just by using extra resources. On the other hand (with machines like D-Wave Systems, and Ising Systems from Toshiba), the latter is limited by uncontrolled noises that are difficult to understand. Therefore, the applicability of analogue quantum computers is limited. Another important feature is that machines from Google and IBM are large machines (because they work with superconducting qubits) requiring the use of cryogenic materials like liquid Helium. Most likely, it will be many decades before we have portable quantum computers, and until then, access to these machines will only be possible through the cloud services (sometimes for free) called QCaaS (or Quantum Computing-as-a-Service). Some quantum hardware manufacturers, for example Amazon Bracket. This company is a fully managed quantum computing service designed to help accelerate scientific research and software development for quantum computing. Use cases Research quantum computing algorithms Accelerate scientific discovery with tools for algorithm development and support from the AWS Cloud Credit for Research Program. Of course, it is unimaginable that any military organization could safely use a quantum computer in a cloud from Google or other – foreign or not - Big Tech. Every armed force all around the world must have, in the near future, its own - purchased or locally developed- quantum computer. Possible quantum computer applications are quantum simulations, quantum cryptoanalysis, quantum searching and quantum walks, and quantum machine learning and AI, all them being essential in military operations [38-41].

Quantum communication and cryptography

The quantum communication technology is related to the information exchange by using two possible channels to operate a quantum network, an optical fiber, or the free space. Since photons are the usual carriers of quantum communication, some physical limitations arise, with the losses of the transmission of information over great distances being the main ones. To solve the problem the quantum network contains quantum repeaters or quantum switches to keep the system properly working. Another quantum technology is quantum cryptography, which is directly associated to quantum communication. By using the so-called quantum keys distribution (QKD) it aims to replace cryptographic systems that uses the same key used by the sender to encrypt the message and by the receiver to decrypt the message. It was the only type of encryption (called conventional encryption) in use prior to the development of public-key encryption. The purpose of the quantum network (which is sometimes called quantum internet or quantum information network) is to transmit the quantum information via different technologies across several channels. Many of these quantum networks applications are based on another quantum phenomena, called quantum entanglement. A very modest quantum processor (for example with just one qubit) is sufficient for most quantum network applications.

Optical or near-optical photons using the free-space quantum channel option are of limited utility since it is well- known that they have a strong atmospheric attenuation. Therefore, in this scenario the best quantum network to be used is the one based in quantum satellites, like China has recently made. The obvious advantage of using that is the possibility of using optical-photon communication since the losses in the link between the ground and the satellite are lower than those between two ground nodes separated from a long distance. Since the use of satellites is expensive, for distances short enough the optical communication using photons in the free-space quantum channel can be done by using drones. At long distances, the quantum communication should use quantum repeaters due to the losses and decoherence of the photons. The quantum similar of classical amplifiers used in conventional optical networks are the intermediate nodes called quantum repeaters having the feature that obey the no-cloning theorem allowing entangling qubits of end nodes. In the case of having two entangled end nodes, it can be used the effect of quantum teleportation. The quantum information can be teleported without a physically sent photon and just a classical communication is required. Quantum entanglement will allow that the quantum information will flow through a quantum network or part of it. These networks will work in parallel with the classical networks, since not all transmitted information needs to be quantically encoded. They are used in many powerful applications of high relevance in military operations. Some of these applications are the quantum key distribution (QKD); post-quantum cryptography; quantum random number generator; a secure transmission of a cryptographic key; blind quantum computing; secure identification; quantum information transmission; network clock synchronization; quantum position verification; distributed quantum computing for several quantum computers; and entangled sensor network among other military applications [38-41].

Quantum sensing and metrology

In terms of Quantum Technologies, the areas with higher TRL values - i.e. the most mature areas - are quantum sensing and quantum metrology since they have improved parameters like timing, sensing, and imaging. Atomic clocks are excellent examples of this quantum sensing contribution. Devices of this type can measure with high precision many physical variables producing very precise information about them. Quantum imaging, directly related to quantum optics, uses photon correlations, and allows both the suppression of the noise and the increase in the resolution of the imaging of the studied object. The protocols of this quantum technology have special relevance in applications like quantum radar, medical imaging and mainly in the detection of the objects in an optically impermeable environment. Both quantum sensing and quantum metrology are based on quantum features like coherence and entanglement, and metrics like sensitivity, dynamic range, sampling rate, operating temperature, spatial resolution at a certain distance and the time required to achieve a specified sensitivity, among other metrics. Typical quantum sensors measure quantities like magnetic and electric fields, rotation, time, force, temperature, and photon counting. Many of these quantum sensors are universal and can measure many physical quantities. The most promising technologies are atomic vapor, cold-atom interferometry, nitrogen-vacancy centers, superconducting circuits, and trapped ions [38-41].

The four quantum technologies described previously play the main role in the development of several applications in security and national defense, starting by quantum computing and the Josephson junction-based machines. Military technologies have more demanding requirements than industrial or public applications since they require greater caution, considering possible deployment on the battlefield. Figures 14 & 15 show various possible military applications. About the so-called Quantum Strategy, the future users of military quantum technologies like those described in figures 14 & 15, will have to think carefully about the way to used financial investment and resources. In general, military organizations are users and not developers of technology but can actively participate in that process. Thus, before the acquisition of the necessary equipment, these military organizations just specify the necessary requirements to the industrial sector. Specifically, in relation to quantum technologies, which are extremely complex and there are almost no engineers available to deal with them properly, the best way to overcome the problem is to have a national ecosystem funded by the government and dedicated to quantum technologies with the participation of both industries and universities/research centers. This quantum ecosystem, coordinated by a specific military organization (such as an institute or a research center), should work based on the so-called triple-helix ecosystem aiming to develop dual technologies for both the national security and defense sectors. The quantum technologies area is as peculiar as interesting, where in general both corporations and universities synergically work together. To do that, the first step is to establish a quantum technology roadmap, i.e., a quantum strategy, especially when the products to be developed are of military interest. In this case the whole process should be led by the military organization.

The roadmap or the strategy should specify all the next steps, from identifying market survey, disruptive quantum solutions, technology and risk evaluation and development itself to prototype testing. Of course, the most critical part is the identification of the most advantageous and disruptive quantum technologies for a specific warfare domain (land, air, space, electronic, cyber, sea and underwater (Figure 14). This procedure also includes the evaluation of technological and scientific aspects to balance the technological risk and the potential advantage of individual quantum technologies. Since this is a new and dynamic both scientific and technological area with both great relevance and financial investments, it is important to remember that many applications are still to come what could completely change the actual scenario [38-41].

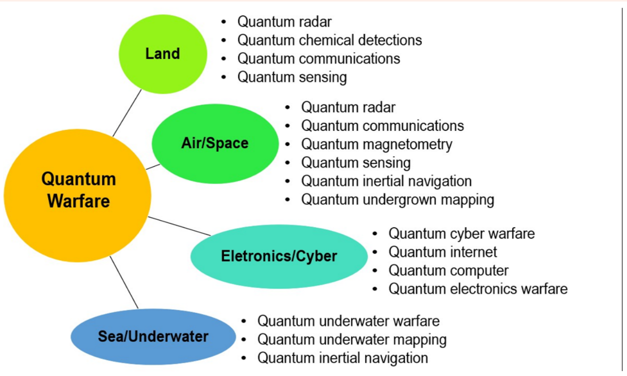

Figure 14: Quantum technology systems applied to quantum warfare; adapted from [38].

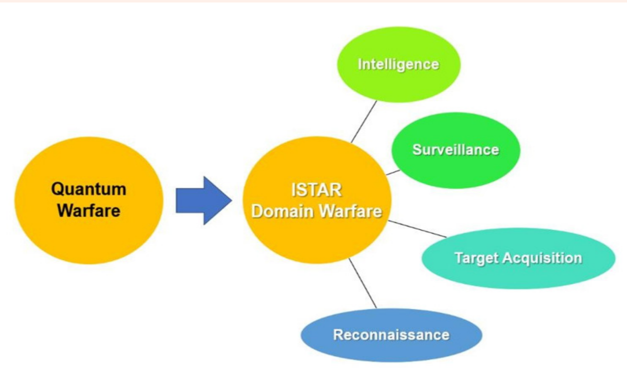

Figure 15: Quantum ISTAR (intelligence, surveillance, target acquisition and reconnaissance) technology systems applied to quantum warfare; this is a key resource for any military operational organization in all battlefields; adapted from [38].

Summary

In this review of our own work, we have shown the physics and applications of Josephson junctions and their bidimensional arrays (JJA) made with this quantum engine. Directly associated to it, and a product of the Second Quantum Revolution, is the so-called area of quantum technologies, a new and disruptive technological field with the power to affect almost all human activities. Based on the properties of quantum mechanics such as quantum tunneling, quantum entanglement, and quantum superposition, these emerging technologies include striking applications like quantum computing, quantum communications, quantum sensing, quantum cryptography, quantum internet, quantum imaging, quantum metrology, quantum biology, among others. For their unique features, these technologies are of the interest of both the defense and security industry, and all involved stakeholders. Quantum technologies provide new military capabilities by increasing effectiveness and accuracy, thus leading to new paradigms and to the so-called quantum warfare in all possible domains, such as land, air, space, electronics, cybernetics and underwater. These technologies also have great strategic relevance in the so-called ISTAR domain (Figure 15). Among those applications mentioned before, quantum computing (like the machines based in superconducting qubits using Josephson junctions) is expected to have a number of important uses such as optimization and machine learning, associated to both quantum artificial intelligence and quantum blockchain.

From the characteristics of quantum computing and military systems, it is possible to verify the existence of an interesting number of security and defense applications of this quantum technology in solving military problems. Quantum computing is likely to be efficient in optimization problems. By using these machines some military problems that could be solved are war or battlefield simulations; logistics management; supply chain optimization; analysis of radio frequency spectrum; and energy management among others. Looking for the optimization of the procedure to get the most effective results, military quantum computer systems should be located in computing farms along with classical computers, which will create a hybrid system that will analyze the tasks of the war zone. Today it is not possible to incorporate a portable quantum computer in any type of transport vehicle, be it land, air, or sea or even in a mobile command center. The best quantum computers (Figures 3 & 4) use superconducting qubits that must be kept in liquid helium (4.2K) or even at lower temperatures beyond this configuration requires mechanical insulation (vibration free), large space and many accessory equipment to function properly. Therefore, in order to obtain a more efficient military application of quantum computers, great efforts must be made focused on obtaining new qubits based on new concepts allowing there use at room temperature. In addition to solving diverse quantum data process, a large quantum computer can give enormous benefits of machine learning and optimization of models related to autonomous and robotic systems. Military applications focused on quantum optimizations could be related to the design of new vehicles and some very special features like stealth and agility. Also, quantum computers dedicated military applications could help in mission planning; logistics for overseas operations and deployment; war games; systems validation and verification, and an important role in Command-and-Control systems. However, at the top of all possible military applications of these machines we find the enhanced decision making, aiming to give support to military operations including the strategic area of predictive analytic. The aim of this application is to analyze and present situational awareness or even give assistance providing planning and monitoring. This must include the simulation of various possible scenarios to provide the best conditions for the best decision. Also, quantum computer can improve and speed up the simulations of different and possible war scenarios and process and analyze the Big Data from ISR domain for enhanced situational awareness including the involvement of quantum-enhanced machine learning and quantum sensors and imaging. Also, the quantum information processing will probably be essential for ISR, or situational awareness providing the capability of filter, decode, correlate, and identify features in captured images and signals from the war zone. It is expected that in the near-term situational awareness and understanding can be benefited from quantum image analysis and pattern detection by using both neural networks and AI. Also, by using neural networks, quantum computers will provide higher quality pattern recognition at a higher speed [38-41].

In the near future, and by using advance mathematics, quantum computers will be able to improve many military strategic areas such as war games simulations, radar cross section calculations, and stealth design modelling as well as the so-called NQEC (Network Quantum Enabled Capability). This consists of a futuristic system that will allow the communication and sharing information across the network between individual units and the commander aiming to get a fast response between the battlefield developments and the coordination of the operation. This can bring secured communication, enhance situational awareness and understanding, remote quantum sensor output fusing and processing, and improved Command and Control, one of the most important systems in military organizations. It is straightforward to conclude that the Quantum Technologies have the potential to significantly affect most of the areas of human activity, especially the security and defense sectors. They have the potential to impact all the domains of modern warfare giving rise to quantum warfare. These technologies have improved the sensitivity and efficiency of all military related areas of defense/attack leading to new types and systems of weapons. However, it is important to remember that we are living in a situation in which many of these mentioned applications are not yet real, because transferring a technology from the laboratory for use in the field (corresponding to TRL values between 4 and 7, within a zone called the valley of death) is neither a simple nor a trivial task.

It must be remembered that the integration of a specific quantum technology into a military system is even more challenging. This is not the case when considering quantum computers since they will be located at data centers similarly to those for civil uses. However, the integration and deployment of other quantum technologies like quantum networks, quantum imaging and quantum sensing will have to confront many challenges. Basically, this is because the increased demands of military use when compared with civil/industry or scientific requirements. This area is still very young, and new technological innovations, positive or negative, may impose other quantum advantages or disadvantages to actual military systems and applications.

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References

1. Eisberg R, Resnick R (1985) Quantum Physics of Atoms, Molecules, Solids, Nuclei, and Particles. (2nd Edition), Wiley & Son, USA.
2. Photoelectric effect - Wikipedia (2023).
3. Wu CS, Shaknov I (1950) The Angular Correlation of Scattered Annihilation Radiation. Physical Review 77: 136.
4. (2022) Quantum technologies - from basic research to market; Federal Ministry of Education and Research (Germany); A Federal Government Framework Program.
5. Simão SEB, Galdino JF, Faddul SAS, Boareto MAJ, Araujo MFM (2023) Josephson Junction, the Quantum Engine: from S.QU.I.D. Sensors to Qubits for Quantum Computers. Research & Development in Material Science 18(5): 2140-2158.
6. Arthur D Little (2023) Quantum computing.
7. (2023) Quantum Computing Modalities - A Qubit Primer Revisited - The Quantum Leap.
8. Reference Module in Materials Science and Materials Engineering, The Josephson Junction - an overview; ScienceDirect Journals and Books (2016).
9. Blamire MG (2021) The Potential of the Josephson Energy; J Supercond Nov Magn 34: 1629-1632.
10. Araujo MFM (2002) The fascinating world of superconductors. Univerciencia Magazine 2: 39.
11. Bouchiat V (1999) Quantum Coherence of Charge States in the Single Electron Box. Journal of Superconductivity 12(6): 789-797.
12. (2023) Adapted from Home for Physics. Physics (uaf.edu) at Applications.
13. Kockum AF, Nori F (2019) Quantum Bits with Josephson Junctions. In: Tafuri F (ed.), in Fundamentals and Frontiers of the Josephson Effect; Springer Series in Materials Science 286.
14. Huang HL, Wu D, Fan D, Zhu X (2020) Superconducting quantum computing: a review. Sci China Inf Sci 63: 180501.
15. Newrock RS, Lobb CJ, Geigenmüller U, Octavio M (2000) The Two-Dimensional Physics of Josephson Junction Arrays. Solid State Physics 54: 263-512.
16. DOI: https://doi.org/10.1016/S0081-1947(08)60250-7.
17. Passos WAC, Araujo MFM, Ortiz WA (2000) Magnetic remanence of Josephson junction arrays. J Appl Phys 87(9): 5555-5557.
18. Araujo MFM, Barbara P, Cawthorne AB, Lobb CJ (1997) Reentrant ac Magnetic Susceptibility in Josephson-Junction Arrays. Phys Rev Lett 78: 4625.
19. Maluf W, Cecato GM, Barbara P, Lobb CJ, Newrock RS, et al. (2001) Magnetic properties of SIS and SNS Josephson junction arrays. Journal of Magnetism and Magnetic Materials 226-230: 290-292.
20. Maluf W, Araujo MFM (2002) Controversial features of granular superconductors studied through the magnetic properties of 2D-Josephson junction arrays. Brazilian Journal of Physics 32(3): 717-730.
21. Barbara P, Araujo FMM, Cawthorne AB, Lobb CJ (1999) Reentrant ac magnetic susceptibility in Josephson-junction arrays: An alternative explanation for the paramagnetic Meissner effect. Phys Rev B 60(10): 7489-7495.
22. Araujo MFM, Ortiz WA (1996) De Lima of Exponential critical state model applied to ac susceptibility data for the superconductor $YBa_2Cu_3O_{7-\delta}$. J Appl Phys 80(6): 3390-3395.
23. Passos WAC, Lisboa FPN, Caparroz R, De Faria CC, Venturini PC, et al. (2001) Granularity in superconductors: intrinsic properties and processing- dependent effects. Physica C: Superconductivity. 354(1-4): 189-196.
24. Ortiz WA, Lisboa FPN, Passos WAC, Araujo MFM (2001) Field-induced networks of weak- links: an experimental demonstration that the paramagnetic Meissner effect is inherent to granularity. Physica C: Superconductivity 361(4): 267-273.
25. Araujo MFM, Maluf W, Sergeenkov S (2005) On the origin of reentrance in 2D Josephson junction arrays. Eur Phys J B 44: 33-39.
26. Araujo MFM, Sergeenkov S (2008) Dynamical reentrance and geometry-imposed quantization effects in Nb–AlO_x–Nb Josephson junction arrays. Supercond Sci Technol 21: 045002.
27. Sergeenkov S, Rotoli G, Filatrella G, Araujo MFM (2007) Thermal expansion of Josephson junctions as an elastic response to an effective stress field. Physical Review B 75(1): 014506.
28. Rotoli G, Sergeenkov S, Filatrella G, Araujo MFM (2008) Thermal expansion of granular superconductors based on elastic response of Josephson junction arrays. Journal of Physics: Conference Series 97: 012235.
29. Sergeenkov S, Cichetto L, Rivera VAG, Stari C, Marega E, et al. (2010) Pinning of Spiral Fluxons by Giant Screw Dislocations in $YBa_2Cu_3O_{7-\delta}$ Single Crystals: Josephson Analog of the Fishtail Effect. JETP Letters 91(1): 30–34.
30. Araujo MFM, Maluf W, Sergeenkov S (2004) Influence of nonuniform critical current density profile on magnetic field behavior of AC susceptibility in 2D Josephson junction arrays. Solid State Communications 131(12): 759-762.
31. Sergeenkov S, Araujo MFM (2004) Manifestation of Geometric Effects in Temperature Behavior of AC Magnetic Response of Josephson Junction Arrays. JETP Letters 80(9): 580-583.
32. Nascimento FM, Sergeenkov S, Araujo MFM (2012) Reconstructing 3D profiles of flux distribution in array of unshunted Josephson junctions from 2D scanning SQUID microscope images. Physics Letters A 376(42-43): 2722-2724.
33. Rivera VAG, Sergeenkov S, Marega E, Araujo MFM (2010) Manifestation of geometric resonance in current dependence of AC susceptibility for unshunted array of Nb–Al_x–Nb Josephson junctions. Physica C 470: 1946-1948.
34. Sergeenkov S, Rivera VAG, Marega E, Araujo MFM (2011) Field induced Kosterlitz–Thouless transition in two-dimensional array of Nb–AlO_x–Nb Josephson junctions. Solid State Communications 151(12): 892–894.
35. Rivera VAG, Sergeenkov S, Marega E, Araujo MFM (2009) Manifestation of π-contacts in magnetic field dependence of I–V characteristics for proximity-type 2D Josephson junction array. Physics Letters A 374(2): 376-379.
36. Sergeenkov S, Rivera VAG, Marega E, Araujo MFM (2010) Universal resistance capacitance crossover in current-voltage characteristics for unshunted array of overdamped Nb–AlO_x–Nb Josephson junctions. Journal of Applied Physics 107: 9.
37. Quantum Manifesto - A New Era of Technology (2023).
38. Araujo MFM (2023) Quantum supremacy and national defense: the new reality. In: Sanches JC, Araujo MFM, Collection of opinion articles on strategic studies in defense and security. (Ed.), pp. 245-247.
39. Krelina M (2021) Quantum technology for military applications. EPJ Quantum Technol 8: 24.
40. (2023) NATO Review - Quantum technologies in defence & security.
41. (2023) National Agenda on Quantum Technology: the Netherlands as an international centre for Quantum Technology - QuTech.
42. (2023) In the war for information, will quantum computers defeat cryptographers? Craig Costello.
43. (2023) Cyber Centre's summary review of final candidates for NIST Post-Quantum Cryptography standards - Canadian Centre for Cyber Security.
44. Scott E, Crawford (2021) Quantum Sensing for Energy Applications: Review and Perspective. Adv Quantum Technol 2100049.
45. (2023) Quantum Sensors Could Let Autonomous Cars 'See' around Corners - Scientific American.
46. Shabir B, Stefano P, David V, Johannes MF (2020) Microwave quantum illumination using a digital receiver. Science Advances 6(19): 0451.