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Quantum Computing: Fundamentals, Implementations and Applications

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ABSTRACT Quantum Computing is a technology, which promises to overcome the drawbacks of conventional CMOS technology for high density and high performance applications. Its potential to revolutionize today's computing world is attracting more and more researchers towards this field. However, due to the involvement of quantum properties, many beginners find it difficult to follow the field. Therefore, in this research note an effort has been made to introduce the various aspects of quantum computing to researchers, quantum engineers and scientists. The historical background and basic concepts necessary to understand quantum computation and information processing have been introduced in a lucid manner. Various physical implementations and potential application areas of quantum computation have also been discussed in this paper. Recent developments in each realization, in the context of the DiVincenzo criteria, including ion traps based quantum computing, superconducting quantum computing, nuclear magnetic resonance (NMR) quantum computing, spintronics and semiconductor based quantum computing have been discussed.

INDEX TERMS Quantum Computing, Quantum Computer, Qubit, Quantum Gates, Spin transfer torque (STT), Quantum Cryptography.

I. INTRODUCTION

Today's computational processors decode information into binary bits 0's and 1's and logic gates based on switching transistors are used to process them. These computers work on sequential principles where processes are carried out in a sequential manner until results are arrived. Currently, computing is governed by the rules of classical physics till the size of semiconductor transistors approaches the dimensions of atom. In 1975 Gordon Moore predicted that transistors in integrated circuits will double after every eighteen month [1]. It is believed within the next 10 years, the clock frequency of current computer processor systems may reach about 40 GHz. It is expected that by 2024, it would be hard for the Moore's law to endure further as size of conventional classical bits approaches dimension of atom [2]. Under such conditions material particles are no longer described by classical physics, and a new model of the computer may be necessary by that time. Subsequently, it is important to accomplish the computing at atomic size that follows non-traditional physics called quantum mechanics. In dealing with the problems presented, the quantum computer is one proposal that may have merit. Quantum computing is attracting more and more interest of industrial sectors, not only broad-interest corporations like Microsoft or Google, but also companies more traditionally linked to the area of nanoelectronics and nanotechnology (e.g., IBM and Intel). The arena of quantum computing was accepted in 1980s. In 1999, first quantum computer was developed out of superconductors by D-Wave Systems a Canadian organization. In 2007, 28-qubit quantum computer was illustrated, trailed by 128 qubits in 2010, 512 qubits in 2013, and 2000 qubits in 2018. As far as quantum computing research and implementation is concerned, at present we have just a couple of quantum computer gadgets in a lab domain. The requirement for quantum computers to recreate quantum physics effectively, was first predicted by Richard Feynman [3]. A quantum computer does the calculations dependent on the quantum mechanics.

Quantum computers aren't constrained to two states; they encode data as quantum bits, or qubits, where bits can be 0 or 1 or both 0 and 1 at the same time in what is called superposition. Moving down to the atomic level quantum computers can be physically realized by atoms, photons, ions or electrons and their corresponding control devices that are working collectively to act as computer processor and memory. At the degree of fundamental research exploration facilities numerous other physical realizations of qubits have been proposed and examined. Recently, solid-state implementations have won overwhelming interest owing to their capacity for scaling to large numbers of qubits. Josephson junctions in superconductors and spin qubits in silicon fall into the course of solid-state qubits. The similarity of silicon qubits with CMOS foundries is an extraordinary resource. Quantum computers utilizing the property of superposition can process and store multiple states simultaneously, thus ensuring it's potential to be millions of times extra dominant than today's most brand influential supercomputers. Moreover, quantum computers guarantee secure transmission, ultrahigh speed and ability to store large amount of information than its classical counterparts.

In order to have broad vision over the field, the revision has been carried out with the target to draw the worldwide research in quantum computing as classified in Scopus database. The mapping pursues to label the field in standards of its growth rate, distribution of research by source type, research yield by using top 12 most prolific nations and dispersal in terms of subject areas.

A. QUANTUM COMPUTING RESEARCH GROWTH

Quantum computing research over the world cumulated to 19778 over all publications from 1923 to 2020, and it enrolled huge development, up from 1923 to 2020 as shown in Fig. 1. The 10-year worldwide yield in the subject showed 47.12% outright growth, up from 7506 in 2000–2010 to 11043 publications in 2011–2020.

B. DISTRIBUTION OF QUANTUM COMPUTING RESEARCH BY SOURCE TYPE

A significant viewpoint for the research distribution is source type. From the revision it has been discovered that of the whole distributions yield, 67.69% (13388) showed up as journals, 22.88% (4525) as conference papers, 6.20% (1228) as book series, 2.40% (480) as books, and 0.8% (154) as trade journals and others as shown in Fig. 2.

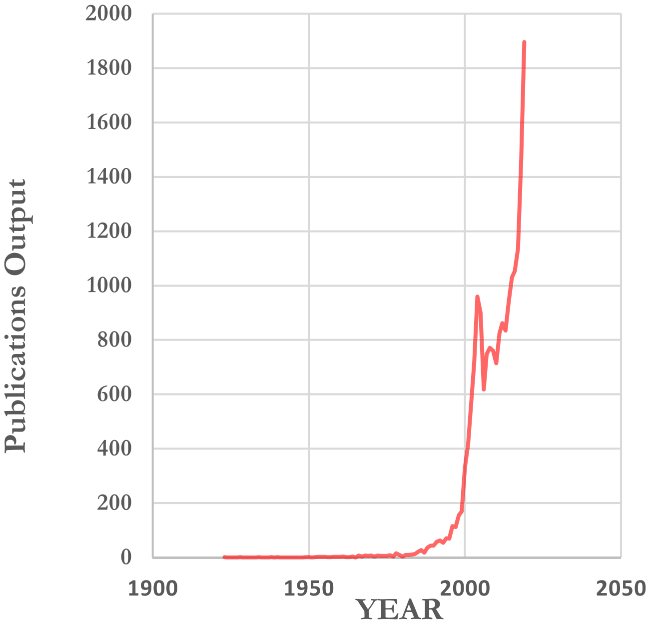

FIGURE 1. **Publications in quantum computing research across the World.**

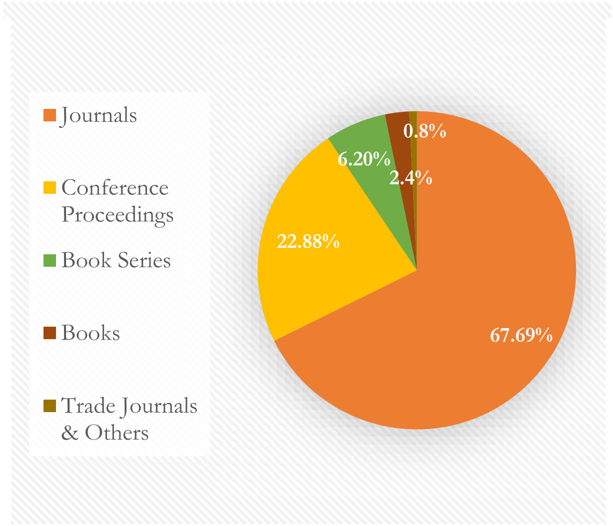

FIGURE 2. **Source-type wise Quantum computing research in world.**

C. TOP 12 MOST PROLIFIC COUNTRIES WORLDWIDE IN QUANTUM COMPUTING RESEARCH

The worldwide quantum computing research yield has coined from about 130 nations. The appropriation of worldwide distributions yield by contributing nations is twisted. Out of the 120 contributing countries, 70 contributed 1–25 papers each, 26 nations 26–100 papers each, 26 nations 101–1000 papers each, 06 nations 1001–5000 papers each and 1 nation over 5000 publications.

Top 12 nations dominated research in quantum computing with 97.68% (19320) worldwide publication share as portrayed in Fig. 3. Separately their worldwide publication share varies from 2.62% to 32.27%. The USA contributed the most noteworthy 32.27% (6383) share, trailed by China 13.04%

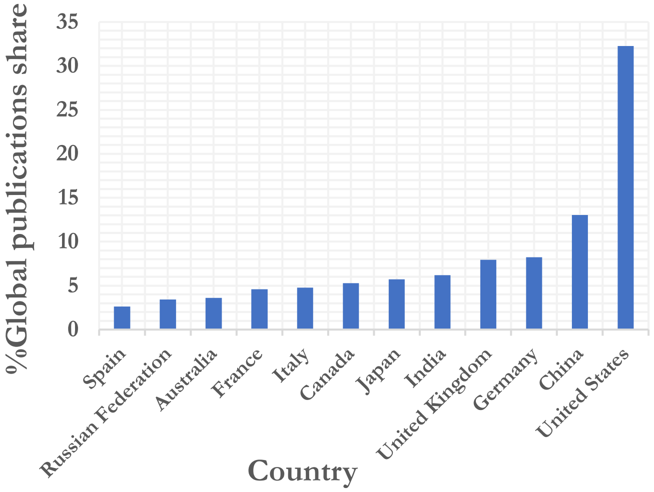

FIGURE 3. Worldwide publications yield of top countries in quantum computing research.

(2579), Germany 8.21% (1625), and so on. Spain placed at base finish of the count contributed 2.62% (519) worldwide distributions share.

D. DISTRIBUTION OF RESEARCH OUTPUT BY SUBJECT AREA

In quantum computing research the output publication yield is disseminated across 27 subject areas of knowledge. The most famous region of exploration in quantum computing research is Physics and Astronomy representing the most elevated global publications share (50.35%), trailed by Computer Science (34.56%), Engineering (26.61%), Mathematics (20.94%), Material science (18.17%), Chemistry (14.42%), Biochemistry, Genetics and Molecular Biology, Multidisciplinary, Chemical Engineering and other sub-fields from 0.01% to 4.83% as shown in Fig. 4. Now a days almost every branch of science is in race of the quantum computing research. Literature covered under different subject areas is overlapping in nature.

E. PROFILE OF TOP 20 GLOBAL AFFILIATIONS

Out of total publications in quantum computing research (from Scopus database), 160 associations contributed 74.8% stake with an average of 91.07 publications per association. The circulation of distribution yield across contributing associations is profoundly skewed. Of the 160 worldwide affiliations, 26 contributed 1–50 papers each, 90 associations contributed 51–100 papers each, and 44 associations added 100–400 publications each. The distribution profitability of topmost 20 gainful associations in quantum processing research over the world differed from 147 to 370 distributions. Collectively they represented 21.34% (4159) distribution share. The scientometric profile of these primary 20 associations is shown in Fig. 5.

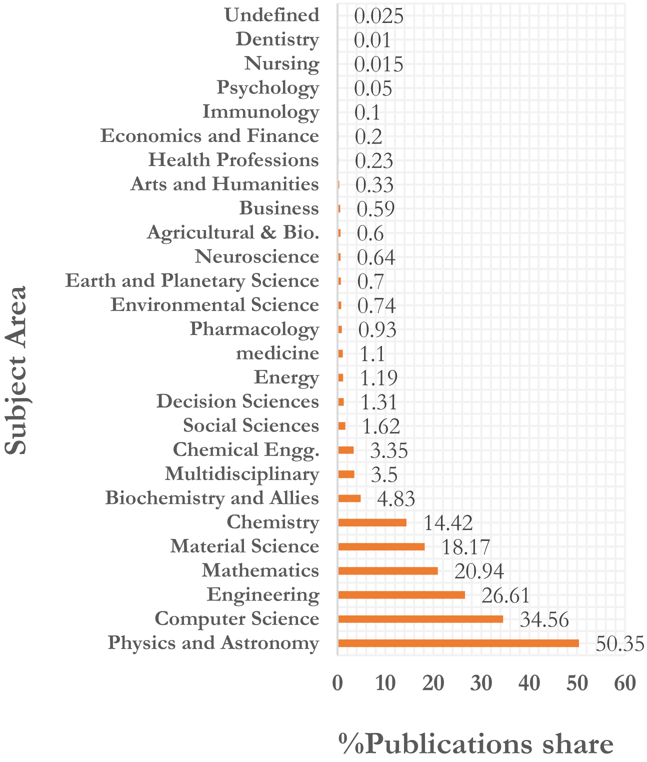

FIGURE 4. Subject-wise division of worldwide publications in quantum computing.

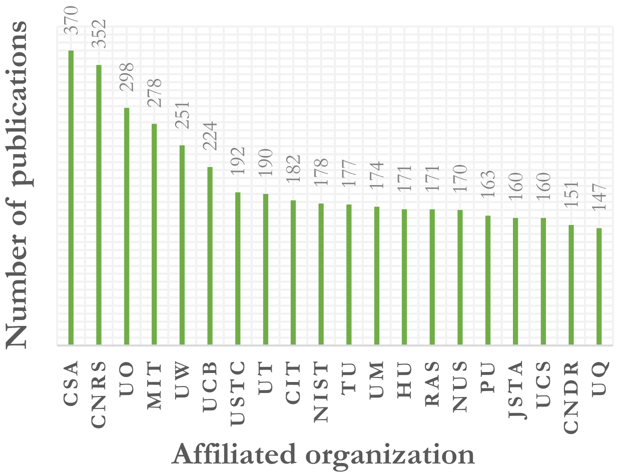

FIGURE 5. Scientometric outline of top 20 most prolific organizations in quantum computing research. CSA: Chinese Academy of Sciences; CNRS: Centre National de la Recharche Scientifique; UO: University of Oxford; MIT: Massachuasetts Institute of Technology; UW: University of Waterloo; UCB: University of California, Berkeley; USTC: University of Science and Technology of China; UT: University of Tokyo; CIT: California Institute of Technology; NIST: National Institute of Standards and Technology; TU: Tsinghua University; UM: University of Maryland; HU: Harvard University; RAS: Russian Academy of Sciences; NUS: National University of Singapore; PU: Princeton University; JSTA: Japan Science and Technology Agency; UCS: University of California, Santa Barbara; CNDR: Consiglio Nazionale Delle Ricerche; UQ: The University of Queensland.

The organization of rest of the paper is as follows: Section II explains the quantum computation systems. Section III explains various physical realizations of quantum computing systems. Section IV discusses potential applications in quantum computing systems. The conclusion is presented in Section V.

II. QUANTUM COMPUTING SYSTEMS

Quantum computation and quantum information is the study of the information processing tasks that can be accomplished using quantum mechanical systems. The study of quantum computing is a subfield of quantum information science. Fundamentally computing systems rely on the ability to store and manipulate information. Bits are manipulated individually by current computers. Quantum computers make use of a quantum-mechanical phenomenon (e.g., superposition and entanglement) that allows data to be represented as quantum bits (qubits) - these are not constrained to conventional 0 or 1 binary values, but instead can be a superposition of zero and one simultaneously. Hence, a set of qubits can represent exponentially more values than their classical-bit counterparts. This makes quantum computing a promising platform which could potentially solve computational problems unmanageable for even the most advanced conventional supercomputer. In this section, the discussions will be presented about the fundamentals of quantum computing, various qubit representations, and quantum properties leveraged by qubits and how they are used to compute.

A. BIT VS QUBIT

In this section we are introducing the properties of qubits, comparing and contrasting their properties to those of classical bits [4]. The fundamental concept of classical computation and classical information is a bit. A bit is either in state 0 or in state 1. Quantum computation is built upon an analogous concept, the quantum bit, or in short qubit. In the quantum regime we have systems in superposition of states. The difference between qubits and bits is that a qubit can be in a state other than 0 or 1, or we can say in a superposition of 0 and 1. Hence, a set of qubits can represent exponentially more values than their classical-bit counterparts. In other words a single qubit can be described by a linear combination of $|0\rangle$ and $|1\rangle$ given as

$$\Psi = \alpha\,|0\rangle + \beta\,|1\rangle \tag{1}$$

Where, α and β are probability amplitudes and can in general both be complex numbers with

$$\alpha^2 + \beta^2 = 1 \tag{2}$$

In two-dimensional complex vector space the state of the qubit can be generalized as a vector. The special states 0 and 1 are known as computational basis states, and form an orthonormal basis for this vector space, being

$$|0\rangle = (0, 1) \text{ and } |1\rangle = (1, 0)$$

One picture useful in thinking about the evolution of the qubit state is the following geometric representation of the pure state space of a two-level quantum mechanical system, named after the physicist Felix Bloch called Bloch sphere representation as shown in Fig. 6.

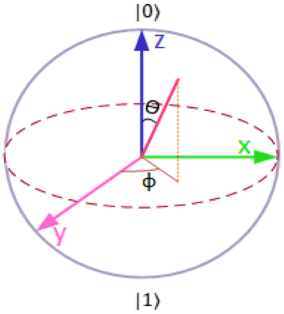

FIGURE 6. Bloch sphere representation of qubit.

B. REPRESENTATION OF QUBITS

In quantum mechanics states are often represented in Dirac notation [5], and by extension in quantum computing as well. Dirac notation is used due to the fact that it is miles more compact than the equivalent matrix representation. Vectors are communicated via "kets" in dirac representation, hence the given vector "a" might be stated as $|a\rangle$ and "bras" are used to express dual vectors, so the dual vector "b" could be stated as $|b\rangle$. Alternatively, matrix representation as expressed in (3) denotes the probability of the qubit to be in some particular state. Within the matrix, the topmost entry symbolizes the probability of collapsing to state 0, and the lower access within the matrix represents the possibility of collapsing to state 1.

$$0 = \begin{bmatrix} 1 \\ 0 \end{bmatrix};\ 1 = \begin{bmatrix} 0 \\ 1 \end{bmatrix} \tag{3}$$

Matrices representing bits 0 and 1

Eq. (4) depicts the overall state of a single qubit in matrix form and Dirac notation.

$$\begin{aligned} &|\Psi\rangle = \alpha_0\,|0\rangle + \alpha_1\,|1\rangle = \begin{bmatrix} \alpha_0 \\ \alpha_1 \end{bmatrix} \\ &|\alpha_0|^2 + |\alpha_1|^2 = 1 \end{aligned} \tag{4}$$

Where α_0 and α_1 are complex numbers and represent the probability amplitudes of state vectors that must add up to 1.

This overall structure can be stretched to n qubits too, and every prospect will lead to a complex entry, with the limit that all squared absolute values sum up to one. It is essential to bring up that these inseparable complex numbers turns to one among the two potential levels dependent totally of their chances to happen. It is important to point out here that the probability amplitudes of every single imaginable state are interconnected and while a qubit state is determined it will "collapse" to one of the potential states. In order to obtain more insight clarification of qubits with regards to processing the pursuer is alluded to [6].

As the number of qubits in a quantum system increases the matrix representation becomes cumbersome, for n number of qubits, there may be n^2 records within the matrix. As matrix is incomplete without all of its entries, subsequently big range of zero entries come into the picture. Benefit in Dirac notation is that zero entries can be left off making it a brief representation, however in matrix representation all of the entries are mandatory. Eq. (5) represents the abstract representation of two qubits.

$$|\Psi\rangle = \alpha_0\,|00\rangle + \alpha_1\,|01\rangle + \alpha_2\,|10\rangle + \alpha_3\,|11\rangle = \begin{bmatrix}\alpha_0\\ \alpha_1\\ \alpha_2\\ \alpha_3\end{bmatrix} \tag{5}$$

Two qubit representation in Dirac notation and matrix form is shown below

$$|00\rangle = \begin{bmatrix}1\\0\\0\\0\end{bmatrix};\ |01\rangle == \begin{bmatrix}0\\1\\0\\0\end{bmatrix};\ |10\rangle = \begin{bmatrix}0\\0\\1\\0\end{bmatrix};\ |11\rangle = \begin{bmatrix}0\\0\\0\\1\end{bmatrix}$$

Two qubits denoted in Dirac representation and matrix form.

C. THE TENSOR PRODUCT

In quantum information processing a single quantum state or qubit is mathematically expressed as a 2 × 1 column vector or column matrix. In order to express multiple-qubit systems mathematically, a special operation of matrices called tensor product is used. Tensor product is also called direct product or Kronecker product. Tensor product can be defined as: If M is p × q matrix and N is x × y matrix, then the tensor product (MN) is (px) × (qy) block matrix representing the multiple-qubit system state. This is not to be confused with matrix multiplication, which is the mathematical equivalent of applying a quantum gate to a quantum system. Let the matrices be defined as

$$M = \begin{bmatrix}a_{11} & a_{12}\\ a_{21} & a_{22}\end{bmatrix};\ N = \begin{bmatrix}b_{11} & b_{12}\\ b_{21} & b_{22}\end{bmatrix}$$

Then the tensor product of M and N can be computed as:

$$M \otimes N = \begin{bmatrix}a_{11}b_{11} & a_{11}b_{12} & a_{12}b_{11} & a_{12}b_{12}\\ a_{11}b_{21} & a_{11}b_{22} & a_{12}b_{21} & a_{12}b_{22}\\ a_{21}b_{11} & a_{21}b_{12} & a_{22}b_{11} & a_{22}b_{12}\\ a_{21}b_{21} & a_{21}b_{22} & a_{22}b_{21} & a_{22}b_{22}\end{bmatrix}$$

In the similar fashion tensor product of higher order matrices can be computed. The tensor product of following quantum states in dirac notation is equivalent to

$$\begin{gathered}|0\rangle \otimes |0\rangle = |00\rangle\\ |0\rangle \otimes |1\rangle = |01\rangle\\ |1\rangle \otimes |0\rangle = |10\rangle\\ |1\rangle \otimes |0\rangle = |11\rangle\end{gathered}$$

By rewriting each of the quantum state in matrix form, the tensor product can be performed as follows:

$$|0\rangle \otimes |0\rangle = \begin{bmatrix}1\\0\end{bmatrix} \otimes \begin{bmatrix}1\\0\end{bmatrix} = \begin{bmatrix}1\\0\\0\\0\end{bmatrix} = |00\rangle$$

$$|0\rangle \otimes |1\rangle = \begin{bmatrix}1\\0\end{bmatrix} \otimes \begin{bmatrix}0\\1\end{bmatrix} = \begin{bmatrix}0\\1\\0\\0\end{bmatrix} = |01\rangle$$

$$|1\rangle \otimes |0\rangle = \begin{bmatrix}0\\1\end{bmatrix} \otimes \begin{bmatrix}1\\0\end{bmatrix} = \begin{bmatrix}0\\0\\1\\0\end{bmatrix} = |10\rangle$$

$$|1\rangle \otimes |1\rangle = \begin{bmatrix}0\\1\end{bmatrix} \otimes \begin{bmatrix}0\\1\end{bmatrix} = \begin{bmatrix}0\\0\\0\\1\end{bmatrix} = |11\rangle$$

D. SUPERPOSITION AND ENTANGLEMENT

The ideas of superposition and entanglement are not practiced in our everyday lives. It is possibly observed when we take a glimpse at the smallest quantum particles – photons, atoms and electrons. Superposition is basically the capacity of a quantum system to be in various states simultaneously — that is, something may be "here" and "there," or "up" and "down" concurrently. This powerful property in quantum computers makes the possibility of achieving parallel computation in real sense. At the same time, each qubit represents two states. Thus, n qubits can represent 2^n states simultaneously. So it is possible to make a superposition of 2^n states as an input and process it in one go to solve the problem for which classical computer needs 2^n steps. Experimental introduction of superposition of unknown photonic quantum states is furnished. Entanglement on the other hand is amazingly solid connection that occurs among quantum particles — so solid, indeed, that at least two quantum particles can be inseparably connected in impeccable harmony, regardless of whether isolated by significant remoteness. This stuff was put forward by Albert Einstein in 1935. Particles are so characteristically associated, they can be said to "dance" in momentary, flawless harmony when set at farthest edges of the universe. This apparently outlandish association motivated Einstein to depict entanglement as "spooky action at a distance".

E. QUANTUM REVERSIBILITY AND QUANTUM GATES

In 1970s the concern of reversibility in computations was raised. Quantum computing depends on the crucial idea of reversible calculation. Reversible computation refers to the fact that input state can be recovered from the output state. There were two related issues, physical reversibility and logical reversibility, which were intimately connected. Physical reversibility refers to the process of erasing one of the inputs whose information has been irretrievably lost. Logical reversibility refers to the ability to reconstruct the input from the output. For instance, the NAND gate is explicitly irreversible, taking two inputs to one output, while the NOT gate is reversible. Reversible logic has the feature to generate one to one mapping between its input and output. As a result, no information is lost and there is no loss of energy. Quantum gates exhibit the property of reversibility. Hence using quantum computer, we can overcome the irreversibility nature of classical computation and avoid information loss.

In quantum circuit model of computation, a quantum gate is a basic quantum circuit operating on a small number of qubits. Quantum gates are the basic building blocks of quantum circuits. There are several common gates or we can say operations that need to be applied to qubits. The fundamental and essential single-qubit quantum gates are *H, X, Y, Z, T, I* and *Phase gate*. *CNOT*, *CZ* and *Swap gate* are fundamental two-qubit quantum gates while as three-qubit gates are *Toffoli* and *Fredkin*. Besides, the conventional logic gates such as NAND, NOR, OR, AND, XOR may be realized utilizing single-qubit and two-qubit quantum gates. These quantum logic gates are represented by unitary matrices, a gate which acts on n qubits is represented by $2^n \times 2^n$ unitary matrix. It needs to mention here that 2×2 matrices represent single qubit gate as shown below, while 4×4 matrices represent two-qubit gate. Several operations on qubits along with their corresponding matrix forms [7] are shown in Table 1.

$$|0\rangle \rightarrow A\,|0\rangle + B\,|1\rangle$$
$$|1\rangle \rightarrow C\,|0\rangle + D\,|1\rangle$$

In matrix form above operation can be written as

$$\begin{bmatrix} A & C \\ B & D \end{bmatrix}$$

The basic single-qubit quantum gates are rotations, defined as

$$R_{\hat{n}}(\theta) = \exp\left[-\frac{i\theta\hat{n}.\vec{\sigma}}{2}\right] \tag{6}$$

Where $\hat{n}$ is a three-dimensional vector specifying the axis of the rotation, θ is the angle of rotation, and $\vec{\sigma} = \sigma_x\hat{x} + \sigma_y\hat{y} + \sigma_z\hat{z}$ is a vector of well-known Pauli matrices σ_x, σ_y and σ_z defined by:

$$\sigma_x = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}; \sigma_y = \begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}; \sigma_z = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$$

Any other single-qubit transformation U can be realized using a sequence of rotations about just two axes, according to Bloch's theorem: for any single-qubit U, there exist real numbers α, β, γ and δ such that

$$U = e^{i\alpha} R_x(\beta) R_y(\gamma) R_z(\delta) \tag{7}$$

The fundamental quantum computing concepts are elaborated in [9], [10]. General rotation of a single qubit gates is represented by a pair of gates $V(\theta, \emptyset)$ and CNOT.

$$V(\theta, \emptyset) = \begin{bmatrix} \cos\left(\frac{\theta}{2}\right) & -ie^{-i\emptyset}\sin\left(\frac{\theta}{2}\right) \\ -ie^{i\emptyset}\sin\left(\frac{\theta}{2}\right) & \cos\left(\frac{\theta}{2}\right) \end{bmatrix} \tag{8}$$

Any $n \times n$ unitary matrix can be formed by composing 2-qubit XOR gates and single qubit rotations. Therefore, this pair of operations is universal for quantum computation.

Imperfect quantum gates affect quantum computation by introducing errors in computed data. Moreover, errors are introduced by imperfect control gates in a processed sequence since the wrong operations are applied. Thus, the use of quantum error correction coding (QECC) is necessary to enable fault-tolerant computing and to deal with quantum errors. The purpose of fault-tolerant design is to ensure the reliability of quantum computers given a threshold, by properly

TABLE 1. Common Single Qubit, Two Qubit and Three Qubit Gate Representation

Gate	Matrix Representation
H (Hadamard gate)	$\frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$
NOT (Pauli X gate)	$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$
Y (Pauli Y gate)	$\begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}$
Z (Pauli Z gate)	$\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$
T ($\frac{\pi}{8}$ phase gate)	$\begin{bmatrix} 1 & 0 \\ 1 & e^{i\frac{\pi}{4}} \end{bmatrix}$
Identity Gate	$\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$
Phase Gate	$\begin{bmatrix} 1 & 0 \\ 0 & i \end{bmatrix}$
CNOT (Controlled Not)	$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$
Swap Gate	$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$
Toffoli Gate	$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}$

implementing the fault-tolerant quantum gates. Dealing with the errors of the quantum gates for real-world implementations requiring optimal error-correction codes is as yet an open issue. QECC is also essential in quantum communication and quantum teleportation applications.

F. QUBIT INTERACTION AND MEASUREMENT

Interaction with qubits depends upon the physical realization of quantum computer. For example, in case of neutral atom realization: an electron can be either in ground state mapped to $|0\rangle$ or in energized state planned to $|1\rangle$. By lighting up atom, with suitable energy and for a suitable timeframe, it is conceivable to make the electron excitation from the ground state to excited state or the other way around. All the more strikingly, by decreasing illumination time, an electron at first in the state $|0\rangle$ can be moved somewhere between $|0\rangle$ and $|1\rangle$ which we call superposition state. Similarly, in case of spin-qubits, the qubits are first initialized via applying a huge static magnetic field of round one Tesla, say all spin-up (representing 0 state). To fetch the qubit into any conceivable state that can be visualized on Bloch sphere in Fig. 1, an electromagnetic pulse is fed to each qubit exclusively. The real qubit state relies upon the amplitude and time of the carried out electromagnetic pulse.

Measurement of qubit state is significant for the physical insight of the quantum processing. In quantum paradigm we don't have provision to make measurement at every point i.e continuous measurement is not possible. With every measurement, certain amount of uncertainty is associated. The physical framework ought to encourage the estimation of all the qubit states to acquire the quantum calculations output. Most significant issue are the readiness of quantum frameworks for the calculations, and the experimental cognizance of the estimations [8] that decodes important data from the quantum states.

III. PHYSICAL REALIZATIONS

Till date few attempts were made to design practical quantum computers but still we can say that implementation is at its early stage or we can say due to technical obstacles, it has not been realized yet. Since quantum computer could execute a multitude of parallel tasks exponentially faster than a classical one in certain applications such as prime factoring and quantum simulation [9]. In the past two decades, the research work on exploring quantum computers have attracted much attention and the conceptions and ideas of quantum computing have been illustrated using different methodologies. In 2000, David DiVincenzo (at IBM), articulated five fundamental requirements for any qubit technology to be a suitable physical implementation and added two conditions related to the communication of quantum information [10].

Requirements for the physical implementation of quantum computation:

- Scalable physical system of well-defined Qubits.
- Preparation of simple, initial, fiducial input state.
- Measurement of qubit state.
- Perform universal gate operations with high fidelity.
- Long coherence times.

Requirements for handling quantum information:

- Interconvert stationary and flying qubits.
- Faithful transmission of qubits between two locations.

Tremendous progress has been made with various systems such as ionic, photonic, linear optics superconducting, quantum dots, solid-state, and nuclear spins, etc. Here, we discuss four of the most important technologies that have been used to demonstrate quantum computing. They are

1. Ion Traps based quantum computing.
2. Superconducting quantum computing.
3. Nuclear Magnetic Resonance (NMR) based quantum computing.
4. Spin transfer torque-based quantum computing.
5. Semiconductor Spin based quantum computing.

A. ION TRAPS BASED QUANTUM COMPUTING

Trapped ions are one among the most promising proposed approaches to realize quantum computers [11]. After the development of Shor's factoring algorithm showing that a quantum computer could effectively tackle helpful assignments that were traditionally obstinate, Cirac and Zoller recommended a usage of such a gadget utilizing individual ionic particles. Trapped ion quantum computer works on the principle that ions can be restricted and suspended in free space utilizing electromagnetic fields. In this scheme, qubits are represented by means of ions restrained in radio frequency (RF) traps, and motional modes of shared ions accomplish the entanglement. Leading benefit of ion traps for quantum computing is the candid method of confining specific ions for lengthy durations of interval. In three-dimensional structuring it is not possible to trap charged entities with the help of static fields alone, localization is only promising either there should be a time reliant electric field or a combination of both static electric and magnetic fields. This is done in order to create effective average potential so as to confine ions [12]. Since 1980, RF Paul traps are utilized to restrict sole ionic particles and had all the earmarks of being a promising stage because of the particle's long inner state rationality, robust trap lifetimes, tough inter ionic interactions and quick validation of interaction between ion's internal states [13], and later multi-ion entangled states were exhibited. From that point forward, trapped charged particles have stayed one of the primary innovation stages for large-scale quantum processing. A few amazing survey papers exist which deal with diverse elements of trapped ion science in detail [14], [15]. As of now, most elevated precision has been found in trapped ion frameworks. Utilizing trapped ions, single-qubit gates realization [16], two-qubit gates realization [17] and preparation of qubit initial state and readout all have been accomplished with fidelity surpassing that prerequisite for fault-tolerant quantum computing. Additional benefit from trapped ions is that every ion from a particular species or isotope are undistinguishable. Accordingly, the laser or microwave frequency necessary to deal with every ion in the system may be same and every particle could have the identical coherence time. Expansions to Cirac and Zoller approach depend on optical spin reliant powers that are free from distinct optical addressing and preparation of ionic movement into a pure quantum state.

However, regardless of the guarantee revealed by iron traps, there are many demanding situations that have to be addressed with the intention to realize valuable quantum machine. Foremost challenge is expanding the number of simultaneously working trapped ions while preserving their individual controlling ability and measurement with high fidelity. Effective disadvantage of trapped ion systems is requirement of cryogenic environment. The recent progress in QC with trapped ions can be studied in detail [15]. As of 2018, the most extreme number of ionic particles to be entangled and controlled are 20. In 2021, researchers from the University of Innsbruck demonstrated a quantum computing demonstrator that fits within two 19-inch server racks, the world's first small trapped ion quantum computer that meets quality standards [18].

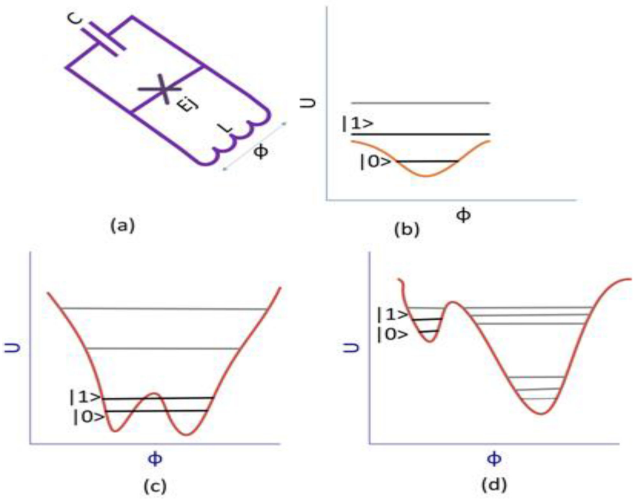

FIGURE 7. **(a) Nominal circuit model of superconducting qubit. b–d, Potential energy U(Φ) (mustard) and qubit energy levels (black) for charge (b), flux (c), and phase qubits (d), respectively.**

B. SUPERCONDUCTING QUANTUM COMPUTING

Superconductivity present a more advanced level of technological development than semiconductors hence is currently a potential candidate for the construction of qubits. Superconducting quantum computing rely on the fact to implement quantum computer in superconducting electronic circuits. Google, IBM, IMEC, BBN Technologies, Rigetti and Intel are the leading organizations conducting research in superconducting quantum computing. The first experimental demonstration of a superconductor qubit was attributed to NEC Corporation in 1999 [19]. Although with an extremely limited coherence time (1 ns), this experiment promoted to the development of superconductor-based devices in laboratories around the world. In 2019, Google's Sycamore claimed quantum advantage and recently in 2021 IBM built its Eagle quantum computer with 127 qubits [20]. To design a qubit in superconducting domain, the ability of the quantum factors of Cooper-pair condensate might be modified by adjusting visibly characterized capacitances (C), inductances (L) etc. So as to accomplish the total quantum control, the potential might be powerfully changed by electrical signals. Added advantage seems that these implementations consequently match with traditional classical integrated circuits and can be comfortably fabricated utilizing existing hardware technology. In superconducting QC Josephson junctions are favorable because, being nonlinear, it is the fundamental circuit element that is needed for the appearance of usable qubit states. In contrast, linear circuit elements such as capacitors and inductors can form low-dissipation superconducting resonators, but are unusable for qubits because the energy-level spacings are degenerate. A Josephson junction is a shrill insulating layer splitting segments of a superconductor. The nonlinearity of the Josephson inductance breaks the degeneracy of the energy level spacings, allowing dynamics of the system to be restricted to only the two qubit states. Initial success of several types of Josephson qubits can be studied from given references [21].

Quantum harmonic oscillator is provided by ordinary LC resonator with charge Q and magnetic flux Φ across the capacitor and inductor respectively. The operative commutator between the two is $[\Phi,\ Q] = i\hbar$, and consequently Q and Φ are correspondingly equivalent to the momentum and position of a single quantum element. The 'potential' energy $\Phi^2/2L$ and the 'kinetic' energy $Q^2/2C$, are two fundamental parameters required to determine dynamics of a system, resulting in the quantization of harmonic oscillator with well-defined equidistant levels. Still, anharmonicity is required that is provided by Josephson junction. Cosine term to the parabola with amplitude defined by Josephson energy E_J, proportional to critical current of the junction is introduced in the potential energy profile of the quantized charged junction. In the resulting anharmonic potential, two of the quantized levels give rise to a qubit.

Fig. 7(a) shows the nominal circuit model of superconducting qubit with X representing Josephson junction. Superconducting qubits are of three basic types: charge, flux and phase qubits with potential profiles (potential U vs magnetic flux (Φ) shown in Fig. 7(b)–(d). A qubit type is identified by the ratio E_J/E_C, where single electron charging energy is given by $E_C = e^2/2C$. This is the ratio that modifies the fluctuations in charge and flux, resulting in change in wave functions.

C. NUCLEAR MAGNETIC RESONANCE-BASED QUANTUM COMPUTING

Nuclear magnetic resonance (NMR) first observed by Bloch and Purcell in 1946 [22], is a method of physical observation in which nuclei in a strong constant magnetic field are perturbed by a weak oscillating magnetic field and respond by producing an electromagnetic signal with a frequency characteristic of the magnetic field at the nucleus [23]. In 1996, few methods were proposed for building small quantum computers using these nuclear spins in conjunction with existing magnetic resonance technology. Another side of NMR computing is liquid-state NMR, first introduced autonomously by Cory *et al.* and Gershenfeld *et al.* [24]. In 1998, Chuang, Cory and Laflamme offered NMR as a device for quantum information processing [25]. In [24] author proposed NMR based quantum computer. Most recent improvements in quantum processing technology drops the supposition that the quantum medium must be minute and insulated from its environment, rather it is possible to use large number of molecules to store the data, each nucleus acts as separate entity in a system. The quantum processor proposed in [24] is a molecule containing ten atoms acting as backbone, with other atoms such as hydrogen attached so as to use up all the chemical bonds. Each interesting entity nuclei has a magnetic moment associated with the nuclear spin, and the spin states provide the qubits. Strong magnetic field is applied to the molecule, and the spin states of the nuclei are manipulated by applying oscillating magnetic fields in pulses of controlled duration. The important role played by the parameter in nuclear resonance is called Larmor frequency. Larmor frequency is the frequency through which nuclear spins can be identified when immersed in a strong magnetic field. Tracking the shielding effect of electrons separately in each bond within a molecule, nuclear Larmor frequency varies from atom to atom. Nuclei are exposed to radio frequency pulses which are resonating in nature, that help in initiating operation of nuclei of different frequencies, resulting in single-qubit gates. Indirect coupling mediated through molecular electrons give rise to two-qubit interactions.

In NMR platform, advancements on quantum implementation techniques have been achieved recently [26], and it has been found that proposed techniques not only promise about carrying out quantum information processing tasks using NMR spectrometer, but also offering gateway for other quantum systems. In order to remove systematic errors produced by imperfection (amplitudes and frequency offsets) in radio frequency pulses, Chuang *et al.* proposed composite pulses techniques in NMR [27]. Liquid state NMR owing to accurate radio-frequency pulses and long decoherence time, often seems as an outstanding stage for quantum simulation. Liquid-state NMR has permitted the operation of quantum processors with up to a dozen qubits along with the realization of Quantum error correction protocols and algorithms [28]. In 2021, SpinQ Gemini a commercial NMR based two qubit desktop quantum computer was manufactured by SpinQ technology [29]. Interesting fellows can move to the following literatures for further insight: Suter and Mahesh (2008), Levitt (2018) for the basics of NMR [30] and Wiseman and Milburn (2010) [31].

D. SPIN TRANSFER TORQUE-BASED QUANTUM COMPUTING

As far as the physical realization of qubits is concerned spin is envisioned as the promising candidate [32]. Spin-a fundamental property like charge or mass, is associated with subatomic particles like protons, electrons and neutrons. From last thirty years there has been gigantic advancement in the field of spintronics boosted by the disclosure of some uncommon new wonders which have made it conceivable to create and recognize valuable degrees of spin potentials and non-equilibrium spin currents. These discoveries have found applications in memory devices [33] and countless recommendations have been sent trying to employ them for traditional and neuromorphic computing applications [34]. The most effective approach to genuinely realize quantum computing is spintronics because of the electron spin analogous to the qubit [35]. A number of promising quantum computing architectures have been forwarded for the physical realization of the quantum computers. Among them spintronics-based computing designs like quantum dot (QD) architecture, nuclear magnetic resonance quantum computer (NMRQC) and nuclear quantum computer have shown encouraging prospects. However, these architectures exhibit development issues. In case of NMR quantum computing, meager scaling of signal to noise ratio was recognized and in case of QDs, precise control and manipulation of individual electrons is very difficult. Spin decoherence, interaction inability at longer distances, spin measurement complexities, and architecture scaling limitation are some other important issues. In order to avoid these problems, several models were proposed such as static and mobile spins interaction in graphene [36], static and flying qubits interaction in a carbon nanotube [37], static and flying qubit entanglement in degenerate mesoscopic systems [38] and solid-state flying qubit's electrical control [39].

In [40], computational space has been encoded into the spin properties of scattering particles and their collision intercommunication has been harnessed to process quantum computing assignments. In this procedure at least two particles are arranged in order to experience scattering and towards the end are eventually measured. In gated quantum information processing, during the realization of one-qubit and two-qubit operations complete control is assumed throughout interaction times. An extraordinary characteristic of scattering-based techniques is that any action is accomplished without any interaction-time throughout tuning. Implementation of two-qubit quantum gate has been proposed in [40] utilizing scattering procedure related to static and flying qubit. Typical arrangement engaged from free particles and a quantum impurity has been focused, where spin degrees couple to one another in the course of scattering practice. In terms of spin-dependent transmission coefficients, a condition has been derived for the prevalence of quantum logic gates and it has been indicated this can be really satisfied through the inclusion of an extra thin potential barrier. Parameter regime existence has been also discussed through

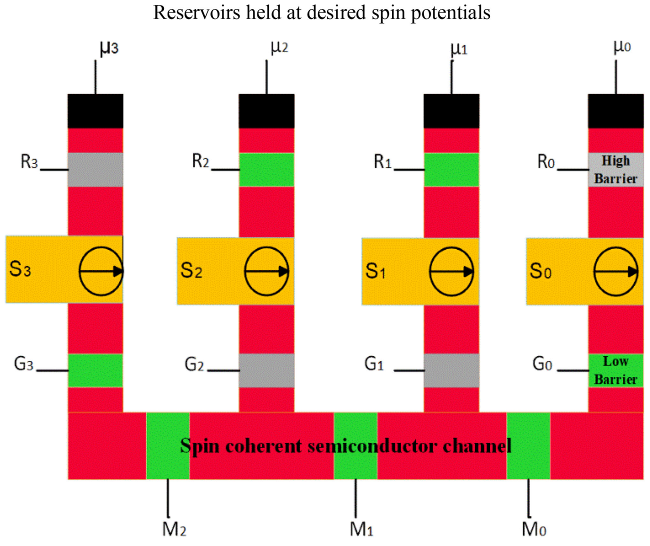

FIGURE 8. Schematic view of architecture with qubits S1 and S2 aligned for single- qubit operations and qubits S0 and S3 for two-qubit operations.

which implementation of gates feasible to establish maximum entanglement is possible. The scheme proposed in [40] has unlocked scaling opportunities for the implementation of spin-based quantum processing in solid-state frameworks.

The phenomena helpful in achieving the goals of robust quantum computing is called spin transfer torque (STT) [41]. Spin is the intrinsic property of charge carriers which is actually a small quantity of angular momentum associated with the particle. Generally electric current is unpolarized (with 50% spin-up and 50% spin-down electrons), a current with more electrons of either spin is called a spin polarized current. Thus, STT [42] is an effect in which the orientation of a magnetic layer in a spin value or magnetic tunnel junction (MTJ) can be changed with a spin polarized current. Employing transmission coefficients matrix modelling technique, a spin-torque based architecture has appeared as novel platform for the realization of single qubit rotations and two qubit entanglement [43] proposed by Brian *et al.* Spin torque has been utilized as an alternative for magnetic fields and has been settled for classical operations as well like nano-magnet switching. It has been revealed "spin torque" alike phenomenon could be utilized to execute quantum processes comprising initialization, rotation and entanglement of qubits. Utilizing ensemble-measurement, qubit readout can be employed via the same architecture given in [43]. Alternatively, the technique might be applied in unification with recognized single shot readout strategies [44], particularly for explicit claims needful of Bell state tests or multi-qubit state tomography.

The architecture employing four localized spins for illustrative purposes has been proposed by Brian *et al.* as shown in Fig. 8. A vital aspect of the plan is the utilization of a massive quantity of itinerant electrons to create the favored qubit operations on static spins. Cumulative interactions involved here are in entangled states and on measurement wave functions collapse ensuring unitary operations. Extra qubits in addition to several descriptions of the same qubit can be included to achieve complete implementation to allow ensemble readout. Spin-coherent semiconductor channel is used to install qubits so as to provide a way for conduction band itinerant or "flying" (f) spins to have an interaction with the static qubits (S_i) positioned at x_i via an interaction of the form

$$\mathcal{H} = J\vec{\sigma}.\overrightarrow{S_i}\,\delta\left(x - x_i\right) \tag{9}$$

Static qubit might be electronic donor spin with exchange interaction J, or a semiconductor embedded with nanoscale magnet, or a neutral-charge nuclear spin like ^{29}Si where J will signify hyperfine interaction instead of exchange interaction and $\vec{\sigma}$ is the flying spin population.

Semiconducting channel is fabricated using materials supporting coherent spin injection and transport [45] or can be realized using silicon [46]. Gates $\mathrm{M_i}$ are inserted in the channel that could be realized using connections that are able to modulate the electrostatics of the channel [47]. Each qubit is in contact with two barriers, G_i and R_i, that are used to deplete the channel beneath by forcing the barrier to be high or low depending upon the particular operation. For any desired specific operation these barriers act as coupling and decoupling elements for qubits from the itinerant spins. Itinerant spins are generated by using various spintronic phenomena such as giant Spin Hall Effect, spin pumping, or magnetic contacts. These can be attached to spin reservoirs seized at definite spin potentials [48] alongside the x, y or z directions in any desired manner. Due to the small size of the nucleus, there is low probability of interaction between static nuclear spin and general itinerant electron. In order to have effective interaction standing waves are produced for itinerant electrons by using gates, G_i and R_i. To achieve the coupled interaction, these standing waves provide the meaningful wave function overlap [49]. In this architecture it has been shown that with proper design tolerable limit can be kept low for the non-unitary component of the operations. In addition, CNOT gate have been implemented with fidelity close to one assuming ideal conditions.

The analytical and matrix methods for the qubit operations presented by Brian *et al.* [43] lack the generalized approach to trace the computing performance in a n-qubit architecture. Besides, the ratio between reflection barrier height and the hyperfine/exchange interaction (Γ_{Rfl}/J) on quantum processes have not been considered. Moreover, quantum information is bound to be collapsed, if the quantum states are measured during the quantum operations. To eliminate the issues faced, an improved transmission coefficient matrix is proposed by Kulkarni *et al.* [50], [51] to incorporate the impact of (Γ_{Rfl}/J) on a single qubit and two-qubit operations. Moreover, generalized fully specified matrix (GFSM) method model has been developed to obtain the performance in n-qubit system. Besides, the performance assessment due to (Γ_{Rfl}/J) has been estimated for the fault-tolerant quantum computation.

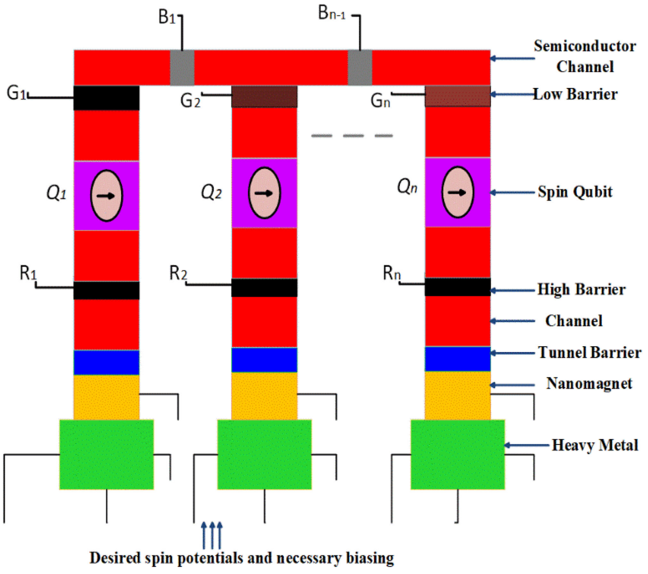

FIGURE 9. Schematic of Spin-Torque based quantum computing Architecture.

The n-qubit architecture proposed by Kulkarni *et al.* [50] is shown schematically in Fig. 9. The qubits are embedded in the non-magnetic Si or graphene-based semiconductor channel with static qubits and flying spin polarized electrons. The spin diffusion lengths of graphene and silicon are 5 μm and 200 nm respectively. Therefore, use of graphene is better choice for increasing efficiency. Spin qubits isolation, initialization and manipulation is controlled by barriers which are positioned on either side of the qubit. For any desired specific operation these barriers help in coupling and decoupling the qubits from the itinerant spins. With desired spin polarization, electrons are injected into the channel utilizing hall metal nanomagnet assembly. Heavy metals like β-W, β-Ta, Pt, or CuBi alloys are favored for generating spin owing to their capability of causing huge spin current. Biasing circuitry along with switches are used in spin generation and for nonlocal spin injection [52]. Nanomagnets prepared of Heusler alloys having approximately 100% spin polarization [53] are used for spin injection.

The design comprises of n static spin qubits $Q_1, Q_2, \ldots, Q_n$ and barrier gates G_1-G_n, R_1-R_n, and B_1-B_n. The duos of R-G hindrances separate or permit a qubit to get involved in an allowed quantum operation. The design executes the essential single qubit rotation or two qubit operation to comprehend the reversible quantum gates.

Mathematically, in n-qubit design, spin polarization of the infused electrons for single qubit operation is characterized by spin density matrix as communicated in (10))

$$\rho_e = \frac{1}{2}[I + \sigma_x\hat{x} + \sigma_y\hat{y} + \sigma_z\hat{z}] \tag{10}$$

where, I represents identity matrix and σ_x, σ_y, σ_z are Pauli spin matrices.

The interactions between injected spins and static (Si) qubits positioned at $\mathrm{x_0}$ can be thought of the form

$$\mathrm{H} = \frac{\mathrm{p}^2}{2\mathrm{m}^*} + \mathrm{J}\rho_\mathrm{e}.\tilde{\mathrm{S}}_\mathrm{I}\delta\,(\mathrm{x}) + \Gamma_{\mathrm{Rfl}}\delta\,(\mathrm{x} - \mathrm{x_0}) \tag{11}$$

where, H is the Hamiltonian for the interaction, m^* and p represents the effective mass and momentum operator of electron, J is the exchange/hyperfine interaction, $\mathrm{x} - \mathrm{x_0}$ denotes the interaction distance, and $\tilde{\mathrm{S}}_\mathrm{I}$ represents the standard basis matrix of $\mathrm{i^{th}}$ qubit.

For n-qubit system, general spin density matrix is given as

$$\rho_s = \rho_{Q_1} \otimes \rho_{Q_2} \otimes \rho_{Q_3} \otimes \rho_{Q_4} \ldots\ldots\ldots\ldots\ldots \otimes \rho_{Q_n} \tag{12}$$

where, $\rho_{Q_1}, \rho_{Q_2}, \rho_{Q_3}, \rho_{Q_4}, \ldots$ ….. and ρ_{Q_n} are the spin density matrices of $Q_1, Q_2, Q_3, Q_4, \ldots$ …. and Q_n respectively.

For complete mathematical solution see [50], [51]. The general completely specified spin density matrix expressing the state evolution of spin qubits because of the interplay among injected electron spins (ρ_e) and spin qubit (ρ_s) is

$$\rho = [R_F]\,[\rho_e \otimes \rho_s]\left[R_F^\dagger\right] \tag{13}$$

Where R_F represents generalized reflection matrix.

Rotation associated with each qubit and measurement of spin qubit state can be apprehended by GFSM and partial trace methods respectively. In the similar fashion two-qubit entanglement and measurement can be realized.

E. SEMICONDUCTOR SPIN QUBITS

Qubits in semiconductors were first technologically advanced in group III-V semiconductor materials, such as GaAs [54]. However, academic research teams have recently produced a variety of spin qubits in silicon with greater spin coherence time, up to more than a few milliseconds [55]. The most frequently used material as semiconductor is silicon and is second most abundant material available on earth. Apart from its remarkable qualities as suitable candidate to host qubits, silicon also offers the advantage of low cost material and added advantage of requiring only minor changes to existing fabrication facilities. The advancement in fabrication technology has made it possible to purify silicon isotopically so as to decrease the effect of nuclear spin on electron spin. The quantum state of a qubit can be decohered by nuclear spins in the parent material. There are two possible ways through which qubits can be employed in silicon semiconductor. One way is to use spins of electrons in quantum dots and another way is to employ electron spin or nuclear spin of dopant atoms embedded in the silicon substrate. The first qubits in silicon were proposed by the University of New South Wales in Sydney [56] followed by CMOS compatible qubit in SOI technology by CEA-Leti in France [57], [58]. A number of research organizations are interested in semiconductor based quantum computing. Recently Hughes Research Laboratory in the US and a Belgian Nano-electronics Centre IMEC has established respective research lines focused on silicon-based quantum computing. Qubits are operated at millikelvin temperatures in order to overcome the effect produced by phonon-assisted excitons and thermal enegy disturbances. Researchers are working to attain room temperature functionality of qubit, recently it was shown that spin qubits can remain functional above 1 kelvin [59], [60]. The primary idea behind the semiconductor physical realization of qubits is that the orientation of spin is used to encode $|0\rangle$ and $|1\rangle$ states. These systems are fabricated with conventional CMOS techniques. Gate-controlled electrodes are employed in CMOS design having the ability to control the silicon substrate's energy landscape. Electron or hole spins are confined and manipulated by fast and slow gate voltages. These electrodes are designed and positioned in such a way that single electron is confined at the interface within the quantum dot. A strong confinement of electron is achieved so that the lowest orbital energy in quantum dot or in single dopant donar atom based silicon substrate is well isolated from other higher excited electronic energy levels. For electron confined in quantum dot, the confinement length is approximately 2 nm and 10 nm in vertical and horizontal directions respectively, whereas for the donar electron this length is 1.5 nm approximately in all the three dimensions [61].

To address silicon spin qubits, a static magnetic field is applied at the interface of dot electron so as to split its orbital degeneracy. Now the energy levels of spin-up $|\uparrow\rangle$ and spin-down $|\downarrow\rangle$ are no longer degenerate and are split by the so called Zeeman effect. The spin states of an unpaired electron confined in a quantum dot form a two level system that is used as qubit. These spin states characterize the computational states $|0\rangle$ and $|1\rangle$. The energy splitting is determined by Zeeman energy $\gamma_e B$, where γ_e is gyromagnetic ratio and B is applied static magnetic field. In case of P^{31} donar electron based qubit system nuclear spin and electron spin are interacted by the hyperfine interaction denoted by A. A large magnetic field B $>$ 1 Tesla is employed for operating the donor qubits such that $(\gamma_e + \gamma_n)B > A$, where γ_n represents the gyromagnetic ratio of the nucleus. In donar semiconductor qubits, the eigen spin states are the tensor products of nuclear spin states and electron spin states. Fig. 10 shows the resultant energies, which indicate how the electron spin qubit splitting is effected by nuclear spin states and vice versa. The electron gyromagnetic ratio and the hyperfine interaction both are dependent on electron's wavefunction, which can be easily tuned by electric fields. Thus, after the silicon qubit devices are fabricated, the qubit splittings are electrically programmable [62]. To manipulate this type of qubit a time varying magnetic field perpendicular to static magnetic field is applied to achieve single qubit rotations. The qubits are subjected to an oscillating magnetic field for spin control. The oscillating field's frequency is selected to be the same as the energy difference between the two spin qubit levels. Transitions between the spin states are then achieved at a rate proportionate to the amplitude of the driving field, governed by the magnetic resonance principles. To create a single qubit gate, the driving field is pulsed correctly to obtain a desired rotation of the spin state.

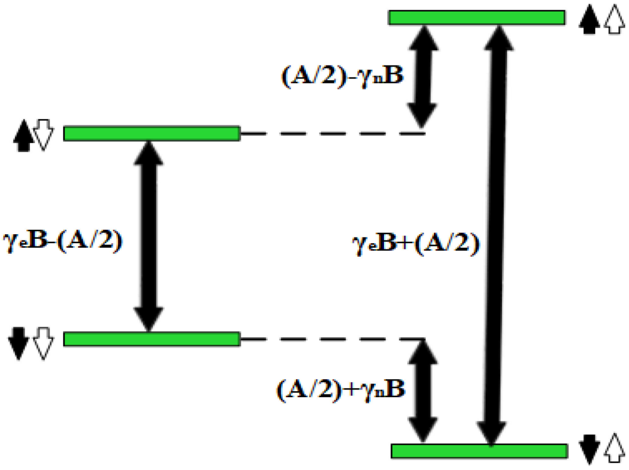

FIGURE 10. Nuclear and electron spin states in P donar.

Spin to charge conversion techniques are extensively used to initialize and measure electron spin qubits [63]. A number of charge sensing devices such as single-electron transistors and quantum point contacts are capacitively connected to the quantum dot (or donor) and are positioned adjacent to it. Gate voltage biasing of charge sensors is done in such a way that the current through them is highly sensitive to the electrostatic vicinity around them. The electron's orbital energy is then electronically adjusted so that, relying on its spin, it can favorably tunnel to the same or neighbouring charge reservoir. A change in current through the charge sensing device detects the absence or presence of the electron in the quantum dot or donar, through which electron spin state can be readout. Same technique with same process is used for initializing the electron spin state in both the platforms.

A comparison has been carried out of various quantum computing technologies in Table 2. There are many ways of implementing qubits and the list below is a selection of the most known rather than an attempt to be exhaustive. We have aimed to distill this into a digestible summary, based on a review of existing sources.

IV. APPLICATIONS OF QUANTUM COMPUTING

Quantum computers are not just faster, smaller versions of today's computers, instead, they represent a fundamentally new paradigm for processing information. In this section, an overview of our in-depth studies of few potential applications areas: quantum cryptography and teleportation, quantum algorithms and quantum supremacy, quantum simulation and quantum chemistry has been presented. Further technical details can be found in the publications referenced in each section.

A. QUANTUM CRYPTOGRAPHY AND QUANTUM TELEPORTATION

Cryptography is defined as art of writing and solving codes. Conventional cryptography is based on algorithms and

TABLE 2. Summary of Qubit Implementations

Qubit Technology	Description	Qubit Life Time	Gate Fidelity	Scalability	Key Challenges
Superconducting Qubits	Two level system of a superconducting circuit which forms a qubit.	50-100 us	99.4%	Moderate	Low Longevity, Low operating temperature, Non-uniform qubit splitting, Fabrication issues, Low coupling rate.
Ion Trap Qubits	Single charged ions trapped in magnetic fields. Energy level of its spin comprises the qubit.	>1000 s	99.9%	Moderate Scalable	Slow operating speed, Relatively brief lifetimes of the phonan states, Difficult initialization and read out of ion's motional states and Moderate scalability.
Nuclear Magnetic Resonance Qubits	Uses the spin states of nuclei within molecules as qubits.	Similar to ion trap	95%	Moderate	Poor scaling of signal to noise ratio, Weak quantum entanglement, Scalability issue
Spin Transfer Torque based Quantum Computing	Charge neutral-nuclear spin or electronic donar spin	1-10 s	99%	Expect High Scalability	Weak Spin orbit coupling, Long spin relaxation times, more power dissipation and more decoherence time.
Semiconductor Spin Qubits	Artificial atoms made by adding an electron to a small piece of pure silicon and electrons state is controlled by microwaves	1-10 s	99%	High Scalability	Development of high fidelity two qubit gates, poor qubit uniformity and background disorder, Short range exchange interaction and donar placement inaccuracy.

mathematical problems. If someone finds an efficient way to crack the algorithm, the information is no longer secure. Here is where the beauty of entanglement lies. Utilizing the method of quantum key distribution, a random secret key is established for cryptography [64]. Any attempt of manipulating will alter the state and can be detected making the communication secure without complex procedures and algorithms [65]. Although, it is very difficult to have realization of this process but cleverly designed systems are used to generate entangled photos such that one can be stored in the memory and other can travel through the fiber [66] ensuring the way for miracle process.

Teleportation involves the transferring of quantum state of a particle to another particle over a distance i.e transmission of quantum information [67]. It is possible only due to the entanglement property of quantum particles. Quantum teleportation can serve as an elementary operation in quantum computers and basic ingredient in distributed quantum networks. First it was demonstrated as a transfer of quantum state of light onto another light beam [68] later developments used optical rays [69] and material particles [70]

B. QUANTUM ALGORITHM AND QUANTUM SUPREMACY

Quantum algorithm is actually a sequence of unitary operations to manipulate initially organized quantum state to attain favored quantum state upon measurement. Simulation of quantum systems, cryptography, solving large systems of linear equations, and search and optimization are the basic areas in which quantum algorithms can be applied [71]. If quantum algorithm is simulated effectively on classical machine, it is not essential that it is going to offer a computational gain. The advantage of quantum computers is primarily dependent on complexity of the algorithm rather than systems ability to carry out rapid operations. The two most important algorithms are Shor's algorithm [72] and Grover's algorithm [73]. Peter Shor in 1994 discovered an efficient algorithm for factoring whole numbers using quantum effects. As there is no known efficient classical method for solving this problem, thus Shor's algorithm illustrates the potential power of quantum computation. Shor's algorithm performs function exponentially faster than its classical equivalent. Experiments are performed and discussed to contribute in its practical implementation [74]. Grover's algorithm functions as the searching of unorganized data. How fast can the basic identification problem be solved? It is generally assumed that this limit is O(N) since there are N items to be examined and a classical algorithm will clearly take O(N) steps. However, quantum systems exhibiting the property of superposition can simultaneously be in multiple states and carry out multiple tasks at a time using phenomenon of quantum parallelism. Grover's paper presents an $O(\sqrt{N})$ step algorithm that runs quadratically faster than its classical counterpart for the searching problem.

Quantum supremacy refers to quantum computers being able to solve a problem that a classical computer cannot. Google used a 53-qubit processor to generate a sequence of millions of numbers which confirmed the validity of particular algorithm [75]. Quantum supremacy assures that nature is fundamentally quantum. It means that nature operates in concrete ways that cannot be simulated by non-quantum models.

Sycamore a Google's quantum computer claimed 'supremacy' because it did the task in 200 seconds that would have been done by super computer in 10,000 years. The concept of Quantum supremacy has been overstated in asserting that quantum computers will far out-perform digital computers, but there is general agreement that realistically quantum computers can out-perform their digital counterparts.

C. SIMULATION OF QUANTUM SYSTEMS

On daily basis, about one million CPU hours are spent worldwide on calculating properties of materials with the aim of identifying new materials that meet specific requirements. In many relevant regimes, powerful classical simulation methods are able to predict properties of quantum many-body systems. If strong correlations are considered, such tools necessarily reach their limit. Even the most powerful classical simulation methods are being seriously challenged. It was in 1982 when Richard Feynman had the seminal idea how to overcome this bottleneck by studying the likelihood of simulating one quantum system by another [3], since then quantum simulation is one of the most important aims of quantum computation. The concept of quantum simulations rests on the idea to use a well controllable quantum system to simulate another system, whose description is beyond our technology. Last few years have witnessed effective results in the development of quantum computation, and it has been found that quantum computers can handle the problems with a level of efficiency much higher than that of classical computers [76]. Quantum computers still need lots of development so as to compete with conventional computers in drug development, chemistry and material science, but they are making progress. Quantum simulation has been realized in various situations, such as system evolution with a many-body interaction Hamiltonian, quantum phase transitions, the dynamics of entanglement, molecular property calculations [77] and many other simulations of the dynamics of quantum systems.

D. QUANTUM CHEMISTRY

The progress and use of quantum computers for natural and chemical applications has the prospective for revolutionary influence on the approach computing is done in the forthcoming. It has been analyzed that challenging opportunities are abundant. One of the key examples is mounting and employing quantum algorithms for answering chemical problems thought to be obstinate for classical computers. Other challenges take in the role of coherence, entanglement, and superposition in complex chemical reactions and photosynthesis. For decades, theoretical chemists have evaluated and examined these quantum effects employing the principles of physical chemistry. Therefore, linking outcomes and visions from the chemical physics community with those of the quantum info community might clue to a fresh understanding of vital chemical processes. One more application lies in quantum-classical combined algorithms with short-profundity quantum circuits for quantum chemistry. One of the most important quantum computing algorithms is Variational Quantum Eigensolver (VQE) [78], appropriate for tackling certain classes of issues utilizing quantum computers reachable in the near future. VQE might be utilized for issues including demonstrating nature, including chemistry as physicists predicted the world to do. VQE is additionally extraordinary at finding nearly ideal arrangements and combinations of things, for instance finding the efficient course for visiting a rundown of urban communities. This is popularly known as the Traveling Salesman Problem, and mathematicians term such difficulties combinatorial improvement issues. The variational quantum eigensolver (VQE) has been actualized on various distinctive quantum equipment stages [79]. Here the focal goal is to attain a decent gauge of the lowest energy state for a chemical science, or general many-body Hamiltonian.

Normally fermionic Hamiltonians are reflected. Using typical methods these Hamiltonians can be promptly planned to qubit/spin degrees of freedom. In order to acquire lowest energy state gauges for an objective Hamiltonian, variational preliminary states are set up on a quantum computer by utilizing superficial circuits with unrestricted boundaries having tentative flexibility. The quantum PC is utilized to assess the average energy of the objective Hamiltonian by estimating the Hamiltonian operators straight forwardly on the quantum computer regarding preliminary state. Energy linked with every preliminary state is served to a classical machine, running a streamlining schedule that provisions another arrangement of parameters. The objective of the developed method is to set up another preliminary express that will in general lower the energy. Continuous iteration of the process occurs until some convergence form is met.

V. CONCLUSION

In this paper, we reviewed the most dominant papers and exponential bearings on quantum computing technology. In view of above outcomes and conversation, the article provides a general picture for the advancement of quantum innovations, as well as detailed trends for quantum computing. Quantum research shows an exponential development in recent years. Global organizations, for example, IBM, Intel, Google, and Microsoft contend furiously for quantum figuring. United States, China and Germany are ending up being driving nations in quantum computing research. We recorded the structure squares of quantum computers, the latest examination results on the physical usage of quantum computers and possible applications. Various physical implementations and potential application areas of quantum computation have also been discussed in this paper. Recent developments in each realization, in the context of the DiVincenzo criteria, including ion traps based quantum computing, superconducting quantum computing, nuclear magnetic resonance, spintronics based quantum computing and semiconductor spin based quantum computing have been discussed. This paper fills the gap between elementary introductions to the subject and highly specialized research papers to allow beginning research scholars to understand the cutting-edge of research in the shortest possible time. The outcomes are encouraging, and the deduction of this paper is positive. Overall, quantum computing is poised at a profoundly captivating expression point. Advancement of quantum computers needs huge investment however uplifting news is that large scale enterprises and governments are making ventures for achievements in practical quantum computer implementation. Quantum information processing, by manipulating the ultimate nature of information opens new possibilities in computing, networking, and communications. Building a handy quantum computer is simply an issue of time. Quantum computers effectively solve applications that aren't possible with assistance of the present computers. This will be probably the greatest advance in science and will undoubtedly revolutionize the practical computing world. Quantum computing technology advances keep on holding gigantic potential for future computations and communication.

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