Journal of Physics: Conference Series **2809** (2024) 012028 doi:10.1088/1742-6596/2809/1/012028

Advances in Electron-Based Qubits: A Review

Zhuoqing Gao[1,2], Gehan Amaratunga[2*], Xiaozhi Wang[1,2*] and Boyang Ma[1,2]

[1] College of Information Science and Electronic Engineering, China
[2] International Joint Innovation Center, Zhejiang University, Haining 314400, China

*E-mail: gehan@intl.zju.edu.cn xw224@zju.edu.cn

Abstract. In the rapidly advancing domain of quantum computing, qubits based on electron properties are increasingly recognized for their capability to enhance quantum information processing and communications. This review offers a detailed examination of three main types of electron-based qubits: electron spin qubits, charge qubits, and hybrid qubits. Initially, the review outlines the essential principles underlying these qubits. Subsequently, it discusses recent developments in the field, focusing on enhancements in coherence times, logical gates, and system scalability. This article aims to provide both theoretical insights and practical recommendations for the development and refinement of quantum computing architectures.

1. Introduction

In recent decades, the development of quantum algorithms has made it possible to solve problems that are difficult to handle via classical methods. Fundamentally, quantum computers have the potential of surpassing classical computers in terms of database searching[1], quantum simulation[2], and optimization algorithms[3]. Analogous to classical computers, quantum computers, in order to perform calculations, need to represent the information to be processed in a suitable physical form in order to perform the calculations. Thus, qubits become the basic carriers of information in quantum computers, corresponding to bits in classical computers[4]. Many efforts have been made to investigate various platforms to realize quantum tasks[5], [6], [7]. Among them, electrons, with their multiple degrees of freedom[8], [9], [10] and ability to realize long coherence times[8], allowing for high-precision quantum control[11] and interaction modulation[12], are naturally suited for this quantum revolution. In this review article, the progress made with electron-based qubits will be reviewed. The article will be divided into two parts, the first one focusing on different implementation schemes of electrons as carriers of quantum information, and the second chapter describing the current state of the art of electron spin qubits, charge qubits, and hybrid qubits, and discussing their respective potentials and areas of application.

2. Fundamentals of electron-based qubits

A qubit is the basic information unit of a quantum computer. Unlike the classical bit, it cannot only be in the "0" and "1" states, but also in the superposition of these two states, thus forming a quantum two-energy system[13]. Quantum information can be encoded in various physical systems, such as photonic states[6], nuclear spin systems[7], ion trap systems[5], superconducting circuits[14], and so on. Among them, spins (both nuclear and electron spins) are natural qubit carriers because information can be encoded in the intrinsic degrees of freedom of elementary particles [15]. Moreover, spins are not directly affected by electric fields and are relatively weakly affected by charge noise caused by the environment. In addition, electron spins have excellent qubit properties, such as long coherence times, and efficient individualized controllability [16]. In addition to the spin degree of freedom, the charge degree of freedom of electrons can also be used to realize qubits, which can be operated by precise control of the charge state. The charge-spin hybrid qubit [17] is an all-electronic controlled, double quantum dot-based qubit that mixes the advantages of both high-speed processing capability and long coherence. In this chapter, theories related to electron spin qubits, charge qubits, and hybrid qubits will be introduced.

2.1 Electron spin qubit

Since the spin of an electron is its inherent two-energy system, the encoding of $|0\rangle$ and $|1\rangle$ can be accomplished by $|\uparrow\rangle$ and $|\downarrow\rangle$ [18]. The encoding of spin-state quantum information is common in many physical systems, and in this paper we focus on the realization of electron spin qubits in gate-defined quantum dots, donor atoms, and other physical systems. This chapter first describes the basic concepts of qubits for different physical systems and explains how their logical states are defined, and finally presents the corresponding initialization and readout methods.

Nanoscale semiconductor particles that are quantum confined in all three dimensions are called quantum dots [19]. Subject to quantum confinement, quantum dots have discrete energy levels and unique optical and electronic properties, which are similar to those of atoms [20], and thus quantum dots are also termed as artificial atoms. In gate-defined quantum dots, the number of free electrons, charge and spin states in the quantum dots, as well as the exchange interactions between the quantum dots, can be effectively manipulated by modulating the capacitively coupled split gate [20]. The structure of a quantum dot is similar to that of a semiconductor transistor, with a source, quantum dot, and drain configuration, which together form a region capable of holding numerous electrons. Under the influence of appropriate source-drain and electrode voltages, electrons are able to be transported through the tunneling effect between the source, the quantum dot, and the drain. The magnitude of the tunneling barrier between the quantum dot and the source/drain directly affects the tunneling speed of the electrons. An increase in the barrier causes the rate of electron transfer during tunneling to slow down, so that the electronic states within the quantum dot will be occupied one by one, under the control of the gate voltage to aligh unoccupied states in the quantum dot with tunnelling electron states, the Coulomb blockade effect [21].

Spin qubits based on gate-defined quantum dots are defined by the spin properties of the electrons in the quantum dot. In this case, in a single-electron spin qubit, i.e., a Loss-DiVincenzo qubit, the logical states are defined by the electron spin states $|0\rangle$ and $|1\rangle$. By applying an in-plane magnetic field, the electron spin undergoes Zeeman splitting, which results in two-energy states, each for a different direction of the electron spin. The control of these qubits can be achieved by magnetic resonance techniques [22] that utilize a static magnetic field to differentiate the energy levels of the spin states, while employing an oscillating magnetic field with a frequency close to the energy level difference of the qubits and a direction perpendicular to the static magnetic field to perform precise manipulation of the Bloch sphere. In addition, a magnetic field can be generated to drive the electrons within the quantum dots by means of applying an alternating current electric field with a frequency of ω[23]. A Qubit in a double

Journal of Physics: Conference Series **2809** (2024) 012028 doi:10.1088/1742-6596/2809/1/012028

quantum dot is defined by controlled singlet state splitting enabled by exchange interactions, to obtain singlet-triplet state qubits [11]. The logical state is defined by the superposition of the two-particle spin singlet and triplet states, i.e., $|0\rangle \equiv |S\rangle$, $|1\rangle \equiv |T_0\rangle$. Rotation of the quantum state of can be achieved by 1) changing the exchange coupling between the two electrons acting on energy detuning 2) applying a local magnetic field gradient.

Gate-defined quantum dots, one of the key candidates for qubits, have become a research topic of particular interest due to their energy state tunability, CMOS compatibility, and long coherence time [24]. Within the last few years, semiconductor quantum computing has become an increasingly important candidate for quantum computing devices due to its unique advantage of being able to use the technology available for classical electronic devices, and therefore potential for large-scale scaling and miniaturization [25].

In 1998, Daniel Loss and David DiVincenzo suggested that the spins of individual electrons in semiconductor quantum dots could form not only models but also real physical qubits [8]. In 2005, Petta succeeded in demonstrating the first experimentally coherent manipulation of electron spins in semiconductor qubits [11].

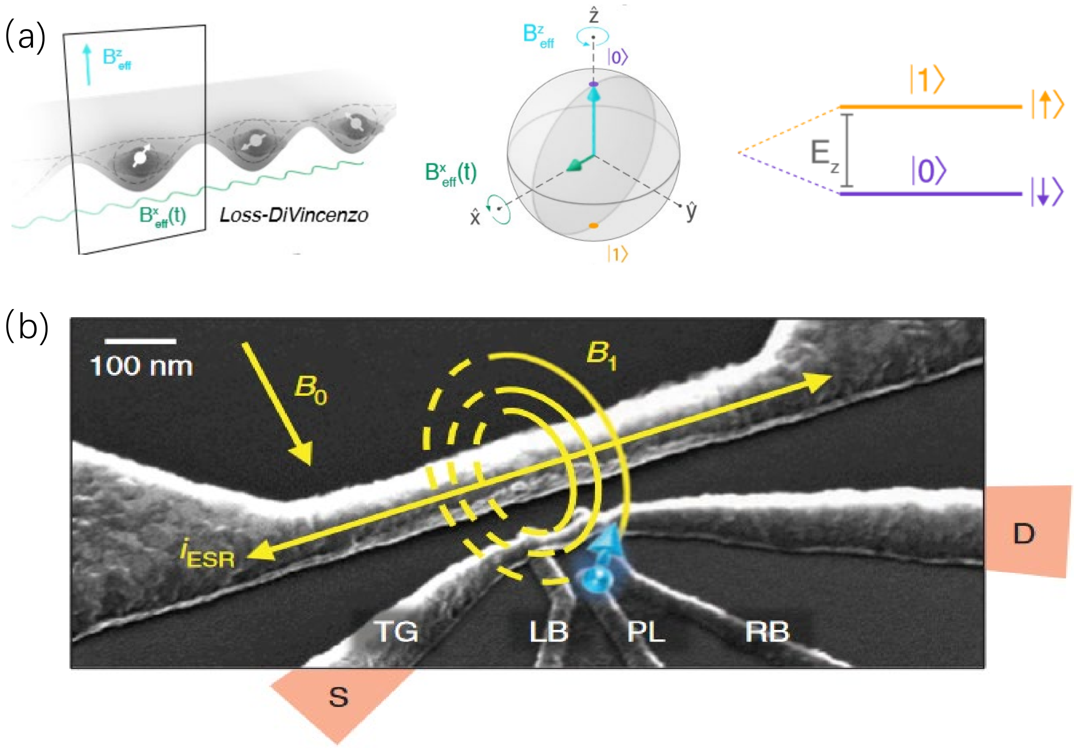

Figure 1. (a) Schematic of electron spin qubits based on gate-defined quantum dots, bloch sphere diagram, energy level diagrams. Reproduced with permission from Guido et al., Reviews of Modern Physics 95, 2 (2023). (b) Schematic diagram of a qubit based on a P donor atom. Reproduced with permission from Pla et al., Nature 489, 541 (2012). Copyright 2012 Springer.

The realization of qubits with low gate densities at low temperatures using P donor atoms in Si was first proposed by Kane [26]. P atoms have a nuclear spin that can interact with the electron spin, providing a suitable system for the formation of qubits. In the presence of a magnetic field, the spin state splits into $|0\rangle$ and $|1\rangle$. The energy difference between these two states defines the desired microwave frequency, i.e., the Larmor frequency. When the microwave frequency generated by the microwave line (shown in Fig. 1(b)) is equal to the Larmor frequency, the electron spin resonance condition is satisfied and the electron is able to absorb the energy of the microwave pulse, causing a shift in the spin state. Depending on the timing of the pulse, the electron spin can either flip from $|0\rangle$ to $|1\rangle$ or be in a superposition of these two states; by changing the phase of the microwave pulse, the phase of the superposition of the electron spin can be controlled.

Donor-based qubits have a large potential in realizing efficient quantum computing operations [27]. This system has a tight-binding potential that provides strong electron localization, which helps to maintain the quantum state of electrons and reduces the leakage of quantum information; the minimized gate density of the system reduces the complexity of the system and makes it more stable; in addition, the strong capacitive coupling enhances the interactions between qubits, and theoretically, it is possible to precisely control the exchange interactions between qubits by adjusting the capacitive coupling.

It is worth noting that a high level of nuclear spin coherence needs to be maintained due to considerations of coherence time and fidelity of single qubit gates [28]. Ideally, since background nuclear spins lead to decoherence, the donor atomic nuclear spins should be embedded in a host material consisting of isotopes with atomic nuclear spin quantum number $I=0$. None of the stable isotopes of common III-V semiconductors (e.g., GaAs) have $I=0$. While Si consists mainly of ^{28}Si and ^{30}Si with $I=0$, the remaining ^{29}Si with $I\neq 0$ can also be removed by isotopic enrichment[29]. Therefore, ^{28}Si is the ideal host material.

At the same time, however, precise control of the donor atom spacing to create a tunable exchange interaction between two electrons is difficult due to the difficulty of determining the atomic distances required to turn on and off the exchange interaction on the condition that a high-fidelity, spin-independent readout is achieved. Finding a balance between qubit placement accuracy and manipulation control is a technical challenge that remains to be solved [27].

2.2 Charge qubit

Charge qubits can be defined by coupling electrons in two adjacent semiconductor quantum dots. Its ground state corresponds to the electrons located on the left or right quantum dot and is labeled as $|L\rangle$ and $|R\rangle$. In the presence of inter-dot tunneling effects bonding and antibonding combinations can be formed and are labeled as $|0\rangle$ and $|1\rangle$, respectively. When the tunneling interactions between the two quantum dots are actually 0, the energy difference between $|L\rangle$ and $|R\rangle$ is defined as the detuning parameter ε. By analyzing the coherence time as a function of the detuning parameter ε, it can be found that the coherence of a qubit is maximal when the detuning parameter ε is 0, highlighting the importance of precise control of the energy level. Manipulating the detuning parameter ε, by adjusting the voltage on a specific gate and controlling the coupling of the inter-dot tunneling, can effectively manage the quantum state of the electron.

The readout of charge qubits began with a method of measuring the coherent oscillations of charge due to electron transport in a quantum dot system. Later, charge-sensitive devices were used to measure the charge occupancy of double quantum dots [30]. This method was able to demonstrate the functionality of fully charged qubits with biaxial control, which is important for realizing quantum logic operations.

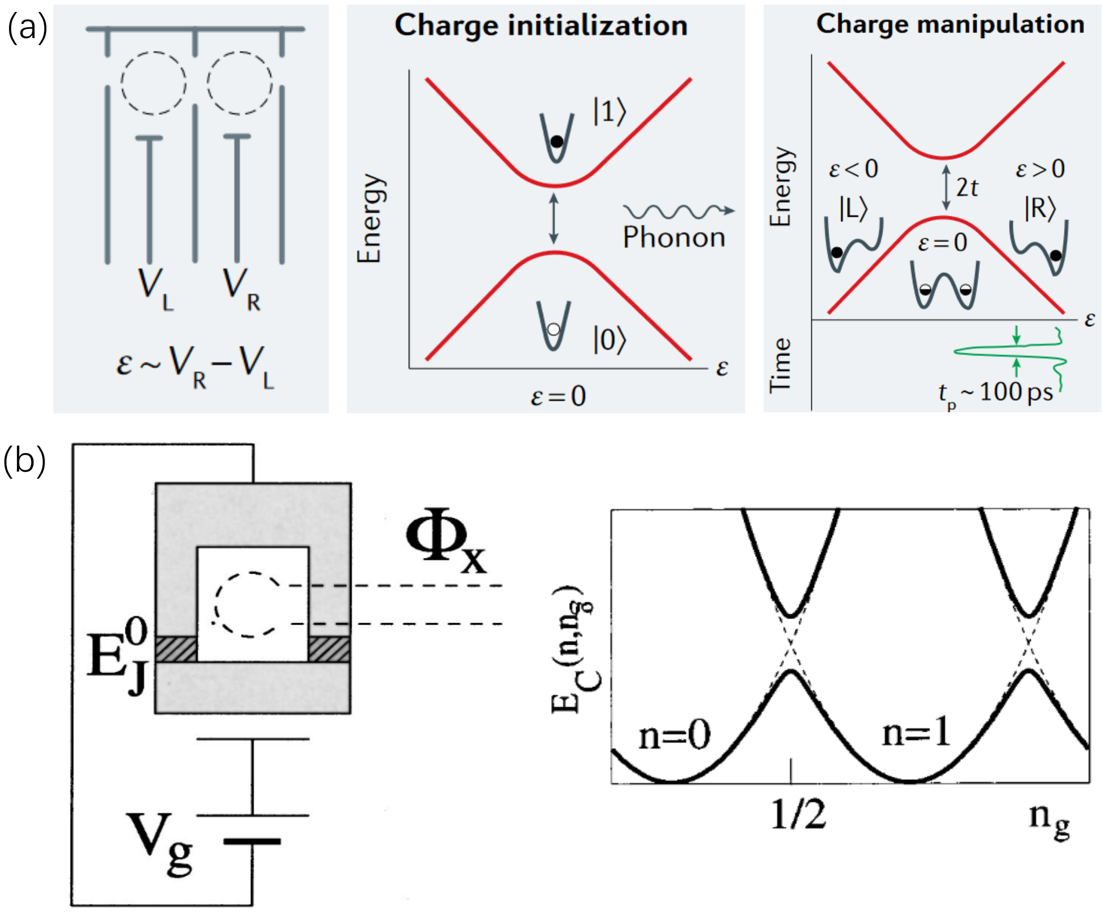

Figure 2. (a) Schematic of charge qubits based on gate-defined quantum dots, charge initialization process, charge manipulation process. Reproduced with permission from Anasua et al., Nature Reviews Physics 3, 3 (2021). Copyright 2021 Springer. (b) Schematic, energy level diagram of charge qubits based on superconducting Josephson junctions. Reproduced with permission from Yuriy et al., Reviews of Modern Physics 73, 2 (2001).

In a superconducting system, a charge qubit consists of a small superconducting island with multiple Cooper-pair charges that is connected to a superconducting electrode via a Josephson junction. In the superconducting state, the electrons on the island exist as Cooper pairs (paired states of two electrons attracted to each other by phonon exchange), forming a macroscopic quantum state. And it relies on the capacitively coupled gate voltage to apply short voltage pulses to control the state of charge on the island (i.e., the number of Cooper pairs) to manipulate the quantum state of the qubits [31].

The specific process of manipulation is as follows: At low temperatures, the system's macroscopic ground state is the charge state of the box with additional n electrons. All Cooper pairs condense into this macroscopic quantum ground state, which is separated from the excited states by a superconducting gap Δ. The superconducting gap Δ is larger than the single electron charging energy E_C, which restricts quasiparticle tunnelling; only Cooper pairs can tunnel coherently from one quantum dot to another within the superconducting junction. When the charging energy E_C exceeds both the Josephson energy E_J and the thermal energy $k_B T$, the system stabilizes in the lowest charge number states of $|0\rangle$ and $|1\rangle$, corresponding to the presence of zero or one Cooper pair in the box, respectively. By adjusting the gate voltage applied to the box, the relative energy between the two energy levels can be controlled, allowing for precise control of the qubit.

Readout of superconducting charge qubits can be accomplished by detecting tunnelling currents [32] or by monitoring changes in the charge environment.

2.3 Hybrid qubit

In charge qubits, the flip rate between states $|L\rangle$ and $|R\rangle$ is determined by the tunnel coupling between the two quantum dots, allowing for very fast flip rates on the order of picoseconds (ps). However, due to strong coupling with environmental noise, the coherence time of charge qubits is relatively short, generally on the order of nanoseconds (ns).

Electron spin qubits typically achieve longer coherence times, generally on the order of microseconds (μs), due to their weaker coupling with environmental noise. However, this also means that spin flips occur slowly, usually on the order of nanoseconds (ns), which significantly limits the operational speed of the qubits [24].

In recent years, many studies have adopted hybrid qubit encoding, combining the high manipulation speed of charge qubits with the long coherence times of spin qubits. As shown in Figure 3, by controlling both the charge and spin states of an electron within a double quantum dot, electrons can tunnel between quantum dots while their spin states are also regulated.

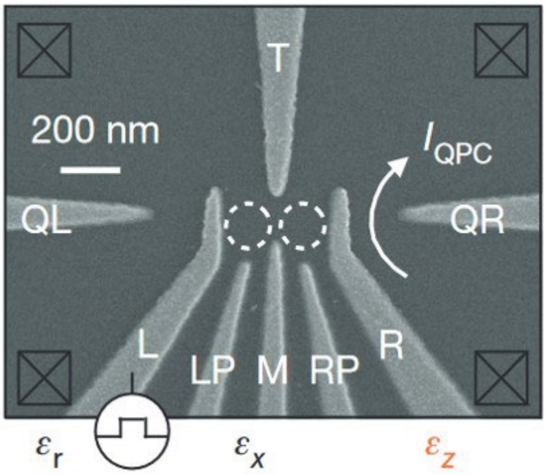

Figure 3. Hybrid qubit based on Si/SiGe heterostructured double quantum dots. Reproduced with permission from Dohun et al., Nature 511, 7507 (2014). Copyright 2014 Springer.

The specific operational process is as follows: In a semiconductor double quantum dot system, gate voltages are adjusted so that the left and right sides are occupied by two and one electrons, respectively, establishing a (2,1) charge configuration. By altering the voltage of the left gate, the detuning parameter ε is increased, prompting a charge state transition to (1,2) due to the principle of energy minimization [33]. Under adiabatic control, changing ε from a positive to a negative value results in the quantum state $|0\rangle \equiv |\downarrow\rangle|S\rangle$, where S is the singlet of the right quantum dot; and the quantum states $|1\rangle \equiv \frac{1}{\sqrt{3}}|\downarrow\rangle|T_0\rangle + \sqrt{\frac{2}{3}}|\uparrow\rangle|T_-\rangle$, T_0 and T_1 being two triplets of the right quantum dot. Unlike typical singlets and triplets, the presence of a third electron imparts charge-like characteristics, allowing for electrical rather than the usual magnetic control used for spin qubits. This facilitates extremely rapid quantum state transitions, evidenced by π rotations within 100 ps[17]. Furthermore, compared to the exchange-only qubit [34] that requires control over three quantum dots, this qubit architecture is simpler as it manages fewer particles and interactions, which aids in achieving faster gate operations critical for effective quantum computing [35].

3. Advancements and Evaluations of Electron-based Qubit Implementations

Theoretically, all the physical systems mentioned above are capable of implementing qubits [15]. However, in practice, certain criteria must be met (such as the DiVincenzo criteria [36]) to be considered for practical realization. In this chapter, we will review the experimental progress of electron spin qubits in different physical systems over recent years, evaluating aspects such as coherence time, fidelity, and scalability.

Fidelity and coherence time are two core metrics for evaluating the performance of qubits, measuring the accuracy of quantum operations and the duration over which quantum states maintain their coherence, respectively. The magnitude of fidelity is directly influenced by coherence time; a longer coherence time allows for the execution of more quantum operations without significant loss of fidelity. Therefore, in the design of quantum systems, it is common to optimize both fidelity and coherence time simultaneously.

Furthermore, for large-scale computation, the number of spin qubits required far exceeds that of current systems. A scalable physical system must be capable of increasing the number of qubits without degrading the quality of operations.

3.1 Electron spin qubit

Due to space constraints, this article primarily focuses on the progress of electron spin qubits based on semiconductor quantum dots. For developments in electron spin qubits in donor atom systems, please refer to references [37] and [38].

Table 1. Current state of art for spin qubit with dynamic decoupling

Ref.	Year	Material	Coherence time	Fidelity
[39]	2023	GaAs–AlGaAs QD	113μs	97.80%
[40]	2022	Si triple QD	720μs	99.99%
[41]	2021	GaAs/AlGaAs QD	10ns	\
[42]	2021	(Al, Ga)As QD	21.9 ± 1.6 ns	\
[43]	2020	GaAs QD	766.7ns	99.04%±0.23%
[44]	2019	Si QD	120μs	99.90%

Journal of Physics: Conference Series **2809** (2024) 012028 doi:10.1088/1742-6596/2809/1/012028

In the context of electron spin qubits, enhancing coherence time is crucial for quantum computing. Recently, several methods have been employed to mitigate factors causing decoherence. I. Due to interactions with a noisy environment, electron spins are susceptible to decoherence. Dynamic decoupling uses precisely timed pulse sequences to periodically flip the qubit's state, averaging out the effects of external noise fluctuations, such as nuclear spin noise, and significantly extending spin coherence time. Table 1 shows some recent results using dynamic decoupling to improve qubit performance. II. Sweet spot operation. Sweet spots are typically defined by external control parameters, such as magnetic field strength or gate voltage. At these points, the qubit's energy has a zero first derivative with respect to noise-induced parameters, minimizing the impact of small fluctuations. For gate-defined quantum dots, operating at sweet spots reduces sensitivity to charge noise. Reference [45] suggests coupling spin qubits to superconducting resonators, allowing qubit readout at sweet spots where operation aligns with high-fidelity quantum actions. Dynamic decoupling and sweet spot operations are often used together to optimize qubit decoherence properties and robustness. Reference [46] achieves high-fidelity two-qubit operations by adjusting gate voltages to control quantum dot coupling, while precisely tuning single and two-qubit gate parameters, such as frequency, amplitude, and phase, to maintain optimal operation points.

To achieve control over a large array of dots, researchers have considered more scalable architectures. One approach involves sharing gates within a quantum dot array for control [47], and using integrated local electrostatic meters to detect electrons in the array [48].

3.2 Charge qubit

Electron charge qubits have become a focal point in quantum computing research, attributed to their simplicity in design, manufacturing, control, and readout. However, these qubits, utilized within traditional semiconductor and superconducting frameworks, are prone to random telegraph noise (RTN) [49]. This exposure results in decoherence, limiting their coherence times to the microsecond (μs) range. An effective mitigation strategy involves operating these qubits at the "sweet spot." At this sweet spot, the energy difference between bonding and anti-bonding states is less sensitive to fluctuations in the electric field [30].

To enhance the coherence time of qubits, considerable attention has been focused on optimizing the dielectric environment surrounding the qubits. This approach primarily addresses the decoherence mechanisms arising from interactions between the qubits and their immediate physical environment. Reference [50] employs a three-quantum-dot system that allows a single electron to be distributed across three dots, providing additional degrees of freedom for tuning qubit properties. In the paper, the authors identify and utilize a third-order sweet spot to minimize the qubit's sensitivity to electric field variations, in theory extending coherence times significantly. Reference [51] explores a charge qubit based on an isolated single electron trapped on an ultra-clean solid neon surface in a vacuum, achieving a coherence time of 0.1 ms. Reference [52] examines a charge qubit in a single quantum dot within a suspended carbon nanotube, offering higher electrical tunability and sensitivity to electric and magnetic fields. This structure balances the simplicity of atomic qubits, coherence time, and tunability of qubits, providing significant advantages in specific types of nano quantum sensing. In addition to optimizing the dielectric environment of qubits, many studies employ techniques such as dynamic decoupling to prolong coherence times. Reference [49] discusses methods using echo signal techniques to mitigate noise effects, nearly quadrupling coherence times and enhancing the lifespan of entangled states. In a GaAs double quantum dot system, it is found that increasing the mutual capacitance between quantum dots significantly reduces the system's sensitivity to charge noise, thus enhancing the coherence time of charge qubits [53]. In superconducting charge qubits, selecting appropriate Josephson energies and temperatures can significantly improve and protect the quantum coherence of qubits [54]. Theoretically, establishing interactions between qubits and phonon baths in a double quantum dot system can substantially reduce environmental noise to maintain the coherence of qubits [55].

Additionally, advanced control strategies are utilized to enhance the fidelity of quantum gates. Through adiabatic shortcuts, charge qubits based on superconducting circuits can achieve faster and more reliable gate operations, while ensuring high gate fidelity and robustness [56]. Ultra-strong coupling between charge qubits and resonators by adjusting the electric dipole moments of the qubits has been demonstrated [53]. This facilitates more effective energy exchange and contributes to more robust quantum operations, thus potentially enhancing gate fidelity. A CNOT gate operation between two Si/SiGe double-dot charge qubits via capacitive coupling, performed at a clock speed of 13.5 GHz, has also demonstrated high robustness [57].

In terms of scalability, advances in CMOS technology have catalyzed key developments in the scalability of charge qubits, facilitating significant progress towards compact and efficient quantum computing systems. Scalability of a quantum computing system based on charge qubits has been verified by integrating quantum dots and their control circuits on a 22-nm FD-SOI CMOS platform, enabling the implementation of large-scale qubit arrays on a single chip [58]. CMOS technology has also been used to realise charge qubits that can be replicated at scale, to build quantum processors that operate at 4K [59].

3.3 Hybrid qubi

In hybrid qubits based on double quantum dots, the primary source of decoherence is environmental noise, which include magnetic noise caused by nuclear spins and charge noise due to electron traps and gate voltage fluctuations [60].

Numerous studies have integrated dynamic decoupling and other noise reduction techniques into hybrid qubit operations to further extend coherence times and improve gate fidelity. significantly enhanced qubit resilience to charge noise by adjusting the qubits to "pseudo-spin" states and tuning the operational points and internal parameters is proposed in [61]. Shaped microwave pulse envelopes to suppress rapid oscillations and leakage, enhanced gate fidelity, together with simulation results demonstrating that the fidelity of hybrid qubits can still exceed 99.99% under strong driving conditions are discussed in [62]. Building on simulation theory, it has been shown that hybrid qubits in silicon-based double quantum dots can use resonance modulation based on double-dot energy detuning to achieve gate fidelities greater than 93% for x-axis rotations and over 96% for z-axis rotations [63]. The use of strong microwave driving for rapid gate operations, while combining detuning parameters and tunnel coupling simultaneously, has made it possible to achieve a gate fidelity greater than 99.9% despite significant charge noise and phonon-mediated noise. Thus the coherence time of hybrid qubits has been extended to over 150 ns using Hahn echo and Carr-Purcell sequences [64]. In Si/SiGe hybrid qubits, single-qubit fidelities of approximately 95% have been measured [65]. Tuning singlet-triplet qubits to the "sweet spot" reduces limitations from charge and nuclear noise, thereby extending coherence times. Impact of noise in double quantum dot systems can also be minmized through adiabatic control, introducing dynamic sweet spots (DSS), enabling the sensitivity to charge noise to be dynamically minimized during qubit operation [66]. Implementing DSS under pulse sequences further enhances the fidelity of the Cz gate to nearly 99.9%, optimizing speed while ensuring fidelity. It has been shown in simulation that

Maintaining hybrid qubits at the sweet spot throughout the operation using DC pulse control and using exchange interactions the Cz gate fidelity can exceed 99.9% [67].

In addition to the methods mentioned above for reducing nuclear and charge noise impacts, some studies have improved qubit performance by altering system configurations. Reference [68] introduces an unconventional charge configuration within double quantum dots: composed of five electrons in (2,3) and (1,4) configurations. This setup benefits from the non-harmonicity of the quantum dots, where asymmetry in one dot introduces new anti-crossing functionalities with quasi-parallel energy levels, effectively reducing the qubit's sensitivity to charge noise and significantly extending the decoherence time of hybrid qubits to tens of ns.

In terms of scalability, semiconductor-based hybrid qubit architectures, which integrate a set of universal logic gates and rapid all-electric qubit operations, are suitable candidates for large-scale quantum information processing. Hybrid qubits compatible with CMOS processes, achieving a maximum logical qubit surface density of 2.6 million qubits/cm^2 are proposed in [69].

4. Conclusion

In this article, we explore various qubits implemented using different degrees of freedom of electrons, including their logical states and readout methods. High-fidelity initialization and readout techniques, rapid gate operations with extended coherence times, and scalability of quantum systems have been demonstrated. This fulfils many criteria required for quantum computing. Each type of qubit presents unique advantages and technical challenges: Semiconductor spin qubits offer strong potential for large-scale miniaturization but require precise fabrication techniques; superconducting charge qubits enable fast gate operations but are limited by their short coherence times due to high sensitivity to electromagnetic noise; hybrid qubits combine the benefits of different electronic degrees of freedom but also suffer from environmental noise interference. It is premature to determine which type of qubit is most suitable for quantum computing. In fact, the optimal approach may involve a combination and balance of multiple quantum systems.

Author Contributions

Zhuoqing Gao: conceptualization, writing up, review and editing. Boyang Ma: investigation, writing up, edit. Gehan Amaratunga and Xiaozhi Wang: supervised the research idea, review and editing, project administration.

References

[1] L. K. Grover, “A fast quantum mechanical algorithm for database search,” in *Proceedings of the twenty-eighth annual ACM symposium on Theory of computing - STOC ’96*, Philadelphia, Pennsylvania, United States: ACM Press, 1996, pp. 212–219. doi: 10.1145/237814.237866.
[2] “Quantum Simulators | Science.” Accessed: Mar. 30, 2024. [Online]. Available: https://www.science.org/doi/full/10.1126/science.1177838
[3] E. Farhi, J. Goldstone, and S. Gutmann, “A Quantum Approximate Optimization Algorithm.” arXiv, Nov. 14, 2014. Accessed: Mar. 30, 2024. [Online]. Available: http://arxiv.org/abs/1411.4028

[4] F. Jazaeri, A. Beckers, A. Tajalli, and J.-M. Sallese, "A Review on Quantum Computing: Qubits, Cryogenic Electronics and Cryogenic MOSFET Physics," in *2019 MIXDES - 26th International Conference "Mixed Design of Integrated Circuits and Systems,"* Rzeszów, Poland: IEEE, Jun. 2019, pp. 15–25. doi: 10.23919/MIXDES.2019.8787164.
[5] C. D. Bruzewicz, J. Chiaverini, R. McConnell, and J. M. Sage, "Trapped-Ion Quantum Computing: Progress and Challenges," *Applied Physics Reviews*, vol. 6, no. 2, p. 021314, Jun. 2019, doi: 10.1063/1.5088164.
[6] F. Flamini, N. Spagnolo, and F. Sciarrino, "Photonic quantum information processing: a review," *Rep Prog Phys*, vol. 82, no. 1, p. 016001, Jan. 2019, doi: 10.1088/1361-6633/aad5b2.
[7] L. M. K. Vandersypen and I. L. Chuang, "NMR Techniques for Quantum Control and Computation," *Rev Mod Phys*, vol. 76, no. 4, pp. 1037–1069, Jan. 2005, doi: 10.1103/RevModPhys.76.1037.
[8] D. Loss and D. P. DiVincenzo, "Quantum computation with quantum dots," *Phys. Rev. A*, vol. 57, no. 1, pp. 120–126, Jan. 1998, doi: 10.1103/PhysRevA.57.120.
[9] G. de Lange *et al.*, "Realization of microwave quantum circuits using hybrid superconducting-semiconducting nanowire Josephson elements," *Phys Rev Lett*, vol. 115, no. 12, p. 127002, Sep. 2015, doi: 10.1103/PhysRevLett.115.127002.
[10] T. Hayashi, T. Fujisawa, H.-D. Cheong, Y.-H. Jeong, and Y. Hirayama, "Coherent manipulation of electronic states in a double quantum dot," *Phys Rev Lett*, vol. 91, no. 22, p. 226804, Nov. 2003, doi: 10.1103/PhysRevLett.91.226804.
[11] J. R. Petta *et al.*, "Coherent Manipulation of Coupled Electron Spins in Semiconductor Quantum Dots," *Science*, vol. 309, no. 5744, pp. 2180–2184, Sep. 2005, doi: 10.1126/science.1116955.
[12] A. V. Kuhlmann *et al.*, "Charge noise and spin noise in a semiconductor quantum device," *Nat Phys*, vol. 9, no. 9, pp. 570–575, Sep. 2013, doi: 10.1038/nphys2688.
[13] Y. Wang, "Quantum Computation and Quantum Information," *Stat Sci*, vol. 27, no. 3, Aug. 2012, doi: 10.1214/11-STS378.
[14] M. H. Devoret, A. Wallraff, and J. M. Martinis, "Superconducting Qubits: A Short Review." arXiv, Nov. 06, 2004. Accessed: Jul. 14, 2023. [Online]. Available: http://arxiv.org/abs/cond-mat/0411174
[15] R.-B. Liu, W. Yao, and L. J. Sham, "Quantum computing by optical control of electron spins," *Advances in Physics*, vol. 59, no. 5, pp. 703–802, Sep. 2010, doi: 10.1080/00018732.2010.505452.
[16] A. Saraiva, W. H. Lim, C. H. Yang, C. C. Escott, A. Laucht, and A. S. Dzurak, "Materials for Silicon Quantum Dots and their Impact on Electron Spin Qubits," *Adv Funct Materials*, vol. 32, no. 3, p. 2105488, Jan. 2022, doi: 10.1002/adfm.202105488.
[17] D. Kim *et al.*, "Quantum control and process tomography of a semiconductor quantum dot hybrid qubit," *Nature*, vol. 511, no. 7507, pp. 70–74, Jul. 2014, doi: 10.1038/nature13407.
[18] S. Datta, *Quantum Transport: Atom to Transistor*. Cambridge: Cambridge University Press, 2005. doi: 10.1017/CBO9781139164313.
[19] R. D. Harris *et al.*, "Electronic Processes within Quantum Dot-Molecule Complexes," *Chem Rev*, vol. 116, no. 21, pp. 12865–12919, Nov. 2016, doi: 10.1021/acs.chemrev.6b00102.
[20] L. Kouwenhoven and C. Marcus, "Quantum dots," *Phys.World*, vol. 11 (6), no. 35, 1998.
[21] C. J. Gorter, "A possible explanation of the increase of the electrical resistance of thin metal films at low temperatures and small field strengths," *Physica*, vol. 17, no. 8, pp. 777–780, Aug. 1951, doi: 10.1016/0031-8914(51)90098-5.
[22] J. J. L. Morton, D. R. McCamey, M. A. Eriksson, and S. A. Lyon, "Embracing the quantum limit in silicon computing," *Nature*, vol. 479, no. 7373, pp. 345–353, Nov. 2011, doi: 10.1038/nature10681.

[23] M. Veldhorst *et al.*, “An addressable quantum dot qubit with fault-tolerant control-fidelity,” *Nature Nanotech*, vol. 9, no. 12, pp. 981–985, Dec. 2014, doi: 10.1038/nnano.2014.216.
[24] P. Yu and Z. M. Wang, Eds., *Quantum Dot Optoelectronic Devices*, vol. 27. in Lecture Notes in Nanoscale Science and Technology, vol. 27. Cham: Springer International Publishing, 2020. doi: 10.1007/978-3-030-35813-6.
[25] Tesi di Laurea Magistrale, “Definition of compact models for the simulation of spin qubits in semiconductor quantum dots,” POLITECNICO DI TORINO, 2022.
[26] B. E. Kane, “A silicon-based nuclear spin quantum computer,” *Nature*, vol. 393, no. 6681, pp. 133–137, May 1998, doi: 10.1038/30156.
[27] Y. He, S. K. Gorman, D. Keith, L. Kranz, J. G. Keizer, and M. Y. Simmons, “A two-qubit gate between phosphorus donor electrons in silicon,” *Nature*, vol. 571, no. 7765, pp. 371–375, Jul. 2019, doi: 10.1038/s41586-019-1381-2.
[28] G. Burkard, T. D. Ladd, A. Pan, J. M. Nichol, and J. R. Petta, “Semiconductor spin qubits,” *Rev. Mod. Phys.*, vol. 95, no. 2, p. 025003, Jun. 2023, doi: 10.1103/RevModPhys.95.025003.
[29] J. T. Muhonen *et al.*, “Storing quantum information for 30 seconds in a nanoelectronic device,” *Nat Nanotechnol*, vol. 9, no. 12, pp. 986–991, Dec. 2014, doi: 10.1038/nnano.2014.211.
[30] K. D. Petersson, J. R. Petta, H. Lu, and A. C. Gossard, “Quantum Coherence in a One-Electron Semiconductor Charge Qubit,” *Phys Rev Lett*, vol. 105, no. 24, p. 246804, Dec. 2010, doi: 10.1103/PhysRevLett.105.246804.
[31] Y. Makhlin, G. Schön, and A. Shnirman, “Quantum-state engineering with Josephson-junction devices,” *Rev Mod Phys*, vol. 73, no. 2, pp. 357–400, May 2001, doi: 10.1103/RevModPhys.73.357.
[32] Y. Nakamura, Yu. A. Pashkin, and J. S. Tsai, “Coherent control of macroscopic quantum states in a single-Cooper-pair box,” *Nature*, vol. 398, no. 6730, pp. 786–788, Apr. 1999, doi: 10.1038/19718.
[33] R. Turton and R. J. Turton, *The Quantum Dot: A Journey Into the Future of Microelectronics*. Oxford University Press, 1996.
[34] E. A. Laird, J. M. Taylor, D. P. DiVincenzo, C. M. Marcus, M. P. Hanson, and A. C. Gossard, “Coherent spin manipulation in an exchange-only qubit,” *Phys Rev B*, vol. 82, no. 7, p. 075403, Aug. 2010, doi: 10.1103/PhysRevB.82.075403.
[35] Z. Shi *et al.*, “Fast Hybrid Silicon Double-Quantum-Dot Qubit,” *Phys. Rev. Lett.*, vol. 108, no. 14, p. 140503, Apr. 2012, doi: 10.1103/PhysRevLett.108.140503.
[36] D. P. DiVincenzo and IBM, “The Physical Implementation of Quantum Computation,” *Fortschr. Phys.*, vol. 48, no. 9–11, pp. 771–783, Sep. 2000, doi: 10.1002/1521-3978(200009)48:9/11<771::AID-PROP771>3.0.CO;2-E.
[37] A. Morello, J. J. Pla, P. Bertet, and D. N. Jamieson, “Donor Spins in Silicon for Quantum Technologies,” *Adv Quantum Technol*, vol. 3, no. 11, p. 2000005, Nov. 2020, doi: 10.1002/qute.202000005.
[38] M. Usman, “Recent progress in atomistic modelling and simulations of donor spin qubits in silicon,” *Comp Mater Sci*, vol. 193, p. 110280, Jun. 2021, doi: 10.1016/j.commatsci.2021.110280.
[39] L. Zaporski *et al.*, “Ideal refocusing of an optically active spin qubit under strong hyperfine interactions,” *Nat Nanotechnol*, vol. 18, no. 3, pp. 257–263, Mar. 2023, doi: 10.1038/s41565-022-01282-2.
[40] B. Sun *et al.*, “Full-permutation dynamical decoupling in triple-quantum-dot spin qubits.” arXiv, Sep. 07, 2022. Accessed: Apr. 15, 2024. [Online]. Available: http://arxiv.org/abs/2208.11784
[41] P.-A. Mortemousque *et al.*, “Coherent control of individual electron spins in a two-dimensional quantum dot array,” *Nat. Nanotechnol.*, vol. 16, no. 3, pp. 296–301, Mar. 2021, doi: 10.1038/s41565-020-00816-w.

[42] P.-A. Mortemousque *et al.*, "Enhanced Spin Coherence while Displacing Electron in a Two-Dimensional Array of Quantum Dots," *PRX Quantum*, vol. 2, no. 3, p. 030331, Aug. 2021, doi: 10.1103/PRXQuantum.2.030331.
[43] T. Nakajima *et al.*, "Coherence of a Driven Electron Spin Qubit Actively Decoupled from Quasistatic Noise," *Phys Rev X*, vol. 10, no. 1, p. 011060, Mar. 2020, doi: 10.1103/PhysRevX.10.011060.
[44] Q. Yao, J. Zhang, X.-F. Yi, L. You, and W. Zhang, "Uniaxial Dynamical Decoupling for an Open Quantum System," *Phys Rev Lett*, vol. 122, no. 1, p. 010408, Jan. 2019, doi: 10.1103/PhysRevLett.122.010408.
[45] R. Ruskov and C. Tahan, "Quantum-limited measurement of spin qubits via curvature couplings to a cavity," *Phys Rev B*, vol. 99, no. 24, p. 245306, Jun. 2019, doi: 10.1103/PhysRevB.99.245306.
[46] J. Y. Huang *et al.*, "High-fidelity spin qubit operation and algorithmic initialization above 1 K," *Nature*, vol. 627, no. 8005, pp. 772–777, Mar. 2024, doi: 10.1038/s41586-024-07160-2.
[47] R. Li *et al.*, "A crossbar network for silicon quantum dot qubits," *Sci Adv*, vol. 4, no. 7, p. eaar3960, Jul. 2018, doi: 10.1126/sciadv.aar3960.
[48] M. Vinet *et al.*, "Towards scalable silicon quantum computing," in *2018 IEEE International Electron Devices Meeting (IEDM)*, San Francisco, CA: IEEE, Dec. 2018, p. 6.5.1-6.5.4. doi: 10.1109/IEDM.2018.8614675.
[49] A. Ayachi, W. Ben Chouikha, and S. Jaziri, "Sustained charge-echo entanglement in a two charge qubits under random telegraph noise," *Quantum Inf Process*, vol. 19, no. 9, p. 286, Sep. 2020, doi: 10.1007/s11128-020-02806-2.
[50] B. Kratochwil *et al.*, "Charge qubit in a triple quantum dot with tunable coherence," *Phys Rev Res*, vol. 3, no. 1, p. 013171, Feb. 2021, doi: 10.1103/PhysRevResearch.3.013171.
[51] X. Zhou *et al.*, "Electron charge qubits with 0.1 millisecond coherence time." arXiv, Feb. 19, 2023. Accessed: Feb. 28, 2024. [Online]. Available: http://arxiv.org/abs/2210.12337
[52] I. Khivrich and S. Ilani, "Atomic-like charge qubit in a carbon nanotube enabling electric and magnetic field nano-sensing," *Nat Commun*, vol. 11, no. 1, p. 2299, May 2020, doi: 10.1038/s41467-020-16001-5.
[53] P. Scarlino *et al.*, "*In situ* Tuning of the Electric-Dipole Strength of a Double-Dot Charge Qubit: Charge-Noise Protection and Ultrastrong Coupling," *Phys Rev X*, vol. 12, no. 3, p. 031004, Jul. 2022, doi: 10.1103/PhysRevX.12.031004.
[54] K. Berrada, S. Abdel-Khalek, and M. Algarni, "Coherence, purity and correlation for superconducting charge qubits," *Results Phys*, vol. 48, p. 106414, May 2023, doi: 10.1016/j.rinp.2023.106414.
[55] A. Purkayastha, G. Guarnieri, M. T. Mitchison, R. Filip, and J. Goold, "Tunable phonon-induced steady-state coherence in a double-quantum-dot charge qubit," *npj Quantum Inf*, vol. 6, no. 1, p. 27, Mar. 2020, doi: 10.1038/s41534-020-0256-6.
[56] Z.-Y. Zhao, R.-Y. Yan, and Z.-B. Feng, "Shortcut-based quantum gates on superconducting qubits in circuit QED*," *Chinese Physics B*, vol. 30, no. 8, p. 088501, Jul. 2021, doi: 10.1088/1674-1056/abea96.
[57] E. R. MacQuarrie *et al.*, "Progress toward a capacitively mediated CNOT between two charge qubits in Si/SiGe," *Npj Quantum Inform*, vol. 6, no. 1, p. 81, Sep. 2020, doi: 10.1038/s41534-020-00314-w.
[58] E. Blokhina, P. Giounanlis, A. Mitchell, D. R. Leipold, and R. B. Staszewski, "CMOS Position-Based Charge Qubits: Theoretical Analysis of Control and Entanglement," *Ieee Access*, vol. 8, pp. 4182–4197, 2020, doi: 10.1109/ACCESS.2019.2960684.

[59] R. B. Staszewski *et al.*, "Position-Based CMOS Charge Qubits for Scalable Quantum Processors at 4K," in *2020 IEEE International Symposium on Circuits and Systems (ISCAS)*, Seville, Spain: IEEE, Oct. 2020, pp. 1–5. doi: 10.1109/ISCAS45731.2020.9180789.
[60] E. Ferraro, M. Fanciulli, and M. De Michielis, "Coherence Time Analysis in Semiconducting Hybrid Qubit under Realistic Experimental Conditions," *Adv Quantum Technol*, vol. 1, no. 3, p. 1800040, Dec. 2018, doi: 10.1002/qute.201800040.
[61] B. Thorgrimsson *et al.*, "Extending the coherence of a quantum dot hybrid qubit," *Npj Quantum Inform*, vol. 3, no. 1, p. 32, Aug. 2017, doi: 10.1038/s41534-017-0034-2.
[62] Y.-C. Yang, S. N. Coppersmith, and M. Friesen, "Achieving high-fidelity single-qubit gates in a strongly driven silicon-quantum-dot hybrid qubit," *Phys Rev A*, vol. 95, no. 6, p. 062321, Jun. 2017, doi: 10.1103/PhysRevA.95.062321.
[63] D. Kim *et al.*, "High-fidelity resonant gating of a silicon-based quantum dot hybrid qubit," *Npj Quantum Inform*, vol. 1, no. 1, p. 15004, Oct. 2015, doi: 10.1038/npjqi.2015.4.
[64] Y.-C. Yang, S. N. Coppersmith, and M. Friesen, "High-fidelity single-qubit gates in a strongly driven quantum-dot hybrid qubit with 1 / f charge noise," *Phys Rev A*, vol. 100, no. 2, p. 022337, Aug. 2019, doi: 10.1103/PhysRevA.100.022337.
[65] W. Uddin, B. Khan, S. Dewan, and S. Das, "Silicon-based qubit technology: progress and future prospects," *B Mater Sci*, vol. 45, no. 1, p. 46, Mar. 2022, doi: 10.1007/s12034-021-02621-0.
[66] A. Frees, S. Mehl, J. K. Gamble, M. Friesen, and S. N. Coppersmith, "Adiabatic two-qubit gates in capacitively coupled quantum dot hybrid qubits," *Npj Quantum Inform*, vol. 5, no. 1, p. 73, Sep. 2019, doi: 10.1038/s41534-019-0190-7.
[67] Y.-C. Yang, S. N. Coppersmith, and M. Friesen, "High-fidelity entangling gates for quantum-dot hybrid qubits based on exchange interactions," *Phys Rev A*, vol. 101, no. 1, p. 012338, Jan. 2020, doi: 10.1103/PhysRevA.101.012338.
[68] G. Cao *et al.*, "Tunable Hybrid Qubit in a GaAs Double Quantum Dot," *Phys Rev Lett*, vol. 116, no. 8, p. 086801, Feb. 2016, doi: 10.1103/PhysRevLett.116.086801.
[69] D. Rotta, M. De Michielis, E. Ferraro, M. Fanciulli, and E. Prati, "Maximum density of quantum information in a scalable CMOS implementation of the hybrid qubit architecture," *Quantum Inf Process*, vol. 15, no. 6, pp. 2253–2274, Jun. 2016, doi: 10.1007/s11128-016-1282-3.